Optical spectroscopy: a vertical path for conceptual learning

Light sources and optical spectroscopy as a bridge between classical and modern physics through the interpretation of the nature of light, of the emission processes and of the structure of matter, recognizing the different roles of the components of a spectroscope and the energetic meaning of an optical spectrum: design and evaluation of research-based educational proposals.

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XXXI cycle
Sbagliando si impara.
Abstract

This content-oriented research focuses on the design of a vertical educational path (from primary pupils to university freshman students) on optical spectroscopy. The research is multi-pronged: it addresses various aspects, such as learning analytics, learning progression, conceptual change, research and development in the design of new experiments and apparatuses, in conjunction with the role that information and communication technologies (ICT) play in overcoming conceptual knots, laboratory work, active learning, and history of physics in contributing to the development of formal thinking. Teacher formation concerning the topic has also been considered and the Bring Your Own Device (BYOD) paradigm has been taken into account, giving as a byproduct of the research a proposal to integrate new opportunities of learning through multimedia tools.

The nature of Physics Education Research carried out has the goal of identifying research-based educational proposals on the topic of optical spectroscopy in a vertical perspective as a bridge from classical to modern physics. The theoretical framework is the Model of Educational Reconstruction (MER) and it is carried out with Design-Based Research (DBR) methods. Therefore, research activities make use of empirical research methods as well as conceptual understanding approaches and qualitative analysis in a multi-faceted way, in particular analyses of the roles of experimental work, the artifact approach, the historical approach, the problem solving in conceptual understanding and in an open perspective of research and development of instruments and methods as well as the role of specific rubrics and active learning methods. Context and sample for data collection are students attending the two last years of secondary school; freshman students in scientific degrees (biotechnology); in-service secondary school teachers; and informal learning environments with pupils. Research outcomes are multiple: design and development of original prototypes for optical spectroscopy experiments, design of classical experiments with an original setting for an experimental approach to the topic, identification of students' conceptual knots, coupled with modalities for overcoming them, as well as reasoning profiles, which represent trajectories in educational paths. Evidence-based educational paths in which historical methods, technological aspects, ICT and educational tools are integrated in a coherent way have been designed and experimented upon. The research involved about 560 secondary school students in 15 experimental settings and about 160 freshman students in 3 experimental settings. Cross-analysis by means of different methods in the different experimentations enabled the comparison of different approaches.

Activities have been conducted within PLS-IDIF06 (Progetto Lauree Scientifiche - Innovazione Didattica in Fisica e Orientamento) project at the University of Udine (IT) with the support of the Italian Ministry of Education.

Keywords

physics education research, optical spectroscopy, content-oriented research, design-based research, model of educational reconstruction
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Introduction

0.1 Physics in the educational process

Physics is centered on the study of nature and it cannot be conducted without establishing a connection with the object of study through activities supporting the conceptual construction and exemplifying the investigation procedures specific to the discipline. For this reason practical activities, operativity and laboratory have always deserved important attention from people involved in physics education: setting and role of such activities have been variously investigated and taken as a cornerstone for educational strategies.

Learning difficulties, identified by a vast literature (Pfundt and Duit, 1993; Duit, 2008) and in particular related to the lack of connection between daily experience and learning in physics, focused on cognitive and learning problems in a perspective of conceptual change (Vosniadou, 2008). It has been seen that the context plays a key role in the learning process. Knowledge is built actively by the learner through experience, as a personal interpretation of the world: meanings are produced by the interaction of the learner with the context and by the exchange with the other learners (Chin, 2006). Decisive aspects for learning in physics are: (a) the active role of the learner and the important function of the error, as already highlighted by Piaget (Kitchener, 1986) (the knowledge cannot be simply transmitted or conveyed ready from the teacher to the learner); (b) the personal involvement with the object of study; (c) the continuity between the personal conceptual schemes and those to be acquired (Jonassen, 1991). Moreover, literature on educational interventions highlights the important role of exploring ideas and reality, of applying hypotheses, of using and comparing argumentative interpretations and discourses (Chin, 2006).

An increasing difficulty in the construction of meaning has been also identified, since learning no longer takes place through direct experience, but through a complex and often chaotic symbolic mediation. Papert (Papert, 1993) revalued the role of concrete thought and of those non-abstract aspects of thought, that the dominant culture tends to neglect in favor of a presumed superiority of the formal and abstract thought, in order to use them as "cognitive mediators" to build interpretative models.

Individual operativity (both practical and conceptual) play thus a crucial role in all physics teaching activities, since the educational path is able to trigger and address an explicit progressive resonance between cognitive dynamics and disciplinary structures (Chiocciariello et al., 1995). Furthermore, the building of knowledge cannot be seen as a process confined inside the mind, but it has to be promoted within the culture and social interactions that accompany exploration of the learner (Caravita and Hallden, 1995): a closed school setting and the self-centering of the class have to be be overcome.

In (Rocard, 2007) the problems encountered in scientific disciplines teaching and learning, including thus also physics, has been analyzed identifying the critical aspects: scientific concepts are often taught too abstractly, without sufficient experimental, observational and interpretative background. As a result, students have a perception of science education as
Revision of contents and methods of scientific education is imposed by the socio-cultural and working complexity of the context in which we live, and it requires the promotion of a knowledge, not static and definitive, but in progressive and continuous evolution, without separating the product from the process in a close relationship with the multiple dimensions of knowledge, to be used as a map for learn to investigate problems and solve them creatively (Caravita and Halken, 1995). Literature on physics learning highlights the need for strategies promoting the conceptual change from common sense to a scientific vision of phenomena (Pfundt and Duit, 1993; Viennot, 1996). Failure in linking daily experience in scientific training has been identified as one of the main causes in learning difficulties in this field. Important components in the building of scientific knowledge are the experimental exploration and personal students’ involvement in the interpretation of phenomena, in particular as concern the construction of models (Gilbert and Boulter, 1998; Hestenes, 1987).

0.2 The role of optical spectroscopy in the physics curriculum

Despite modern physics is recognized as a fundamental part of all European scholastic curricula (see Par. 3.4) its treatment in school and university is even today more linked to a superficial review of the problems and the relative solutions, that is on the history of physics at the beginning of the XX century, rather than to a disciplinary approach that founds a culture linked to new theories with tools and methods typical of physics as a discipline. The interpretative problem concerning the link between classical modern physics in the history of physics is twofold: from one side there is the interpretation of the atomic structure of matter and from the other one there is the nature of radiation. A thematic area fertile in providing the experimental basis for the atomic structure of matter, for the nature of light and for the relative interactions is undoubtedly represented by spectroscopy, in particular the optical band, representing the link to set up a coherent framework able to describe involved processes. The Physics Education Research Unit (Unità di Ricerca in Didattica della Fisica - URDF) at the University of Udine aims at developing a vertical research-based educational path on the subject of optical spectroscopy for the construction of bridges between classical and modern physics, in which students are directly involved in experimental and interpretative studies founding its basis. Problems and challenges faced during history of physics are in fact often implicitly in educational settings in textbooks and in scholastic practice in different disciplines (physics, chemistry, biology, astronomy). Examples are: (a) interference and diffraction phenomena addressed only following a wave approach; (b) description of structure of matter using uniquely a Bohr-Sommerfeld model (orienting to a spatial representation of the atom) or the concept of orbital; (c) the reading and interpretation of spectra and (d) the functional role of the different components of a spectroscope. Historically, it played a crucial role in the study of radiation emission leading to the construction of the quantized atomic model, starting from Planck’s quantum hypothesis, up to Balmer’s empirical formula, whose interpretation is due to Bohr. Einstein’s photon hypothesis in order to interpret photoelectric effect paved the way in the study of quantized interaction between radiation and matter, while optical spectroscopy started to represent an interpretative referent and an investigation tool in semi-classical perspective.

Educational values of optical spectroscopy are present on different plans: epistemological, cultural, applicative and disciplinary. From an epistemological point of view, it is a validation modality of interpretative models through indirect measures and a way to
interpret a code in order to get information on the changes and on the states of a physical system; in particular it is an important example on how physics obtain information and build models on the microscopic world by means of interaction of radiation and energy transformation and conservation giving the formal quantitative validation contribution to ideas, with the possibility to extend the same approach to the whole electromagnetic spectrum. Thus optical spectroscopy provides a significant and emblematic methodology of how physics works with indirect energy-based measurements to derive information and validate models, representing therefore a methodological context in which the tools and methods of connection between experiment and theory in physics are prominent. It allows to gain experience about the specific way of investigation in physics, offering the possibility to address the problem of understanding the Nature of Science in operative terms. On a cultural plan, optical spectroscopy represents the experimental evidence of the atom existence as a microscopic structure, and it has an important applicative value in different fields: biomedical, astrophysical, conservation of cultural heritage and technological applications in general. On disciplinary plan its relevance regards the fact that absorption and emission of quantized electromagnetic radiation are fundamental concepts in physics representing some of the main investigative tools based on light-matter interaction. Optical spectroscopy, in particular, represents a context in which to understand the role of the energy in physics analysis, addressing the role of the energy conservation principle and inserting its treatment in the wider framework of optics.

In Physics Education Research literature this topic is mainly addressed to learning difficulties related to specific contexts. An organic path in which optical spectroscopy is integrated as curricular contribution on interpretative plan is a recognized necessity. The research described in this thesis aimed at building educational proposal in a vertical perspective; it is not a curricular research, but rather it addresses different aspects and perspectives: learning analytics, learning progression, conceptual change, research and development in the design of new experiments and apparatuses in conjunction with information and communication technologies (ICT) role in overcoming conceptual knots, laboratory work, active learning and history of physics in contributing to the development of formal thinking. Teacher formation concerning the topic has also been considered and the Bring Your Own Device (BYOD) paradigm has been taken into account to integrate new opportunities of learning through multimodal tools resulting in a proposal as a by-product of the research.

0.3 Physics Education Research

It’s been a long time since the prevailing mindset concerning the nature of teaching activities was accurately represented by an emblematic statement by Floyd K. Richtmyer appearing in the very first article in the premier issue of the American Journal of Physics (Richtmyer, 1933):

"Teaching, I say, is an art, and not a science."

The establishment of Physics Education Research (PER) as a legitimate structured subfield within physics research has rapidly progressed only recently, in particular in the last three decades (Beichner, 2009). The main goal of PER is to deepen the understanding of the cognitive and social progresses resulting in an effective learning, in order to use this acquired knowledge to redesign learning environments and materials, allowing students to learn more effectively (Sawyer, 2006). In the past, physics education researchers had a background in more traditional physics research areas, only nowadays it is becoming common practice for a researcher to be trained specifically in PER, so, an increasing number
of universities offer in their graduate or post-graduate programs PER as a research career. PER development was surprisingly fast and very different approaches arose. In order to describe the theoretical framework and the assumption at the basis of the research described here, a brief critical analysis on the main existing research approaches, situations and aspects influencing PER is required. This introduction does not pretend to be exhaustive, rather it aims at providing an overview concerning how the different facets of PER have been considered in carrying out the research described in this thesis; in particular, since the described research is multi-perspective, different main areas of PER played a role in structuring it. PER encompasses many different areas (Beichner, 2009). The research described in this thesis is transversal to many of them in the way it is described below:

- **Constructivism.** It relies on the idea that the knowledge could not be simply transmitted from the instructor to the learner (a typical behaviorism approach) but it has to be constructed by the learner itself (Piaget, 1973). In this perspective the naïve knowledge of the learner has a key role since that they do not represent an obstacle for learning, rather they are a starting point for building the knowledge and designing effective learning environments. In a constructivist perspective, the focus of the teaching-learning process is the activity of the student in building the knowledge, overcoming the model of the teacher as a dispenser of explicit information to unaware students. In (Ogborn, 1997) the fundamental aspects of constructivism are resumed, i.e. (a) science is made up of ideas created by human beings; (b) design of educational activities should give maximum priority to the construction of significant situation for students, using what they already know, and facing the difficulties of inferring consequences from their hypotheses; (c) students’ ideas are a starting point and not an obstacle, for this they deserve consideration; (d) students have to be actively involved in the educational activities. It is thus necessary to step from a teacher-centered to a learner-centered approach to teaching and learning. Crucial point of this paradigm shift are evidenced in Tab. 1. An employed educational strategy of the research, the Inquiry-Based Learning approach, is framed within a constructivist approach since students build themselves their knowledge starting from observation of phenomena and critically evaluate their previous knowledge to build a scientific

<table>
<thead>
<tr>
<th>Passive learning</th>
<th>Active learning</th>
</tr>
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<tbody>
<tr>
<td>The teacher is identified as the keeper and source of</td>
<td>Physical world is the source of the knowledge;</td>
</tr>
<tr>
<td>a consolidate knowledge.</td>
<td>teacher acts as a guide and the learning is built</td>
</tr>
<tr>
<td>Learners’ pre-existing conceptions are not taken into</td>
<td>by the learner itself.</td>
</tr>
<tr>
<td>account and remain unchanged.</td>
<td></td>
</tr>
<tr>
<td>Experimental results are shown as evidence; laboratorial experiences serve to confirm theories.</td>
<td>Experimental results are observed and interpreted; laboratorial experiences are used to build concepts and a physics way of thinking.</td>
</tr>
</tbody>
</table>
view of the topic. According to a constructivist point of view, exploration of students' spontaneous ideas, regesian interviews and peer discussions as well as critical analyses after exploration of phenomena and artifacts characterized the educational interventions carried out in order to collect data using tutorial worksheets guiding students' reasonings and, at the same time, to elicit critical issues (Chap. 6, 7, 8);

- **Cognitive science.** When, during the nineties, concepts as "representation", "expertise" and "problem solving" became central in the study of educational research cognitive science began to have a central role. In cognitive science, learning understood as "deep understanding" refers to the richness of conceptual representation, to its pertinence to the specific topic, and to the number of connections among the different concepts (Grotzer, 1999). Deep understanding then means that learned concepts are relevant, numerous and well connected, i.e. connected in a logical and meaningful way. Research in the field of cognitive science established that deep knowledge of a topic implies the ability to recall it without the need of memoryizing it (Zirbel, 2004), what constitutes an important aspect of effective learning. Cognitive aspects, even if not central in the described work, have been taken into account when analyzing students' mental models and reasoning concerning the micro-interpretation and modelling of phenomena, focusing on the internal coherence of the built knowledge;

- **Educational technology.** It was introduced in the seventies with the development of specifically-designed software for education. In the following decades, as computers became part of our lives, the use of educational technologies was widely promoted in learning environments. Several attempts were made in order to integrate Information and Communication Technologies (ICTs) in PER with the aim of evaluating the effectiveness of those tools in learning physics providing students with a connection between the real world and abstract representations of that reality. Thornton and Sokoloff (Thornton and Sokoloff, 1990) developed one of the earliest position sensors based on ultrasonic sound detection; video-based labs (VBL) were developed, among the others, by Beichner (Beichner et al., 1988). Student response systems, or "clickers", have proven (Caldwell, 2007) to be effective in the traditional lecture setting and are becoming popular as a "low-cost, low-effort" means of implementing PER. Additional work on simulations, like that of Steinberg, (Steinberg, 2000) Dancy, (Dancy and Beichner, 2006) as well as studies of web-based assessment systems like that of Bonham (Bonham et al., 2000) shows that instructional technology is still a fruitful area of investigation. A wide spectrum of interactive simulation developed form educational purposes by University of Colorado are available on a web-platform 1. Several researches (Cuban, 2001; Sawyer, 2006) showed that the highly instructionist adopted approaches resulted in poor students’ performances since the years 2000. For this reason in the last decade, different research-based softwares were developed in order to use computers and simulations as cognitive facilitators helping students in the processes of critical construction of knowledge. In the research work described here, this dimension is taken into consideration implementing data acquisition systems connected to the elaborator to graphically represent in real-time a digitalized spectrum or a diffraction pattern in order to interpret phenomena, give meaning to the involved physical quantities and phenomenologically obtain the physical laws;

- **Socio-cultural studies.** These aspects take into account the fact that the process of learning could not be understood as a mental process occurring in the mind of a single

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1https://phet.colorado.edu/en/simulations/category/new
learner, but rather all intelligent behaviors are realized in complex environments characterized by the presence of several objects, phenomena and individuals (Greeno, 2006; Salomon, 1993). Some of the main researches in this field are linked to the investigation of the learning in informal contexts (Cole, 1996; Saxe, 1991) and became the basis for the study of peer cooperation, collaborative discourse and project teams (Sawyer, 2006). The research with pupils (see Chap. 8) inevitably regard this aspect since the research environment was an informal one in which discussion occurs in group;

- **Disciplinary knowledge study.** The needs of addressing specific learning problems require to take into account the nature of the content in which the learning knot is. From this point of view, the analysis of the context and the learning environment is not enough: the majority of the learning knots have to be studied as particular cases that are tightly related to the content. The central core of the design of the research regards this aspect in particular: the Model of Educational Reconstruction (see Sect. 1.1.2) requires a deep analysis of the founding cores of the topic together with a study of the disciplinary learning knot on the topic. The analysis of the structure of the contents and the clarification of the contents themselves in order to identify the conceptual elements and hierarchies, the epistemic bases and the disciplinary character is a preliminary and indispensable study for every research, in particular this one, which preludes to the identification of the educational significance of the contents, of the elementary elements that underpin the educational goals, without taking into account the approach.

- **Conceptual understanding.** Most of the work in PER has been looking at what students know and how they learn. The very first researches looked for students' "misconceptions", "naïve interpretations", "difficulties" or "intuitive understanding". This work formed the basis of most early PER as content was systematically scanned topic by topic and student difficulties were uncovered and analyzed in an attempt to produce a sort of "zoology" of the emerged evidences. Most recent studies rather focus on how students' ideas are modified as they learn, giving birth to the area of physics conceptual development and change (Brown and Hammer, 2008; Dykstra et al., 1992; Clement, 1982; Posner et al., 1982). The research described here aims at producing evidences on students' reasoning when faced with an interpretative challenge, rather than produce a list of difficulties of misconceptions, that are, anyhow, taken into account both when founding the research, studying the known-in-literature learning problems, and in the emerging results from students' responses (see Sect. 1.1.2);

- **Problem solving.** The underlying mental processes and strategies relevant to attacking physical problems have been of great interest to PER (Maloney, 1993). Recent work is trying to evaluate the cognitive processes underlying the solving of difficult problems (Heller and Hollabaugh, 1992; Heller et al., 1992). An attempt to take into account this dimension has been made developing a series of conceptual exercises that elicit the most common wrong interpretation of discrete optical spectra;

- **Evaluation of specific instructional interventions.** Several researches reported the educational impact of different approaches. At University of Washington, specific instruments named Tutorials in Introductory Physics (McDermott and Shaffer, 2002) allow thousand of students and pre-service teachers to learn physics. Saul (Saul,
made a comparison of some modern research-based curricular approaches. Interactive lecture demonstrations (ILD) have been evaluated by Sokoloff and Thornton (Sokoloff and Thornton, 1997). As noted previously, cooperative group problem solving was studied (Heller and Hollabaugh, 1992; Heller et al., 1992) at the University of Minnesota as well as research on students response systems (i.e. clickers). Approaches used in this research encompasses both interactive lecture demonstrations, laboratorial sessions both guided by worksheets understand as "tutorials" guiding students' reasoning;

- **Instructional materials.** Research-based instructional materials have become more and more used as their efficacy was shown: Physics by Inquiry (McDermott et al., 1996) led the way in this area, and **Tutorials in Introductory Physics** (McDermott and Shaffer, 2002) provided the standard for obtaining feedback between research and curriculum development. Among the earliest, coherent physics textbooks incorporating PER findings were written by Serway and Beichner. (Serway et al., 2000) and Knight (Knight, 2017). Real-Time Physics (Sokoloff et al., 2011) works to incorporate PER into a more traditional laboratory setting. E.F. Redish took one of the most popular textbooks (Halliday, Resnick and Walker) (Halliday et al., 2014), updating it with the latest applications of PER. The **Tasks Inspired by Physics Education Research (TIPERs)** project (Hieggelke et al., 2011) produced a wide spectrum of activities proven to be effective in the classroom. The task is nowadays faced with the development of Investigative Science Learning Environment (ISLE) materials. Instructional materials that are a byproduct of this research, and that can be used in scholastic practice, are represented by the set-up experiments, tutorial worksheets guiding the instruction, pre- and post-tests to evaluate the effectiveness of the approach, new experimental devices (see Chap. 4) as well as educational paths differentiated by schooling levels and adopted approach.

Particularly in its first stages, data were reported using qualitative and/or anecdotal styles; more recently commonly accepted assessment instruments has been developed and their use grew in order to quantitatively measure observables like conceptual understanding, scientific reasoning and students' attitudes just to name some. These instruments, as for example the Force Concept Inventory, or the Classroom Learning Attitudes about Science Survey, allow researchers to compare learning and teaching techniques for different samples of students, in different context and learning environments.

### 0.4 The role of content-oriented research in physics education

The need to strengthen the weight of scientific disciplines, physics in particular, in the formative process to create in all future citizens a cultural base which overcomes the scientific illiteracy was recently denounced by the PISA survey and considered by all European countries as one of the most urgent challenges to be faced (Euler, 2003). Cultural and educational potentialities of physics must be recognized in the curriculum as indispensable values, overcoming the vision attributing to this area of knowledge a subordinate role to other ones (for example, preparatory to technology, with tasks related only to practical

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2<http://www2.physics.umd.edu/~redish/Book/>

3<https://www.islephysics.net/>

4To get an overview of the most commonly used instruments search<https://www.compadre.org/per/> and <https://www.physport.org/>.
knowledge). In the same way, teaching physics should not be reduced to the presentation of results, answers to not-well posed or defined questions and lists of formulas whose meanings, powerfulness and limits are not mastered.

The transmission of basic general information in the most concise and structured possible form, as well as the showing of results rather than the analysis of the processes, results in experience physics as a discipline speaking of nonexistent things (the material point, or the ideal gas, just to mention a few) through difficult laws, which students does not know when to use. Hardly, the formalization process has been given a great attention or made explicit. Approximations and simplifications are declared, often not motivated, almost never chosen or justified by the students themselves. In this way, the beauty, the usefulness and the vast use of physics, understand as a discipline, rarely emerge (Michelini, 2007). Regarding this aspect, someone argued that physics could not be taught before having built a solid mathematical competence; this point of view led to read physics as a formal discipline, neglecting to build that conceptual bridge upon which its interpretative capacity is based. This is at the basis of the dichotomy between a vision of the world based upon common sense, from one side, and based upon a scientific point of view, from the other, which a vast literature concerning learning problems identified as conceptual knots (Duit, 2008).

PER can help in designing effective teaching strategies and environments, but the poor impact on educational practice is due to the lack of attention paid to the disciplinary contents. Theories on learning, teaching, curricular development or concerning the organization of the class were almost useless when uncorrelated to the specific topic, since they do not provide useful guidelines to the teacher (Lijnse, 2000). The research physics education described in this thesis is linked to the construction of skills to produce specific disciplinary learning (see Sect. 1.1.1).

0.5 Vertical perspective

A retraining of school in terms of student-build learning demands a spreading of constructivist principles among the ordinary educational practice (Bottani, 2002); in particular the need to put into effect laboratorial practice emerges, as a context for teaching-learning processes centered on problematization, hypothesis and errors, in other words, on the active role of students in building knowledge (Fiorentini, 2008).

Unfortunately laboratorial practice is marginal in schools, and among the causes of this lack, there is the missing of the implementation of the so called "vertical curriculum" (Fiorentini, 2008), understood as a re-thinking in unitary perspective of the disciplinary knowledge proposed to different schooling levels. An essential aspect of the building of a vertical curriculum is the individuation of the essential knowledge typical of every age, putting students' reasoning at the center of the process of knowledge building, allowing a quality instruction for different schooling grades (Fiorentini, 2008). Education in vertical perspective faces the problem of the discontinuity between different grades of schooling, both guiding students in gradually gaining the knowledge and in contributing to reduce the dropout and reinforcing the interest toward scientific disciplines. In a vertical perspective for designing an educational path, laboratorial activity based on an in-context learning is different from the traditional teaching, often de-contextualized, and so not suitable for students (see Par. 0.1). In a vertical-perspective design of a teaching/learning path, laboratorial activities based on in-context learning is sharply distinguished from traditional scientific teaching, which often takes into account de-contextualized situations, intelligible only to adult minds and so, as a consequence, not suitable for the younger students, that often acquire them mechanically (Rocard, 2007).
The vertical perspective in this thesis is used to design a teaching-learning path on optical spectroscopy in which intellectual challenges are offered to students of different grades, avoiding reductionism, activating and stimulating the concepts re-organizational process in order to learn.

0.6 Conceptual learning

It is crucial to distinguish between "physics concepts for school" and "physics cognitive conceptions": the former represent scientific community currently accepted ideas, selected for the physics curriculum, the latter are the research-detected mental models students elaborate (Gilbert et al., 1998a,b). Having understood a concept means essentially to hold a mental model of it after instruction. Mental models are interior representations, by which students try to make personal sense of the physical world, by explaining and predicting phenomena. They supply information on the structure of physical systems and on their behaviour in students' language, by means of analogies (Greca and Moreira, 2002). Learning process may be associated to a sequence of different successively developed conceptions, with the scientific concept to be learnt being the arrival point (Niedderer et al., 2007). Learning is characterized by a change in both mental processes and knowledge structures.

Human mind can manipulate and combine simple concepts in order to achieve deductions and represent complex ideas (Carey, 2000). Concepts, as the nodes in a network, allow to build more sophisticated ideas or abstract representations in the form of images or models. Learning is a mental process involving perception and awareness of how stimuli and new ideas are integrated in the framework of the previous knowledge (Kitchener, 1986). Through reasoning, the whole knowledge is re-arranged with renovation of pre-existing structures and the creation of new of them: adding new information is only a part of the process of learning, since the whole action, known as "accommodation", (Kitchener, 1986) involves re-organization, integration and creation of new knowledge. In cognitive sciences, learning in the form of "deep understanding" usually refers to the richness of the conceptual representation, to its relevancy with the specific topic and to the numerosity of the link with different concepts in a logic and significant way (Grotzer, 1999). Deep knowledge of a topic implies the ability to remember it without need of memorizing (Zirbel, 2004), a distinctive feature of the effective learning. Quite often students are unable to face problems or new situations, due to a lack of conceptual learning: this aspect is at the basis of the ability of using physical ideas in order to interpret everyday situations, and this should be part of the cultural baggage of every citizen. If the goal is that students reach a deep and persistent comprehension, they have to be supported in coherently integrating new knowledge in the structure of the existing one, and this requires the renunciation to the traditional role of the teacher who should be a facilitator of the process of gradual building knowledge rather than the source of the knowledge itself. From this point of view, the role of the teacher is to support reasoning of the students, and not to perform them: this implies an enhanced responsibility from the teacher who has to provide a coherent design of the various steps of the educational path, avoiding discontinuities and the usage of not previously addressed concepts.

Within this setting, in this thesis the choice of phenomenological contexts, adequate to the designed building and re-organization of the concepts as well as the structuring of the worksheets accompanying students in their learning path, providing significant stimuli to face the interpretative challenges. No hypotheses are formulated concerning students' mind behaviour, rather the found knowledge has a local value (Niedderer et al., 2007).
this research, students' conceptions are explored in this framework in order to find their ways of reasoning. Conceptual learning played a crucial role in the thesis in the case of the hydrogen atom: since it is generally used to justify discrete spectra using Bohr's model, the problem that has been faced regards the generalization of the conceptual link between discrete emission spectra and quantized energy in matter, also for those atoms that cannot be described through the Bohr's model.

0.7 Research setting

The research approach adopted in this thesis is of the content-oriented type, since the focus is put upon the physics contents and the way they are addressed. With respect to a student-oriented approach it is closer to a scientific approach, since it aims at analyzing the effectiveness of an educational intervention in the measure it allows students in appropriating of the right scientific concepts and models (see Sect. 1.1.1). There is however, the need to strongly relate the building of the physical concepts and their whole organization with the conceptual reconstruction, which is an internal process typical of the single student. In a student-oriented approach, the focus is put on the specific way of reasoning and on individual profiles of development of ideas in the context of a common educational activity to promote alternative stimuli to face every conceptual aspect. The restoring of the knowledge network of the single student is monitored such as the learning outcomes can be identified as elements linked to differentiated educational paths.

The physical contents taken into account address the phenomenologies of light-matter interactions and in particular light emission from matter, related to the interpretation of optical spectra: the study has been driven by the open research problem of how students interpret the conceptual link between discrete spectral emission and the quantized energy structure in atoms. Even if the research has a strong "content-oriented" setting, it has also a "student-oriented" nature since the focus is often set on students' learning difficulties faced with the aim of conceptual change from spontaneous ideas towards a scientific vision of the topic.

The design of an educational activity starts with the clarification of the disciplinary contents, in parallel with a study of the historical development of ideas, of the founding cores of the topic and of the significant phenomenological aspects. In the thesis problem arising from educational practice are in addition faced on additional plans: analyses of textbooks and existing educational proposals on the topic of optical spectroscopy are carried out, taking into account students' conceptual knots (i.e. their learning obstacles and difficulties) according to a PER literature review, that anticipates the stage of inquiry on students' ideas and interpretative reasoning of the phenomenology under study. The goal is to analyze the educational significance of the topic in order to reach an "educational reconstruction" of the topics used for the design and implementation of an educational path, used to monitor students' learning processes.

The research approach requires that the first step is to re-think scientific content as a problematic issue, to re-build this in an educational perspective, according to the employed theoretical framework, i.e. the Model of Educational Reconstruction (MER, see Sect. 1.1.2) used also as a model for educational innovation. The structuring of a teaching/learning path in vertical perspective expects the design of conceptual micro-steps in which strategies of active learning produce the overcoming of the conceptual knots and the appropriation of the disciplinary founding elements. Vertical educational paths are designed, understand as "learning corridors" for allowing individual learning trajectories and step-by-step appropriation of concepts modalities. The exploration of the spontaneous interpretative models
is thus an important phase of the process of structuring the rationale of the educational proposals.

Analysis of students’ learning difficulties and the design of an educational path take place in a Design-Based Research (DBR, see Sect. 1.1.3) context, in which the conceptual modules are designed, experimented, evaluated and cyclically re-elaborated in order to give an evolutive and flexible trait to the research, including interventions in different formal and informal contexts differentiated by schooling level and characterized by the evolution of supporting and evaluation materials. Production of such materials, as well as proposals for T/L paths and devices for laboratory activities, tightly linked to the work of conceptual exploration, has been modified according to the analysis of the outcome of every intervention. This is realized in the form of an empirical research, in an action-research environment in a collaborative dialectic between schools and researchers, in order to contribute to classroom practice. A byproduct of this work is the development of teaching/learning (T/L) sequences proposals for contributing to educational practice as well as monitoring instruments for learning outcomes and original experiments and devices (see Chap. 4).

DBR methodologies have been recently embedded in the MER framework, establishing the standard reference for the design of innovative educational intervention: think back to the problems concerning scientific contents in terms of disciplinary foundation and re-build them in educational perspective is the core of this educational research.

Approaches are not purely based upon disciplinary contents in order to identify strategies for conceptual change (see Sect. 1.2.1): attention is paid on identifying strategic angles, on critical details used by common knowledge to interpret phenomena, on studying spontaneous reasoning paths and on finding new approaches to physics knowledge, avoiding reductionism and offering opportunities of learning interpretative solutions and results, becoming able to manage physical concepts and building competences of instruments and methods typical of physics understood as a discipline.

Every module is faced with a methodology typical of the Inquiry-Based Learning (IBL, see Sect. 1.2.2) strategies, in which the problematization occurs through experimental activities during which students are asked to identify peculiar characteristics of the phenomena and the way they are first described and then interpreted, overcoming the limits of the traditional educational setting.

The whole research activity can be summarized in Fig. 1. The flux of the various stages was designed according to DBR methods producing the following structure for the thesis:

0.8 Thesis structure

This thesis reports the work, carried out within Physics Education Research Unit (PERU) at University of Udine (IT), of investigation of primary pupils, secondary and university student understanding of optical spectra, the work was carried out in order to answer to general and specific research questions for different schooling levels (addressing the emerged conceptual and reasoning difficulties) and the applicability of the proposals analyzing secondary school teachers educational projects.

The previous described setting determined the organization of the thesis in chapters. In chapter 1 the different methods employed in the research are critically described: from the methods employed for the research itself (Par. 1.1) to the strategies used in the educational experimentations (Par. 1.2), ending with the description of the motivation setting the focus of the research alongside with the general research questions (Par. 1.3).

In chapter 2, historical aspects related to spectra interpretation, functional to educa-
Figure 1: *The research flux scheme of the activities. In the central part the evaluation cycles of each conceptual micro-step is depicted. Each micro-step represent a conceptual aspect, linked to other ones, that is iteratively designed, experimented, evaluated and revised according to a DBR approach.*

Additional reconstruction as well as models for explaining spectra in modern physics are addressed and discussed. Basic issues regarding the addressed educational reconstruction of the disciplinary contents i.e. both the founding cores and the epistemological aspects are outlined.

In chapter 3 a review of research literature concerning learning knots (Par. 3.1), previous educational researches and evaluation instruments on students’s spectra interpretations (Par. 3.2) existing educational proposals (Par. 3.3) are presented and discussed. Moreover, since optical spectroscopy plays a crucial role in teaching modern physics in schools, an analysis of the current state of instruments, contexts and methods concerning the teaching of modern physics is critically performed (Par. 3.4 and 3.5).

Chapter 4 describes an innovative prototype for a digital spectrometer developed for educational purposes and implemented in the last experimentations.

The educational path on optical spectroscopy is described in chapter 5: it is centered on the disciplinary addressed contents. In particular, the rationale (i.e. the conceptual structure) of the path is outlined as well as the structuring of the various experimentations as well as the design, evaluation and revision phases of the monitoring instruments.

Chapters from 6 to 8 address the various phases of the educational interventions carried out during the research with students and teachers differentiated by schooling level, answering the specific research questions, taking into account the addressed aspects and justifying the modifications in the different experimentations, of the strategies and of the monitoring instruments in a DBR approach.

In chapter 9 an activity carried out with in-service secondary school teachers allowed to analyze the transferability of the developed educational proposals in terms of educational paths designed by teachers.

In the last chapter results of the research are resumed.
Chapter 1

Theoretical framework of the research

1.1 Research methodologies

Starting from the description of the nature of the research itself, i.e. the meaning of a "content-oriented" research (Sect. 1.1.1), the theoretical framework of the MER is described (Sect. 1.1.2) as well as the main features of a DBR approach (Sect. 1.1.3). Data analysis methods employed are outlined in Sect. 1.1.4. The specific implementations of those methods are addressed in Sect. 1.1.5.

1.1.1 Content-oriented research

Researches in physics education can be framed according to two big paradigms in the European tradition (Duit, 2006):

- **Content-oriented**, linked to the specific scientific domain, in order to design T/L sequences;
- **Student-oriented**, focused on students' problems in order to point out approaches for conceptual change (Schnotz et al., 1998; Vosniadou, 2008)

In the following, the two approaches are briefly described and compared, in order support the choices followed in the work described in this thesis, in order to build a content-oriented research.

Research in physics education has two main objectives (Andersson and Wallin, 2006): design and test "useful products and good practices" to be put in action (i.e. teachers guides and study materials for students) and contribute to the development of educational science (i.e. analyze and understand conditions for the learning of a given topic). The former is close to a "student-oriented" research approach, the latter is close to a "content-oriented" research approach.

As concern student-oriented researches, PER often derives theoretical inspirations from outside its own field, for example psychology and epistemology, belonging to the long-established pedagogical guidelines. One example is represented by the educational relevance of constructivism, summarized in the form of four main ideas (Ogborn, 1997):

- The importance of students' active involvement in thinking if anything like understanding is to be reached;
- The importance of respect for students and for their own ideas;
• The concept that science consists of ideas created by human beings;

• The idea that the design of teaching should give high priority to making sense to students, capitalizing on and using what they know and addressing difficulties that may arise from how they imagine things to be.

Another example takes into account socio-cultural aspects: the paradigm of this approach deals with providing a number of practical recommendations for teaching (Lemke, 1990):

"Teachers should use Q&A dialogue less than they do now and organize more class time for students questions, individual and group reports, true dialogue, cross-discussions and small group work. Students should do more science writing during class, always following oral discussion of topics."

The aforementioned general recommendations and guidelines can contribute in providing a productive direction to improving educational practice, but the turn out to be useless when it comes to design the teaching of a given topic in detail. The answers to the research questions addressed in the research described in this thesis must be found in combination with content-specific research: the results cannot be deduced from a general approach, but they have to be generated (and they will differ) topic by topic. According to (Lijnse, 2000) this approach is not particularly common in science education research:

"What seems to be apparent from the literature is that science education research does not aim to develop content-specific didactical knowledge but to contribute to (if only by simply applying) general educational and/or psychological theories. I consider this flight away from content detrimental, because thereby a level is skipped that I consider necessary for making a real impact on science education and for making didactical progress."

The author points thus out that the neglected dimension in PER is the focus on the disciplinary content and he argues that this is one of the main cause of the poor impact of PER on educational practice. In particular he points out that theories on learning, teaching, curricular development or concerning the organization of the class were almost useless when uncorrelated to the specific topic, since they do not provide useful guidelines to the teacher. Teaching/learning, curriculum development or class organization theories if uncorrelated with the specific subject, focus of the teaching, do not provide useful guidelines for the practitioners. Starting from those assumptions, a theoretical referent for Science Education Research has been developed in (Lijnse and Klaassen, 2004) known as "Developmental Research" where the need of an education centered on the specific contents is outlined.

Dissatisfaction with student-oriented approach is expressed also in (Cobb et al., 2003):

"General philosophical orientations to educational matters—such as constructivism are important to educational practice, but they often fail to provide detailed guidance in organizing instruction. The critical question that must be asked is whether the theory informs prospective design and, if so, in precisely what way?"

The focus on the specific content is necessary since the learning process is content-dependent and because learning is intimately linked to "the learning of something" (Marton and Booth, 1997), leading to the concept of "content structure" (Brückmann and Duit, 2007).

A content-oriented research is designed in close relationship with the addressed scientific content and relies thus on several aspects pointed out by Niedderer (Niedderer, 2010):

• Content-specific objectives and relevant contexts have to be determined;
• Students’ conceptions, learning pathways and learning processes are taken into account;

• Content-specific tests have to be developed;

• Concepts which are helpful/necessary to work with in relevant contexts are taken into account, while unnecessary ones are removed;

The first step to develop a content-oriented research is the detection of the main learning problems, called learning knots, characterizing the specific topic. This set of learning knots represents the starting point for the design of effective teaching strategies. Learning knots may be related to naïve students’ ideas or particular alternative conceptions raised by following a specific learning path. The research described in this thesis, accepting the aforementioned suggestions, provides guidelines orienting towards a research on education focusing on the specific topic of optical spectroscopy, through the structuring of conceptual micro-steps and of instruments of an educational path founded upon physics. Bridging from the physical culture to education requires a great effort in order to point out thematics, founding cores and the phenomenology to be put in a coherent interpretative frame on optical spectroscopy.

In the scope of the content-research, an important theoretical framework allowing the conduction of a research based on a constructivist approach is the Model of Educational Reconstruction, described hereafter.

1.1.2 The Model of Educational Reconstruction - MER

The need to take into account all the multidisciplinary aspects related to educational research, without focusing only on some of them, led Duit et al. (Duit et al., 2005) in developing the Model of Educational Reconstruction (MER) that could represent both a guide to develop educational proposal and a theoretical framework for designing and structuring a research. In both cases, it aims at overcoming the problem of focusing only on the contents or the pedagogical aspects. The MER is framed within a constructivist approach to learning (Duit and Treagust, 1998, 2003; Phillips, 2000; Duit et al., 2012) presenting two main key aspects:

• The learner builds new knowledge on the basis of the old ones: the intuitive conceptions still present in learners’ minds have not to be considered as an obstacle, but rather as a starting point in order to build new knowledge.

• The structuring of the contents finalized to education does not simply reflect the scientific one, but it has to be designed on the basis of the learning goals of the specific topic.

Duit et al. (Duit et al., 2005) point out that teachers and learners usually have two different visions concerning the content structure of a specific topic. Thus, for educational purposes, the scientific content structure has to be reconstructed taking into account both the educational goal and the point of view of the learners. In this research, the MER has been used as the theoretical framework referent for planning, design and perform the research; in particular the following aspects have been taken into account:

• Physical content structure analysis from the point of view of the conceptual knowledge that learners have to reach. This analysis allows to highlight the founding cores related to the specific thematic;
Integration between the educational reconstruction and the knowledge of the specific conceptual knots deriving from an analysis of the research literature and from an exploration of learners’ spontaneous ideas.

Comparison between the historical development of ideas that could turn out to be useful in order to face the interpretative problems related to the phenomenology addressed in the path, since historical difficulties relies on the deep comprehension of the topic.

Disciplinary contents clarifications pointing out the significant founding cores for the teaching of the specific topic comes before the building of the instruction and plays an important role in the planning of an empirical study of teaching/learning (Méheut, 2004). Starting from its original formulation (Kattman et al., 1995) the MER become more and more an organizational principle for educational research in different intertwined areas, as highlighted in the diagram in Fig. 1.1. The key ideas of the MER are that the science content has to be re-constructed by taking into account the goals of instruction and learners’ perspectives and that the science content structure and the science content structure for instruction have to be clearly differentiated. Three main phases characterize the MER (Fig. 1.2).

Figure 1.1: The MER as a organizational principle of the educational research.

Figure 1.2: Intertwined phases characterizing the structure of the MER.
The analysis of the content structure and the subject matter clarification represents a preliminary study indispensable for every research, aiming at clarifying the conceptual elements and hierarchies as well as the epistemic bases of the topic under inspection. This phase requires to study the topic starting from high level textbooks and/or key or historical publications. The educational significance analysis comes immediately after this phase, as well as the founding of the learning goals, but not yet the approach, since, as emerged in various researches (Viennot, 2003; Michelini, 2006) it depends from the angles of attack related to the phenomenology rather than from disciplinary structures. Also the analysis of historical interpretations related to the topic helps the disciplinary reconstruction both of the topic and of the significance of the interpretative evolutions on conceptual plan to point out the founding elements. The science content structure then undergoes a process of elementarization, which is not a simplification in reductionist terms to build a sequence of disciplinary structured notions, allowing to extract the key ideas at the basis of the topic in terms of epistemic knowledge and founding from a conceptual point of view. The build-up of the content knowledge for educational purposes is thus a theoretical part of the research, implying a deep study on several plans: disciplinary, historical, epistemic and of relationship between physics with other areas.

The research on teaching and learning concerns the empirical research. It has an autonomous nature, but in our studies it is an integral part of the research, characterized by a critical investigation of the learners’ spontaneous conceptions as well as the teaching/learning processes. Since at least twenty years, the paradigm according to which a list of conceptual errors is the outcome of this phase, has been criticized in favor of a most fertile approach, aiming at studying reasoning processes and mental models, very often in relationship with the specific context and the conceptual path. An analysis and a re-elaboration of relevant PER literature results and/or empirical research pilot studies have to be carried out to gain an overview of the learning knots and the learning difficulties that have to be addressed. Teachers’ point of view and approaches as well as their role in the learning process are aspect that have not to be neglected in researches founded on the MER.

The development and evaluation of (pilot) instructions concerns the experimentation and evaluation of the proposed educational materials, which preliminary versions are implemented in a real contexts, setting known as "action-research" or "practitioner-research". A tight link connects this phase with DBR approach, in particular with the design and revision of formative intervention modules following results on learning outcomes (Haagen-Schützenhöfer, 2017). On the basis of the collected data and of the obtained results, the proposed material are thus optimized and improved. Research and Development (R&D) of experiments, prototypes, hardware and software apparatuses, educational paths, tutorials and educational materials is embedded in this phase, which evaluate also the in-context learners’ reasoning, the role of laboratory and the methods to produce an effective active engagement of the learners.

Research on curricular issues and science education policies implies a comparison between educational paths in a global perspective, the setting up of evaluation instruments and methods, and standard for policy makers.

The approach proposed by the MER is thus a recursive process involving intertwined phases that, through successive improvements, refines the quality of the proposal. The
MER represents the theoretical framework of the research described in this thesis: the first step is to re-think to contents to be taught in problematic terms in order to be reconstructed in an educational perspective. The research takes into account the way to observe the phenomenology, common reasoning and their dynamical evolution intertwined with teaching in order to use them as anchor to design educational proposals. In particular, the following aspects of the model were taken into account and developed:

- The clarification of the disciplinary contents
- The individuation of the founding cores
- The recognition of the conceptual knots and the spontaneous conceptions
- The design of an educational path (strategies and materials)
- The comparison between expected and obtained learning outcomes through the using of monitoring sheets, pre- and post-tests

A peculiar characteristic of the MER is the reciprocal influence between the analysis of the scientific content structure and learners' conceptions, which are given equal importance as important parameters in the process of educational reconstruction in order to reach the learning goals.

Despite, as described, the MER is a theoretical framework for educational research, among the original elements of the work described in this thesis, there is the attempt to translate the MER in a working method for designing and conducting an educational activity, i.e. the MER has been interpreted as a planning guide for education.

1.1.3 Design-Based Research - DBR

Educational design research can be defined as a type of research providing the context for empirical investigation in which the iterative development of solutions to practical and complex educational problems taken from the real world yields theoretical understanding that can inform the work of others, usually practitioners (McKenney and Reeves, 2012). Research is performed through experiments understood as scientific investigations in which the researcher deliberately and systematically manipulates one or more independent variables, controls any other relevant variables, and observes the effect on the dependent variable(s). Clearly, only research problems allowing conditions manipulations are suitable, since the goal of experimental research is to determine whether a causal relationship exists between two or more variables. This type of research method provides the most convincing evidence of the effect that one variable has on another (Ary et al., 2010), p.265. A design research approach can be described in the the scheme shown in Fig. 1.3. The first two stages of the process shown in Fig. 1.3 witness the link between a design research approach and the framework of the MER: identifying problems and developing prototype solutions according to the known literature concerning existing proposals and problems to be faced are common features.

The research tradition known as Design-Based Research (DBR) deals with the link between education research and practice in a research-action environment characterized by an approach based on design. Currently, educational researchers generally have been pushed to justify how their claims are “scientific” and “evidence-based” (Council, 2012). Arising from those needs, DBR evolved from the beginning of the XXI century and it was declared as a practical research methodology that could effectively bridge the gap between research and practice in education (Anderson and Shattuck, 2012) producing scientific and
reliable results. Historically speaking, the foundation of DBR methodologies is ascribed to Brown (Brown, 1992) and Collins (Collins, 1992) describing DBR as a research methodology intending to address need and issues related to the study of learning, including the needs to link theoretical issues (about the nature of in-context learning) and the study of learning phenomena in real settings.

DBR is a research methodology used by educational researchers, whose basic process involves developing possible solutions (called "interventions") to learning problems or obstacles. The interventions are put in practice to test how well they work. The iterations may then be adapted and re-tested to collect more data. The purpose of this approach is to generate new theories for conceptualizing learning, instruction design processes, and educational reform (Johnson et al., 2017). Data analysis often takes the form of iterative comparisons. The cores of DBR in education is the design effort (Edelson, 2002) and the assumption according to which individual and learning environment are tightly correlated, if not inseparable (Barab, 2014) in contrast with the "experimental psychology" (Greeno, 2006) according to which analyzing individual cognitive processes apart from a specific context would be possible.

To be more specific, if the goal of education research is the improvement of the quality of instruction, the most useful results for this purpose are the design of activities, materials and scenarios, thus DBR approach is considered to be a modality to reach this goal (Rissanen, 2010).

The effective achievement is linked to important characteristics of a DBR approach (Sandoval and Bell, 2004; Andersson and Wallin, 2006):

- Iterativity: the work is iterative in the sense that the design is tested, analyzed and evaluated formatively, revised and re-tested in several cycles;

- Role of the researcher: the researchers is seldom simply a researcher, but is also a designer, teacher and teacher trainer;

- Real settings: the problems are addressed addressing in real contexts, eventually in collaboration with practitioners: the researcher is directly involved in improving teaching and must account for the design of practice in real settings;

- Useful products: the arrival point is to produce sharable theories that support the dissemination of relevant implications to practitioners and researchers, and the work has to lead to "usable products" such as teachers’ guides and study material for students that can directly be put into practice;

- Useful theories: The work aims at contributing to the development of educational science (e.g. by increasing understanding of conditions that favour learning of given
topics) relying on known and/or design principles to propose plausible solutions to learning problems. Cobb (Cobb et al., 2003) refers to this aspects in the following manner: "Design experiments are conducted to develop theories, not merely to empirically tune "what works". These theories are relatively humble in that they target domain-specific learning processes.[...] A theory of this type would specify successive patterns in students’ reasoning together with the substantiated means by which the emergence of those successive patterns can be supported."

Using DBR as a methodological tool for education research has several advantages (Ejerbo et al., 2008): designing an artifact can act as a source for finding relevant research topics and help to organize the complexity in education research; also, empirical knowledge about learning is always highly contextualized. Extracting more or less generalizable knowledge from such contextualized phenomena requires conscious choices and value judgments. Barab and Squire (Barab and Squire, 2004) define DBR as "a series of approaches, with the intent of producing new theories, artifacts and practices that account for and potentially impact learning and teaching in naturalistic settings". According to DBR Collective (Design-Based Research Collective, 2003) DBR goals are "to go beyond merely designing and testing particular interventions: they embody specific theoretical claims about teaching and learning, and reflect a commitment to understanding the relationships among theory, designed artifacts, and practice. At the same time, research on specific interventions can contribute to theories of learning and teaching". In other words, DBR is a specific methodology used in education research to study learning environments designed and systematically revised by the researcher; it is a collection of approaches involving a commitment to studying activity in real settings, with the goal of advancing theories and, at the same time, directly impact practice through multiple iterations, to develop new practices to be generalized in other settings (Barab, 2014). The "collection of approaches" regards the fact that in the research literature many different paradigms are used to characterize the DBR approach, labeled as "research based on design" (Kelly, 2003), "development research" (Van den Akker et al., 2006; Lijnse and Klaassen, 2004), "design research" (Reeves et al., 2005), "developmental research" (Lijnse, 1995; McKenney and Van den Akker, 2005), "design experiments" (Brown, 1992; Collins, 1992; Cobb et al., 2003; Collins et al., 2004), and "formative research" (Newman, 1990). In particular the development research (Lijnse and Klaassen, 2004) points out the need of an educational research environment built upon specific contents. This approach gave birth to a strand of studies developed in the direction of investigate physics education in a content-related framework, as the one implemented in the research described in this thesis. This approach relies on the design of focused and narrow formative intervention in order to address very specific learning problems, called conceptual knots, characterizing a specific aspect of the knowledge, thus focusing on a specific physics topic.

Independently from the definition, DBR represents a useful instrument in order to improve both theoretical and methodological contributions and some aspects are largely shared by the different approaches, in particular (Design-Based Research Collective, 2003):

- Research implies a work in real contexts (the subject of study is a complex system involving emergent properties that arise from the interaction of more variables than are initially known to researchers);

- A pluralistic approach to theories, methods and instruments is assumed as a base;

- Design of educational materials and interventions is a process related with the evidences of learning (both qualitative and quantitative)
It is desirable to point out the characterizing elements and aspects of the research approach. They regards (Lijnse, 2000)

- The internal coherence of the sequential structure of the different concepts and their links
- The choice of examples, models and analogies and the way they are presented, evaluated by data
- The link between concepts and supporting materials
- The resources granting that every learner can access the significant disciplinary ideas

An educational teaching/learning proposal concerning a specific content whose design is the goal of a DBR needs to specify those elements. From this point of view, DBR methodology contributes in building an educational knowledge that lend itself to be shared and discussed and it is very useful since it allows to examine how systematic changes, deliberately introduced by the researcher, influence both the learning and the practice (Barab and Squire, 2004). DBR involves more than simply describing the design and the conditions under which it changed: design experiments are carried out to develop coherent proposals, not merely to empirically tune "what works" (Cobb et al., 2003). The contribution to the research consist thus in increasing the knowledge of the favorable conditions to the learning of the specific topic, in producing effective materials (i.e. educational paths, teachers guides, experiments, examples, exercises, simulations, analogies), in making explicit hypothesis and decisions in the design of a educational proposals and materials, that very often are implicit (i.e. remarks used by teacher in order to accompany and present the different activities). In a DBR perspective, the design of an educational proposal starts with the definition of a problem and the description of a possible solution. The theoretical analysis of the problem characterizes needs, opportunities, goals and comes before a series of empirical interventions ending with the presentation of an output that can be an artifact, an educational path or supporting materials (Rissanen, 2010). From this point of view, DBR differs from other methodology of developing educational materials, as the simpler "Predictive Research" (Fig. 1.4) or the so-known "Backward Design" in which thinking about assessment early in the planning process helps to clarify the intended outcomes, which in turn helps to determine the most appropriate learning activities (Whitehouse, 2014; Wiggins and McTighe, 2005). Learning environments are complex systems, thus it

![Figure 1.4: Predictive and Design-Based Research approaches in educational research.](image)
is extremely difficult to test the consequences in the change of single variables: DBR iterative cycle in different contexts helps both in overcoming this problem (Barab, 2014) and to point out reasons at the basis of the educational choices, consolidating results turned out to be more effective. DBR process develops collecting data that influence further design via a typical "feedback process" (Brown, 1992; Collins, 1992; Haagen-Schützenhöfer, 2017) (Fig. 1.5). DBR faces the complexity of a real educational environment with a strong intentional approach (Tiberghien et al., 2009): this design phase aims at bringing a significant contribution in terms of learning perspectives, innovative pedagogical approaches and educational instruments inside a real context. Fundamental disciplinary ideas, conceptual referents and the different reasoning constituting the learning goals are defined drawing from research literature concerning the specific topic and synthesizing it. In well-studied and well-known areas, this provides the necessary awareness concerning spontaneous interpretations and initial conceptions of learners, however it can be necessary to carry out preliminary interventions in order to point out:

- Inedited aspects concerning learners’ conceptions that have to be considered
- The consequences of the previous teaching on learners’ ideas

Typically those kind of interventions are carried out with a small sample of learners in order to study in depth and with great detail a small-scaled version of the educational intervention. The implementation of a typical DBR intervention consists in data collection setting-up campaigns, supporting the systematic analysis of the learning process under inspection. The analysis accounts for the learning outcomes, framed in a real environment allowing to foresee the results of future interventions since they are correlated to the instruments and strategies used in order to implement them. The consequence is thus the theoretical knowledge on the teaching/learning processes related to the specific topic. One of the main limit of the DBR approach is the possibility to generalize the results of the experimentations obtained in a particular controlled environment due to the complexity of the involved interactions. DBR has to describe both the theory and the environmental setting allowing to understand how to re-contextualize the experimentation (Barab, 2014). The research described here faces the educational problem in its whole complexity since sample of learners and teachers involved in the experimentations underwent no preventive selection on the basis of appropriate prerequisites functional to the intervention (i.e. specific preparation or background) or to the goals of the research, but they belong to real scholastic or university environment; moreover the role of the context in this research is fundamental, since it is an important part of the complex environment that causes the phenomenon under inspection. In order to face this complex and heterogeneous situation,
trying to generalize as much as possible the obtained results, the following choices were

- The research was set up with a prominent flexible nature, realized through the cyclic succession of four phases: design, experimentation, evaluation and revision. Monitoring was performed by using tutorial and tests in order to have evidence-based specific indications.

- Research were carried out in vertical perspective, in order to explore the different contexts the validation of hypothesis, of the theoretical elements and of the educational materials upon which the design is performed, taking into account both the educational level and the age of the learners involved.

The evaluation of the performed interventions facilitates in noticing the inadequacies in the analysis of the educational problem, and in exploring the conditions under which a particular evidence could occur understanding the underlying reasons that cannot be pointed out with a simple theoretical reflection process alone, since DBR approach has an highly interventionists characterization.

According to literature, indeed, DBR is a valid and a reliable methodology to design new instruments, experiments and learning paths, making sure that in the final product both curricular and pedagogical aspects are taken into account.

1.1.4 Content analysis

Qualitative vs quantitative content analysis

Collecting and analyzing students data is at the core of PER, in particular two different approaches for investigation are possible: quantitative and qualitative analysis. They have different roots arising from different assumptions driving the way in which research approach problems, collect and analyze data; the choice of one method with respect to the other thus strongly depends from the type of available data and from what the researcher wants to find out. A reported in (Ary et al., 2010) quantitative and qualitative research stem from different assumptions shaping the ways researchers approach problems, collect and analyze data. Quantitative research relies on the assumption that general principles or laws govern the social world as they do in the physical one and that through objective procedures researchers can discover these principles and apply them to understand human behavior. Qualitative research is based on a different approach, which sees the individual and his or her world as so interconnected that researchers can only understand human behavior by focusing on the meanings that events have for the people involved. It has to look not only at what people do but also at how they think and behave. The intended result of a qualitative research study is a narrative, but rich and comprehensive, report able to allow the understanding of the social reality experienced by the participants. Quantitative procedures employ quantitative measures as frequencies, means, correlations, and statistical tests; in contrast, qualitative research employs words and images to answer questions: qualitative researchers seek to understand a phenomenon by focusing on the total picture rather than breaking it down into variables. The goal is a global understanding rather than a numeric analysis of data.

Concerning educational research, even if during the XX century the dominant approach was the quantitative one, at the end of the century, researchers began to look forward for new way to investigate students’ reasoning: they decided to engage in qualitative methods since they could not ignore participants’ experiences and perspectives (Guba and Lincoln,
this is due to the need to obtain more details that can help to understand the obtained trends. Both qualitative and quantitative research share the common feature of using evidence to make and support claims about physics teaching and learning. The salient features of qualitative and quantitative methods are compared in Tab. 1.1. As pointed out in (Otero and Harlow, 2009) qualitative research tends to be inductive in the sense that the researcher first explores the context of the study, and from this works toward a general model that attempts to explain the data; in quantitative research, typically, a-priori assumptions are made and the research consists in determining whether the data are consistent with them or not. Qualitative research tends to be subjective rather than objective: attempts are made to describe the world from the perspective of the studied subjects and no attempts are made to generalize findings to all members of a specific group. In many cases, the qualitative researcher does not attempt to control variables, preferring instead to observe the context as it is, making the study not generalizable: qualitative research assumes a dynamic reality rather than a static reality in the sense that every descriptive or explanatory model created only claims to explain a particular situation. While it may be possible to make assumptions about other populations on the basis of a qualitative research study, the study only claims to describe the situation at hand. It is quite unusual that a qualitative research study seek to confirm results. Qualitative research can provide what is known as a “thick description” of a situation and the actors that shape it, and this can be extremely valuable for making further inferences about the types of motivations and actions that drive observable behaviors in similar situations. Overall, qualitative research is different from, but complementary to, quantitative research and both have their costs and benefits (Otero and Harlow, 2009).

A closer look at qualitative content analysis

As reported in (Miles et al., 2014) “one major feature of well-collected qualitative data is that they focus on naturally occurring, ordinary events in natural settings, so that we have a strong handle on what real life is like”. Qualitative methods for data analysis look in fact at the whole situation under study, without searching for specific variables. The goal is to reach a deep understanding that could not be reached by means of simple numeric data analysis, i.e. via quantitative research. The focus is on a small group of students, in order to study them in great detail through observation and detailed interviews (Flick et al., 2004). Several different types of qualitative research are possible; a general summary of the different types of qualitative research was proposed in (Ary et al., 2010).
as reported in Tab. 1.2. In order to obtain specific inferences on samples of subjects,

Table 1.2: Different kinds of qualitative research and their peculiar characteristics.  
Adapted from (Ary et al., 2010).

<table>
<thead>
<tr>
<th>Type</th>
<th>Major question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic interpretative study</td>
<td>How are events, processes and activities perceived by the participant?</td>
</tr>
<tr>
<td>Case study</td>
<td>What are the characteristics of this individual organization or group?</td>
</tr>
<tr>
<td>Document analysis</td>
<td>What can be learned about this phenomenon by studying certain documents?</td>
</tr>
<tr>
<td>Ethnography</td>
<td>What are the culture and the perspectives of this group of people in its natural setting?</td>
</tr>
<tr>
<td>Grounded theory</td>
<td>What theory can be derived inductively about a phenomenon from the data collected in a particular setting?</td>
</tr>
<tr>
<td>Historical studies</td>
<td>What insights or conclusions can be reached about this past event?</td>
</tr>
<tr>
<td>Narrative inquiry</td>
<td>What insights and understanding about an issue emerge from examining life stories?</td>
</tr>
<tr>
<td>Phenomenological study</td>
<td>What does this experience mean for the participants in the experience?</td>
</tr>
</tbody>
</table>

An ensemble of techniques for systematic analysis of text (written answers to interviews or questionnaires, transcriptions of audio recording, etc...) have been developed since 30 years. This type of analysis is known as qualitative content analysis (Mayring, 2004). This process of analysis is centered on the operative definition of the categories in which answers are classified. Research questions found the definition of the various categories, and they can be iteratively re-defined during the analysis. The adopted approach in this research is based on the inductive definition of the categories (Mayring, 2004): they are as close as possible to students' sentences and they are formulated according to them. The theoretical context and/or the research questions drive the choosing of a criterion that determines the aspects of the produced material that have to be taken into account. The analysis is thus carried out according to this criterion and collected data are classified in provisory and indicative categories. During analysis, new categories could be formulated, old categories could vanish or put together, till the definition of the definitive categories: this revision process found the basis of the inductive definition of the categories. Once the final categories have been defined, the interpretation of the results is based on the determination of the frequencies of the mutually exclusive categories that can be expressed in absolute or relative terms, according to the numerosity of the sample. A synthesis frame can provide explicit definitions, examples or classification rules for every category. Since this approach allows to assign meaning to collected data, to share and discuss them and to generalize the results, inferring consequences and outlining observations, this analysis modality is adopted in the research described in this thesis.

Three dimensions of the legitimation of the results are taken into account in this thesis (Maxwell, 1992):
• Descriptive, understood as accurate report of the documentation by the researcher (i.e. reading and transcription);

• Interpretative, in the measure in which researcher searches for an interpretation for a reliable comprehension of the collected material;

• Generalizable, to the extent that results can be generalized from a context to another.

The evaluation of the results of a teaching/learning experiment is influenced by the intrinsic complexity of the system due to subjective elements that introduce inaccuracies difficult to estimate. In this research, difficulties in generalizing the obtained results from a limited sample has been faced paying attention to the randomness of the subject, so that the sample significantly represented the population under study.

The strictness of the analysis procedure, determining the results to present and discuss, relies on three fundamental elements (Tashakkori and Teddlie, 2008), taken into account in the research described in this thesis and outlined in Tab. 1.3.

Table 1.3: Elements characterizing the analysis process.

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretative agreement</td>
<td>Level of coherence of results obtained with different samples</td>
<td>The vertical perspective characterizing the research allowed to recognize same categories in different-aged students.</td>
</tr>
<tr>
<td>Interpretative uniqueness</td>
<td>The extent to which other possible interpretation of data are excluded</td>
<td>Interpretation of data relies only upon the categories defined in tight relationship with students’ sentences and statements.</td>
</tr>
<tr>
<td>Theoretical coherence</td>
<td>The alignment between the obtained results and the knowledge in the field</td>
<td>Categories already known in literature have been found.</td>
</tr>
</tbody>
</table>

A classic set of analytic stages arranged in sequence is reported in (Miles et al., 2014):

• Assigning codes or themes to a set of field notes, interview transcripts, or documents;

• Sorting and sifting through these coded materials to identify similar phrases, relationships between variables, patterns, themes, categories, distinct differences between subgroups, and common sequences;

• Isolating these patterns and processes, and commonalities and differences, and taking them out to the field in the next wave of data collection;

• Pointing out reflections or other remarks in notes, journals, and analytic memos;

• Gradually elaborating a small set of assertions, propositions, and generalizations that cover the consistencies discerned in the database;

• Comparing those generalizations with a formalized body of knowledge in the form of constructs or theories.
As pointed out in (Ary et al., 2010) qualitative analysis involves reducing and organizing the data, synthesizing, searching for significant patterns, and discovering what is important. The researcher must organize what has been seen, heard, and read and try to make sense of it in order to create explanations, develop theories, or pose new questions. Qualitative analysis is messy and nonlinear: data analysis in qualitative research is often done concurrently or simultaneously with data collection through an iterative, recursive, and dynamic process. All qualitative analysis involves attempts to comprehend the phenomenon under study, synthesize information and explain relationships, theorize about how and why the relationships appear as they do, and reconnect the new knowledge with what is already known. The task of analyzing qualitative data can appear overwhelming but becomes manageable when broken down into three key stages: organizing and familiarizing; coding and reducing; interpreting and representing.

Considering that educational activities and experimentations, at the core of this work of research, are social events, the outcomes are tightly dependent from the context and influenced by complex external factors, interconnected and difficult to estimate quantitatively. For this reason a qualitative data analysis approach (Flick et al., 2004) has been chosen in order to give significance to data collected in written form: single students’ answers and drawings have been inductively classified in categories based on the research questions and subsequently refined according to the outcomes. Students’ interpretative process has been evaluated during all the experimentations, allowing a detailed analysis of the specific learning situations in order to refine the hypothesis at the basis of the proposed teaching/learning path, based on design, and the materials proposed to students as experiments and worksheets. About the employed worksheets, although differentiated with respect to the different context in which they have been used, several common aspects are present:

- presentation of the considered situation anticipates every question;
- every question is eventually splitted out into different points, everyone regarding a specific aspect of the phenomenon/experiment taken into account.

Validation of the worksheets was performed a-posteriori: the comparison between the expected answers and the actual answers given by students allowed the testing of the measure, checking if every aspect under analysis could be measured; if not, a process of revision of the questions was carried out. This modality ensures that the research methods are able to catch the significance looked for and are thus adequate to answer the research questions.

In this thesis, data analysis is understood as a systematic search for significance (Hatch, 2002), in the sense that represents a way to elaborate collected data in order to communicate what emerged and inferred. Data were thus organized and analyzed in order to identify models, expose relationships, provide explanations, suggest interpretations, develop theories and compare different situations. The goal of data analysis, understood in this sense, is to orientate the researcher, avoid standard way of thinking, support inductive reasoning, clarify research hypotheses, give answers to research questions, allow use of concepts and point out categories useful for the research. Such work has been performed in this thesis on the basis of the analysis of students’ answers to semi-structured questionnaires (Cohen et al., 2007).

1.1.5 Implementation of methodologies in the research

The research described in this thesis is framed in the context of the empirical researches in which qualitative analysis often play a crucial role, in contrast with the American tradition
in which quantitative and statistical methods are widely employed to validate educational proposals. It is finalized in contributing to the educational practice and in producing T/L proposals (Jenkins, 2001), but it is not restricted simply to what works in the practice. According to Millar (Millar, 2003):

"The role of the research is not only to tell us what works. Some of the most valuable research studies have been ones that made people aware of problems in current practices. Research can inform practice in a range of ways that stop short of providing clear and defined answer: by providing the kind of insights that enable us to see the familiar in a new way, by sharpening thinking, by directing attention to important issues, by clarifying problems, challenging established views, encouraging debate and stimulating curiosity."

Even if the nature of the research is content-oriented, a close analysis at students’ learning processes is carried out during experimentations of educational proposals. The research is oriented towards the study of the building of formal thinking in younger pupils and the basic ideas of modern physics is secondary school students. The roles of peculiar methodological aspects as playing, operativity, problem solving, informal education in the processes of learning physical concepts are taken into account, with the aim of producing educational materials sustaining innovation and orienting the practice with methodological proposals and with research and development (R&D) materials (Millar, 2003).

Approaches in the research are not purely based on aspects regarding the disciplinary contents, but attention is paid on the context, to the extent it influences students’ responses (Fischer, 2005). In designing new T/L proposals scientific issues, students’ need and learning environments are given equal consideration, in order to point out effective approaches for the evolution of ideas from common sense to scientific ones.

Re-think to scientific contents in problematic terms and not only in relation to their teaching and re-build them from an educational perspective is the first step of the research described here, conducted integrating empirical research and research-action in a cooperation between school and university (Fensham, 2001), switching the responsibility roles of individuating research problems, collecting and discussing data as hoped in an integrated vision of educational practice improving (Dahndke et al., 2001). This cooperation, seen as an integrated research for the improvement of the educational practice, produced new modalities of inquiry, comparison, research itself and teacher training.

The repercussion of research in the practice is realized in an environment in which the research itself represents an activation element for research-action activities by teachers, collaborating as reflective professionals. The research on T/L paths starts from the studies on the discipline (disciplinary nodes and epistemological aspects) and on the learning processes, paying particular attention to the dynamics of reasoning in the connection between common experience and physical interpretation of phenomenology. Strategic angles of attack and critical details are important elements for studying a paths for building formal thinking in physics. In this perspective, these strategic angles of attack used to analyze the common sense knowledge do not correspond with the canonical structuring of the discipline: the consolidated disciplinary structure, whose emblematic case is represented in the detailed index of a textbook, fixes preparatory elements and an organization of the knowledge, which often does not correspond to the perspective according to which scientific learning occurs. For this reason, transversal approaches have been taken into account focusing in depth critical details (Viennot, 2003) emerging as interpretative keys of whole phenomenological contexts, as reported in the case of optical polarization for the analysis of quantum states (Santi et al., 2004; Stefanel and Michelini, 2007), of magnetic field lines for studying magnetic phenomena (Bradamante et al., 2005), of the interpretation of thermal
sensation for thermal phenomena (Michelini, 2004a) or for studying free-fall (Bradamante and Michelini, 2006).

In planning and experimenting attention is paid to the role of spontaneous, analogical and objectual models. In the research periodic cycles of modular experiments, which are well described by DBR type researches are performed, and the MER is the theoretical reference framework not only in terms of setting, but also in terms of research program: conducted studies are divided into phases of the MER areas into vertical thematic proposals.

The research aims at investigating common students' reasoning in order to take them into account in the study of T/L paths: focusing on students' spontaneous ideas (Viennot, 2003) is not limited to analyze the internal logic of the spontaneous reasoning to catch its resistance and structure in terms of "mental models" (Gilbert and Boulter, 1998) but, and mostly, to analyze the dynamical evolution of the spontaneous ideas exploring in an operative way the phenomenologies in the various stages of the experimentation (Michelini, 2003).

In this research perspective, rather than general results or lists of difficulties, the focus is on the hurdles to be overcome in order to approach a scientific level of reasoning and the construction of formal thinking: for this reason, the description of the different types of reasoning is the main research result, serving as a setting for developing T/L proposals (It is worth remember that in the Eighties and in the Ninties, the most common research focus was put in the ambit of the so-called "misconceptions" or "wrong ideas", representing common-sense hurdles to the scientific learning, to be located and pointed out to let practitioners aware, so that they would have taken them into account in practice of teaching.).

Different starting situations have been taken into account in order to produce different reasoning evolutions, recognizable in categories, setting light on the useful tracks to produce effective learning: according to Gilbert and Boulter (Gilbert and Boulter, 1998) in fact, learning is activated in specific situations, understand as a specific external environment which is turned into a context at a particular time by the mental activity of an individual. Choosing the specific situations, the materials and the inquiry methods to collect data concerning this dynamical evolution of ideas is never neutral: the intervention is preceded on researches on disciplinary foundations, together with an analysis of available textbooks and of existing educational proposals. Reviews on students' conceptual difficulties guide the inquiry phase on ideas and typical interpretative reasoning of the phenomenology under study, according to the MER. The exploration does not consist in a single action or phase, but more interventions in the same contexts are carried out, characterized by the evolution of the supporting (tutorials, experiments) and evaluation materials (pre- and post-tests) which have to be revised according to the outcome of every intervention, according to a DBR approach.

Collected experimental data concerning common ways of reasoning allow to highlight the critical areas concerning specific physics issues to take into account with respect to the learning goals, also to point out what is indispensable to the T/L paths. Having always clear the boundaries of the research results helps in producing focused proposals, that turn out to be useful for practitioners to be used both as a reference point to reflect on the concepts, and for elaborate activities in class, but it is work to remark that the goal of the research work described in this thesis is oriented to the analysis of the reasoning and on the building of the formal thinking rather than the conditions of effectiveness of a particular approach.
Qualitative data analysis of contents was chosen for the research described in this thesis (Krippendorff, 1989; Mayring, 2000, 2004; Zhang and Wildemuth, 2009) aiming at analyzing materials produced by students (texts, drawings) in order to find out regularities and to account for data contents in a synthetic way. Different categories are induced directly from data through a selection criterion (Mayring, 2004). To allow obtained results to go beyond the performed contextual activity, previous research findings and theoretical research questions defined a-priori allow the categories to come out. Some categories are unavoidably defined a-posteriori from the raw data themselves. Conclusions not stemming from data (i.e. due to researcher's preconceptions), or conclusions not accounting for data variety have been avoided. Categories have been operationally defined, in the same ways as operational definition in physics: for each question, a set of quotations from students' answers has been chosen and grouped when they were considered to have the same conceptual content. Each set of answers built in this way represents a category. In particular, conceptual elements present in students' answers have been pointed out and combined together in order to build different mutually exclusive categories, refined or changed by reading the answers in subsequent experimentations, according to the guidelines of qualitative content analysis. Frequencies of the different categories constitute the distribution of the sample and they are used for conceptual understanding evaluation and/or to follow students' different ways of reasoning witnessed by the different answering styles. When possible, pre- and post-distributions have been compared in order to discuss the eventually occurred conceptual change. Students' reasoning path empirical models can be thus inferred, allowing context-specific statements about their learning (Mayring, 2004). If the sample is randomized, i.e. no selection criteria was applied (or, for using an expression from (Mayring, 2004): "including cases with all relevant attributes as in the population"), students' statements, transformed into categories, may be generalized, and thus inferences are drawn on the entire population under these conditions, since the sample is statistically representative of the environment under study, which are 16-19 years old Italian students attending scientific lyceums (i.e. secondary school specialized in scientific studies), freshmen in biotechnology (students with different scholastic background attending the introductory physics course) and pupils form Italian primary schools.

1.2 Educational strategies

1.2.1 Conceptual change and critical details approach

Learning of complex concepts, like the ones encountered in physics classrooms, can occur under at least three different conditions of prior knowledge (Chi, 2008): first, students may have no prior knowledge concerning the to-be-learned concepts (even if they may have some related knowledge); second, students may have some correct prior knowledge about the concepts to be learnt, but that knowledge is incomplete; in a third condition, students may have acquired ideas, either in school or from everyday experience, that are in conflict with the concepts that have to be learnt (Vosniadou, 2004). In the former case, prior knowledge is missing, and learning consists of adding new knowledge; in the second case, learning can be conceived of as gap filling. In both missing and incomplete knowledge conditions, knowledge acquisition represent an "enriching" (Carey, 1991). Knowledge acquisition under the latter case is of the conceptual change kind.

According to Piaget (Kitchener, 1986), cognitive development is the result of a continuous negotiation between internal cognitive structures and external reality. This contrasts with the idea according to which students' mind is a "tabula rasa" with no pre-conception
Concerning the topic that is taught, which was the driving paradigm of traditional teaching based on the passive transmission of knowledge from the teacher to the student (Rissanen, 2010).

In the sixties, science education research has been influenced by Kuhn's theories, rooting the one named "conceptual change" (Vosniadou, 2008): he questioned the attempts to treat scientific theories as sets of axioms that could be formulated in mathematical logic. Kuhn proposed that normal science operates within sets of shared assumptions and practices constituting paradigms; discoveries that cannot be accommodated within the existing paradigm emerge over time. When these anomalies accumulate, science enters a period of crisis which is eventually resolved by a revolutionary change in paradigm. Following this line, he depicted the need for a theoretical framework able to face students' difficulties in learning science concepts. As pointed out in (Viennot, 1979; Driver and Easley, 1978; McCloskey et al., 1983) students possess persistent pre-conception, misconception or alternative believes, sometimes quite close to the ones characterizing earlier physics theories (McCloskey et al., 1983). Many researches in different fields of scientific education showed in fact that the students' mind is not a "tabula rasa", rather they have intuitive and spontaneous conceptions built upon everyday experience through reasoning based on common sense. The knowledge students thus have prior the instruction is thus formulated in vague and/or ambiguous terms: even if it presents coherence areas, it appears fragmentary and it is refractory to refutations (Viennot, 2001).

These ideas and conceptions can be deeply rooted and rarely in agreement with the scientific view (when not even in sharp contrast). These ideas remain implicit and persist if they are not brought out and discussed. In a wider sense, the conceptual change indicates the result of the educational action guiding students from spontaneous conceptions towards a scientific vision of the topic (Duit and Treagust, 2003). It has been shown (Periago and Bohigas, 2005) that passive teaching of scientific ideas seldom allow students to abandon their alternative ideas, which tend to remain unchanged in the long period, coexisting with scientific ones. The result is that students maintain two parallel regimes of knowledge: on one side the academic knowledge of phenomena, theories, laws, formulas and methods, which they use at school in order to solve exercises, on the other side students maintain their set of alternative concepts used to understand reality and interact with the real world. Educational approaches based on conceptual change look at misconceptions as the consequence of a reasonable and personal way of giving meaning to things; these misconceptions can evolve and change towards the scientific knowledge if the educator designs teaching strategies taking them into account and using them as a starting point for education (Hammer, 1996).

Based on those considerations, Posner (Posner et al., 1982) outlined an analogy between students' need of change and Kuhn's explanation of the conceptual changes often occurring in the history of science building an educational theory based on four basic conditions, promoting conceptual change:

- There must be dissatisfaction with the previous conception;
- There must be a new conception that is intelligible;
- The new conception must appear to be plausible;
- The new conception has to be fruitful.

In the previous list, it is important to note that students do not assimilate a new conceptual framework if the need to change it is not felt. Therefore, the meaningful learning of
science will take place not through the passive accumulation of transmitted information, but through a conceptual change, according to a process that seems similar to scientific progress (Vosniadou, 2008): students must therefore be aware of the need for conceptual change to be actively involved in learning new concepts. In the constructivist perspective of teaching/learning, students, faced with a situation to be understood, can contribute to the learning process with his own pre-existing patterns of reasoning.

In this environment, known as "classical approach to conceptual change" students play the role of scientists exploring new theories: conceptual change is mainly promoted through cognitive conflict between student previous knowledge and explored phenomena. This framework was the leading paradigm in education research for several years and it keeps the main one in science education research nowadays (Vosniadou, 2008). However, students' alternative conceptions do not represent the only variable to be considered for conceptual change: learning can in fact be hindered by factors related to the internal conceptual knots of the discipline that required a troubled historical process to be coherently placed within a scientific theory.

Despite conceptual change seems to be an effective approach to scientific (in particular physics) education, several points of disagreement emerged. One of this regards students' knowledge structure: from one side it is considered to have a "theory-like" structure (Vosniadou, 2008), from the other side the status of "theory" is lightened, preferring to consider students' knowledge structure a "schema" (Parmaves et al., 2008).

Understand which concepts are present and how the change occurs is a still an open problem (Vosniadou, 2008). Concerning the first aspect, usually researchers use an historical view of concepts (Murphy and P.A., 2008; Fodor, 1996), while concerning the occurring of conceptual change, it has been argued that it changes in several ways from the most trivial to the most radical (Thagard, 2008).

In particular the mechanism of the process of the conceptual change is another point of debate: according to Kuhn, it takes place in a short period of time, resulting in an abrupt change. Even if during learning processes this rapid change may occur, it has been shown that this is not the usual way (Vosniadou, 2008): conceptual change is a slow and conservative process (Caravita and Hallden, 1994; Vosniadou, 2003; Hatano, 1994; Wiser and Smith, 2008). Students use mainly additive, enrichment types of mechanism that are largely conscious and that these mechanisms can produce conceptual changes in the long run: they operate changing one by one the beliefs and assumptions of the previous theory that are in conflict with the new ones (Vosniadou, 2008), moreover some misconceptions rise up when new information is added on the wrong schema (Chi, 2008). In other words, it means that conceptual change does not stand for a process of simple replacement of spontaneous conceptions with scientific ones: learning is a gradual process during which students' spontaneous conceptual interpretative structures are taken into account and continuously enriched and restructured through observation of phenomena and comparison with the results of experiments. This position has a direct and significant influence on the design and methodological choices adopted in the present research.

Another disagreement regards the role of a student as a scientist: students whose knowledge has a theory-like structure lack in metaconceptual awareness, have difficulties in engaging in systematic hypothesis testing and have a lack of knowledge about the role of theories and scientific models and general epistemological understanding (Wiser and Smith, 2008).

The path designed in this thesis allows students to actively build his knowledge by practicing a method similar to that of scientific work even in the aspect of participation in a scientific debate. This favors the attitude towards a critical attitude, also regarding one's
own ideas, supported by an adequate skepticism, but also of trust in the critical rationality that guides the building process of knowledge.

So, learning is always a question of negotiating with students’ knowledge, so for a teacher it is crucial to know students’ prior ideas and their ways of thinking on the specific topic. In the work of research education the awareness of two opposed aspects is crucial for the researchers: the scientific/physical theories on one side and the common sense reasoning on the other (Viennot, 2001).

When student are proposed to follow a learning path, recognizable trends of reasoning that are not compatible with taught theory are found, and are remarkably frequent and stable both during and after instruction (Viennot, 2001), since their degree of coherence contributes to their resistance. An effective way to promote conceptual change is to cast light on the incoherences produced by pre-conceptions or show that they have no counterpart in the real world. Frequently it is not enough to focus on this, or to provoke a critical examination since in this way the danger is to make the process of learning boring and uncertain mastered since academic knowledge and natural reasoning may coexist in students’ minds.

1.2.2 Inquiry-based learning - IBL

The National Research Council (Council, 2012) identifies three major stages in the development of scientific practice, listed according to growing level of analysis:

- Empirical investigation based on the simple observation of the real world;
- Development of explanations using reasoning, creative thinking, known theories and interpretative models;
- Critical analysis, discussion and evaluation of emerged ideas, such as the adequacy of models and explanations.

The way in which science constructs explanations of the world represents both a basic element for scientific education and a regulating principle in the programming and practical implementation of educational activity. In a scholastic context the realization of these stages requires that students activate heterogeneous resources in terms of knowledge and skills, formulating questions, performing observation, conducting experiments, using imagination, reasoning, calculation and forecasting methods, as well as inductive and deductive mental processes and adopting different languages, both natural and formal.

An educational approach centered on the phenomenology brings with it an added cognitive value, often poor in traditional teaching, integrating of different types of knowledge (Colombo, 2011): perceptual knowledge (based upon sensations), common sense knowledge (eliciting ingenious ideas), experimental knowledge (setting of experiments and measurements), abstract knowledge (for example representations with graphs), variational knowledge (analysis of the consequences of varying experimental conditions) and correlative knowledge (putting in relation different representation of the same phenomenon comapring different models).

Inquiry-based learning (IBL) is a method of learning that, concerning scientific education research, was mainly developed in the USA by the McDermott’s (1992) research groups in the nineties (McDermott and Shaffer, 1992), now become one of the main adopted approaches in learning strategies. It consists in making observations, asking questions, searching for information, planning and designing surveys, using tools to collect, analyze and interpret data, explaining and communicating results (Linn et al., 2004). Evidently,
this method implies an active learning approach in which the student is the center of
the learning process: in fact the core of the IBL approach is the formulation of specific
questions related to particular problematic situation to e interpreted. The role of these
questions is promoting students’ reasoning while the phenomenology is under inspection.
When adopting an IBL strategy, teacher’s role is completely different with respect to the
traditional one: teacher is not the bearer of the expert knowledge, but a facilitator having
the role of motivating the students.

There are many points of view on IBL in education research (Schwarz and Gwekwerere,
2006): often it is understood simply as a laboratory activity, but this does not exhaust the
complex meaning of the term. In particular four level of inquiry can be defined (Banchi
and Bell, 2008):

- Confirmation inquiry. Used when an idea or a concept, already introduced, has to be
  reinforced: the research focus is on the way in which students argue them to confirm
  the presented concept;

- Structured inquiry. Both questions and procedures are provided by teachers while
  students generate an explanation supported by the evidence they collected;

- Guided inquiry. Questions only are provided by teachers. Students had to design
  the procedure to answer these questions and analyze the results.

- Open inquiry. This is the highest and demanding level of inquiry requiring the most
  scientific reasoning and cognitive effort from students, who have the opportunity to
  act like a real scientist, deriving questions, designing and carrying out investigations,
  and communicating their results.

Concerning the two highest level of inquiry, i.e. guided inquiry and open inquiry, there
is an open debate on what can be considered "authentic inquiry" as well as how it can be
implemented in the scholastic practice. Assuming that in the case of scientific disciplines
the authentic inquiry concerns the practice of professional scientists (Schwarz and Gwek-
werere, 2006) and that in the scholastic education only some analogies can be present, some
essential characteristics of scientific practice that can be imported into scholastic reality
are outlined as methodological indications for an inquiry-based teaching (Pirrami, 2010):

1. A real problematic scenario will be presented to students. Subsequently, after a first
   personal reflection, followed by group discussion, one or more significant questions
   will arise;

2. Students will be asked to search for information identified as important, to analyze
   and summarize it;

3. Hypotheses will be formulated in order to answer the elicited questions and/or to
   solve the posed problem. Interpretative models of reality will be proposed.

4. Simple experimental protocols or research projects will be designed with the aim of
   validating what has been hypothesized, taking care to clearly select the variables to
   be considered;

5. Qualitative or quantitative data will be collected;

6. Representation and analysis of the collected data will be performed, organizing them
   in tables and/or graphs in order to test the initially formulated hypotheses or models;
7. Students will reflect on the compatibility between data collected and their adequacy to the goal initially set (procedures containing errors are more educational than the tested and reliable experimental protocols: if the teacher finds that the proposed procedures has elements of inaccuracy, should refrain from making it notice before the activity takes place and then guiding the students to reflect on the results);

8. Students will reflect and discuss how what they experienced, observed or collected, they will identify the relationships between variables and the relationship between the causes and consequences of the phenomena under analysis. They will also be called upon to choose between different explanations or possibilities and to argue their choices, based on the emerged evidences;

9. The reflections and the discussions will lead to the formalization of the final implications and considerations, concerning both the methodology used and the addressed topic;

10. Students, especially when they have gained more experience, may be asked to compare their work with other relevant studies.

The Eurydice Report\footnote{Eurydice (2006) L’insegnamento delle scienze nelle scuole in Europa. Politiche e ricerca. Bruxelles: Direzione Generale Istruzione e Cultura della Commissione Europea. Available at: http://www.indire.it/eurydice/content/index.php?action=read_cnt&id_cnt=3130} on science teaching in European schools highlights that experimental activities play a priority role in learning only if they are carried out in non-stereotyped or passive forms. From this point of view, IBL is a new paradigm for guiding scholastic activities so that the limits of the traditional scholastic approach to the scientific method, understood in the perspective of verification of known laws and based on an inductivist procedure articulated in the experiment phases, observations, measures and conclusions, are overcome (Windschitl et al., 2008).

1.2.3 The artifacts method

Artifacts can be defined intentionally designed and built objects to achieve a goal: they are the result of intentional actions serving to increase the effectiveness of an action in order to obtain a specific result. More specifically, a cognitive artifact is an object, a configuration or a mental process allowing to extend the acquisition and management of knowledge: a sort of "linking object" allowing to change perspective from one point of view to another. To learn, the mind needs to construct real objects and devices or represent reality, through a process of coding it. The learning process may occur with discussion, analysis, comparison, exposure, testing, construction, disassembling and reconstruction of cognitive artefacts. Cognitive artifacts (Hutchins, 1999) are artificial devices (real objects, set of orders, codes and procedures allowing the description of reality) designed to act on information and thus expanding cognitive abilities (Norman, 1993): an artificial device designed to preserve information, present it or work on it in order to ensure a representative function and influence human cognitive activity. Artifacts do not simply amplify the human potential, but guide mental activity and can modify the execution of a task. Between different perspectives it is necessary to establish bridges to facilitate interaction. All this requires cognitive artifacts, passing from one world to another: each world examines some facets, produces its own interpretation, modifies some aspects, before sharing it again with others. The use of a cognitive artifact transforms the knowledge itself for which it was designed: this transformation concerns both the reorganization of the perceptive-motor modes of
interaction with the environment, and the way of thinking and the planning methods of actions and social relations; in fact, in performing more efficiently the functions typical of the mind of human beings, it provides devices or supports that externalize mechanical operations and in this way frees the mind and allows to refine new and more complex skills.

Semiotics is a form of inquiry through which humans shape raw sensory information into knowledge-based categories through signs creation and interpretation. Signs that penetrate the flux of information are intelligent selections which are taken in by senses or intuitions, allowing the encoding of what is perceived as meaningful in it and, thus, to learn and remember it (Danesi, 2010). The introduction of the exploration of artifacts constitute an important context in which to create a bridge between semiotic and education research (Bartolini Bussi and Mariotti, 2009, 2008) that, through the structured exploration of selected artifact could promote the exploitation of the way in which students apply the knowledge to new situations.

1.2.4 Pedagogic content knowledge - PCK

The leap from a teacher-centered to a learner-centered approach requires a conceptual change from the teacher, helped by a specific formation. Traditionally, in teacher education programs, teachers are taught both content knowledge and pedagogical knowledge. The link between the two kinds of knowledge, the content specific pedagogical knowledge, is however usually missing (Duit, 2006).

Schulman's theory of the Pedagogical Content Knowledge (PCK) (Shulman, 1986) is the most adopted methodology in teacher formation processes. PCKC is rooted in the need of synthesis between aspects regarding both the pedagogical knowledge and the content knowledge: obviously, if a teacher does not master at least the basis of the content knowledge of the discipline this can result in students receiving incorrect information and develop misconception about the taught concepts (Council, 2012). One may thus think that a good preparation concerning the content knowledge is enough for the teacher, this is not completely true, since also a good level of pedagogical knowledge has to be acquired. This pedagogical knowledge is defined as "a deep knowledge about the processes and the practice and methods of teaching and learning that and it encompasses overall educational purposes, values and aims" (Koehler and Mishra, 2009). The central aspect of Shulman's PCK theory is the notion of the transformation of the subject matter for teaching and the synthesis of the content and the pedagogical knowledge: under this assumption, an effective teacher formation programme, not only has to take into account these two types of aspects, but they have to be addressed together. This paradigm shift occurs "as the teacher interprets the subject matter, finds multiple ways to represent it and adapts and tailored the instructional materials to alternative conceptions and students' prior knowledge" (Shulman, 1986).

Employing a PCK formation means to allow teachers in developing the needed skills for transforming educational tools and subject content structure to maximize the quality and effectiveness of learning: in other words, the teacher has to be able in transforming the content knowledge and in adapting the educational tools to the students' needs. On a deeper level, in order to reconstruct the content to be addressed taking into account students' learning knots, the teacher has to be aware of the main students' preconceptions, models and representations adopted in interpreting the phenomena, the main ways those models evolve, as well as the role and effectiveness of the educational tools that are suitable for addressing students' need and the capability of choosing and adapting them.

PCK and MER seem similar according to their aim in reconstructing the subject content for the purposes of instruction, but they differ since PCK represents a level that had to
be reached to provide an effective teaching, while the MER is a process aiming at the production of effective teaching materials (as well as a driving methodology for educational research).

1.2.5 Informal learning

The connection between disciplinary contents and the context in which they are applied is the central problem of education, in particular the scientific one (Michelini, 2004b). Knowledge cannot in fact be conveyed already ready (most often summarized and/or reworked) but it must be framed in a phenomenological context and in reference to interpretative models to be compared in a personal and critical way (Michelini, 2004b). A vast literature on learning processes (Miettinen, 2000; Ajello, 2004) shows how simulated or oversimplified experiences are to be considered inadequate to produce a mastery of learning, since the activation of what has been learnt does not occur in different contexts. To overcome the limited boundaries of classroom learning, different learning environments are proposed to gain access to knowledge out of the school and thus induce collaborative learning (Salomon, 1996; Sinko and Lehtinen, 1999). It is therefore important to offer children the opportunity to understand the characteristics of successful actions for learning even outside the school itself (Gardner, 1990). Unlike the so-called "formal learning" which has as its objective the direct transmission of the disciplines as a set of systematically sedimented and organized knowledge and of the so-called "non-formal learning" that has as its objective a knowledge aimed at the operative action and that does not activate or analyze of concepts nor does it require reflections and explanations, "informal learning" is characterized as a result connected to taking an active part in situations being involved in an activity whose meaning is recognized (Michelini, 2004b). Informal learning is a way of establishing contacts between different experiences perceived in relation to a common aspect, and for this reason it is confronted with the question of how to cross the social and cultural boundaries between education and its use (Tuomi-Gröhn and Engestrom, 2003). Informal education plays an important role in learning as it enhances the playful aspect in a conceptual context within which the student autonomously constructs rules and interpretative schemes of phenomena observed in first person (Ajello, 2004; Michelini, 2004b). This is particularly important with regard to scientific disciplines, as the basis of scientific learning processes are both the personal involvement of the student and the manual and conceptual operations that are essential for meaningful learning. Through laboratory teaching, the learner has the possibility of using conceptual re-elaboration tools that can be used in different contexts as knowledge is constructed through a personal interpretative path linked to experience.

1.2.6 Conceptual Laboratories of Operative Exploration - CLOE

An informal learning context suitable to students of different ages, from kindergarten to middle school, and flexible in its use modalities is represented by the GEI (Giochi, Esperien
ten, Idee - Games, Experiments, Ideas) exhibition (Michelini, 2004b). The exhibition is offered to the world of schools by the Research Unit in Didactics of Physics of the University of Udine. The exhibition is divided into thematic sections (such as electrical phenomena, magnetic phenomena, optics, sound, just to name a few) and offers the possibility of conducting individual or small group experimental explorations both in an exhibition context and in the classroom. It consists of simple apparatuses made by assembling in the simplest form easily available and reproducible materials, and makes use of the use of new technologies, such as for example the measurement sensors connected in line with the computer. The accessible and familiar nature of the apparatuses that make up the exhibition
represents the main value both for the learning objectives and for the organization of the activities in the classroom: the teachers can in fact organize different activities simply by borrowing the materials or proposing their reproduction to their students.

As a result of the educational research for learning activities, among the various proposals developed in the exhibition GEI are the Cognitive Labs of Operative Exploration (CLOE). Through these activities the active role of the student finds its expression starting from the interpretative need of a problematic phenomenological situation that is articulated by conceptual micro-steps that stimulate hypotheses starting from the phenomena themselves. The CLOE laboratories are activities led by a researcher or a teacher with groups of children or students on a specific topic: a semi-structured interview protocol is followed, which is the basis on which the conceptual paths and reasoning of the students are developed and followed. On the basis of the stimuli offered through IBL strategies. Through the evocation of family scenarios an initial exploration of the ideas of the participants is carried out on the conceptual knots that are subsequently investigated with experimental and operational proposals. Through the CLOE laboratories, both students and teachers are offered the opportunity to approach contexts and themes that are not dealt with in basic school due to lack of time or because they are considered too difficult. Not only students can benefit from these activities, but also teachers, as they constitute a significant moment for their initial and in-service training on how the proposed themes can be addressed in a research perspective. The CLOE laboratories also provide researchers in physics education with an excellent opportunity to obtain information and indications on reasoning sequences, on the ways in which knowledge is structured, on the evolution of interpretative representations and on the ways in which the relationship between real objects and conceptual structures evolve into a pattern of reasoning proper to children and students and to the ways in which they formalize their knowledge (both past and spontaneous in the field) so as to allow specific insights and development of further proposals useful for learning.

1.2.7 The strategies of the research

Several strategies were adopted in the research work described in this thesis. The choices were mostly driven by the choice of performing qualitative methods of analysis in order to collect and discuss different type of data concerning students’ reasoning and their development. Designed learning paths are characterized by a strong component of active learning allowing students to be personally involved in the process of knowledge construction. Single strategies adopted in the different activities will be justified in depth in the presentation of the activities themselves, but the general approach of the research is to adopt the widest range of possible strategies during the whole work, pointing out for each activity the suitable strategy to be used.

A semiotic strategy based on the analysis of the artifacts, for example, has been adopted in order to explore how student approach the use of a simple object for spectroscopic analysis (i.e. a spectroscope) having never seen such an object before.

Educational approaches based on conceptual change are more effective on learning with respect to the traditional ones (Duit and Treagust, 2003). Learning is suggested to be evaluated on the base of the ongoing monitoring and in terms of comparisons between pre- and post-tests (Psillos and Kariotoglou, 1999) looking at the persistence and stability of conceptions and the way they are used by students in order to give meaning to experimental situations observed during educational interventions. Aspects characterizing ongoing conceptual change (Givry and Tiberghien, 2005) such as: (a) express a new idea, (b) increase or decrease the domain of validity of a certain idea; (c) express link between
different experimental situation have been taken into account in designing educational interventions contributing in designing a vertical path on optical spectroscopy. However, the implementation of the path in a real school setting requires the teacher to move away from the traditional style based on the transmission of knowledge, and build a learning context promoting student’s cognitive activation in which knowledge is built.

The fact that the learning of concepts related to optical spectroscopy can turn out to be difficult has been taken into account: implied concepts of energy states, photon, absorption or emission of radiation, for example, are abstract and their relationship with students’ everyday experience are scarce, or even missing. In this case one of the referent for the negotiation process (i.e. the external reality) and necessary for the cognitive development described by Piaget, is missing. So, considering that the learning of microscopic model accounting for the formation of spectra implies this kind of obstacle, in this research, this difficulty has been taken into account through a gradual path in which information linked to macroscopic observations and the mathematical relationships describing them are compared to produce a physical meaning about the phenomenology. Moreover, microscopic models have been implemented in different problem-solving exercises to foster reasoning development based on models.

The IBL approach has been adopted during the learning paths experimentations in order to allow students face situations to be analyzed and discussed among peers using an argumentative approach and thus creating situation and interpretations that can be used by the students in addressing particular difficult problem solving-like situations proposed during the path. The drawing-up of the monitoring sheets and educational interventions developed in this research followed the guidelines described in (Pirrami, 2010), taking into account that: (a) students samples were not familiar with an IBL approach; (b) given the available times, the inquiry level implied only some of the described stages, offering at the same time, a guidance and a quite strong support to learning. As concern this aspect, the exploration of the phenomenologies was not completely free (typical of an open inquiry), but organized around few but pivotal concepts (i.e. the reading of light-matter interaction in terms of energy avoiding concepts as wavelengths). The adopted inquiry methodology has been guided by a preliminary planning leading students to gradually face real and/or abstract problematic situations, in order to promote a gradual growth of understanding. This approach does not coincide with providing extensive expositions of theory, since learning in physics starts from the exploration of phenomenology and develops through a process of continuous discussion of ideas based on the elements known to allow the student to build knowledge. The formulation of criticisms from students to the proposed explanations has been stimulated to favor the development of critical thinking (Duschl and Grandy, 2008). Taking into account these guidelines, models for optical spectra formation are developed in the research described in this thesis, according to five epistemic characteristics of the scientific knowledge (Windschitl et al., 2008): a model has to be controllable (through comparison between experimental data), revisable (changing according to new proofs or conceptualizations), explicative (it provides causal explanations of phenomena and processes), conjectural (explanations are often based on hypotheses and/or not directly observable processes) and generative (allows forecasting).

As concerns the implementation of the CLOE activities with younger students, the following guidelines have been taken into account: the understanding that the interpretation of an optical spectrum is linked to the energy structure of the source since in an optical spectrum the distribution of the energies representing the only ones that the system is able to lose, requires the use of a global perspective in which all the variables involved in the production of light are simultaneously considered. Pupils must therefore learn to take this
into consideration, just as experienced physicists also need to have in mind the energy mechanism underlying the formation of spectra in order to interpret them correctly. This is the first step in the process that allows pupils to associate the correct meaning with physical laws. For these reasons, direct phenomenological experience must be the first step in the construction of formal thinking that must not be the prerogative of more advanced ages, especially using inappropriate models. The development of formal thought requires the identification of phenomenological aspects and their arrangement in an explanatory scheme linked to the local vision of observed behavior and that reaches the interpretative dimension to the extent that it is able to extend it to different contexts, preserving the founding nuclei and the reference schemes that constitute the heart of interpretative models in application terms. Especially in the case of younger students the expression "knowing the phenomenology" cannot and must not only mean having done a collection of experiments, but implies the observation of what happens in different situations explored with the aim of gradually developing the conceptual referents and adjust the experiences in an interpretative model, which in this case is represented by what physicists call "light spectrum". Specific strategies must be developed to stimulate pupils to make conceptual references explicit, since it is not a spontaneous practice.

1.3 Focus of the research and research questions

The work described in this thesis regards the design and experimentation of an educational path on optical spectroscopy for pupils, upper secondary school and university students, in particular problems arising from educational practice concerning the teaching of the topic are taken into account and analyzed.

The motivation that led us to choose optical spectroscopy and light emission mechanisms as the main topic is manifold: on a cultural plan, the relevance of those phenomena in everyday life, in particular from a technological point of view; the importance of optical spectroscopy on epistemological plan, since it represents a way to obtain information on macroscopic and microscopic systems (stars, galaxies, atoms, structure of matter, ...) using indirect measures based on energy as physicists do; the role that optical spectroscopy has in linking classical and modern physics; the fact that it represent a fertile context allowing students to identify the characterizing elements and the theoretical models that drive the processes under analysis. The research described in this thesis, relying on the guidelines suggested by content-oriented research, provides guidelines directly oriented to the instructional practice on the specific content of optical spectroscopy through the structuring of the conceptual steps and of the instruments of an educational path founded on physics. A relevant aspect is the comparison between expected and obtained students’ learning, that can provide information concerning the validity of the approach upon which the educational path described in this thesis relies on; this comparison is carried out on the basis of semi-structured open-ended questionnaires filled out by students and described in detail hereafter. It is beyond doubt that the step from a physical culture to education requires a great effort in order to point out themes, founding cores and the phenomenology to be put in a coherent interpretative frame on optical spectroscopy.

An investigation concerning the role of modern physics in upper secondary curricula pointed out that there is a need of coherently introducing modern physics in schools; a proposal on optical spectroscopy is suggested as a considerable topic both for its conceptual and applicative implications. Spectroscopy, and in particular optical spectroscopy, plays in fact a pivotal role in modern physics: the first observations of discrete line spectra motivated the idea that matter, atoms in particular, can be described by a set of quantized
energy levels, contributing to the development of modern quantum mechanics. The topic is taught from secondary school to graduate level at university (both for physics students and not-physics students). Typically optical spectroscopy is introduced after addressing geometrical and physical optics, so students have to make a transition from thinking of light as a wave to developing a model in which light consists of photons, whose energies are quantized. Typically, when spectra are observed in the classroom, the experimental setup includes a light source, a slit used as a diaphragm, and a prism or grating and spectra are projected on a distant screen. Despite its importance, very often this topic is not integrated in an organic way in physics curricula, preferring to be addressed in the chemistry courses, or never addressed at all, despite it represents a fertile link between knowledge of models and experimental data on an interpretative plan from a physical point of view. This analysis technique offers an important disciplinary contribution on the epistemological plan of physics, since absorption and emission of quantized radiation are fundamental concepts, representing some of the main investigative tools based on light-matter interaction. Optical spectroscopy represents a context in which to address the role of energy in physical analysis, a validation instrument of interpretative models through indirect measures and a way to interpret a code in order to get information on the changes and the states of a physical system. Moreover it is a methodological context in which tools and methods connecting theory and experiment in physics are prominent, allowing students to gain experience concerning the specific ways of investigation in physics. Moreover, the role of the experimental lab is undervalued, since students do not experience the role of the addressed concepts which are, in the end, analysis techniques.

1.3.1 Hierarchy of research questions

The described theoretical framework set the basis for this work of thesis, structuring and driving modalities according to which research and educational design have been managed. The research, carried out in a perspective according to MER (see section 1.1.2), incorporates a disciplinary (both historical and epistemological) analysis and pedagogical analysis (focused on pointing out spontaneous conceptions, possible learning difficulties and existing educational approaches). This phase represented the preliminary analysis of the educational problem faced in this research, carried out with DBR methods (see Section 1.1.3).

Three levels of research questions (general, specific and detailed) drove the data analysis. General research questions (GRQs) are:

GRQ1) How do students approach conceptual knots individuated by the historical/educational reconstruction of physical basics concepts and by the conceptual understanding of the specific topics (according with literature outcomes and direct inquiry)?

GRQ2) How do activities, simulations and experiments allow to produce students’ conceptual change from spontaneous ideas to a scientific vision of the phenomenology?

GRQ3) How do stimuli questions elicit students’ reasoning and which difficulties persist?

Specific research questions (SRQs) are:

SRQ1) How do the three areas of optics (light propagation phenomena, light-matter interaction and light sources) can be faced to build a coherent vertical path on optical spectroscopy?

SRQ2) How do different approaches contribute in overcoming the conceptual knots?
SRQ3) How do students explain light emission?

SRQ4) How do students coherently correlate macroscopic and microscopic levels of representation?

SRQ5) How do students relate discrete emissions from atoms and their intrinsic quantized energetic structure?

Detailed research questions (DRQs) are reported in Par. 5.4.

Answers to these research questions establish the study of the conditions promoting the learning of optical spectroscopy and they have been searched for defining the specific and founding physical contents to be taken into account.
Chapter 2

An historical study of contents for educational reconstruction

Since optical spectroscopy represents one of the main links from classical to modern physics, its conceptual reconstruction is deeply linked to the historical reconstruction of ideas and of the interpretative models that marked the passage from the two visions of the physical world. The reconstruction for educational purposes that has been carried out in this research work is thus centered on the historical and interpretative evolution of optical spectroscopy, due also to its strong correlation among microscopic interpretation of the light emission processes, the light-matter interaction and on propagation phenomena on an energetic plan. The chosen disciplinary content of the research, imposing an iterative interpretative analysis and revision of models to be compared with experimental data, provides students an important contribution on both epistemological and cultural plan.

In the following both the carried out analysis of historical development of ideas, founding cores and the epistemological aspects taken into account for designing educational paths are described.

2.1 The contribution of history of physics to education: the case of optical spectroscopy

When faced with a phenomenon, often students unconsciously retrace past scientists’ reasoning. Therefore, teacher’s awareness of the history of physical interpretations may give rise to significant considerations. It is important to encourage teachers to reflect on the fundamental concepts of theories and to reconstruct the interpretation of phenomenology (Michelini, 2007). The contribution of historical investigation therefore seems indispensable both in the context of didactic planning and in that of teacher training.

Moreover, taking into account history of physics in the subject’s education might be useful according to its capability in promoting the understanding about the nature of science, in providing scientific clarification of the concepts to be taught and in overcoming conceptual difficulties. Unfortunately, effective implementation of history of physics in standard school and university physics textbooks is rarely satisfying, since textbooks often include just a bit of history, either in a separate chapter or in scattered references, biographical inserts, or schematics representations of pretentious crucial experiments (Matthews, 2015). Rather than simply take into account sporadic historical episodes or anecdotes (turning out in obvious selection biases in choosing the topics to be addressed) or unclear pictures of the relationships between theory and experiment (Robotti et al., 2018) an effective ap-
A approach for including the history of physics in an educational proposal is to rely on the different plans offering a critical analysis of the involved physical concepts. In particular, concerning optical spectroscopy:

- **Epistemological:** in giving meaning to empirical laws describing the phenomenology (for example Balmer's formula describing the position of the optical emission in the hydrogen spectra or Kirchhoff's empirical laws on emission and absorption), concerning the role of interpretative models (for example the energy levels model for atomic structure) and in analyzing the predictive potentialities of the new theories;

- **Historical:** to the extent that the limits of the classical hypotheses about the process of light emission by matter are analyzed and the hypotheses that led to the foundation of modern quantum mechanics are taken into account;

- **Disciplinary:** the path on optical spectroscopy is included in a wider module on optics, building an educational proposal contributing in giving experience both on contents (discussing qualitative and quantitative characteristics of phenomena, involved physical quantities and conservation principles with the corresponding laws and the new considered models, as the one of photon) and on methods (measurements, theoretical previsions, potentialities and limits of an interpretations and mathematical formalism);

- **Educational:** to the extent that the proposal is framed within a consolidated research methodology (i.e. the MER, see Par. 1.1.2) aiming at overcoming the known-in-literature conceptual knots, taking into account also the historical development of ideas.

The role of history in teaching/learning physics configure thus itself as multi-perspective, since it involves differentiated elements founding the connection between education and history: (a) the reproduction of historical experiments; (b) the analysis of original documents, reports and scientific papers; (c) the in-depth analysis of interpretative aspects integrating storytelling; (d) a critical reflection on problematic contents, conceptual knots, alternative theories in crucial moments of the developing of ideas and (e) making use of references to inventories and documentations (De Maria and Ianiello, 2006; Bevilacqua, 1983). Particularly fertile contributions in the history of physics for education are those concerning the epistemic, cultural and methodological aspects (Galili, 2018) and those allowing an in-depth analysis of the spontaneous ideas and conceptual knots, which often coincide with historically documented temporary or partial interpretations. The latter offers a set of arguments for intellectual challenges orienting towards a physical way of thinking placing it in the correct perspective of the evolution of interpretations, each with potentialities and limits.

Since PER literature emphasizes then role of students’ active involvement in the construction of knowledge (Viennot and Raison, 1999; Vosniadou, 2001) and the way it produces the development of formal thinking needed to bridge from common sense ideas to the scientific interpretation overcoming conceptual knots (Michelini, 2006; McDermott, 2004), providing situations in which students investigate themselves the knowledge to be achieved with instruments and methods reproducing the experience of the research is essential. An analysis of the development in the history of physics of the crucial ideas, in particular those ones characterizing the scientific revolutions (Kuhn, 1962), could be the ideal starting point from which building a research on physics education. The analysis of the historical development of ideas turned out to be useful in order to face the interpretative problems related to the phenomenologies/situations addressed in the educational path,
since interpretative difficulties in the history of physics regard the deep comprehension of
the topics, as the guidelines of the MER suggest. In particular, a preliminary historical
analysis of the main physical concepts makes possible to identify which are the important
elements ensuing students to be involved in taking their own path of research and analysis
of phenomena, implying the overcoming of students’ learning difficulties, very often
present also as historical conceptual knots. Taking into account historical aspects related
to the development of scientific ideas and models, students are thus provided with the
elements to achieve a deep understanding of the phenomenology, crucial experiments and
of the empirical laws which enabled the building of the modern theories related to optical
spectroscopy.

Several emblematic publications regarding the development of historical ideas concerning
the interpretation of optical spectra have been selected and analyzed; in the following a
brief review of the main stages describing the development of ideas on different plans (See
Tab. 2.1) is provided.

2.1.1 Descartes and Newton on the production of colors from white light

The composite nature of white light was first demonstrated in 1664 by Newton when he
allowed a beam of sunlight to pass through a triangular glass prism and fall on a screen,
but one of the first attempts to account for the production of colors from the interaction
of white light with a transparent prism was made by Descartes in 1637: according to the
French philosopher, the sensation of color originates from the different rotation given to
particles by the phenomenon of refraction, whereby the eye undergoes a diversified pressure:
a greater rotation causes a greater pressure and it is associated with the sensation of red,
while the sensation of blue is given by a minor pressure. Descartes imagined that the prism
had the power to "transform" the kinetic properties of light passing through it. Newton
imagined and performed an "Experimentum Crucis" (Fig. 2.1) to prove the groundlessness
of Descartes' hypothesis: a thin beam of light, which enters through a small hole in the
window shutter, crosses a first prism, producing a fan of colors onto a perforated panel,
placed at a distance of about three meters and a half. In this way, a rainbow-colored
figure is projected, oblong in the vertical direction, but with horizontal bands of color in
succession from red to blue. Newton added a second panel and a second prism. He drilled a
hole in the panel, allowing a part of the oblong band of light directed toward the other side
to pass through it and then directed the beam that emerged towards the wall. By rotating
the first prism, he could move the oblong band up and down, so that a light of different
colors would pass through the hole, and then through the second prism, towards the wall.
He then observed exactly what was happening: the blue light, which was very refracted by
the first prism, was also from the second; similarly the red light, which was less refracted
by the first prism, was less refracted by the second. He also noted that the way these rays
were refracted did not depend on the angle of incidence (the angle at which they hit the
surface of the prism). Newton concluded that the extent to which the rays were reflected
was a property of the rays themselves and not of the prism. The rays, passing through the
two prisms, maintained their refraction: the prisms did not modify the rays of light, but
limited themselves to separate them according to their different refrangibility. Conclusions
drawn by Newton are thus the following (Newton, 1993):

"Then light consists of rays differently refrangible, which, without any respect to a
difference in their incidence, were, according to their degrees of refrangibility, trans-
mitted towards divers parts of the wall. [...] Light itself is a heterogeneous mixture of
differently refrangible rays."

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Table 2.1: *Chronology of significant discoveries, theories and crucial experiments about optical spectroscopy. Review from (Meggers, 1964; Beherens, 1943).*

<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Theme</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. Descartes (1637)</td>
<td>Colors are generated inside a prism</td>
</tr>
<tr>
<td>I. Newton (1664)</td>
<td>White light is composed by colors (Newton, 1993)</td>
</tr>
<tr>
<td>T. Melvill (1752)</td>
<td>First observation of emission discrete spectra (Watson, 1952)</td>
</tr>
<tr>
<td>W. Herschel (1800)</td>
<td>Discovery of IR radiation</td>
</tr>
<tr>
<td>J.W. Ritter (1801)</td>
<td>Discovery of UV radiation</td>
</tr>
<tr>
<td>T. Young (1802)</td>
<td>Measurements of wavelength of different colors</td>
</tr>
<tr>
<td>W.H. Wollaston (1802)</td>
<td>First observation of absorption lines in sunlight spectrum</td>
</tr>
<tr>
<td>J. von Fraunhofer (1814-17)</td>
<td>Measurements of absorption lines wavelength in sunlight spectrum</td>
</tr>
<tr>
<td>G.R. Kirchhoff and R.W. Bunsen (1860)</td>
<td>Measurements of emission lines wavelength in different gases (Kirchhoff and Bunsen, 1860)</td>
</tr>
<tr>
<td>L. Boltzmann and J. Stefan (1879-1884)</td>
<td>Empirical law for thermal emission (Stefan, 1879; Boltzmann, 1884)</td>
</tr>
<tr>
<td>A.J. Ångström, H.A. Rowland and A.A. Michelson (1868-1892)</td>
<td>Measurements of emission/absorption lines wavelength in astronomical sources</td>
</tr>
<tr>
<td>J.J. Balmer (1885)</td>
<td>First empirical formula describing wavelengths in H spectrum (Banet, 1966, 1970; Balmer, 1885, 1897)</td>
</tr>
<tr>
<td>J.R. Rydberg (1889)</td>
<td>Use of wavenumber to describe series in discrete spectra (Bohr, 1954)</td>
</tr>
<tr>
<td>J.J. Thomson (1904)</td>
<td>Oscillating electrons in a &quot;plum-pudding&quot; atomic models (Thomson, 1904; Beherens, 1943)</td>
</tr>
<tr>
<td>A. Einstein (1905)</td>
<td>Model for the photoelectric effect (Arons and Peppard, 1965)</td>
</tr>
<tr>
<td>W. Ritz (1908)</td>
<td>Magnetic model of atom (Ritz, 1908; Beherens, 1943)</td>
</tr>
<tr>
<td>H. Nagaoka (1904)</td>
<td>First planetary model of the atom (Nagaoka, 1904; Beherens, 1943)</td>
</tr>
<tr>
<td>E. Rutherford (1911)</td>
<td>Planetary model of the atom (Rutherford, 1911; Beherens, 1943)</td>
</tr>
<tr>
<td>A.E. Haas (1910)</td>
<td>First quantized planetary model of the atom (Haas, 1910; Beherens, 1943)</td>
</tr>
<tr>
<td>N. Bohr (1913)</td>
<td>Final quantized planetary model of the atom (Bohr, 1913; Heilbron and Kuhn, 1969)</td>
</tr>
</tbody>
</table>
2.1.2 Melvill and the first observation of discrete spectra

The first use of a prism to study the light from colored flames is due to Melvill in 1752, and the discovery of discontinuous emissions spectra coming from his studies was no accident: it was clearly the result of a mind having set itself the job of extending the earlier work of Newton (Watson, 1952):

"Having placed a paste-board with a circular hole in it between my eye and the flame of the spirits, in order to diminish and circumscribe my object, I examined the constitution of these different lights with a prism and found that in the first case when sal. ammon alum or potash fell into the spiritus, all sorts of rays were emitted, but not in equal quantities: the yellow being vastly more copious than all the rest put together, and red more faint than the green and blue. In the light of spirits mixed with nitre or sea-salt, I could still observe some blue, tho’ excessively weak and dilute: with the latter, the green was equally faint, but, with the former, pretty copious. [...] The proportion in which the bright yellow exceeds the other colours in this light, is still more extraordinary than in the former, insomuch that the hole seen thro’ the prism appears uniformly of this yellow."

Melvill speaks of heterogeneous lights, in the sense that light composed by different amount of colors can exist and the spectral features are characteristic of a given element. That is indeed a clear observation of a discontinuous emission spectrum, even though a circular aperture instead of a narrow slit is used (as Newton did), as pointed out by Melvill himself (Watson, 1952):

"Because the hole appears thro’ the prism quite circular and uniform in colour: the transition from it [yellow] to the fainter colour adjoining is not gradual, but immediate."

The importance of Melville’s observations relies on the fact that until then almost all optical experiments have been made with sunlight, and no one seems to have thought of comparing this with the light of other burning bodies, from which it is possible that considerable discoveries might arise (Priestley, 1772). The implications of his pioneeristic observation were clear to Melvill, who realized the importance of the spectroscopic analysis of light emitted by different bodies in order to characterize them form a physical point of view (Watson, 1952):

"Are not the rays, emitted by all sort of luminous bodies, similar to those of the sun, both as to colour and degree of refrangibility? And, do not luminous bodies differ from one another only according to the colours which they emit most plentifully, in like manner as opaque bodies are distinguished by the colours of incident light which they reflect in greatest abundance? But to make our induction sufficiently strong ought not experiments to be made with lights of a greater variety of bodies?"
2.1.3 Herschel and Ritter: crucial experiments on light carrying energy

Light is an entity carrying energy. Two crucial experiments have been made in order to demonstrate this fact. In order to explore the heating power of different colors in the sunlight spectrum, in the year 1800 Herschel measured the registered temperature in different parts of the spectrum. In the original experiment, he used three thermometers (two monitored the temperature in the room, the third was illuminated by light that had passed through the prism). He found that as this third thermometer was moved from the violet end to the red end of the spectrum, the temperature got progressively higher, showing that the intensity of the radiation was increasing. Noticing this trend, he placed the thermometer just outside of the red edge of the spectrum, where no light seemed to be falling, and found that at that location the temperature was the highest. This indicated the presence of a sort of invisible light, he called "dark heat" or "caloric rays". He also found that this radiation, now known as infrared rays, is reflected, refracted, absorbed, and transmitted just like visible light.

Inspired by the discovery of IR radiation and by the theoretical idea that bipolar nature characterizes every natural phenomenon, Ritter in 1801 wondered if, existing an invisible radiation beyond one edge of the spectrum, there was another over the other edge. Knowing that the silver chloride became dark in the presence of light, he placed a sheet soaked in silver chloride to collect the radiation decomposed by a prism and he noticed that red light caused little dark changes while the area beyond the violet edge turned dark much more intensely and quickly, witnessing the presence of a radiation able to activate chemical reactions.

2.1.4 Young and the measures of colors' wavelengths

In 1802, Young substituted his wave theory of light for Newton's corpuscular theory explaining interference phenomena and calculating the approximate wavelengths of the seven colors recognized by Newton (red, orange, yellow, green, blue, indigo and violet).

2.1.5 Wollaston and von Fraunhofer: observations of discrete absorptions in sunlight spectrum

In 1802 Wollaston reported for the first time the presence of few dark lines in the spectrum of sunlight, but only in 1814 Fraunhofer used a telescope and a narrow slit to systematically observe the solar spectrum; he observed the colored spectrum observed by Newton 150 years before interrupted by many hundreds of dark lines (lacking light, known as "absorption lines") as shown in Fig. 2.2. He labeled the principal ones with the letters A, B, C, D, ... providing a reference marks in the solar spectrum, without explaining their origin.

2.1.6 Kirchhoff and the empirical laws of emission and absorption

Fraunhofer was the first to observe that high-voltage electrical discharges between metal electrodes in a gas produced a discontinuous spectrum of bright lines. After him, many other scientists investigated emission spectra of substances excited in flames or through electrical arcs, but none of them clearly recognized that both absorption and emission features are characteristics of the atoms or molecules producing them. Although it was observed that certain bright lines in emission spectra produced in laboratory seemed to correspond with some dark absorption lines in the solar spectrum, it remained for Kirchhoff, in 1859, to formulate the general empirical laws connecting absorption and emission of light,
emphasizing the fact that each species of atom has a uniquely characteristic spectrum. Kirchhoff’s law are the following:

- A hot solid, liquid or gas under high pressure produces a continuous spectrum;
- A hot gas under low pressure produces a bright-line emission line spectrum;
- A dark line or absorption line spectrum is seen when a source of a continuous spectrum is viewed behind a cool gas under pressure. For the same gas, absorption lines are in the same position of the emission lines.

Using Kirchhoff’s own words (Kirchhoff, 1863):

"I also have a few points to mention concerning the history of the chemical analysis of the solar atmosphere. The core of the theory of solar chemistry that I have developed consists of a proposition that, shortly stated, says: For each kind of (heat or light) rays, the relation between the emission power and absorption power is the same for all bodies at the same temperature. From this proposition it easily follows that a glowing body that only emits light rays of certain wavelengths, also only absorbs light rays of the same wavelengths; whereas it is revealed how it is possible to know the constituents of the solar atmosphere from the dark lines of the solar spectrum."

This statement had the form of a simple law of equilibrium, having nothing to do with specific models for atomic or spectral structure; what makes this historical example so interesting (Stern, 2014) is that Kirchhoff did not provide an adequate theory for the cause of spectral emission and absorption.

### 2.1.7 Kirchhoff and Bunsen on the cataloging of elements using spectra

A careful and systematic comparison between the position and relative intensities of Fraunhofer lines and the emission lines emitted by flames or sparks in gases (using the purest elements available at that time) was performed by Kirchhoff and Bunsen in 1860 allowing the first chemical analysis of the sun’s atmosphere and founding the spectrochemical analysis. The invention of a nonluminous gas burner, due to Bunsen, was a great advantage for their work, in the course of which two new chemical elements, i.e. cesium and rubidium were discovered after the observation of unmatched emission lines using a prism spectrograph (Fig. 2.3). The greatest obstacle preventing the development of spectral analysis was the complexity of observed spectra. Fortunately for Kirchhoff and Bunsen, the limitations of the equipment they were using compelled them to work with oversimplified data, containing only the more evident characteristics of each analyzed spectrum.
Ångström, Rowland and Michelson: refining standards and detecting spectral features in astronomical sources

The great achievements obtained by Kirchhoff and Bunsen greatly stimulated spectroscopic research stressing the need for accurate standards of wavelengths also for the calibration of new instruments. The first useful standards were provided in 1868 by Ångström, who used plane diffraction gratings instead of prisms in order to produce clearer spectra. He measured the wavelengths of about 1000 Fraunhofer lines publishing the results of his depth research in *Recherches sur le spectre solaire* (1868) (Meggers, 1964). To be noticed that the relevant physical quantity employed to measure the position of lines, in a wave model for light is the wavelength. Ångström was the first, in 1867, to examine the aurora boreal spectrum, in which he identified and measured the characteristic bright line in the yellow-green region of the optical spectrum.

Further refinements in setting a standards were made by Rowland, who invented the concave diffraction grating to map the solar spectrum, while in 1892, Michelson used an interferometer, invented by him, to measure the wavelengths of 48 cadmium lines with high accuracy.

Spectroscopists began to obtain data concerning wavelengths of several million lines observed in atomic, ionic and molecular spectra which presented great variety and complexity, ranging from about 50 lines for hydrogen, to over 100000 for uranium. Since the wavelengths of these lines were fundamental for chemical identification of elements, they had to be measured as accurately as possible. By employing interferometers or highly dispensing diffraction gratings, thousand of wavelengths had been accurately determined up to 8 significant figures.

Balmer and Rydberg: searching for regularities in discrete spectra patterns

Atomic spectra, with the exception of hydrogen, generally appear to consist of a random distribution of lines of different wavelengths and intensities. After a period of huge effort to generate catalogues of wavelengths, a new line of research began to look for regularities in the observed spectral pattern. In 1885 Balmer succeeded in the attempt to find a special numerical relation among lines, announcing the discovery of the formula representing the wavelengths of four visible lines in the hydrogen (the simplest of all atoms) spectra that
were arranged in a convergent series:

\[ \lambda = 3645.6 \cdot \frac{n^2}{n^2 - 4} \\text{Å} \]

where \( n = 3, 4, 5, 6 \) for the first, second, third and fourth observed line. Balmer’s intuition, allowing him to see the patterns he then described using the previous formula, was based on models written in the language of projective and descriptive geometry and embedded in the context of classical architecture (Banet, 1966, 1970). Such language and context are disconnected from physics, so perceived as exogenous, extraneous or exotic. Moreover, the models used by Balmer, based on geometry, and the target application in spectroscopy, seem to be unrelated in time (Stern, 2014). Balmer trial-and-error attempts to obtain a reliable formula are clearly expressed by him (Balmer, 1897):

"Extending the calculations based on the last estimated constants to the following (spectral) lines, resulted in an average deviation from the measured wavelengths of only about 1/4 of a unit. Obtaining such a closely correct result in the first trial of this formula - using only round integer numbers for the first and second constants, was for me a great surprise, that strengthened to the highest degree my conviction that this formula is the most adequate expression for a physical truth."

Balmer suggested for the first time that spectral lines may occur in convergent series and that the position of such lines may be represented by a constant and by small whole numbers. Subsequently, in later years, five additional series in hydrogen spectrum were found by Lyman, Paschen, Pfund, Brackett and Humphreys. Each of them resembles Balmer series, with different integers. These series are displayed in Fig. 2.4. The evident periodicity in the physical and chemical properties of the elements when arranged in order of increasing atomic weights led Rydberg, who had a special disposition for numerical calculations, to search for regularities in the optical spectra of the elements. The great refinements of measurements available permitted him to establish arithmetical relationships with high accuracy. A great step towards the interpretation of discrete spectra occurred in 1889 when he began to use wavenumbers \((1/\lambda)\) rather than wavelengths \((\lambda)\) in order to describe the positions of the lines and the relationships between them. A new pattern arose, since he found that wavenumbers of spectral lines forming convergent series could be represented by the difference between two numerical quantities, named "spectral terms":

Figure 2.4: Diagram showing energy levels for neutral hydrogen, giving rise to different spectral series (Meggers, 1964).
\[ \frac{1}{\lambda} = L - \frac{R}{(n + \mu)^2} \]

where \( L \) is a constant limit of the series (corresponding to \( n = \infty \)), \( R \) the Rydberg universal constant \( (R = 109737.31 \text{cm}^{-1}) \) and \( n \) assumes successive integral values to which a constant term, depending from the element, \( \mu \) is added. Rydberg's formula turns out to correspond to the Balmer's one if \( \mu = 0 \). Spectral series of lines are characterized by similarities in apparence (sharp, diffuse, etc, ...) as well as by gradual armonious decreasing in intensity and separation. As reported in (Bohr, 1954):

For Rydberg's great achievements in this respect, it was a happy intuition from the beginning to look for relations not between the directly measured wavelengths of the spectral lines, but between the reciprocal figures expressing the number of waves per unit length, now know as wave numbers. To this choice he was led through the constant differences between wave numbers occurring in so-called doublet and triplet lines. [...] The tracing of these equal spacing was an original discovery. [...] Rydberg extensively used wave number differences as a main tool for his disentangling of spectral regularities.

The idea for his formula, came to Rydberg after observing that in all the series in the analyzed spectra when described by means of wave numbers and suitably arranged by displacement of the wave number scale, showed such close relationships that he was led to represent the wave numbers for the lines in each series by the difference between a constant term \( L \) and a term \( \phi(n + \mu) \) which commonly to all series, decreased when progressing through the series according to the integer index \( n \). This general relation is expressed by the formula:

\[ \frac{1}{\lambda} = L - \phi(n + \mu) \]

As a first attempt to determine the unknown function \( \phi(n + \mu) \), which has to converge to zero for increasing \( n \), Rybberg tried the form:

\[ \phi(n + \mu) = \frac{C}{n + \mu} \]

obtaining neither a satisfactory agreement for any longer series nor the required constancy for the parameter \( C \) for all series. A second attempt led Rydberg to try with the form:

\[ \phi(n + \mu) = \frac{R}{(n + \mu)^2} \]

When testing this new version of his formula, Rydberg become aware of Balmer simple empirical formula for hydrogen, which with extraordinary accuracy accounted the wavelengths of the well-known series of hydrogen lines. Substituting wavelength by the corresponding wave numbers, Rydberg wrote the Balmer formula in the following form, representing a special case of his own one:

\[ \frac{1}{\lambda} = \frac{R}{2^2} - \frac{R}{n^2} \]

Following this way, Rydberg traced even more intimate connections between the different series in the spectrum of an element: he found not only that certain series with different values for \( \mu \) had the same value for the parameter \( L \), but that quite generally the value of the constant term \( L \) in any given series coincided with a member of the sequence of the variable terms in some other series of the same element: the difference between the limit for the series labeled \( P \) and the common limit for series labelled \( D \) and \( S \) was
equal to the wave number of the first member of P series, an empirical rule, known as "Ritz combination principle". Rydberg thus proposed a comprehensive formula for every spectral line of an element, according to which each series corresponds to a constant value of \( n_1 \) and a sequence of values for \( n_2 \):

\[
\frac{1}{\lambda} = \frac{R}{(n_1 + \mu_1)^2} - \frac{R}{(n_2 + \mu_2)^2}
\]

2.1.10 Thomson, Ritz, Nagaoka, Haas on developing atomic models accounting for spectra

At the beginning of the twentieth century, phenomena such as the density distribution of the energy of the radiation emitted by a blackbody, or the discrete spectra of gases could not be adequately explained using classical physics based on electromagnetic waves assumption. The aforementioned phenomena regards emission and absorption of electromagnetic radiation; in fact it was the attempt to explain how electromagnetic radiation interacts with matter that challenged physics with new contradictions producing crisis (Einstein and Infeld, 1938). Empirically, it was known that every element in the gaseous state, if heated, emits a light composed of characteristic colors. This property led physicists to hypothesize that the spectrum must be related to the atomic structure of the emitting element.

After Rydberg’s pionieristic work, the search for physical mechanisms able to explain the spectral regularities encountered apparently insurmountable difficulties. This section will deal mainly with the quantum interpretation of spectra and the development of hypotheses concerning atomic structure and atomic properties: after about three centuries, physical models for atoms accounting for the formation of spectral lines began to be suggested, overcoming simple qualitative analysis or calibration measures, that, on the other hand, provided the basis for comparing theoretical previsions with experimental results.

Starting from the presupposition that any acceptable theory of atomic structure had to explain the emission of lne spectra, the first of this theory trying to account for discrete spectral emissions was offered in 1904 by Thomson (Thomson, 1904; Beherens, 1943). He was aware that the mass of an electron is of the order of 1/2000 the mass of an hydrogen atom, moreover the electromagnetic theory postulated the existence in the atom of elementary particles normally at rest, but which on being disturbed would vibrate with the frequency required to produce the characteristics line spectra. The reasonable assumption that the electrons (and not the positively charged parts of the atom) would vibrate and thus emit radiation is due to their much lighter mass. Thomson described an atom consisting of a sphere positively charged with dimension of the order of \( 10^{-10} \text{cm} \) throughout which electrons were distributed in fixed positions thanks to electrostatic forces. If electrons were displaced from their equilibrium positions, they would be acted on by a return force proportional to the displacement, giving rise to an harmonic motion and thus producing radiation of corresponding frequency. Despite this attempt, this model failed in accounting for atomic spectra: the hydrogen atom, for example, has one electron which Thomson’s theory placed at the center (the only possible equilibrium position). If displaced from this position it would vibrate with a certain frequency and would be capable of emitting radiation of only that frequency, turning out in a spectrum with a single line, in evident contrast with the evidences. Moreover, according to the classical theory of oscillation, a series of frequency composed by a fundamental one and multiple harmonics is expected, instead, it turned out to be impossible to obtain expressions for wavelengths/frequencies of the spectral lines depending from the square of a quantity,
as the empirical evidences suggested. The final blow causing the Thomson model to be
obsolete came in 1912 from the experimental work by Rutherford, proving that the central
positive charge in atoms must occupy a very small volume with respect to the whole volume
occupied by the atom. Moreover, as early as in 1906, Rayleigh suggested to set up the
problem in a different way with respect to the classical theories: spectral lines could be
caused by a perturbation of the equilibrium condition of the atom, condition that, before
perturbation, prevent the emission to occur, and the emitted frequencies could correspond
to the initial distribution of the electrons rather than their oscillations.

An interesting attempt to arrive at an atomic model explaining the law of spectral series
was made by Ritz in 1908 (Ritz, 1908; Beherens, 1943) giving results formally equivalent
to the ones obtained by Rydberg: starting from the observation that any analysis of the
normal modes of vibrations of a stable mechanical system leads to a relation involving the
squares of the frequencies, and not the frequency themselves as reported by experimental
data, guided Ritz in introducing the idea of atomic magnetic field, whose effect on the
electric constituents of the atom, in contrast to ordinary mechanical forces, depend intrin-
secally on the velocities. He pointed out that the known series laws involve the frequency
\( \nu = c/\lambda \) instead of \( \nu^2 \) as would be expected, since the acceleration is \( (d^2/dt^2)[\sin(\nu t)] \).
Thus the forces appear to be proportional not to the position, but to the velocity of the
electron, as in the case of motion of a charge in a magnetic field. This suggested Ritz the
hypothesis that the frequencies in spectral series are generated by purely magnetic forces.
A massive charged particle (with mass \( m \) and charge \( e \)) in a magnetic field of magnitude
\( H \) parallel to the \( z \) axis has the following equation of motion:

\[
\begin{align*}
    m\ddot{x} &= \frac{eH}{c}\dot{y} \\
    m\ddot{y} &= -\frac{eH}{c}\dot{x} \\
    m\ddot{z} &= 0
\end{align*}
\]

whose solutions are the ones describing an helicoidal motion (with a circular vibration
frequency of \( \frac{eH}{2\pi mc} \)):

\[
\begin{align*}
    x &= A \sin \left( \frac{eH}{mc}t \right) \\
    y &= A \cos \left( \frac{eH}{mc}t \right) \\
    z &= z_0 - Bt
\end{align*}
\]

with \( A, B, z_0 \) arbitrary constants. Ritz assumed that \( H \) is due to an atomic magnet
of strength \( \mu \) and length \( l \). Assuming the electron to be located on the axis of the magnet
produced a distance \( r \) from its nearest pole, one obtains:

\[
H = \mu \left[ \frac{1}{r^2} - \frac{1}{(r+l)^2} \right] \tag{2.1}
\]

giving:

\[
\nu = \frac{\mu}{e mc} \left[ \frac{1}{r^2} - \frac{1}{(r+l)^2} \right] \tag{2.2}
\]

Since wavenumber and frequency are directly proportional, this equation is formally equi-
valent to the Rydberg one, involving a difference between two quantities. Ritz considered
the similarity very significant, taking into account also a formula he derived empirically by
himself:

$$\nu = R \left[ \frac{1}{a^2} - \frac{1}{(n+a+b/n^2)^2} \right]$$  \hspace{1cm} (2.3)$$

where \( R \) is the Rydberg constant, \( a \) and \( b \) are constants depending on the kind of atom and series considered and \( n \) takes successive integer values. In the case of hydrogen \( b = 0, a = 2 \), \( n = 1, 2, 3, \ldots \) and the previous formula become:

$$\nu = R \left[ \frac{1}{a^2} - \frac{1}{(n+a)^2} \right]$$  \hspace{1cm} (2.4)$$

If in Eq.2.2 it is set \( r = as \) and \( l = ns \) with \( s = \text{const} \):

$$\nu = \frac{\mu e}{s^2 mc} \left[ \frac{1}{a^2} - \frac{1}{(n+a)^2} \right]$$  \hspace{1cm} (2.5)$$

It is evident that this equation is identical with Eq.2.2 if \( R = \mu e/s^2 mc \). Since \( l \) is the length of the magnet and \( n \) is an integer, it appears that this magnet, the length of which is a multiple of \( s \) must be formed by placing \( n \) magnets of length \( s \) pole to pole. Ritz showed that these magnets might be electrons, possibly of a cylindrical shape, with their charge distributed uniformly over the surface and spinning about their own axes. As an hypothesis, the spinning electrons would not radiate energy, and this was a prime consideration in all atomic theory prior to Bohr. If the length of the elementary magnet is changed and \( r \) is varied properly, Eq. 2.2 can be rewritten:

$$\nu = R \left[ \frac{1}{(a+\alpha)^2} - \frac{1}{(n+\beta)^2} \right]$$  \hspace{1cm} (2.6)$$

where \( \alpha \) and \( \beta \) are constant depending on the kind of atom, and this is the Rydberg formula.

The first attempt in constructing a nuclear atom was made by Nagaoka in 1904, when he proposed a model of atom composed of a large number of electrons equally spaced in a circle, with a heavy nucleus at the center (the so-called "saturnian model"). The particle could oscillate either radially or normally to the plane of the orbit, while maintaining constant speed in the circular orbit. He did not calculate any frequencies of radiated energy. He suggested the breaking of the ring as a possible cause of radioactive emission (Behrens, 1943).

In 1911 Rutherford proposed his well-known atomic model, which differed essentially from the Thomson one in that the positive charge was concentrated in the center instead of being uniformly distributed, with electrons moving around it. It was however impossible to explain how equilibrium could be secured: since if the electrons were at rest, they would fall into the nucleus due to electrostatic attraction; the electrons could have a circular motion around the nucleus ensuring a dynamical equilibrium. However, an accelerated charge emits radiation and consequently it looses energy. This causes the electrons to approach the nucleus by a spiral path and to emit radiation on increasing frequency. This is in contradiction to the observed sharpness of spectral lines.

2.1.11 The quantized atom

Attempts to use the classical theory to suggest a model of the atom failed. A new point of view was suggested by Planck in 1900 (Planck, 1901) when he proposed, for blackbody radiation, that the elementary oscillators causing the emission possess all possible frequencies of vibration, but not all energy of vibration, assuming that the energy of each oscillator
must be an integer multiple of the quantity $h\nu$. Even if it was impossible to reconcile this assumption with the theory that light travels as a wave, on the basis of a corpuscular theory of light, as the one suggested by Einstein in 1905 (Arons and Peppard, 1965), quantization of light energy could be easily conceived. As an obvious step it was worth to try to apply this new theory to the explanation of spectral radiation and to atomic structure. Another clue was hidden in the well-known fact that it was impossible, starting from the two characteristics describing the atom (mass and charge), deriving a quantity with the dimension of a length or a frequency, needed for describing spectral lines. Thomson’s model provided the typical dimension of the atom, but when the model became obsolete, it was necessary to introduce, near the atomic parameters another physical quantity, and Planck’s constant $h$ seemed to be appropriate.

The first attempt of using quantization to the modelling of the atomic structure is due to Haas (Haas, 1910): he computed the total energy of the hydrogen atom according to Thomson’s model by making use of ordinary mechanical formulae, then he computed $h\nu$ for this atom and compared the results. He imagined an atom of radius $a$ inside which an electron moves in a circular orbit of radius $r$. The force with wich the electron is attracted to the center of the atom is $e^2/a^3$ and its kinetic energy is $e^2r^2/2a^3$ equal to the potential one. If $r = a$ the energy (both kinetic and potential) is $e^2/2a$ and the total energy is $e^2/a$. The frequency of vibration was evaluated as follows: the force acting on a particle undergoing simple harmonic motion is $4\pi^2\nu^2r$; equating this to $e^2r/a^3$ Haas obtained:

$$\nu = \frac{e}{2a\pi(am)^{1/2}}$$

Assuming certain values (see (Beherens, 1943)) he obtained the ratio $e^2/a$ to $h\nu$ almost equal to unity, that is $h\nu$ was about equal to the total energy of the atom.

The sketchy attempt by Haas at quantizing the atom was followed, in 1912, by a more ambitious effort by Nicholson: he assumed a series of hypothetical elements with the simplest possible types of atoms. He supposed to have an atom consisting in a nucleus of negligible size surrounded by a ring of four electrons supposed to vibrate in a direction normal to the plane of the ring. The energy of the system was calculated from the principles of mechanics, and was found to bear a constant ratio to the frequencies with which the electrons would have to vibrate in order to emit certain wavelengths. This led Nicholson to think that the atom might be considered from the point of view of the Planck oscillator (McCormmach, 1966):

"According to Planck theory, we are led to suppose that the lines of a spectral series can be emitted not only from the same atom, but from atoms whose internal angular momentum has diminished of discrete quantities. According to this hypothesis different types of hydrogen atoms should exist, with same chemical properties and same weight, but different in their internal motions. [...] if an atom losses its energy by discrete amounts rather than in a continuous way should result in a spectrum composed by a finite number of lines, each corresponding a possible energy state. Moreover its inability of emitting in a continuous way, should ensure the sharpness of the observed spectral lines, [...] since the variable part of the energy of an atomic system of the present form is proportional to $mn^2\nu^2$ so $E/\nu = mn^2\nu$ or $mn\nu$, which equals the total angular momentum of the electrons around the nucleus. [...] it may mean that the angular momentum of an atom can only rise or fall by discrete amounts when electrons leave or return."

This is one of Bohr’s fundamental assumptions, even if he pointed out that Nicholson’s theory does not seem able to account for Balmer and Rydberg’s laws. Moreover he underlined that (Bohr, 1913):
"In Nicholson's calculations the frequency of lines in a spectrum is identified with the frequency of vibration of a mechanical system in a specific state of equilibrium. As a relation from Planck's theory is used, we might expect that the radiation is sent out in quanta, but system like those considered, in which the frequency is a function of energy, cannot emit a finite amount of a homogeneous radiation, for, as soon as the emission of radiation is started, the energy, and also the frequency of the system is altered. [...] Finally, according to Nicholson, the systems are unstable for some mode of vibration."

This last observation is linked to the observed sharpness of the lines: this evidence demands that the radius of the ring of electrons should remain invariable, or should have only a definite number of possible values, jumping from one to the other instantaneously as the energy is lost by radiation.

The aforementioned theories paved the way to Bohr's model from the atom (Robotti, 1906, 1978), valid in the simple case of the hydrogen atom and based on a series of three ad-hoc hypotheses (Bohr, 1913)

- In the hydrogen atom, the electron can be found only in certain equilibrium states (named "stationary states") defined by their energy $E_n$. In these states, the electron's acceleration does not result in radiation and energy loss, contrary to what classical electromagnetism suggests;

- Classical mechanics is valid only to determine the dynamical equilibrium of those stationary states (i.e. to determine radii and orbital frequencies of the orbits);

- Radiation is emitted only when an electron changes its energy state two stationary states, emitting a radiation of frequency $\nu$ such that $E_{n1} - E_{n2} = h\nu$.

Under those assumptions it is possible to evaluate the different radii of the orbits, as well as their energies making use of classical calculus. Bohr's initial goal was to develop an atomic model consistent with the nuclear one proposed by Rutherford. Even if at the beginning he realized that the frequencies of the spectral lines could be simply a guide for developing a satisfactory model, without directly taking spectra into account, the main result of the model was the excellent ability in predicting the known observed spectral frequencies in hydrogen spectra. The conceptual innovation was represented by abandoning the classical model according to which an oscillating charge emits an electromagnetic wave with a frequency equal to the oscillation one. In Bohr's hypotheses, the emissions of radiation was due to transitions between stationary states with a well-defined energy.

In the following the reasoning followed by Bohr in order to obtain the energy of the stationary states is reported, in order to highlight the quantization hypotheses he made: he imagined a bi-dimensional model of an hydrogenoid atom consisting in a nucleus with mass $M$ and charge $+Ze$ around which an electron (charge $-e$) with mass $m \ll M$ moves in a circular orbit of radius $r$ (the hypothesis of a circular orbit is not justified, but used to simplify the calculations). In the light of the hypothesis made, the total energy of such a system is:

$$E_n = E_k + E_p = \frac{1}{2}mv^2 - \frac{kZe^2}{r}$$

(2.7)

Since in a circular motion, the centripetal force keeping an electron on its orbit equals the electrostatic one:

$$ma_c = m\frac{v^2}{r} = \frac{kZe^2}{r^2} \Rightarrow mv^2 = \frac{kZe^2}{r}$$

(2.8)
Equation 2.7 can be rewritten in a simpler fashion (the minus sign has the meaning that $E$ is a bonding energy, i.e. in order to separate the electron from the nucleus a certain amount of energy has to be spent):

$$E_n = -\frac{kZ^2e^2}{r}$$  \hspace{1cm} (2.9)

Bohr defines $E = -E_n$ as the energy irradiated in forming such a bond system, i.e. to bring an electron from $r = \infty$ to an orbit of radius $r$. It is possible to compute the value for the frequency of the electron moving around the circular orbit $\nu = \nu(E)$ using the relation for the circular motion $v = 2\pi r\nu$ and the Equations 2.7 and 2.8,

$$\nu = \frac{\sqrt{2E^3/2}}{\sqrt{m\pi kZe^2}}$$  \hspace{1cm} (2.10)

As Bohr smartly suggested, if $E$ is not assigned, it is not possible to assign values to $\nu$; in order to define $E$ (the irradiated energy in forming the system) Bohr relied on Planck’s hypothesis (Planck, 1901):

*The central point in Planck’s radiation theory is the hypothesis that the irradiation of an atomic system is not a continuous process, as supposed in ordinary electrodynamics, but that it occurs through separate processes such that the emitted amount of energy from an atomic oscillator of frequency $\nu$ is $nh\nu$ where $n$ is an integer number and $h$ a universal constant.*

Bohr thus considered the process of bringing an electron from $r = \infty$ to an orbit of radius $r$ characterized by the previous computed frequency $\nu$:

$$E = nh\nu$$  \hspace{1cm} (2.11)

To be honest, in this point of the reasoning, Bohr introduced an ad-hoc hypothesis, according to which, instead of relation 2.11 he used:

$$E = \frac{nh\nu}{2}$$  \hspace{1cm} (2.12)

which differs from Planck’s relation due to the presence of the factor 1/2. He justified this assumption on the basis of the calculus of the average frequency between the one corresponding to the electron at $r = \infty$ ($\nu = 0$) and the previous frequency for the electron revolving on an orbit of radius $r$. Substituting Equation 2.12 in Equation 2.10 the energy released by the system in forming a stationary state:

$$E = \frac{2\pi^2k^2Z^2e^4m}{n^2h^2}$$  \hspace{1cm} (2.13)

Assigning different integers values to $n$ a series of discrete values for $E$ emerges, representing the energy releas to reach a stable configuration from $r = \infty$. Bohr pointed thus out:

"According to the aforementioned considerations, we are guided to formulate the hypothesis that these configurations correspond to states of the system in which no irradiation occurs, and so they are stationary until the system is perturbed by external actions."

Being $E = -E_n$, it is possible to assign a value to the energy of the stationary states:

$$E_n = -\frac{2\pi^2k^2Z^2e^4m}{n^2h^2}$$  \hspace{1cm} (2.14)
Since the energy $E_n$ is a function of the radius $r$ it is obvious that also the allowed radii can assume discrete values. The application of this model to the observed spectra is straightforward: if the electron can move from one orbit to another (characterized by energies $E_2 < E_1$) the amount of emitted energy will be $E_1 - E_2 = h\nu$. The emitted radiation will thus be characterized by a wavenumber:

$$\frac{1}{\lambda} = \frac{E_1}{hc} - \frac{E_2}{hc}$$  \hspace{1cm} (2.15)\

As shown by Rydberg, in particular in the case of the hydrogen atom, wavenumbers corresponding to the emitted radiation can be empirically evaluated by the formula:

$$\frac{1}{\lambda} = \frac{R}{n_1^2} - \frac{R}{n_2^2}$$  \hspace{1cm} (2.16)\

Since, according to Bohr's model $E_n \propto 1/n^2$ the empirically obtained spectral terms correspond without doubt to the energies of the stationary states of one atom, also according to the fact that the value of the Rydberg's constant $R$ can be compared with the value provided by Bohr's theory, i.e. $\frac{2\pi^2k^2e^4m_e}{h^3c}$. The two values are the same in the limit of the uncertainties with which the values of the constants entering the formula are known.

Bohr tried to justify Equation 2.12 on a mechanical base: For a particle in a circular orbit the angular momentum $L$ can be evaluated ($E_k$= kinetic energy $\nu$=frequency of rotation):

$$L = \frac{E_k}{\pi\nu}$$  \hspace{1cm} (2.17)\

but as it can be easily shown: $E_k = E$ so, Equation 2.17 can be rewritten:

$$L = \frac{W}{\pi\nu} \Rightarrow W = L\pi\nu$$  \hspace{1cm} (2.18)\

Comparing Equation 2.18 with Equation 2.12 it turns out:

$$L = n \cdot \frac{h}{2\pi} = n\hbar$$  \hspace{1cm} (2.19)\

corresponding to the quantization of the angular momentum of the electron, which often is treated as the hypothesis Bohr used in developing his model, rather than a consequence born to justify an ad-hoc hypothesis. Nevertheless, the quantization of angular momentum will have great importance in the developing of the following theories on quantum mechanics.

Bohr (Bohr, 1913) concludes:

"If we suppose that the orbit of the stationary states are circular, the result [E = $n\hbar\nu/2$] can be thus expressed by the fact that the angular momentum of the electron with respect to the nucleus in a stationary state corresponds to an integer multiple of a universal constant, independent bynucleus charge. The importance of the angular momentum in discussing atomic systems related to Planck's theory has been underlined by Nicholson."

Bohr's original model was able to explain the hydrogen spectral lines, but several weak aspects of his theory have to be considered:

- Only hydrogen or hydrogenoid atoms could be modeled according to the model. More complex atoms, i.e. with more than one electron could not be modeled;
- A series of ad-hoc hypotheses were made (bi-dimensional model, circular orbits, ...);
• Emitted radiation consisted in electromagnetic waves, in contrast with Einstein’s idea of photon, that was accepted only in the following (Jammer, 1966), p.30-37. The quantum model for light is used still today;

• In producing absorption spectra, when atoms in their ground state, no emissions are detected for transitions from one excited state to to a higher energy state: those transitions are highly improbable (Rutherford et al., 1970). Only if the gas temperature is high enough there would be atoms in excited states and so, emissions could be detected in the absorption spectrum. If such transitions were not highly improbable, the hydrogen atom would easily ionize: after making an initial transition from the ground state to the first excited state, absorption of other photons would lead to ionization: physically speaking de-excitation occurs before further exciting the atom;

• A complete model explaining the emission and absorption of radiation must take into account not only the position of the emission (in wavelengths or frequencies) but also their intensity. The prediction of emission intensities was not possible in Bohr’s model. It was Einstein (Einstein, 1917) who linked the emissions with the different probability of transition leading to different intensities. This stochastic nature of atomic transitions makes impossible to make predictions about the atom’s future behavior if not in terms of probability (Jammer, 1966), p. 170-171.

2.2 Implementation of historical ideas in the educational path

History of physics has been used, in this case, as an educational resource for developing a path. Its role is not merely reduced to storytelling, but rather the history served as supporting the addressed concepts (Buongiorno and Michelini, 2017b).

Newton’s reasoning on white light dispersion by means of a prism has been exploited in terms of problematic issues in order to support the idea that a prism is able to separate the different chromatic components and does not operate a transformation. This evidence has been used as a starting point to search for other dispersive mechanisms for light, as the diffraction, for which an experimental activity allows to identify its phenomenological laws and the dispersion role of a grating in the analysis of polychromatic lights.

Despite the qualitativenss of Melville’s observations, they account for two important steps adopted in the educational path: the need for a diaphragm to circumscribe the light source and the evidence that lights composed by a finite number of colors exist and they are associated with different elements. In particular, the possibility of identifying the presence of gaseous substances through flame tests highlights the important role of the spectrum in the recognition of the elements, having been presented as an experience to recognize the ways in which different light sources can be characterized by the color of the light they emits and by the relative chromatic composition. An emblematic example is represented by the discovery of cesium, rubidium and helium thanks to spectroscopy, an experience narrated to consolidate the role of a spectrum as an "identity card" of the elements.

The phenomenological law of Stefan-Boltzmann (Stefan, 1879; Boltzmann, 1884) the identification of the emissive and absorbing powers and the dependence of their relationship only of the temperature orient the analysis of the emission process with the increase of the supplied power and emitted by an incandescent source.

Phenomenological evidences allows to assign a role to experimental data in problematic terms to pose the interpretative problem of light interaction with matter: the discovery of infrared and ultraviolet radiation consolidates the idea that the emission of radiation can occur beyond the visible, in different energies, and get used to seeing the colors in a
spectrum such as radiation with different energies, having different interactions with matter and different effects: heating, penetration and ionization. Such historical experiences are recalled with the role of identifying light in more general terms of broad-spectrum radiation, not only visible, and to identify differentiated effects regarding light-matter interaction.

The quantum nature of light in terms of photons of energy corresponding to the color and intensity corresponding to their number is based on the analysis of the photoelectric effect and on the measurement of the threshold voltage of different colored LEDs. The analysis of this effect was used to found the idea of the photon based on the properties manifested on the experimental plane.

Balmer's work inspires the operative proposal of the analysis of the regularity of the positions of the lines in the hydrogen spectrum and the preparation of the phenomenological law which describes the position of the first four lines of the series. The usage of wavenumbers, proportional to frequency, in turn proportional to energy, allows an energetic reading of Rydberg's formula inspiring the hypothesis of the description of the emitting systems in terms of permitted energetic states and of the emission as discrete energetic de-energization. The works of Balmer first, and then Rydberg, have been proposed as problem solving to retrace the meanings and to explain the process of emission in terms of energy through the link between levels and spectral lines.

2.3 Founding cores

Atomic spectra, in particular the phenomena of quantum emission and absorption of radiation are fundamental concepts in physics. Historically speaking, at the end of the XIX century the classical models for emission and absorption of light, based on the model of oscillating charges put in motion by electromagnetic waves with certain frequencies, was not able to explain the emission of certain spectral lines from gases. The topic of atomic spectra represents a fertile area to study some quantum concepts that students and teachers tend to form: the correct interpretation of atomic spectra requires a correct understanding of the quantized nature of light, of the quantized energy structure of matter as well as the way they interact.

The phenomenological context of optical spectroscopy regards the emission of light from different materials, both solids or gases. Optical spectroscopy is one of the main investigative tool in physics based on light matter interaction; it is important from different points of view: (a) it represents an epistemological contribution to physical culture (it is a bridge between classical and modern physics, it is a context in which the role of energy in physical investigation can be addressed, it represents a validation modality of interpretative micro and macro models through indirect measures); (b) it contributes on education on different plans (to build a coherent frames in the study of optics, to the conceptual basis of modern physics, to link instruments and methods linking experiment and theories); (c) it represents a socio-technological relevant contribution to various applications, both daily and specific.

The emission of radiation from matter is conditioned by different factors: (a) the temperature of the sample: in fact in the case of solid bodies, it enters only as a parameter shaping the blackbody spectrum and it is independent from the material, while in gaseous samples it influences the populated energy levels and so, the absorption and emission lines; (b) the pressure conditions: low pressures allow atoms to be considered separated and independent by each other turning out in a discrete spectrum, higher pressures constrain atoms to stay closer, so the interaction between them influence the spectral profile, without mentioning that only in condition of extremely low pressures certain emission lines can be
observed: the so-called "prohibited transitions" that occur only when atoms do not undergo de-excitation through collisions but they have enough time to de-excite by emission of radiation; (c) motion of the source, in the sense that Doppler shift effects can alter the position or the width of the spectral lines; (d) degeneracy removal via, for example, a magnetic field as in the case of the Zeeman effect; (e) type of gaseous matter, since different elements/molecules have different spectra according to their energy structure; (f) last but not least, the resolution of the spectrooscope used to observe the emitted light from a source, linked to the width of the slit and the pitch of the used grating that allows (or not) the resolution of two emissions with similar wavelength/energy. Choices had to be done in addressing all those factors, so in the thesis attention has been paid on how physical theories and models account for the different type of gaseous matter (from the point of view of the link between discrete emissions and energy levels) and on the role of the different part of a spectrooscope, linking macro and micro levels of interpretations.

Optics plays an important role in the interpretation of the phenomenology since it addresses the problem of how light is produced, the way it propagates and the way it interacts with matter. Different levels of modelling could be implemented: geometrical optics, treating light as rays propagating through straight lines and undergoing refraction or refraction only; physical optics, treating the light as a wave propagating at a constant speed, with different frequencies and wavelengths, accounting for interference and diffraction phenomena; quantum optics, treating light as a flux of photons with energy depending from the color. The importance of quantum optics in physics resides in the fact that it constitutes a founding part of modern physics, treating quantum objects and their interactions only from an energetic point of view.

At the basis of every microscopic model accounting for optical spectra there are two elements: the energy/wavelength of the emitted radiation and the structure of the atom. Every model has to specify properties and interactions between those elements, taking into account a physical theory, that assumes the existence of light waves, atoms and their structure. In education, in particular in education research, it is necessary to prove the existence of such entities and of their properties, before using them as established concepts. The step from physical knowledge to education set the issue of justifying on phenomenological basis: (a) the existence of atoms and their properties; (b) the presence of an interaction between matter and radiation; (c) the nature of light as an entity carrying energy; (d) the properties of certain objects to decompose light rather than transform it. On the educational plan seems to be possible to justify the existence of different types of atoms from the evidence that they have each a characteristic spectrum, and those features are present in chemical compounds. It has been taken into account that students believe in the existence of atoms in relation to Dalton's laws or the brownian motion. A founding aspects related to interaction between light and matter regards the transfer of energy, and this issue accounts also for the properties of light as an entity carrying energy. Examples are provided with phenomenological situations, during which students realize that light has the ability to heat objects, cause electron emission, yield fluorescence or phosphorescence phenomena as well as activate chemical reactions, all aspects including energy transfer. On educational plan this aspect can be faced measuring the threshold voltage for turning on a LED and correlating it with its color. This sets the need on the educational plan of the nature of the color, in particular for white light which contains all the other visible colors, turning out to be a property of light the one to be decomposed (and not transformed) by a glass prism. In this case the process can be studied using two prisms, the former separating a beam of white light, the second recomposing it.

The performed historical study showed that the problem of how matter absorbs and
emits light brings with it the needed interest and capability of structuring educational paths bridging from classical to modern physics. In the same way, the goal to be reached is that students are able to explain emission and absorption process in atoms, using a model in which they go beyond the simplified and misleading Bohr model based on the description of atoms in term of classical orbits travelled by electrons. Overcoming the description of any other atom in terms of orbits turned in favor of a more generic and physically correct model in which every atom is described in terms of equilibrium energy states has been taken into account.

Moreover to reach a coherent frame for optics, students have to overcome the classical teaching approach, according to which light is an entity that propagates as a wave and interacts with matter as a particle.

The conceptual reconstruction was carried out by pointing out, iteratively expanding, deepening and integrating the key conceptual elements in new perspectives that have been dealt in innovative ways. Nature of light, energy carried by it and light-matter interaction are the most important concepts that underwent examination. The aforementioned key concepts have been organized in founding cores common to all different experimented conceptual paths, while other aspects have been differently focused between different paths.

The role of wavelength in describing light in physical optics was thus studied from original science publications for an historical reconstruction, in particular to build a historical line and in scholastic textbooks. The problem arose in describing light in terms of energy carried by different colors, which involves the fundamental content for learning the energy-frequency-wavelength relationship.

Einstein’s paper on photoelectric effect (Einstein, 1917), whose experimental evidences relate the frequency of a certain radiation with its photons’ energy.

The important sequence of ideas, described in detail in the rationale of the paths (see Chap. 5) is that an energy source can be considered as a system transforming energy from one form to radiant one; if the spectrum is discrete, only specific amount of energies can be emitted and taking into account energy conservation principle, each light source can be uniquely described by a set of energy levels leading to the formation of a characteristic spectrum. In order to be able to relate discrete spectra to atomic energy levels some aspects have to be recognized: each color has a proper energy; light direction of propagation appears to bend at different angles depending on its color (both using a prism or a diffraction grating); a discrete spectrum is produced by light emitted during energy transitions of the system from one energy state to another and the emitted energy $E$ is equal to the difference among a couple of energy levels $E = E_1 - E_2$.

### 2.4 Epistemological aspects

The attempt to develop, in an ever deeper way, a physical model describing quantized emission and absorption of radiation from atoms is deeply intertwined with the history of the development of atomic models, starting from Thomson’s one in 1904 and triggered a process of scientific development of ideas lasted about 40 years separating the first pionieristic work of Balmer in 1885, from the Schrödinger quantum atomic model describing both the structure of complex atoms and the formation of spectra in 1926 (Fig. 2.5). This led to a formulation of a complete theory on the structure of matter contributing significantly to the evolution of quantum mechanics (Heisenberg, 1975). This represents a concrete example of the modalities and processes involved in the development of a scientific theory, in particular the energy structure of the matter. It is useful to point out the relationships, often mutual and synergistic, between different plans: theoretical, experimental and mod-
melling (Bunge, 1973). Firstly, the formulation of the classic atomic model is based, on one side, on the theoretical structure of classical electrodynamics, on the other on various experimental evidences as the existence of electrons, the property of an oscillating charge to emit radiation and the evidence of light emission from atoms when excited. Secondly, the evolution and refinements of the microscopic models for atomic structure has been guided by the need to explain discrete spectra, to extend the model in a wider phenomenological context (i.e. all atoms, not only the hydrogen one, but also for accounting second order evidences as the Zeeman effect or the fine structures of spectra) and to embed in the model new hypotheses, such as Planck’s theory for black body or Einstein’s suggestion for the existence of the photon. Moreover, the discordance between expectations based on models and the experimental evidences, for example the forecasting of certain spectral emissions, stimulated the refinement of the theory and the development of new models including new theoretical elements, often in the form of not-justified conceptual leaps, as for example the Bohr’s hypotheses. In the majority of the areas of physics it is possible to infer information on the properties of a system analyzing the phenomenology, in particular in the specific field of optical spectroscopy, the pattern of the optical spectral lines in hydrogen spectrum provides information concerning the values of the parameters entering in the Bohr’s model.

To be noticed that Bohr aimed at designing a model representing spatially an atom, so why he described the atom in terms of "electron orbits". Another perspective is to focus on the founding properties of a system: since the orbits actually do not exist, from an epistemic, but also educational point of view, it is more appropriate to speak of "energy states", which lives in an abstract space, rather than in the real one, but describe more in general a quantum system.

Important physical quantities in the description of light-matter interactions and in the formation of spectra are represented by the gap between energy states, in atoms, or bands, in solids as well as the intensities of the various emissions. An analysis of the information coded in a spectrum allow to obtain such information. The aforementioned considerations support the educational value of dealing the topic of optical spectroscopy starting from
the phenomenology, for example the study of a LED spectrum varying the voltage, or the study of discrete spectra searching for regularities. The following choices have been made in order to give epistemological meaning to the proposed paths: (a) an approach starting from optics, in particular from light sources and the properties of the emitted light has been adopted; (b) according to the various experimentations, energy or wavelength have been used as conceptual referent for reading and interpreting spectra; (c) comparison between continuous, band and discrete spectra searching for interpretation has been proposed as a challenge; (d) integration of experimental explorations and measures enriched the paths; (e) implementation of the artifact method in the specific case of a spectroscope in order to give meaning and to search for the functionalities of each part of it; (f) attention has been paid to the link between macroscopic evidences and microscopic models; (g) no historical storytelling has been used, rather historical ideas has been used in order to support the concepts, sometimes turning in anachronistic sequence of facts.
Chapter 3

Review of research literature

The starting point for a well-designed content-based research is the consultation and analysis of the existing-in-literature contributions on the addressed topic: their discussion provides solid bases to the ongoing research work, since it integrates the significant existing contributions showing the starting assumption and hypotheses. It is here discussed a review of PER literature concerning (a) learning knots; (b) the contribution of history of physics; (c) validation and testing of specific monitoring instruments; (d) studies and surveys on learning difficulties; (e) some existing educational proposals/approaches in order to introduce optical spectroscopy for different schooling grades, from primary (Palmquist, 2002), lower and high secondary (Mantovani, 2001) and university (Blue et al., 2010). According to the MER guidelines, students known-in-literature learning knots and conceptual difficulties emerged in the history of physics have to be taken into account to ground the research, so this chapter begins with the discussion of those two aspects.

3.1 Learning knots on optical spectroscopy

Despite various works emphasize the fundamental role of spectroscopy in different fields of study (Aroca et al., 2008; Bailey et al., 2012; Bardar et al., 2006; Lee and Schneider, 2015b), to date conceptual learning knots (i.e. learning difficulties) regarding formation and interpretation of light spectra have been systematically explored in a relatively narrow manner in PER literature: there have been relatively few studies of the problems associated with teaching and learning about spectra. Nevertheless, the evidence show a set of learning obstacles fertile enough to build the research. Regarding optical spectroscopy, the research literature highlights a series of learning knots for different schools grades (secondary and university students), present also among secondary school teachers. The learning difficulties can be divided in five broad categories:

- The conceptual link between spectral lines in a discrete spectrum and the atomic energy levels;
- The role of the experimental setup in order to produce and observe a spectra;
- The distinction between a diffraction pattern and a spectrum;
- The model of interaction between light and matter;
- The recognition of peculiar features in a spectrum.

As concerns the first category, emerge a very common belief allowing the associating of each line in a discrete spectrum with a single energy level in the source (in general, an atom)
(Zollman et al., 2002; Rebello et al., 1998; Korhasan and Wang, 2016; Ivanjek et al., 2015a; Ivanjek, 2012; Savall-Alemany et al., 2016) ignoring the concept of transition between energy levels. To be more specific, students are able to evaluate the energy of a line in a discrete spectrum via the Einstein relationship $E = h \cdot f$, in which the energy of a photon is directly proportional to the corresponding light frequency, but they associate this value, which is positive, to the energy of a specific atomic level (which has to be negative, since it represents a bonding energy) (Korhasan and Wang, 2016; Ivanjek, 2012). Concerning the link between spectral lines and energy levels, students argue that the amount of emitted radiation is linked only to the final or starting level. Also the role of the ground levels turns out to be controversial: students’ explanatory models also regards the fact that they fail in treating the ground energy level of a quantum system as an energy level (Ivanjek et al., 2015a), or they believe that atomic transitions always involve the ground energy level (Ivanjek et al., 2015a; Savall-Alemany et al., 2016; Zollman et al., 2002; Rebello et al., 1998). The diffuse and persistent presence of students’ idea according to which it has zero energy (Ivanjek et al., 2015a,b; Savall-Alemany et al., 2016), causing difficulty in assigning a meaning to negative energy values of the excited levels (Ivanjek et al., 2015a,b) has been also pointed out.

As concern the role of experimental setup, students often fail in giving a functional role to each component: conceptions according to which a prism always produces a continuous spectrum, independently by the nature of the emitting source, or the idea that a discrete spectrum is always visible even without a dispersive element (as a prism or a diffraction grating) are present among students (Ivanjek, 2012).

The question concerning the distinction between a diffraction pattern and a spectrum emerges in students arguing that a discrete spectrum can only be observed in the case of monochromatic sources or using a diffraction grating (independently by the nature of the source). The same problem emerges when students are not able to distinguish a diffraction pattern from a discrete spectrum, confusing diffraction maxima with spectral lines (Ivanjek, 2012).

Another set of learning knots regards the model of interaction between light and matter in the special case of discrete spectra (Savall-Alemany et al., 2016). Three possible sub-cases emerge:

- **Difficulties linked to the quantization of energy in atoms**: photons are always absorbed so the atom gaining an energy that should not be allowed, the ground level has zero energy, and it is not always clear how to give meaning to negative energy values;

- **Difficulties related to the quantization of radiation energy**: a photon can be partially absorbed, light intensity is not linked to the number of photons, but rather to their color;

- **Difficulties regarding the interaction light-atom itself**: greater intensity of emitted light corresponds to a greater number of electrons in a level or to a greater energy of the level itself, the energy conservation principle is not considered (the atom must always make a transition between levels, although the energy of the photon does not allow it), atoms can absorb photons passing to higher and higher energy levels until they ionize (the very low probability of this occurring is not taken into account).

Regarding the last category, i.e. the difficulties that students have in recognizing the peculiar features in a spectrum, it emerges (Ivanjek et al., 2015a) that students tend to focus on the number of apparent distinct colors in a discrete spectrum, rather than on the
total number of lines. Another study (Lee, 2002) pointed out that students correlate the energy of the light to its intensity rather than its color.

The quoted researches highlight several other minor misconceptions, for example: students confuse additive color mixing (typical of colored lights) with subtractive color mixing (typical of paints), experimenting troubles when dealing with the decomposition of light into its constituent colors (the color black is the presence of all colors rather than their absence). Moreover, students tend to use in an equivalent manner terms referred to different concepts as for example "energetic level", "spectral line", "orbit", "orbital" (Korhasan and Wang, 2016) and also a genuine confusion between distinct concepts emerges (energy of the photon, of the line, of the level, of the state) leading students to use incorrect models for the emission of radiation quoting statements like "photon changes states" (Ivanjek et al., 2015a). A confirmation of the described learning knots can be found in (Sinarcas and Solbes, 2013) where it is shown how students struggle in explaining the formation of spectral lines within the Bohr model: the correlation between electronic transitions and observed emissions is correctly described only by the minority of the sample.

The need for microscopic models as interpretative instruments to overcome the conceptual knots of the system's behavior has been addressed by means of simulation tools (Zollman et al., 2002; Rebello et al., 1998). The persistent presence of students' spontaneous models concerning the formation of discrete line spectra and their link with the discrete energy structure of an atom is evidenced by the above mentioned studies; such models have to be overcome in order to gain a scientific view of the topic (Gilbert et al., 1998a,b) and develop formal thinking (Michelini, 2010).

Even if other studies do not explicitly address issues related to optical spectroscopy, they focus on students' difficulties in optics and atomic structure, that may influence interpretation of atomic spectra, given that an understanding of the nature of light and atomic structure is a major prerequisite for understanding quantum emission and absorption of radiation: a lack of understanding of the dual nature of light as a particle and as a wave is pointed out in (Ambrose et al., 1999) as well as the tendency to conceive photon as a classical particle (Fischler and Lichfeld, 1992). Concerning atomic models, it has been shown that students mix up classical and quantum concepts (Budde et al., 2002; Fischler, 2002).

### 3.2 Previous related research

As mentioned in Par. 3.1 only few systematic research have been published concerning students' understanding of optical spectroscopy. Here studies focusing on teaching/learning difficulties are reported and commented, as well as the developing of monitoring instruments and educational tools with comments on results and effectiveness.

Teaching effectively spectroscopy implies addressing numerous and important concepts, employed in all scientific courses dealing with quantum mechanics and/or its applications, as for example the concept of photon, discrete energy states in atoms and transition among those states. These concepts are basic in order to describe a spectrum, its formation and the information coded in it; in particular in astrophysics courses, optical spectroscopy is the main frame to contextualize the study of celestial light sources. In order to understand the fundamental role of spectroscopy in astrophysical analysis, the various multidisciplinary approaches with other disciplines, as chemistry or modern physics, and to contextualize disciplinary contents, a series of practical educational activities have been designed for upper secondary school students (Aroca et al., 2008). Light is a fundamental way in which astrophysical information is conveyed: spectral features represent the fingerprint
of the Universe, unveiling temperature, composition, relative motion and other physical properties of celestial objects. It is not surprising that the central topic in introductory astronomy courses is light and spectroscopy.

A study concerning the interpretation of astronomical images among students in introductory astronomy courses is reported in (Lee and Schneider, 2015b). Authors underline that it is essential to understand spectroscopy concepts in order to properly manage the way in which information concerning composition, temperature, distance and motion of celestial objects can be obtained. In particular the interpretation of experimental images and spectra is an indispensable skill, especially in astronomy and astrophysics where images and spectra are often the only carriers of information regarding the objects under study. Results concerning the most common students’ misinterpretations are (Lee and Schneider, 2015a):

- the wrong interpretation of the Doppler shift of spectral lines, as representative of a change in temperature, composition or age;
- the difficulty in employing Wien’s law to correlate stellar spectra and temperature of the object;
- the typical error of correlating higher temperatures with a redder emissions with respect to a bluer one.

An abstract of a wider study (Comins, 2001) concerning the most common misconceptions in astronomy and astrophysics by students, limited to the ones concerning nature of light and spectroscopy is reported in Fig. 3.1. Assumed the importance of a good comprehension of optical spectroscopy, a need in PER emerged in developing monitoring instruments in order to evaluate students’ competences and difficulties concerning this topic. The developing of the Star Properties Concept Inventory (SPCI) is described in (Bailey et al., 2012); this monitoring instruments is meant for students in introductory astronomy courses and the questions regard stellar properties (mass, temperature, luminosity and lifetime), stellar formation and nuclear fusion. In this work the central role of the nature of

<table>
<thead>
<tr>
<th>STELLAR TEMPERATURES</th>
<th>- The bigger the star is, the hotter it is</th>
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<tr>
<td></td>
<td>- red stars are hottest (red = hot, blue = cold)</td>
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<tr>
<td></td>
<td>- stars of equal temperature all have equal brightness</td>
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<tr>
<td>STELLAR SIZES</td>
<td>- the bigger the star is, the brighter it is</td>
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<tr>
<td>STELLAR SPECTRA</td>
<td>- stars emit only one color of light</td>
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<td>- stars only give off visible light</td>
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<td></td>
<td>- heat and light from stars are unrelated</td>
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<tr>
<td>STELLAR SPECTRA</td>
<td>- stellar size, color and temperature are unrelated</td>
</tr>
<tr>
<td>PHOTONS</td>
<td>- longest wavelength photons carry the most energy</td>
</tr>
<tr>
<td></td>
<td>- photons behave only like particles</td>
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<tr>
<td></td>
<td>- photons travel on waves</td>
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<tr>
<td>SPEED</td>
<td>- different kinds of electromagnetic radiation travel with different speeds</td>
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<td></td>
<td>- radio waves travel at the speed of sound</td>
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<tr>
<td>GENERAL</td>
<td>- visible light is fundamentally different from other types of electromagnetic radiation</td>
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<td></td>
<td>- all spectra are continuous</td>
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<tr>
<td></td>
<td>- the spectrum of light is the shape the light makes</td>
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<tr>
<td></td>
<td>- all electromagnetic radiation is visible</td>
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</table>

Figure 3.1: Abstract of students’ most common misconceptions in astronomy and astrophysics concerning light and spectra (Comins, 2001). Adapted from (Ivanjek, 2012).
light and the way in which spectroscopy is used to study celestial objects and phenomena are underlined as key aspect of modern astrophysics.

The need for an assessing instrument of learning concerning optical spectroscopy is pointed out also in (Bardar et al., 2006, 2007) since students in introductory astronomy courses show difficulties in understanding fundamental concepts related to light and spectra, as for example blackbody radiation, Wien and Stefan-Boltzmann laws, but mostly the nature and the causes of formation of discrete emission and absorption spectra. The *Light and Spectroscopy Concept Inventory (LSCI)* (Bardar, 2006) is a monitoring instruments developed to probe students’ understanding of light and spectroscopy in introductory astronomy courses. It includes multiple-choice questions related to the treatment of light as a wave, to spectral lines and to the emission and absorption mechanism, in particular focusing on the following points:

- the nature of electromagnetic spectrum, including the relationships between wavelength, frequency, energy and velocity of a wave;
- the interpretation of Doppler shift as a tracer of the radial motion of objects rather than their colors;
- the correlation between peak wavelength and temperature of thermal emitter;
- the connection between spectral features and the physical process responsible for the emission.

The *LSCI* show sufficient content validity in order to be employed as an instrument of validation concerning introductory astronomy courses students' understanding of nature of light and of the interpretation of spectra (Bardar, 2008). From the analysis of students’ answers it emerges that they struggle in correlating wavelength, frequency, energy and velocity of a wave, as well as they show difficulties in correlating emission and absorption processes with spectral features (in particular significant difficulties were revealed by questions that asked students to identify the process in which an absorption line or emission line is formed). Those results put in evidence that the majority of the students do not master the understanding of light emission and absorption processes, both before and after instruction.

A study reported in (Lee, 2002) examines the extent to which university students, through the use of a diffraction grating, look at spectra from different sources (incandescent lamps, incandescent lamps covered with colored filters, hydrogen lamps) correlating their observation to the energy and colors of the light. In particular the research describes how students observe spectra, inquiries their ideas on spectra, as well as their ideas about light and energy. The study consists in four stages: developing teaching materials, conducting a preliminary study, conducting interviews and conducting surveys. Students were asked a series of questions to see if and how they related their observations to energy of light. The research method is the phenomenographic analysis.

A selection of interactive materials designed to work on spectra from different sources (gases, LEDs, fluorescent and phosphorescent objects) is presented in (Rebello et al., 1998; Zollman et al., 2002). These materials, collected in the *Spectroscopy Lab Suite* are part of a wider platform named *Visual Quantum Mechanics (VQM)* ¹ and lead students to grasp the main ideas of quantum mechanics such as energy quantizations in atoms by observing their spectra, considered an accessible starting point, via a computer simulation. Students have the possibility to look at an emission spectrum and then use their knowledge.

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¹https://web.phys.ksu.edu/vqm/software/online/vqm/index.html
of energy conservation to model an energy level structure that is supposed characteristic of the emitting atom. From this challenge students come to the conclusion that because only a few energies are present in the spectrum, the atom energy structure must be composed by only few energy levels. Students are asked to interactively build some energy level models using a program enabling them to match the light that would be emitted by their model with the observed spectrum (see Fig. 3.2). The effort consists in using only the observation of the visible spectrum as data: based only on this evidence, the energy level model is not univocal: it is not trivial to distinguish between the various possibility, so students become aware that creating a model from limited data is not always easy. Figure 3.3 shows three models created by students for the same spectrum containing four lines. In the discussion that follows, students are challenged to determine which one is correct, evidencing that any one of these three models could be correct to explain just this one observation. Adding more information helps in narrowing the acceptable choices: for example, students are asked what other transitions could occur with each of their models. Frequently, they find some transitions that would result in emissions outside the visible region. So, students look at data for the infrared and ultraviolet spectra and eliminate some models. According to the author, this process help students learn about how physicists build and refine models of nature, having also a direct experience showing how models can be incomplete when the
amount of evidence is limited. *Spectroscopy Lab Suite* allows students observe spectra of different LEDs: asking them to use as many single energy levels as they need to create a spectrum matching to the observed one (i.e. a band spectrum), leads to build energy bands with gaps between them. Evidently these procedures are empirical, but they represent an opportunity to see how students can build energy level models of atoms and of solids from just a little bit of information. Authors argue that by using those materials, successful results in both students’ learning and attitudes are obtained.

A study conducted with secondary school students (Sinarcas and Solbes, 2013) shows how they struggle in explaining discrete spectra formation using Bohr’s atomic model model in answering an open question (“How do you explain discontinuous spectra using the Bohr atomic model?”). The aim of the research was to assess how students relate electronic transitions to observed emissions, in particular to assess whether students understand the role of models and to find out whether they relate the electron transition between two levels with the corresponding color line in the spectra. Although this study does not thoroughly investigate the interpretative models and does not produce any data concerning students’ learning problems or reasoning, it shows how students encounter difficulties even only in qualitatively justifying the formation of a discrete spectrum: the results show that only 19% of the sample does not present difficulties in describing the emissions observed in terms of electronic transitions between well-defined energy orbits. These students correctly explain that the emission or absorption of radiation occurs when the electron moves from one state to another, establishing a relationship of proportionality between the radiation frequency and the energy difference between levels. A higher percentage of students (54%) does not answer the question, while the remaining 27% provide inconsistent descriptions.

A more detailed investigation on undergraduate physics students’ understanding of emission spectra is reported in (Ivanjek et al., 2015a). Students’ ability in relating spectral lines wavelengths with the electronic transitions between atomic energy levels were investigated. In the preliminary investigation, participants were tested on the following problematic issues: (a) to state the maximum number of spectral lines that can be generated from a given number of energy levels, (b) to identify which line is formed in an emission spectrum when a transition takes place between the two closest energy levels, and (c) to state which is the lowest number of energy levels necessary to form an emission spectrum with a given number of lines. Results showed that many students had an incomplete or incorrect understanding of how energy levels and transitions of electrons between them are related to discrete line spectra: many of them did not recognize that each spectral emission is a result of a transition of an electron between two energy levels; a strong tendency to associate each spectral line with one energy level emerged. Authors concluded that there was a need for instructional materials addressing the specific conceptual and reasoning difficulties identified and helping students connect the formalism taught in their courses with their observations of spectra. Even though discrete spectra are typically introduced to help motivate the idea of energy levels and transitions of electrons between them, few students seemed to understand the connection between these ideas. The "Atomic spectra tutorial" described in (Ivanjek et al., 2015b) was developed for guiding students through some of the steps in the reasoning that are involved in relating spectral lines to transitions of electrons between atomic energy levels: in the process, students recognize the conflict between their initial ideas and the outcome predicted by the physics formalism and come to understand the reasoning required for resolution. The structure of each tutorial evolves as a result of careful analysis of student reasoning and ongoing observations of students as they work through it. Comparison between pre- and post-tests show that students reach a better understanding of the link between energy levels and spectral lines after worked on
A deeper and more articulated study is described in (Ivanjek, 2012) where research with university students attending physics introductory courses focuses on:

- Evaluate students’ difficulties in assigning a role to the different components (light source, diaphragm, diffraction grating, prism) of an experiment aimed at performing spectroscopic analysis;

- Evaluate their conceptual difficulties in relating atomic spectral lines with atomic energy levels, in particular analyze the conceptual link that students employ in relating emission lines wavelengths and transitions between energetic levels.

Emerged students’ difficulties are thus organized into two overlapping general categories: (a) difficulties in relating line spectra, energy levels, and transition, and (b) difficulties elicited by the experimental set-up used to observe line spectra. Through the informal observation of the students, analysis of the written answers to questionnaires and individual interviews, investigations are carried out on students’ conceptions trying to highlight the one not in agreement with the scientific vision. Students’ answers regarding the role of the various components in an experimental setup, in particular, show difficulties in understanding as regard the phenomena of interference and diffraction. These specific difficulties are symptomatic of more general problems emerged from the research: the conviction that discrete spectra can be observed for any type of source and difficulty in associating the emissions in the discrete spectra with the atomic transitions. Few students therefore seem to clearly understand the connection between these last two aspects, despite the discrete spectra being typically introduced to motivate the idea of energy levels and discrete transitions between them. Moreover, in (Ivanjek, 2012), the design and evaluation (by pre- and post-test) of two tutorials aimed at overcoming the identified conceptual knots, both for the experimental part and for the part concerning transitions, is described. The results show that students achieve a better understanding of atomic transitions after working on tutorials, even if the same improvements are not visible with regards to the problems related to the role of the various experimental components. Therefore the need to develop this part of educational material is suggested.

Two recent papers (Korhasan and Wang, 2016; Savall-Alemany et al., 2016) conducted on the basis of the previously illustrated studies, investigate the specific difficulties encountered by students and teachers about the interpretation of atomic spectra. In particular in (Korhasan and Wang, 2016) the spontaneous models of nine university students (attending the second year of physics) are investigated to explain the phenomenon of the formation of discrete spectra. The aim is to investigate how they coherently organize the fundamental concepts to explain the phenomenon, in particular the research examined students’ mental models of atomic spectra by a qualitative approach, in order to point out their scientific and unscientific conceptions. Responses to a semi-structured interview with 4 questions represented the collected data. The questions were designed in order to reveal students’ cognitive structures and to encourage them to conceptually explain the phenomenon of formation of atomic spectral lines. In the first question, students were asked to interpret the lines in the atomic emission and absorption spectra. In the second question, they explained some basic terms related to atomic spectra: energy with negative values, discrete energy levels, electronic transition, and photon emission. In the third question, they were asked how the transition of an electron between energy levels is related to the emission of a photon. In the last question, students made qualitative reasoning about the behavior of an electron and the resulting atomic spectra in a hypothetical situation where the electron in the hydrogen atom obeys classical mechanics rather than quantum mechanics.
The analysis revealed that students use 4 different types of model (that authors name the scientific model, the primitive scientific model, the photon-free model, and the orbit model) based on of a developed code comprising 6 fundamental concepts (bound electron, discrete energy levels, spectral lines, photon energy, electronic transitions and orbits). Although the study focuses on the description of mental models used by students, conceptual knots highlighted in previous research emerge, in particular the association between a spectral line and an atomic level. This association is made by the students, most of them using the "photon-free model", in which the radiation energy, \( hf \), is associated to the level as well as to the corresponding line, without mentioning the concept of photon. The authors stress that this conception is probably due to the fact that students largely use Bohr's model for orbits, associating the orbits with the levels, incorrectly interpreting the symbolic representation of the orbits, making trivial connections with the observed lines. The hypothesis put forward to justify this misinterpretation of spectra is that students do not correctly interpret the symbolic representations of energy levels and classical orbits (Fig. 3.4), thus making wrong connections with spectral lines (which represent the only observable reality). In other words, as is often observed, misconceptions often arise from incorrect interpretations of symbolic representations, which are not always clearly defined. In the same work, the authors finally note how students use terms that are equivalent to very different concepts such as "energy level", "spectral line", "orbit" or "orbital", as well as in other studies on quantum mechanics it emerged that the words "operator" and "observable" are used interchangeably. Despite all students were aware of discrete energy

![Figure 3.4: Interpretation of energy levels in terms of orbits from one student of the sample: "if we consider this small region (on the orbit), we do not see as a curve but we see it as a line, that is an energy level (Korhasan and Wang, 2016).".](image)

levels and spectral lines, they thought that they are the same concepts. More specifically, students thought that an electron in an atom has energy levels and these different energies correspond to the different spectral lines. It is also observed that students try to use irrelevant mathematical models to interpret the visual representations, in particular \( hf \) is not considered as the energy for a photon, but the energy level that corresponds to a spectral line. Results show how students intended to concretize abstract concepts with observable elements (e.g. spectral lines) with wrong or unjustified associations.

The study described in (Savall-Alemany et al., 2016) aims to broaden the analysis conducted in the previously described researches, in particular it aims to investigate how students and teachers are able to predict emissions or absorptions in an atomic spectrum based on their conceptions and their models about the interaction between radiation and
matter. The study, conducted with 37 high school students, 34 university students (at the end of their studies) and 30 high school teachers with many years of teaching experience, shows that most of the sample is not able to correctly predict the way in which atoms and radiation interact. The results show that both students and teachers manifest the same difficulties regarding the models used to describe the structure of the atom, the nature of the radiation and the interactions between them. The authors attribute these difficulties to an "iconic" and static conception of the atom that includes the quantization of energies, but without any predictive and/or functional capacity. The study aims to investigate in detail the concept of indivisibility of photons, the prediction of emitted or absorbed frequencies/energies, the justification for the different intensity of the lines and the transitions between the fundamental level and the excited states; to do this, it was developed progressively based on the following steps:

- review of historical and theoretical frameworks;
- identification of key concepts (quantized energies of the atom, quantized energy of the radiation, emission and absorption mechanism, for atoms in the ground state are extremely improbable transitions with higher energy between excited states) necessary to interpret the position and intensity of the spectral lines;
- design of 2 questionnaires: one for teachers and the other for students. Both consist of 3 questions, which were submitted in written form, to the students and in the form of an interview with the teachers;
- answer analysis and discussion of the results.

The 3 questions require making predictions and/or justifying experimental observations regarding the emissions or absorption of radiation by atoms in specified conditions, as well as regarding the intensity of the observed lines. Results show that less than 10% of high school students are able to correctly predict and interpret emissions and removals. In the case of university students, this percentage is higher (50% for emission and 23% for absorption). In the case of teachers, only 39% are able to correctly explain the emission process, while as regards the absorption process, the percentage of correct answers falls to less than 30%. Results therefore suggest that both students and teachers do not interpret spectra using a consistent model, rather they use a different one depending on the posed question, making use of alternative conceptions.

3.3 Some educational proposals on optical spectroscopy

Educational research analyzed the conceptual knots to be faced and the learning difficulties to overcome, suggesting strategies that, with different approaches, setting and addressed contents, outline possible paths to introduce significant aspects of optical spectroscopy. A discussion is needed on existing published proposals on teaching optical spectroscopy, even if these works do not inquiry learning difficulties, but limits themselves to suggest educational approaches, sessions or paths. The educational proposals reviewed and analyzed in the following, have been chosen as emblematic of the main approaches that can be found in literature.

In (Blue et al., 2010) an university laboratory course in atomic and molecular spectroscopy is described. The course has been designed to assist students in understanding the fundamental connections between atomic and molecular spectra and the underlying
structures using a selection of laboratory experiences. Students observe atomic and molecular spectra and are then challenged to understand how the spectra relate to the structures of the associated atoms or molecules. At first students qualitatively observe, through a spectrometer, blackbody spectra at different temperatures, the spectra of the two simplest atoms, hydrogen and helium and the spectrum of a heavy element that is commonly found in mercury-vapor lamps. At this stage the author suggests that important experimental considerations such as the relative spectral response of spectroscopy systems can be addressed by investigating the various optical components and considering the spectral sensitivity of the human eye, used as a detector. Moreover, it is possible to discuss the fact that the average electron energy in AC capillary discharge tubes is small compared to the separation between the ground and first excited states of atomic hydrogen, resulting in a Boltzmann factor that decrease the excited states population as the excitation energy value increase. Asking students to compare the brightness of the Balmer $\text{H}_\alpha$ and $\text{H}_\beta$ lines almost always results in the opinion that they appear to be roughly the same intensity. The population argument based on the previous argument suggests that $\text{H}_\alpha$ should be brighter than $\text{H}_\beta$, so the conclusion is that the eyes is more sensitive in the blue-green region than in the red one. Qualitative visual comparison of the spectra of hydrogen and helium provides a convincing argument that the addition of a second electron enormously complicates the emission spectrum. A first quantitative laboratory experiment involves the isotope shift observed in a capillary discharge in a mixture of hydrogen and deuterium: measurements of the spectra of hydrogen and deuterium allow an estimates of the binding energy of the deuteron (the isotope shift is the largest possible because it involves the maximum fractional difference in the nuclear mass). This activity shows the effect of a purely classical mechanical effect (different reduced masses for the two atomic systems) in a quantum mechanical system. The study of the spectrum of helium follows: prediction of ground and excited state terms are discussed, and dipole selection rules are established. Students are asked to determine the spectroscopic notation of the levels involved in each observed transition, verify that the dipole selection rules are followed, and to discuss the general character of the term diagram in conjunction with the observed relative intensities of the various recorded transitions. Positive outcomes of this experiment include students concluding that two term diagrams are necessary to explain the spectrum of He, since that both singlet and triplet excited states are possible once an electron is excited out of the ground state. Alkali elements represent the simplest analogs of the hydrogen atom and their emission doublets D lines are simple to identify since they are the brightest emission lines. The proposal suggest to measure the wavelengths of each pair of D lines, followed by conversion to photon energy and subtraction, leading the spin-orbit interaction energy for electrons in the first excited states of each alkali. Because the energy splitting is given by twice the Bohr magneton multiplied by the magnetic field due to the orbital motion of the excited electron, the magnetic field experienced by the electron in the first excited state of each alkali is easily calculated. Students are told that the energy splitting is proportional to $Z$ raised to some power divided by the principal quantum number cubed and are asked to discover the $Z$-dependence. Plotting the observed energy splitting versus $Z^4/n^3$ yields a straight line. The proposal suggests to analyze, in the flowing sequence, the Zeeman effect in sodium (in order to offer a direct demonstration of the atomic origins of polarization), the hyperfine structure of rubidium, the Raman scattering in liquid nitrogen, ending with a study of molecular spectra to explore the vibrational structure of $\text{N}_2$ and the rotational structure of $\text{N}_2^+$ in order to assist students in understanding the vibrational structure of diatomic molecule and the deviation of real molecular potentials from the simple harmonic oscillator model.
Other university proposals are based on the assumption that the emphasis of the course has to be put on students' ability to interpret spectra, but it also necessary that students would understand why the various features of the spectra appear as they do, and not just interpret the peak positions from tables of data. In (Lucas and Rowley, 2011) the experiences of first year chemistry students of an Enquiry-Based Learning (EBL) approach to learning spectroscopy has been explored with an investigation of how students’ perceived confidences changes as a result of their experience of using EBL in the spectroscopy course. Changes in students’ perceived confidence (both in their understanding of how spectroscopic techniques work and in their ability to interpret spectra) were examined.

An interesting attempt of building an IBL vertical path based on phenomenological exploration is described in (Mantovani, 2001). The author outlines a series of stimulus questions and activities differentiated for students of different ages (from primary to middle school ending with secondary school) that elicit curiosity through a series of explorations aimed at clarify some concept, that, however are not complete enough to build a coherent path to be put in practice, but representing (using the author’s own words) "some important goals reached in a rigorous, and at the same time fun, way". A summary of the proposed aspect to be addressed is outlined: for primary pupils (a) the existence of discrete spectra and continuous spectra is observed; (b) the visible spectrum is only a little fraction of a wider one; (c) spectra are studied with the aid of a spectroscope. For middle school students (a) the evidence that the spectrum depends from the substance is pointed out; (b) absorption and emission spectra are connected; (c) to investigate the composition of distant luminous sources (stars or planets) it is enough to observe their absorption or emission spectrum; (d) the spectrum depends on the density of the substance that absorbs/emits the light; (e) gases produce discrete or band spectra. For secondary school students quantitative aspects are taken into account, for example that (a) the spectrum depends on the temperature of the substance that it absorbs or emits; (b) The difference between absorption spectra in liquids and gases is due to molecular interactions.

A conceptual path aimed at clarifying discrete emission from hydrogen and its atomic structure in terms of quantization of energy structure (Fig. 3.5) is described in (Rittenhouse, 2015). Even if no laboratorial or operative activity is implemented, the proposed

![Figure 3.5: The guiding question for the proposed path described in (Rittenhouse, 2015).](image-url)
between electron and proton to derive a general expression for the n-th energy level value. The attempt is that students grasp the discovery themselves following specific steps to better understand the importance of the discovery of discrete atomic energy levels and its implications in the formation of atomic spectra. The author describes the simplest, most direct, yet rigorous, pathway leading from the evidence of the existence of discrete spectra to the important conclusion that energy in atoms is quantized. The proposed path differs from the historical one, taking advantage of hindsight to promote clarity, not limiting to storytelling. The author presents an approach employing only the essential concepts and connections needed to rigorously demonstrate that quantized atomic energy must be the cause responsible for the discrete nature of atomic emission spectra.

3.4 Modern physics in secondary school

Dealing with modern physics (MP) in secondary school cannot be neglected for epistemological, cultural, educational and technological reasons: the innovative interpretative and modelling methods characterizing MP outline a new cultural perspective (Michelini et al., 2008), moreover it has to be considered that MP is the basis of main of the modern technology, whose relevant applications are ubiquitous in students’ everyday life. Dealing with MP in secondary school, moreover, enhances the development of theoretical thinking (Michelini, 2010): in particular, it allows the building of innovative concepts and new interpretive hypotheses, often without a classical counterpart (Stefanel, 2007).

Introducing modern physics in secondary school is a challenge involving the possibility to transfer to the future generations a culture in which physics does not play a marginal role, but is an integrated part, in a way allowing students to manage them in moments of organized analysis, in everyday life and in social decisions. It involves different planes: curriculum innovation, teacher education and physics education research (Michelini, 2010).

Motivation driving the introduction of modern physics, understanding as the theory of quantum mechanics, in school are essentially the following (Pospiech, 1999):

- MP plays a significant role in nearly all modern developments of physics. Many recent experiments and research in nanostructures with large applicability in technology rely on quantum effects;
- MP has important philosophical aspects. Many people are highly interested in interpretation and understanding quantum theory as shows up in the many popular books about this subject;
- Students, and young people in general, try to understand the world and are open for philosophical hints that help them in building their own world view.

MP has been an important part of university physics and engineering education for a long time, but the abstract and mathematical teaching practices used have been in dispute for several years (Johnston and Fletcher, 1998; Krijtenburg-Lewerissa et al., 2017). Nowadays, since great attention is paid upon visualization and conceptual understanding (Cataloglu and Robinett, 2002; Kohnle et al., 2014), introducing MP at an earlier stage became possible (Krijtenburg-Lewerissa et al., 2017), and therefore it has become part of the secondary school curriculum in many countries. Despite since more than 10 years modern physics (MP) is recognized as an indispensable content in every European country secondary school curricula (Michelini et al., 2000) and it appears in corresponding textbooks, the problems of the modalities to be employed, the contents to be addressed (Michelini et al., 2014) and the internal coherence (Hake, 2000) remain open. In particular, in the majority of the
cases, the canonical approach to MP is limited by a quick and rough review of the crucial conceptual problematics and relative theoretical solutions, characterizing the history of physics at the beginning of the twentieth century at the expence of a disciplinary operative approach founding a culture linking new theories with instruments and methods typical of physics. The major emphasis is put on typical topics regarding not-well justified "quantization rules" in particular in treating the photoelectric effect, the atomic models and wave function properties (Fletcher and Johnston, 1999; Savall-Alemany et al., 2016).

As concerning the implementation of MP in secondary school curricula, two main positions exist (Michelini, 2004a): from one side, conceptual knots in classical physics are quoted in order to support the exclusion of MP, from the other one, there is an animated discussion on goals, contents, instruments, methods, methodological orientation and type of students. The main research open questions regard the relation among the goal of introducing MP, its role (in terms of citizen culture, guidance, popularization, education) and aspects to be focused (founding cores, technological, applicative) (Hake, 2000). In particular, those different approaches leave many questions regarding the educational strategies open: is the simple story telling of the main features useful to a functional understanding of the involved topic? is there the need of argumentating the crucial problems starting from the classical interpretation? Is it counterproductive to integrate classical physics in MP? Is MP to be treated simply as a complementary part of curriculum? Who must MP be addressed to? (all citizens or only future scientist or talent students?).

Beyond the evidence of the inexistence of agreement on different plans, it turns out to be no consensus even concerning the role of classical physics as a conceptual referent for MP, for example the role of the semi-classical Bohr model (Justi and Gilbert, 2000; Fischler and Lichfeld, 1992; Taber, 2001; McKagan et al., 2008): Fischler and Lichfeld (Fischler and Lichfeld, 1992) claim that in the treatment of the hydrogen atom, the Bohr model should be avoided” since it represents an obstacle to learning the true quantum nature of atoms and state, while, on the other side, McKagan et al. (McKagan et al., 2008) arm that teaching the Bohr model does not prevent students from learning the Schrödinger (quantum) model.

On a deeper level, several education researches focused the problem of aspects related to the ontological differences between classical and MP (Kalkanis et al., 2003; Hadzidaki, 2008) and students’ interpretation of quantum phenomena (Baily and Findelstein, 2015). Also the problems of the mathematical formalism to be employed is focused in several researches (Michelini et al., 2000), since it is nearly impossible to understand MP without considering its mathematical structure (Pospiech, 1999, 2000) and often this highly fascinating subject is avoided at school because of mathematical and conceptual difficulties.

Since it is evident that PER recognized the importance of focusing on the difficulties that classical physics faced in explaining some experimental phenomena, which led to the establishment of MP theories (Gil and Solbes, 1993; Singh, 2001) and optical spectroscopy represents one of those inexplicable phenomenon, it is surprising that there has been little research on how students and teachers interpret atomic spectra.

### 3.5 Optical spectroscopy in the curriculum: problems and potentialities

No actual insight into optical spectroscopy topic may be gained without considering it within modern physics: interpretation of spectra (both discrete and continuous) as well as quantized absorption and emission of radiation are fundamental concepts in physics, being among the ones that paved the way for the developing of the new theory of quantum
mechanics. Not surprisingly, phenomena related to spectra and to absorption of radiation, as the photoelectric effect, have been included in school curricula. Despite its importance, optical spectroscopy is not a common-addressed topic; generally is part of the physics curriculum in introductory university physics courses and in secondary school, even if is often addressed in the chemistry courses, neglecting the fact that some aspects could be addressed even in early scientific instruction. Typically, electromagnetic spectra are introduced after students have studied physical optics, so that they have to make a transition from thinking of light as a ray first, an electromagnetic wave, then, ending with the developing of a conceptual model in which light consists of photons with discrete energies.

Spectroscopy played a key role in the history of MP (see Par. 2.1): observations of discrete emission and absorption spectra at the beginning of the nineteenth century gradually motivated the idea of building a model for atoms and molecules in which the total energy of the system is quantized and the light is emitted as photons of certain discrete frequencies when the system changes its energy, paving the way for the developing of the rising theory of quantum mechanics. It played a crucial role in the study of radiation emission leading to the construction of the quantized atomic model (Beherens, 1943; Hindmarsh and ter Haar, 1967), starting from Planck’s quantum hypothesis (Planck, 1901), up to Balmer’s series (Balmer, 1885) interpretation due to Bohr (Bohr, 1913). Einstein’s photon hypothesis in order to interpret photoelectric effect (Arons and Peppard, 1965) paved the way in the searching of single-photon sources, while optical spectroscopy started to represent an interpretative referent and an investigation tool in semi-classical perspective.

Optical spectroscopy offers, moreover, an important disciplinary contribution on the epistemological plan of physics, since it represents a conceptual bridge between classical physics and MP since absorption and emission of quantized electromagnetic radiation are fundamental concepts in physics representing some of the main investigative tools based on light-matter interaction. From this point of view, it is a validation modality of interpretative models through indirect measures based on energy exchanges and a way to interpret a code (i.e. a spectrum) in order to get information on the changes and on the states of a physical system. Optical spectroscopy is therefore a methodological context in which the tools and methods of connection between experiment and theory in physics are prominent, since it allows to gain experience about its specific ways of investigation.

On didactical plan its relevance regards the great contribution that can be given to the interpretative frame of optics and to the conceptual basis of MP as well as to the instruments and methods linking theory and experiment since experimental activities achievable with simple and cheap spectrosopes allow to highlight the link between the energy-level model for atoms and the corresponding luminous emissions, offering the possibility of addressing the problem of understanding the Nature of Science (NOS) in operative terms (Lederman, 2007; McComas et al., 2002).

Today optical spectroscopy is one of the main interpretative tools in the framework of the model in which, at microscopic level, structure of matter is quantized and it has an important applicative value in different fields: biomedical, astrophysical, social, conservation of cultural heritage and technological applications in general. Despite its disciplinary, educational and social value, there is no correspondence with an equally wide educational treatment: in fact, concerning optical spectroscopy there are no proposals for coherent educational paths and even more rare are the research-based studies on learning processes.
3.6 Discussion

The performed analysis of the literature highlighted both the main approaches at the basis of teaching/learning proposal on optical spectroscopy and students' learning difficulties. There is a wide convergence on the educational validity of the laboratorial approach implementing light sources and dispersive elements commonly used in approaching the topic of optical spectroscopy in school, a process that has been implemented in the proposal described in this thesis. In educational research, taken into account the described critical issues in learning, a broad convergence on the need to connect the microscopic model to macroscopic phenomenology, planning the learning process as a conscious and systematic spanning of different levels of reasoning. There is thus the need to found educational paths based on research, taking into account conceptual knots and reasoning of students, aspect taken in account only in the form of hypotheses in the proposed educational paths. Among the ideas at the basis of the analyzed educational proposals, the following one have been taken into account, implemented and/or modified to found the described experimentations:

1. Coherent integration between macroscopic phenomenology (light emission and evidence of spectral lines) and the microscopic interpretation of phenomena;

2. Link between the emission spectra and the structure of the atom (not related to a spatial distribution of charge, but rather founding a description of microscopic systems in terms of energy states);

3. Negative energy levels values supporting the idea of a bond system;

4. Avoiding of the double lecture of spectra in terms of wavelength and energy levels in terms of energy promoting a coherent vision in terms of energy of light-matter interactions;

5. Founding the idea of photons of certain energies based upon experimental evidences of the photoelectric effect;

6. The integration of optical spectroscopy in the wider framework of optics, justifying light propagation processes (as for example refraction) from the point of view of light-matter interaction is an original part of the work;

7. The interpretation of spectral emissions as a consequence of a change in energy of the emitting system.

A reflection on the nature of light as entity carrying energy seems to be absent in all the mentioned proposals, but in the context of optical spectroscopy it appears to have a central role since founds the nature of the interaction between light and matter from an energetic point of view. It seems to be a relevant aspect to the conceptual integration between the field of geometrical optics and the general phenomenology of light emission and interaction with matter. The listed choices constitute the basis for the research experimentations framework performed for different schooling levels. Such experimentations allow to survey the role of spontaneous ideas, to collect and analyze students’ reasoning with the aim of evaluating the educational effectiveness of the choices selected as founding. For this reason, the experimentations play the role of deepening elements for the adopted choices and for the feasibility check and educational effectiveness and they are resumed organically in the proposed teaching/learning path. The vertical perspective of the path recovers the relevant concepts emerged from the analysis of the learning outcomes in the experimentations integrating different activities elements both as propedeutic for the path and as elements
of the path itself. The experimentations with students and the outcome of the conceptual organization in the context of teacher training provide further evidences for the design of the path that arises as a global product of the research, oriented towards a constructivist vision of learning within which the need to understand the nature of students’ ideas and reasoning, both before and after education, and to use the gained knowledge in educational design is fundamental.
Chapter 4

Research and Development: 
SPETTROGRAFO, a prototype for a digital spectrometer

4.1 Experimental activities and optical spectroscopy

The role of experimental activity in physics education and in particular students’ active involvement in solving problematic situations is the core of learning (Etkina et al., 2002) with different approaches as for example IBL (McDermott et al., 1996) and Investigative Science Learning Environment (ISLE) methodology (Etkina and Van Heuvelen, 2007). In the specific field of optical spectroscopy it plays a central role since the representation of the experimental outcomes becomes an interpretative challenge of the microscopic processes of emission and absorption of light. Despite experiments and educational devices to perform optical spectroscopic measures are among the most significant and feasible, existing experimental proposals for education are essentially of two kinds: expensive apparatuses quite similar to professional tools or simple apparatuses able to perform qualitative or semi-quantitative measurements. Proposals are thus quite limited and often implemented in expensive and excessively structured devices (the so-called "black box") that do not allow students to understand the mechanisms and principles of functioning, rather orienting students to the functional learning. Indeed, obtaining optical spectra of luminous sources is quite easy: a CD or a cheap diffraction grating are quite available objects and the produced spectra can be collected with a digital camera or a Smartphone and analyzed (quantitatively or qualitatively) with specific APPs. Different educational proposals for optical spectroscopy activities are indeed present in the literature with various performances (Luo and Gerritsen, 1993; Ouseph, 2007; Scheeline, 2009; Amrani, 2014; Onorato et al., 2015) allowing traditional measurements. Those experiments represent important educational activities contributing to the learning process concerning both disciplinary and methodological aspects. Those proposals have been designed and implemented in specific and limited contexts; generally speaking, laboratorial educational proposals are offered in the form of commercial devices, and teacher have the task of integrating them in a coherent educational path, since the proposals are mostly demo activities not coherently inserted in a learning path based on the research.

Important aspects that are generally missing in the proposals are (a) the focus on the calibration process with the awareness of how a diffraction grating works as well as of the functioning of a digital sensor as a CCD; (b) the possibility that students could modify the experimental settings according to the environmental conditions or the characteristic of
the source under examination (i.e. the lighting conditions); (c) the focus on the energetic nature of the colors and the reading of a spectrum as a scale in energy rather than a scale in wavelength only and (d) the possibility to change the diffraction grating and to be aware of the change in resolution in the spectrum.

Since one of the byproduct of the thesis is the developing of an educational path on optical spectroscopy in which students are directly involved in experimental and interpretative studies, a laboratorial activity is essential and new technologies allows new opportunities to teach and learn physics, as already discussed in the case of the educational path on optical diffraction from a single slit (Gervasio and Michelini, 2009; Michelini and Stefanel, 2015). In this perspective a prototype for a digital spectrometer implementing some proposals based on ICT (Information and Communication Technologies) making use of a webcam and of a specifically-designed software allowing qualitative and quantitative analysis of a digitalized spectrum has been developed. After having analyzed the main available commercial devices and APPs performing spectroscopic analyses, a complete low-cost technical solution that will be illustrated in the following with examples of significant measures has been designed and implemented.

4.2 Some existing proposals

The PASCO PS-2600 wireless spectrometer (Fig. 4.1, left, https://www.pasco.com/prodCatalog/PS/PS-2600_wireless-spectrometer/index.cfm) integrates a CCD sensor upon which the spectra of light, in the range $380 - 980 nm$, of a certain source is registered. Light is guided to the dispersive element, that creates the spectrum, by an optic fiber. Thanks to a USB or Bluetooth connection, the software automatically shows the emission spectrum as a function of the wavelength, with no need for a calibration (Fig. 4.1, right). Obtained spectra, with a resolution of about $3 nm$, can be compared with discrete reference spectra. The device allows also the analysis of absorption and fluorescence spectra: a test tube with the sample can be inserted inside. Absorption spectra are obtained by illuminating the sample with a reference white LED light and the fluorescence spectra are obtained by illuminating the sample with light of $405 nm$ or $500 nm$. The absorbance curve is automatically shown. User has only to perform automatic actions without having access to the physics characterizing the measure or data analysis. A spectrometer implementing a focusing elements, rather than an optical fiber, is the RSPEC EXPLORER SYSTEM digital spectrometer (Fig. 4.2, left, https://www.fieldtestedsystems.com/). A diffraction grating is placed in front of a webcam connected via USB to the PC. Once the webcam points towards the source, the software allows to register the whole image of the frame with the spectrum in the range $390 - 700 nm$. Users limits himself to select the portion of

![Figure 4.1: PASCO PS-2600 digital spectrometer (left) and user interface (right).](image-url)
the frame where the spectrum is present. The software digitalizes it, providing a graph in which intensity (in arbitrary units) is shown as a function of the wavelength. The pitch of the grating is fixed, as well as its distance from the CCD sensor: it is enough to line up the image of the source with a reference to automatically and uniquely associate a position along the pixel array with a specific wavelength (Fig. 4.2, right). The good quality of the measures, which resolution is about $3 \text{nm}$, allows to compare the recorded spectra with reference ones. A digital analysis of a spectral recorded image obtained from a smartphone

![Figure 4.2: RSPEC EXPLORER SYSTEM digital spectrometer (left) and user interface (right).](image)

is allowed by mobile APPs named SpectraUPB, AspectraMini (available only for Android operating systems) and Light Analyzer (available both for Android and IOS operating systems). A diffraction grating or a simple homemade spectroscope are enough to produce the image of a emission spectrum that can be collected with the smartphone digital camera. Those APPs allows to obtain graphs of intensity as a function of the position along the spectrum, i.e. in different position of the digital image (Fig. 4.3). The main limit is the impossibility to calibrate the spectrum, obtaining only a qualitative intensity profile, or when the calibration process is allowed, the procedure is quite qualitative, user-dependent and based upon a specific wavelength that could not be present in the recorded spectrum. SPETTROGRAFO is a new system that implements the simplicity of use of the existing commercial devices and the feasibility of the analysis algorithms with new functionalities that allows the user a better control of the measuring process and on the physics of the involved processes, ensuring a good accuracy in the measured quantities.

![Figure 4.3: User interfaces of three APPs performing spectroscopic measurements. From left to right SpectraUPB, AspectraMini and Light Analyzer.](image)
4.3 The **SPETTROGRAFO** System

In the following, the hardware and software components of the designed and realized prototype will be described. It allows measures of optical spectra obtained by diffraction grating with different pitches. The goal was to create a low-cost device allowing quantitative and accurate analysis of discrete, continuous and band spectra (Buongiorno et al., 2019a, 2017).

### 4.3.1 Hardware

The equipment is assembled in a very simple way: a commercial webcam is inserted inside an aluminum case (6x6x6 cm$^3$) mounted on an adjustable tripod (Fig. 4.4). The webcam has a resolution of 640x480pix interpolated by a 1.2Mpix CCD and it focuses images from 15cm to infinity. The field of view is 60° and the frame-rate is 60fps. A support allows to place the diffraction grating in front of the webcam. The digital image registered on the sensor is sent to PC thanks to a USB connection. Gratings with pitches of 1000 lines/mm and 500 lines/mm can be used, both allowing spectral analysis in the range 380 – 700nm. 1000 lines/mm grating allows to see only the first diffraction order with a resolution of 1.3nm/pix, while with the 500 lines/mm the second order is visible, but the resolution decreases to 2.6nm/pix. A couple of Polaroid filters can be inserted in front of the webcam to tune the intensity of the source, avoiding the saturation of the sensor. In this way students become aware both of the functioning of a CCD sensor that implements a matrix of pixels, and of the need to record a spectrum collected by undersaturated pixels in order to preserve its genuine profile. Colored filters can be also inserted to study selective absorption of colors (Fig. 4.4). The device can be used also with extended light sources, making use of an external slit, working as a diaphragm; this feature helps students in recognizing that the shape of the spectral lines depends strongly on the shape of the slit used to select the light that illuminates the grating.

![Figure 4.4: **SPETTROGRAFO** system and accessories: diffraction gratings, colored and Polaroid filters.](image)

### 4.3.2 Software

Software was developed in a Microsoft "framework.NET" environment using C# language. As shown in Fig. 4.5, it allows to visualize the image as registered by the webcam, containing both the source and its spectrum, and to select the area to be analyzed (reproduced in
the upper right of the user interface). Digitalization of the spectrum occurs making a sum of the digital information of each pixel (proportional to the incident intensity) along every column. The intensity as a function of the position along the spectrum (decomposable in the R, G and B channels) in the graph in the lower right of the user interface is represented in arbitrary units and it is proportional to the mean intensity incident on the pixels of a same column. It is possible to switch to a calibrated graph, in which the horizontal axis is an energy or wavelength scale: it is enough to select in the user panel the employed diffraction grating (this information fixes the pixel-wavelength or energy relationship). A calibration source can also be used. A secondary panel allows these operations. Students have thus the possibility to face directly the process of calibration and to gain awareness of what a transfer function of a certain measuring instrument is. After having calibrated the system, quantitative measures can be performed and a reference spectrum appears under the graph showing an eV energy scale. Two movable markers allows to sign the position of the image (0th order) and a generic position along the spectrum of the 1st order, resulting in a univocal measure of wavelength (expressed in nm) or energy (expressed in eV) (Fig. 4.6). Data can be exported in tabular form allowing further analysis with a spreadsheet. The possibility of reading a spectrum as a sequence of energies corresponding to the colors was voluntarily inserted in the user interface so that students can describe the light emission or absorption processes in energetic terms.

4.3.3 Examples of measures

The SPETTROGRAFO system allows qualitative and quantitative measures of continuous spectra from incandescent lamps, discrete spectra from gas discharge or fluorescent lamps, band spectra from LEDs and absorption spectra. To perform a measure, it is enough to target the source with the device (Fig. 4.7), eventually screening it with a panel with a slit. No optical bench is needed, it is enough to assure the alignment between source, grating and sensor in a way that the spectrum is horizontal with respect to the array of pixels. In the following some examples of measures that can be performed with the device are described.

Figure 4.5: Main user interface. Recorded image by the webcam (left panel) from which it is possible to select the area to be analyzed (source + spectrum) that is automatically digitalized in a graph (bottom right panel). In this example the source is a column of LEDs observed with a 1000 lines/mm grating.
Figure 4.6: Calibrated yellow LED spectra.

Figure 4.7: SPETTROGRAFO connected to PC, pointing the source.
Spectral lines

The shape of the slit shielding the light of a gas discharge lamp is reproduced in different colors in different positions on the CCD sensor, showing the source spectrum. Once it has been digitalized, it is possible to observe and measure position, width and relative intensity of the various emissions (Fig. 4.8). This allows to discuss about the functioning of an optical sensor and about the peculiar spectral characteristics of the light emitted; the spectral features can be characterized by a wavelength or energy value. As an example, some visible wavelengths in cadmium and helium spectra have been measured and they are reported in Tab. 4.1, compared with standard values.

![Spectral lines](image)

Figure 4.8: Spectra of a cadmium gas-discharge lamp recorded with the SPETTROGRAFO system.

<table>
<thead>
<tr>
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<th></th>
<th>Helium</th>
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<td>$\lambda_{\text{std}}$ (nm)</td>
<td>$\Delta%$</td>
<td>$\lambda_{\text{meas}}$ (nm)</td>
<td>$\lambda_{\text{std}}$ (nm)</td>
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<td>-</td>
<td>-</td>
<td>447</td>
<td>447.15</td>
</tr>
</tbody>
</table>

Table 4.1: Measure of the main emission lines of Cd and He performed with SPETTROGRAFO compared with standard values (https://www.nist.gov/pml/atomic-spectra-database).

Spectral lines - optical goniometer

An alternative modality of performing measures with SPETTROGRAFO system is to place it on a rotating basis: the diffraction grating is no longer joint in front of the sensor, but it is fixed on a support at the center of the rotating base (Fig. 4.9). The system thus works as an optical goniometer. Different spectral emissions are thus observed a function of the diffraction angle $\alpha$, represented by the angle of rotation of the sensor around the grating, which has pitch $d$. The angle is measured on a graduated scale with a sensibility
of 1°. Wavelengths are evaluated with the formula to the various orders $m$:

$$d \cdot \sin \alpha = m \cdot \lambda$$

In this modality no calibration procedure is needed, except for the 0th angle, that has to correspond to the position of the source. A movable marker, appearing on the image acquired by the sensor, is used as a reference while the system rotates. In this way, beyond performing qualitative measures on different spectra, the angular and symmetrical features of diffraction grating phenomena are highlighted. In the following, measures performed in optical goniometer modality on the spectrum of a blue LED with a 500 lines/mm grating are shown (Tab. 4.2).

![Figure 4.9: SPETTROGRAFO system used as an optical goniometer.](image)

<table>
<thead>
<tr>
<th>$m=1$</th>
<th>$m=2$</th>
<th>$m=-1$</th>
<th>$m=-2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$\lambda (nm)$</td>
<td>$\alpha$</td>
<td>$\lambda (nm)$</td>
</tr>
<tr>
<td>13°</td>
<td>449.9</td>
<td>27°</td>
<td>454.0</td>
</tr>
</tbody>
</table>

**Transmissivity curve**

A white light source, as a LED, is used to obtain a reference spectrum (Fig. 4.10, left) which is modified if a colored filter is placed in front of it (Fig. 4.10, right). Software allows to extract data in a tabular form, that can be further analyzed with a spreadsheet in order to quantitatively evaluate the absorbance in various zones of the spectrum. In particular, named $I_0(\lambda)$ the intensity of the reference spectrum as a function of the wavelength and $I(\lambda)$ the intensity of the absorption spectrum, the quantity $T(\lambda) = I(\lambda)/I_0(\lambda)$ can be evaluated, representing the transmittance of the filter, or its transfer function (Fig. 4.11).

### 4.4 Conclusions

After having analyzed potentialities and limits of some commercial digital spectrometers and mobile APPs, we pointed out the main needs for an effective educational laboratory on
Figure 4.10: White LED spectra, chosen as a reference (left) and absorption spectrum having placed a blue filter in front of the source (right).
optical spectroscopy: the importance of the calibration process, the insight into the physical processes accounting for the observations, the possibility to change the grating and data acquisition modality. A simple digital device, SPETTROGRAFO, has been designed and realized; it allows real-time study of diffraction phenomena with subsequent analysis of optical spectra of different light sources. The SPETTROGRAFO system allows significant quantitative measurements overcoming the main limitations of the existing proposals. The device allows the whole control of the experiment, from its setting-up to the calibration process and the acquisition modalities: the goal was to build and offer students an open environment of design, experimentation, data collection and analysis both in "static" and in "optical goniometer" modalities. The measure outputs both in terms of wavelength and energy allow its implementation in an educational path in which the approach to optical spectroscopy could be dealt both from a quantum point of view (treating light as photons of certain energies) or traditionally, treating light as a wave of certain wavelengths.

The system consists of a commercial webcam, to be connected via USB to PC, inside an aluminum case. Different diffraction gratings can be placed in front of it, as well as Polaroid filters to dim the source luminosity, or colored filters to study selective absorption of colors. Virtual images of spectra are recorded on the CCD sensor of the webcam and observed with the aid of a specifically designed software. It is therefore possible to perform qualitative observations concerning shape and main features of different kind of spectra: continuous, discrete or bands to various diffractive orders, according to the used grating. Real-time observations of the modification of a spectrum with the presence of a colored filter can be observed too. Calibration occurs via software by selecting the used diffraction grating or with the aid of a calibration source with known wavelength (e.g. a laser). In this way a column of pixels is assigned to a specific wavelength, or energy, allowing quantitative measures with uncertainty less than 5%, depending mostly from the alignment between source and detector. Recorded spectra are digitalized in a graph representing luminous

Figure 4.11: Elaboration with a spreadsheet: light spectrum from a white LED compared with the spectrum of the same light passing through a blue filter. Abscissa values refer to the column of pixel; on the left the peak due to the source is visible (top) and transmittance of a the blue filter (bottom).
intensity as a function of the wavelength, or energy, in arbitrary units proportional to the luminous intensity on a portion of the sensor. The device can be mounted on a rotating base allowing to measure the diffraction angle and thus quantitatively evaluate the wavelength, as in the classical experiment of the optical goniometer, with an uncertainty less than 5%. *SPETTROGRAFO* system, prototype for a digital spectrometer, offers itself to be used both in secondary school educational labs and in university introductive physics courses, thanks to its inexpensiveness with respect to other commercial devices, to its easiness in use and to the possibility to explore the functional role of every components of the measure setup. The device avoids the "closed box" problem: it allows students to develop a functional understanding, which is one of the main goal of an educational lab. Observations and measures of spectra allows to characterize different kind of luminous sources, elements and absorption mechanisms.
Chapter 5

The experimentations

5.1 Rationale of the path

The rationale, i.e. the conceptual structure of the path, maintains a certain flexibility in order to be adapted to the various educational settings, in a DBR perspective; the following scheme describes the core of the educational path, highlighting the different phases (Ph).

Three different thematic areas in the framework of optics are outlined (Ph1): light sources, light propagation and light/matter interaction as well as the corresponding perspectives (emission processes, description and formalization of optical paths and microscopic interpretation of light/matter interaction). In this phase, optical phenomena are discussed in order to build a basic idea of light as a massless entity travelling in space which possess energy which guides the description of processes in which light itself interacts with matter causing different effects, such as heating, penetration, ionization and fluorescence). The difference between the Snell’s law for refraction and the phenomenology of light transmission through a transparent medium is discussed in order to recognize and distinguish the plan of formalized phenomenological description in macroscopic terms and the plan according to which light/matter interaction processes are discussed in energetic terms.

The problem of what "see" means is posed, with the aim of identify, from the discussion of spontaneous models, the role of the observer, of the observed object and of the light (Ph2).

A fundamental parameter enters in the description of the vision mechanism: the color (Ph3). Radiation gains a significant role in this perspective and poses the question of what does the color physically represent, starting from the observation that what is seen depends on the type of light used. Surface absorption and nano-structuring allows to understand the mechanism according to which different objects appear differently colored, in particular the color of an object result from the fraction of diffuse light, and this depends on the type of radiation that it is used to illuminate the object.

A review and classification of different natural and artificial sources helps in recognizing a light source as a system able to transform in radiant energy any other form of energy, as well as to recognize the need to interpret the emission mechanism (Ph4). This represent a valid context to reinforce the idea that the light emission process has to be read from an energetic point of view. Sources are analyzed in structural and functional terms, and according to the emitted light. Incandescent, fluorescence, phosphorescence emissions as well as halogen, gas discharge lamps, LED and LASERs are examined (Fig. 5.1) identifying the process of energy transformation and discussing the different characteristics. Characteristics of light emitted by different sources are examined and discussed in terms of color and intensity (Ph5). Concerning color, the exploration of the modalities allowing
the production of light of different colors leads to focus on additive and subtractive mechanisms, exploring if the light could be generated inherently colored, performing also flame essays of different chemical compounds/elements. The presence of an energy exchange within a light source emerges from the analysis of the emission of an incandescent bulb: as the electric power supplied to the system increases, emitted light appears of different intensities and colors. The Stefan-Boltzmann phenomenological laws, the identification of the emissive and absorbing power and of the important law of nature that their relationship is only a function of temperature, leads to the examination of the emission process with the increase of the power supplied to a source. The discovery of infrared radiation lies in this context, in which the idea that the emission of radiation occurs at every temperature and that the radiation emitted by the bodies can be outside the visible is consolidated. The historical discovery of ultraviolet radiation confirms this idea experimentally and accustomed to see the colors of the visible spectrum as different radiations of different energy and with different effects (heating for the IR radiation and activation of chemical reactions for the UV radiation). The question if white light can be considered a color is answered by analyzing Newton’s double prism experiment, confirming that white light is composed of different colors (Fig. 5.2). The usage of simple spectrosopes implementing a slit, a

Figure 5.2: A prism has the property of decomposing the light and not of transforming it.
the spectrum of the emitted light (Fig. 5.3, bottom). Emission spectra of the different sources listed above are examined: the phenomenological exploration of the spectra allows their classification into three categories: continuous, discrete and band spectra (Ph6). The

spectroscopy is examined as an artifact (Ph7) to recognize its functions, structure and role of the individual components (slit, grating, tube) with the method of the artifacts, which brings an initial global description, the subsequent discussion of the functions of the described parts and constructive alternatives, so as to give meaning to the functional role of each component of the object.

The diffraction is experimentally studied (Ph8) with data acquisition of luminous intensity as a function of the position (Gervasio and Michelini, 2009; Buongiorno et al., 2016, 2018b) (Fig. 5.4) starting from the exploration of the distribution of the diffraction light intensity produced with monochromatic light from a single slit, up to the examination of the light distribution produced by a diffraction grating (Buongiorno et al., 2018c), always in monochromatic light, thus giving to the diffraction the role of a dispersive mechanism capable of highlighting the chromatic structure of light, previously highlighted by the interaction of white light with a prism. The phenomenological laws can be derived from the students themselves (Ph8.1), addressing the questions with IBL methodologies. The quantum nature of light (Ph9) in terms of photons of energy corresponding to the color and intensity corresponding to the number of photons relies on the analysis of the photoelectric effect.

Figure 5.3: A simple spectroscopy (top) is used to observe spectra from different light sources (bottom).
An analysis of the Balmer series of hydrogen (Fig. 5.5) is proposed as a context in which to look for regularities in the observed discrete spectra (Ph10). Students are thus protagonists with their reasoning to relive the historical development of ideas: the coefficients obtained by Balmer allow the reading of the experimental results in which the wavelengths of the first four lines of the visible hydrogen spectrum are obtained with the empirical formula \( \lambda_n = k \cdot \frac{n^2}{n^2 - 4} \) with \( k = 364.56\text{nm} \) and \( n = 3, 4, 5, 6 \), which is reworked for a law of general validity in terms of wave numbers \( \frac{1}{k} = k'(\frac{1}{4} - \frac{1}{n^2}) \), as did Rydberg to associate with each color of the emitted radiation. Since \( \frac{1}{k} \propto E \) with \( E \) representing the energy of the color according to Einstein's interpretation of photoelectric effect, the reading in energy terms suggests how the energy of a specific light emission in a discrete spectrum is caused by an energetic variation at the microscopic level in the emitting system. In the first versions of the path the empirical formula was proposed to the students in terms of wave number (Ph10.1) or directly in energy (Ph10.2) for the search for interpretations, in particular in light of the hypothesis of the photoelectric effect. The history of physics in support of concepts has here an essential role in making students relive the same experience as Balmer and Rydberg in identifying the rules with which one can describe the spectral lines and then look for an interpretation of the emission processes.

The original articles by Balmer and Rydberg inspire the operational proposal of hydrogen spectrum analysis and the drafting of the law of the series of lines emitted by the hydrogen atom in the optical band, whose structure inspires the hypothesis of describing the emitting systems for equilibrium states and of the emission as energetic de-excitation (Ph11). The semiclassical model of the Bohr atom allows to justify the negative value of the total energies that characterize a bound system. The description in terms of energy
levels is proposed with an analogy regarding the equilibrium states assumed by a chair in the gravitational field. The energetic state of the chair is described according to the position in which the center of mass is placed when the chair system is disturbed: the center of mass of the chair moves to different levels of gravitational potential energy corresponding to the different configurations assumed when given different pushed to the chair (Fig. 5.6). It is an effective and rigorous conceptual analogy described in (Golab-Meyer, 1991). It is decided to describe the energetic state of an atom (which is not visible) in a similar way: a perturbation associated with an energy transformation leads to another state in the atom, which then decays, losing the energy acquired in the interaction. The discovery of cadmium and rubidium highlight the important role of the spectrum in the recognition of the elements. The emission process is explained by the link between energy levels and spectral lines (Ph12), whose nature in terms of line energy, corresponding to energy differences between atomic levels, requires consolidation exercises, in particular the design of energy levels and related emissions (Ph12.1) or vice-versa with the reconstruction of a structure of energy levels starting from a discrete spectrum (Ph11.2).

The conceptual elements are summarized in Tab. 5.1.

5.2 Implementation of experiments in the paths

Two experimental activities have been implemented in the path for enriching the educational proposals. Their effectiveness in eliciting students' spontaneous ideas and in developing formal thinking has been tested through specific questions in the monitoring instruments (see Sect. 5.4) addressing issues related to the observed phenomenologies and the performed measurements. The two experimental activities are described in the following. In the last stages of the research a third experimental activity has been implemented in the path, making use of an original device allowing the digitalization and quantitative analysis of different kinds of spectra, developed during the research programme (see Chap. 4). Thanks to the proposed experiments students observe different kinds of spectra, the discrete one emitted by a gas-discharge lamp and a non-complete continuous one with an emission peak typical of LEDs. Activities have been always performed in groups of 3-4 students, while the answers in the monitoring instruments have been collected individually. The two experiments described in the following, despite widely used in spectroscopy
Table 5.1: *Rationale of the path.*

<table>
<thead>
<tr>
<th>Phase</th>
<th>Protocol step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ph1</td>
<td>The three perspective in optics</td>
</tr>
<tr>
<td>Ph2</td>
<td>The mechanism of vision</td>
</tr>
<tr>
<td>Ph3</td>
<td>The nature of colors</td>
</tr>
<tr>
<td>Ph4</td>
<td>Light sources</td>
</tr>
<tr>
<td>Ph5</td>
<td>Light emitted by different sources</td>
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<tr>
<td>Ph6</td>
<td>Exploration with spectroscope</td>
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<td>Ph7</td>
<td>The spectroscope</td>
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<td>Ph8</td>
<td>Phenomenology of diffraction</td>
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<td>Ph8.1</td>
<td>Phenomenology of diffraction (IBL approach)</td>
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<tr>
<td>Ph9</td>
<td>Energetic interpretation of colors</td>
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<td>Ph10</td>
<td>Balmer and Rydberg’s formulae</td>
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<td>Bohr’s model</td>
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<td>From levels to lines</td>
</tr>
<tr>
<td>Ph12.2</td>
<td>From lines to levels</td>
</tr>
</tbody>
</table>

lessons, assumed an original role since they have been coupled with targeted questions to inquiry students’ reasoning.

### 5.2.1 The optical goniometer experiment

The proposed laboratory activity was based on the classical experiment of the optical goniometer (Fig. 5.7). The goal was to observed the light pattern produced by the interaction of the light emitted from a gas-discharge lamp (different lamps were available containing different elements (cadmium, helium, zinc, mercury) with a diffraction grating, in order to measure the wavelengths and energies corresponding to the various emissions. The analysis was conducted at first at a qualitative level, observing the spectra corresponding to the various orders, then at a quantitative level by measuring the diffraction angle of every chromatic component and associating it with the corresponding wavelength and energy. Starting from the measure of an angle \( \theta \), students evaluate the corresponding wavelength using the formula \( d \cdot \sin \theta = m \cdot \lambda \) (grating formula) and then they convert it into energy using the relation \( E = hc/\lambda \), where \( h \) is Planck’s constant and \( c \) is the speed of light.

### 5.2.2 The LED experiment

The LED experiment implements an original low-cost setup (Fig. 5.7 top) allowing of observing the spectrum of the light emitted from LEDs of different colors along a ruler (Buongiorno et al., 2018a). Simple diffraction toy glasses are used as dispersive element. Students can observe the general features of the emitted spectrum and they are guided in measuring the position of the light peak corresponding to the dominant color. Simple geometrical measures allow to evaluate the diffraction angle of the peak; the grating formula associate it with a specific wavelength and thus energy. LEDs are supplied with a variable voltage ranging from 0 to 3 V, students have the possibility to measure the threshold voltage of each LED thanks to a potentiometer in the self-build supply board, allowing
Figure 5.7: The optical goniometer experiment: the light of the lamp passes through a diaphragm (slit), it is collimated and hits perpendicularly the grating producing discrete spectra in different orders. A rotating spyglass allows to measure the different diffraction angles at the various orders. Gratings with 300 or 600 lines/mm could be used.

current-voltage measurements (Fig. 5.9). Since the majority of secondary students involved in the experimentations did not have any confidence with the concept of electric voltage it has been spoken of energy for unit of charge, in order to give meaning to the energy supplied to the system. The linear correlation between threshold voltage and energy of the emitted color, consequence of the inverse photoelectric effect which is the working mechanism thanks to which a LED produces light, highlight the energetic nature of colors.

5.3 Design-based Research and formative intervention modules

Nineteen formative experimentations have been carried out with different sample of students and collection data modalities. Twenty-eight classroom of secondary school students, three university interventions and one experimentation with primary pupils were implemented. A tuning phase started during the first year made by two experiments for setting out strategies and methods and evolved into more stable and structured experimenting phases during second and third year (see Tab. 5.2).
Figure 5.8: The LED experiment: the light emitted from a LED passes through a
diffraction grating with 1000 lines/mm and the virtual image of its spectrum is visible
along the ruler (top). Energy peak of emitted light can be correlated with the threshold
voltage specif of each LED (bottom).

Figure 5.9: The self-build supply board, allowing current-voltage measurements for LEDs
of different colors.
Table 5.2: Overview of the different experimentation carried out. The intervention ID in the form `A_B_YYYY` reports the global chronological progressive number `A`, the yearly chronological progressive number `B` followed by the year `YYYY`). In the last columns the employed monitoring instruments (tutorial, pre- and post-test) and the participants number sample are reported; the codes allow to refer to the materials collected in the Appendix.

<table>
<thead>
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<td>secondary (5th year)</td>
<td>2</td>
<td>G_17_TUTORIAL</td>
<td>33</td>
</tr>
<tr>
<td>7_5_2017</td>
<td>secondary (4th, 5th year)</td>
<td>2</td>
<td>G_17_TUTORIAL</td>
<td>35</td>
</tr>
<tr>
<td>8_6_2017</td>
<td>secondary (4th year)</td>
<td>2</td>
<td>H_17_TUTORIAL</td>
<td>22</td>
</tr>
<tr>
<td>9_7_2017</td>
<td>secondary (4th year)</td>
<td>2</td>
<td>J_17_TUTORIAL</td>
<td>32</td>
</tr>
<tr>
<td>10_8_2017</td>
<td>secondary (5th year)</td>
<td>1</td>
<td>K_17_TUTORIAL</td>
<td>11</td>
</tr>
<tr>
<td>11_9_2017</td>
<td>secondary (4th year)</td>
<td>1</td>
<td>L_17_TESTIN</td>
<td>31</td>
</tr>
<tr>
<td>12_10_2017</td>
<td>secondary (4th year)</td>
<td>4</td>
<td>M_17_TUTORIAL</td>
<td>77</td>
</tr>
<tr>
<td>13_1_2018</td>
<td>university (1st year)</td>
<td>1</td>
<td>N_18_TESTIN</td>
<td>49</td>
</tr>
<tr>
<td>14_2_2018</td>
<td>secondary (4th year)</td>
<td>2</td>
<td>O_18_TESTIN</td>
<td>49</td>
</tr>
<tr>
<td>15_3_2018</td>
<td>secondary (5th year)</td>
<td>2</td>
<td>O_18_TESTIN</td>
<td>41</td>
</tr>
<tr>
<td>16_4_2018</td>
<td>secondary (4th year)</td>
<td>2</td>
<td>P_18_TESTIN</td>
<td>41</td>
</tr>
<tr>
<td>17_5_2018</td>
<td>secondary (4th year)</td>
<td>2</td>
<td>P_18_TESTIN</td>
<td>44</td>
</tr>
<tr>
<td>18_7_2018</td>
<td>secondary (5th year)</td>
<td>1</td>
<td>Q_18_TUTORIAL</td>
<td>18</td>
</tr>
<tr>
<td>19_8_2018</td>
<td>secondary (4th year)</td>
<td>1</td>
<td>S_18_TUTORIAL</td>
<td>20</td>
</tr>
</tbody>
</table>
5.4 Design of the monitoring instruments during the research and specific RQs

The rationale of the path described before represents the conceptual structure of the different paths experimented. An educational path is essentially a sequence of reasonings guiding students toward the physical interpretation of phenomena. During the research different paths have been designed and experimented, following different approaches and perspectives (see Chap. 6); it is natural that, in a DBR approach, the employed monitoring instruments underwent an iterative review. For example, the tutorials, used to guide students reasoning have been modified according to the sequences of conceptual steps characterizing the path. Also the structuring of specific questions has been refined during time in order to avoid emerged misconceptions from students' answers or to clarify the required reasoning. The whole set of questions have been organized into broad categories, representing conceptual steps of the paths (see Tab. 5.3). Each question posed to students aims at investigating specific aspects in order to infer the followed reasoning or the adopted models. Detailed research questions guided the qualitative data analysis of students' answers. In tables from 5.5 to 5.24 questions from each category are reported with the associated detailed research questions. To be noticed that some question codes apper with a progressive suffix: such questions are the ones that aim at inquiry the same aspect, but that, during the evolution of the research, underwent change in the formulation for the purposes described before (see Tab. 5.4). In paragraphs from 5.4.1 to 5.4.20 the questions are detailed shown.

Table 5.3: Conceptual steps of the paths.

<table>
<thead>
<tr>
<th>LS</th>
<th>Light sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>EL</td>
<td>Emitted light</td>
</tr>
<tr>
<td>CL</td>
<td>Colored lights</td>
</tr>
<tr>
<td>LM</td>
<td>Light-matter interaction</td>
</tr>
<tr>
<td>ML</td>
<td>Monochromatic light</td>
</tr>
<tr>
<td>DD</td>
<td>Diffraction as dispersive mechanism</td>
</tr>
<tr>
<td>ES</td>
<td>Exploration of light sources with spectroscope</td>
</tr>
<tr>
<td>EG</td>
<td>Exploration of light sources with diffraction toy glasses</td>
</tr>
<tr>
<td>FS</td>
<td>Functioning of a spectroscope</td>
</tr>
<tr>
<td>LP</td>
<td>Light emission process</td>
</tr>
<tr>
<td>BM</td>
<td>Bohr's model</td>
</tr>
<tr>
<td>SS</td>
<td>From the spectrum to the energetic structure of source</td>
</tr>
<tr>
<td>BR</td>
<td>Balmer and Rydberg's formulae</td>
</tr>
<tr>
<td>LIN</td>
<td>From lines to level</td>
</tr>
<tr>
<td>LEV</td>
<td>From levels to lines</td>
</tr>
<tr>
<td>LR</td>
<td>Levels representation</td>
</tr>
<tr>
<td>NL</td>
<td>Nature of levels</td>
</tr>
<tr>
<td>IS</td>
<td>Information coded in a spectrum</td>
</tr>
<tr>
<td>DIG</td>
<td>Digital spectra interpretation</td>
</tr>
<tr>
<td>LED</td>
<td>LED experiment</td>
</tr>
</tbody>
</table>
Table 5.4: Overview of the different implementations of used questions in the monitoring instruments (reported in Appendix). The table allows to appreciate both the sequences of question in every test (tutorial, pre- and post-test) along each column and the number of time(s) each question has been used (NUM). Formal modification/s of some questions, according to a DBR approach are also highlighted by using different suffixes.

| TABLE TO BE INSERTED. TOO BIG: TO BE FORMATTED! |
5.4.1 Light sources

Table 5.5: Light sources: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>List three light sources of different nature.</td>
<td>Which are the most familiar evoked light sources?</td>
</tr>
<tr>
<td>LS2</td>
<td>Which main types of sources is it possible to identify?</td>
<td>How do students classify different light sources?</td>
</tr>
<tr>
<td>LS3</td>
<td>According to which criteria is it possible to classify different light sources? Give some examples.</td>
<td>How are the selected criteria used to classify light sources?</td>
</tr>
<tr>
<td>LS4</td>
<td>What are the main working mechanisms of light sources (which physical processes producing light do you know)?</td>
<td>How do students look at the way of working of light sources? How are macro/micro levels used for the explanations?</td>
</tr>
<tr>
<td>LS5</td>
<td>What does characterize a light source from a physical point of view?</td>
<td>How do students characterize light sources? Which physical quantities are used to characterize light sources? Which common features are identified?</td>
</tr>
<tr>
<td>LS6</td>
<td>Different chemical compounds produce lights of different colors in a flame. Which type of associations is it possible to make between flame colors and the elements in the compounds?</td>
<td>How do students relate the color of a flame with the chemical nature of the burned compound? How do students explain the relationship eventually individuated? How do students frame the description in terms of light source?</td>
</tr>
</tbody>
</table>

The questions were designed in order to elicit students’ in recalling the most familiar light source and in the course of the research work question were added in order to inquiry also the mechanisms of functioning, ending with the introduction a question LS5 since the concept of a light source as system transforming energy is crucial in the path. Eliciting the reasoning on the different light sources from a technological, functional and physical point of view aimed at highlighting the different way in which light sources could be classified on general and specific levels and at eliciting the reasoning on the production of light.
### 5.4.2 Emitted light

Table 5.6: Emitted light: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EL1_a</td>
<td>Which color is the light emitted from different sources?</td>
<td>How do students describe the light emitted by different sources? Are color and intensity identified as independent quantities? What sort of referents are used to describe the lights emitted by different sources? Is the description plan quantitative or qualitative? How is description based on physical quantities? How does the nature of light model influence students' light description?</td>
</tr>
<tr>
<td>EL1_b</td>
<td>After observing the lights emitted by different sources (incandescent lamp, fluorescent lamp, LED, hydrogen lamp ...) describe them emphasizing similarities and differences.</td>
<td></td>
</tr>
<tr>
<td>EL1_c</td>
<td>Observe the emitted light from different sources and describe its characteristics.</td>
<td></td>
</tr>
<tr>
<td>EL1_d</td>
<td>Which physical quantities describes the lights emitted from different sources?</td>
<td></td>
</tr>
</tbody>
</table>

The reasoning on colors and intensity as essential characteristic of the emitted light was first inquired at qualitative levels. Students’ answers were too generic so the questions have been modified in order to elicit students reasoning in comparing different light and in describing quantitatively the observed lights.
### 5.4.3 Colored lights

Table 5.7: Colored lights: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL1</td>
<td>List three examples of sources emitting colored light.</td>
<td>Which are the most familiar evoked colored light sources?</td>
</tr>
<tr>
<td>CL2</td>
<td>Describe the main modalities to produce colored light.</td>
<td>How do students identify processes in producing colored light? How do students describe the main modalities of producing colored light? Is the physical process prominent in the description or do the operative-technological aspects prevail?</td>
</tr>
<tr>
<td>CL3</td>
<td>Explain processes able to produce colored light.</td>
<td>How do students explain the production of colored lights? Do students explain the processes from a macro or from a micro point of view? Which models are employed? Which hypotheses are formulated?</td>
</tr>
<tr>
<td>CL4</td>
<td>Is the color a physical quantity? Explain.</td>
<td>How do students attribute properties at the quantity &quot;color&quot;? How do they support their ideas?</td>
</tr>
</tbody>
</table>

The questions aim at eliciting students’ reasoning on the production of colored light, during the research specific questions regarding the physical mechanisms responsible for the production of colored light substituted the more generic ones in which students were not stimulate to reason on the processes.
### 5.4.4 Light-matter interaction

Table 5.8: *Light-matter interaction: detailed research questions.*

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM1</td>
<td>Which are the main light propagation phenomena? List them.</td>
<td>Which are students’ main familiar phenomena concerning light propagation?</td>
</tr>
<tr>
<td>LM2</td>
<td>Do you believe that the list is homogeneous in its contents? Explain.</td>
<td>How do students identify light interaction processes distinguishing them from light propagation phenomena in a list of different kind of processes?</td>
</tr>
<tr>
<td>LM3</td>
<td>Take into consideration the phenomena of refraction and transmission: which characteristics do they have in common? Which differences?</td>
<td>How do students distinguish transmission and refraction? How do students distinguish the simple optical path from light-matter interaction? How do students identify light interaction processes distinguishing them from light propagation phenomena in a list of different kind of processes? How do students look at the two plans? Which conceptual referents are used to describe the two phenomena? Which conceptual referent are used to describe the two phenomena?</td>
</tr>
<tr>
<td>LM4</td>
<td>Is it possible to identify different plans concerning light propagation phenomena? Explain.</td>
<td>How do students take into account macro/micro phenomenological description with respect to light-matter interaction? How do students use descriptive/phenomenological and interpretative plan in optical phenomena?</td>
</tr>
<tr>
<td>LM5_1</td>
<td>Take into account the case in which light passes through a transparent body: what does Snell’s law tell us?</td>
<td>How do students identify the descriptive nature of the phenomenological Snell’s law with respect to absorption and transmission processes involved in the same phenomena? In particular how do students take into account relationship between macro and micro level in analyzing the velocity of light in the matter?</td>
</tr>
<tr>
<td>LM5_2</td>
<td>Take into account the case in which light passes through a transparent body: how do you explain the change in velocity of the light?</td>
<td></td>
</tr>
<tr>
<td>LM5_3</td>
<td>Take into account the case in which light passes through a transparent body: which physical quantities are involved in the process?</td>
<td></td>
</tr>
<tr>
<td>LM6</td>
<td>To characterize with a physical quantity the color of light I study its interaction with matter. I illuminate the same system with lights of different colors studying the gain in internal energy: using the same lamp and different color filters to produce different colored lights I illuminate the same mass of water. What does emerge from the analysis of the obtained data? (explain).</td>
<td></td>
</tr>
<tr>
<td>LM7_a</td>
<td>Three cuvettes of water painted with trans, white and black increase the temperature in different way when they are illuminated by light. In the light of the results of the experiment, what association can be made between the color of the light and the carried energy?</td>
<td></td>
</tr>
<tr>
<td>LM7_b</td>
<td>If an object is illuminated, it heats up. How do you explain this evidence?</td>
<td></td>
</tr>
<tr>
<td>LM8</td>
<td>Is the heating of a body the only consequences of having illuminated it?</td>
<td></td>
</tr>
<tr>
<td>LM9_a</td>
<td>According to which characteristics of the light do you expect the heating depends on? Justify your answer.</td>
<td></td>
</tr>
<tr>
<td>LM9_b</td>
<td>A piece of matter is illuminated in order to increase its temperature: which parameters of the light would you modify, and how, in order to achieve a more effective heating?</td>
<td></td>
</tr>
<tr>
<td>LM9_c</td>
<td>IR rays heat up matter. Using IR rays with increasing intensity, do you expect an increasing heating or other effects? Explain.</td>
<td></td>
</tr>
<tr>
<td>Question</td>
<td>Analysis</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>LM9_d Illuminating a piece of matter with X rays no heating occurs.</td>
<td>How do you explain this evidence?</td>
<td></td>
</tr>
<tr>
<td>LM9_e Consider other phenomena of light-matter interaction: by</td>
<td>How do you explain these evidences?</td>
<td></td>
</tr>
<tr>
<td>illuminating an object it heats up; light impresses photographic films</td>
<td></td>
<td></td>
</tr>
<tr>
<td>and is able to tan the skin; light activates phenomena of fluorescence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>or phosphorescence.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM10 Take into account light-matter interaction: point out the main</td>
<td>Do students use a coherent description or they adapt the model according</td>
<td></td>
</tr>
<tr>
<td>phenomena and describe how do you explain them.</td>
<td>to the specific situation? Which conceptual referents are used to describe</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the phenomenologies? How do students explain or interpret phenomena using</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the same model attributing coherent roles to light and the associated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>quantities?</td>
<td></td>
</tr>
<tr>
<td>LM11_a Which physical quantities describe light-matter interaction?</td>
<td>How do students quantitatively describe light-matter interaction</td>
<td></td>
</tr>
<tr>
<td>Explain using examples.</td>
<td>processes? Which process do they spontaneously quote? Are students able</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to provide a homogeneous interpretation or they describe different</td>
<td></td>
</tr>
<tr>
<td></td>
<td>processes from different perspectives? How are physical quantities are</td>
<td></td>
</tr>
<tr>
<td></td>
<td>correlated to quoted examples?</td>
<td></td>
</tr>
<tr>
<td>LM11_b Take into account light-matter interaction processes as</td>
<td>Which specific light-matter interaction is chosen by students as a</td>
<td></td>
</tr>
<tr>
<td>transmission, reflection and absorption. What physical quantities are</td>
<td>referent? How do students discuss the phenomenology in terms of light-</td>
<td></td>
</tr>
<tr>
<td>useful to characterize them quantitatively? Provide examples.</td>
<td>matter interaction?</td>
<td></td>
</tr>
<tr>
<td>LM12 Discuss and explain a light-matter interaction phenomena</td>
<td></td>
<td></td>
</tr>
<tr>
<td>producing colored light.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Questions have been chosen to inquiry students’ ideas on light-matter interaction phenomena. Firstly only heating processes have been taken into account for justifying the interaction between light and matter and to identify light as an entity carrying energy. Students’ reasoning unfortunately were led to reason in terms of "red light carries a greater amount of energy wrt blue light since its heating power is greater", so it has been started to take into account other phenomenology of light matter interaction, beyond the simple heating, to elicit students’ reasoning on the involved physical quantities in the different processes. Also the inquiry instruments to link macro and micro interpretation (Snell’s law as a descriptor of the optical path vs a description in terms of light speed change in a medium) underwent some changes during the research, suggesting students to analyze directly the situation of the light propagating through a transparent medium rather than general phenomena involving light-matter interactions.
5.4.5 Monochromatic light

Table 5.9: Monochromatic light: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML1</td>
<td>What does a transparent prism do: does it separate or does it transform the light passing through it? Discuss an experiment allowing to discriminate the two hypotheses.</td>
<td>How do students interpret the production of colored light from a prism? Which experimental activities do students suggest in order to confirm their hypotheses?</td>
</tr>
<tr>
<td>ML2</td>
<td>Could a light appearing of a single color have a chromatic structure?</td>
<td>How do students models colored light and white light in terms of chromatic composition? How do students see a colored light in terms of its chromatic structure?</td>
</tr>
<tr>
<td>ML3_a</td>
<td>After having observed the phenomenology of diffraction by a single slit and by a grating, describe the diffraction role as a dispersive mechanism comparing with the light dispersion phenomena operating by a prism.</td>
<td>How do students compare the role of two different physical mechanisms in producing the same macroscopic effect? Which role do students attribute to diffraction in order to act as a dispersive mechanism? Which aspects are identified as inalienable in order to describe diffraction as a dispersive mechanism?</td>
</tr>
<tr>
<td>ML3_b</td>
<td>White light is divided into its component colors if it passes through a prism. Can the phenomenon of diffraction be used to separate it in the same way? Explain.</td>
<td>Question ML3_a was modified in question ML3_b to clarify students, that seemed to not understand the question posed in the first way, since they associated the phenomena of diffraction with monochromatic light and the diffraction by a prism with white light. The aim was to promote students’ reasoning in associating the separation of light into colors to its nature and not on the specific dispersive mechanism used, since from students’ answers emerged that they associate a chromatic structure only to white light and not to colored light.</td>
</tr>
</tbody>
</table>
### 5.4.6 Diffraction as dispersive mechanism

Table 5.10: Diffraction as dispersive mechanism: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD1</td>
<td>How does single-slit diffraction pattern change varying the color of the light?</td>
<td>How do students describe the single-slit diffraction pattern as a function of the color?</td>
</tr>
<tr>
<td>DD2</td>
<td>How does single-slit monochromatic diffraction pattern change bringing slit and screen closer?</td>
<td>How do students discuss the properties of the single-slit diffraction pattern emerging from this evidence?</td>
</tr>
<tr>
<td>DD3</td>
<td>How does single-slit diffraction pattern change varying the width of the slit?</td>
<td>How do students describe the single-slit diffraction pattern as a function of the slit width?</td>
</tr>
<tr>
<td>DD4</td>
<td>According to a wave nature of light, how can be written the condition for observing a minimum of intensity on the screen in the single-slit diffraction experiment?</td>
<td>Which strategies do students use to obtain a law describing the position of minimum of intensity on the screen in the single-slit diffraction experiment? Which difficulties emerge in taking into account the wavelength?</td>
</tr>
<tr>
<td>DD5</td>
<td>According to a wave nature of light, how can be written the condition for observing a maximum of intensity on the screen in the single-slit diffraction experiment?</td>
<td>Which strategies do students use to obtain a law describing the position of maximum of intensity on the screen in the single-slit diffraction experiment? Which difficulties emerge in taking into account the wavelength?</td>
</tr>
<tr>
<td>DD6</td>
<td>In the case of two slits, how is it possible to determine the position of the maximum intensity points? (explain and write down the formal relation).</td>
<td>How do students re-use the experimental exploration used to study the single-slit diffraction experiment to obtain the law in the case of two slits? Which kind of difficulties emerge?</td>
</tr>
<tr>
<td>DD7</td>
<td>In the case of a grating, how is it possible to determine the position of the maximum intensity points? (explain and write down the formal relation).</td>
<td>How do students re-use the experimental exploration used to study the single-slit diffraction experiment to obtain the law in the case of a grating? Which kind of difficulties emerge?</td>
</tr>
<tr>
<td>DD8</td>
<td>From which parameters does the single-slit diffraction pattern depend from?</td>
<td>How do students recognize parameters' role in the phenomenology? How are the features of the pattern illustrated?</td>
</tr>
<tr>
<td>DD9_a</td>
<td>According to the sample data, design an experiment allowing to determine the single-slit diffraction phenomena laws.</td>
<td>How do students design an experiment to find out a law? Which difficulties emerges? Are the quoted parameters used? How do students support the their choices?</td>
</tr>
<tr>
<td>Question</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>DD9_b</td>
<td>Which are the parameters a single-slit diffraction pattern depends on? To answer, imagine to design an experiment: which quantities do you fix and/or modify in the apparatus? Explain the role of each parameter and make a forecast of the changing occurring changing the various parameters.</td>
<td></td>
</tr>
<tr>
<td>DD10</td>
<td>In the light of the performed analysis, how do you expect that the intensity pattern would change according to the color of the used light? How do students identify the role of the color as a parameter in the experimental law?</td>
<td></td>
</tr>
<tr>
<td>DD11</td>
<td>In the case of 2 slits, point out the other parameter(s) to be taken into account. How do students identify the role of the new parameters in the experimental setup?</td>
<td></td>
</tr>
<tr>
<td>DD12_a</td>
<td>A grating is composed by many slits extremely close to each other. Which peculiar characteristics the diffraction pattern have and which laws describe them? How do students relate the constructive features of a grating with the observed light pattern? Which aspects are identified in the transition between a diffraction pattern and a spectrum? How do students describe the features of a diffraction pattern from a grating?</td>
<td></td>
</tr>
<tr>
<td>DD12_b</td>
<td>How do you interpret the effect of decomposition of light from a diffraction grating? (description+drawing).</td>
<td></td>
</tr>
</tbody>
</table>

Questions regarding diffraction mechanism aim at eliciting students’ reasoning on the role of experimental parameters in the diffraction phenomena to step from the single slit diffraction pattern to a diffraction pattern produced by a grating. Only in the very last experimentations the conceptual step were faced one-by-one analyzing in detail the role of each parameter. In the first experimentations only the single slit diffraction phenomenology was taken deeply into account and the gratings’ formula was given to students without any experimental support. In question DD12_b a drawing was requested to students since in questions DD12_a they limited themselves to describe the diffraction pattern and the laws governing it in the case of monochromatic light, without mentioning its role in decomposition of light.
5.4.7 Exploration of light sources with spectroscope

Table 5.11: *Exploration with spectroscope: detailed research questions.*

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES1_a</td>
<td>What can I discover observing different light sources with a simple spectroscope?</td>
<td>Which conceptual referents are used by students in order to describe different spectra? Which aspects are noticed by students in describing different spectra? How do students describe the observed spectra? How do students justify the differences between spectra?</td>
</tr>
<tr>
<td>ES1_b</td>
<td>Point out similarities and differences between the emission spectra of an incandescent light bulb, a gas discharge lamp and a LED, justifying the main differences.</td>
<td></td>
</tr>
<tr>
<td>ES1_c</td>
<td>Observe the lights emitted by the different sources with the spectroscope. Point out the different peculiar features.</td>
<td></td>
</tr>
<tr>
<td>ES1_d</td>
<td>Explore the light emitted from different sources with the spectroscope. What types of spectra did you reveal?</td>
<td></td>
</tr>
<tr>
<td>ES2</td>
<td>I observe some LED sources with a spectroscope. What are the characteristics of the spectrum?</td>
<td>How do students describe a band spectra? How do they relate the observed spectrum to the color of the LED?</td>
</tr>
<tr>
<td>ES3</td>
<td>A spectrum provides quantitative information about the lights emitted by different sources. Quantitatively characterizes the spectra shown below in terms of wavelengths.</td>
<td>How do students describe different spectra having quantitatively information available? Which aspects are identified?</td>
</tr>
</tbody>
</table>

Questions from ES1_a to ES1_d were progressively modified in order to guide students in compare different spectra in a more quantitatively way since they limited themselves to describe the observed spectra. Other questions were implemented in the last experimentations in order to explicitly stimulate students to link a quantitative description of a spectra with the emitting source.
5.4.8 Exploration of light sources with diffraction toy glasses

Table 5.12: Exploration with diffraction toy glasses: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EG1</td>
<td>Explore light sources with diffraction toy glasses: which differences do you notice with respect to the exploration with the spectroscope?</td>
<td>Do students identify the role of the slit in producing the shape of a spectrum? How do students correlate the main features of the emitted spectra to the device used to detect it?</td>
</tr>
<tr>
<td>EG2</td>
<td>Explore different light sources with diffraction toy glasses: which is the shape of the image you observe?</td>
<td>Do students recognize that, without a diaphragm, the spectrum image appears with the shape of the source itself?</td>
</tr>
<tr>
<td>EG3</td>
<td>Explore different light sources with diffraction toy glasses: which elements produces the shape of the spectrum?</td>
<td>Do students recognize that, without a diaphragm, the spectrum image appears with the shape of the source itself?</td>
</tr>
<tr>
<td>EG4</td>
<td>Explore light sources with diffraction toy glasses. Point out similarities and differences reporting detailed observations.</td>
<td>How do students describe the spectra observed with a raw apparatus? Do they point out the main features of the spectra?</td>
</tr>
</tbody>
</table>
### Table 5.13: Functioning of a spectroscope: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS1</td>
<td>Grating's role: how do you justify the presence of lines of different colors?</td>
<td>How do students describe the dispersive mechanism of a diffraction grating? Which model do they employ? How is diffraction phenomena used to describe the phenomenology?</td>
</tr>
<tr>
<td>FS2_a</td>
<td>Grating's role: if the source were monochromatic, what do you expect to observe?</td>
<td>How do students interpret the interaction between a mono/bichromatic light and a diffraction grating? Do students focus on the single spectrum or the whole diffraction pattern?</td>
</tr>
<tr>
<td>FS2_b</td>
<td>If the source were monochromatic, what do you expect to observe? (description + drawing)</td>
<td></td>
</tr>
<tr>
<td>FS2_c</td>
<td>Observing a purple light with a spectroscope, how do you imagine the spectrum?</td>
<td></td>
</tr>
<tr>
<td>FS3</td>
<td>Grating's role: what is the shape of the lines due to?</td>
<td>What kind of hypotheses are formulated in order to account for the shape of the spectral lines? What is the role attributed to the grating in justifying the shape of the spectral lines?</td>
</tr>
<tr>
<td>FS4</td>
<td>Spectral lines extend indefinitely to the right and to the left (even if we do not see them)?</td>
<td>How do students describe the formation of a spectrum? How do they link with diffraction phenomena?</td>
</tr>
<tr>
<td>FS5</td>
<td>What would you see in the angular range 0 °–180 ° of the optical goniometer if you use an incandescent lamp?</td>
<td>How do students associate the functional role of the grating in producing a spectrum independently by the light source?</td>
</tr>
<tr>
<td>FS6_a</td>
<td>What do you expect to observe if the grating were removed by the experimental apparatus?</td>
<td></td>
</tr>
<tr>
<td>FS6_b</td>
<td>Apparatuses for optical spectroscopy measurements consist of a slit and a prism or a diffraction grating, through which the source under examination is observed. What would you observe if the grating were removed in the optical goniometer? Explain and illustrate, using a drawing.</td>
<td>Which role is attributed to the diffraction grating in producing a spectrum? How do students describe the macroscopic effect of colors separation?</td>
</tr>
<tr>
<td>FS6_c</td>
<td>Apparatuses for optical spectroscopy measurements consist of a slit and a prism or a diffraction grating, through which the source under examination is observed. Explain the role of the prism or the grating.</td>
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</tr>
<tr>
<td>FS7</td>
<td>With a gas discharge lamp and the apparatus of the optical goniometer used in the laboratory, spectral images in the shape of lines are observed. Is it possible to obtain spectral images of another shape with the same gas discharge lamp? How?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>How do students relate spectral lines’ shape with the employed apparatus?</td>
<td></td>
</tr>
<tr>
<td>FS8</td>
<td>Observe the spectroscopy structure and explain its functioning.</td>
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</tr>
<tr>
<td></td>
<td>How do students approach spontaneously the artifacts exploration looking to the phenomena involved? In which operative ways do students recognize the functioning of an artifact? How exploratory elements are used by students in the interpretation of an artifact?</td>
<td></td>
</tr>
<tr>
<td>FS9</td>
<td>Explore and describe the role of each part of a spectroscope (diaphragm, grating, tube).</td>
<td></td>
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<tr>
<td></td>
<td>How an operative exploration may help students to identified the roles of the single components of a spectroscope?</td>
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</tr>
<tr>
<td>FS10</td>
<td>What do you expect to observe changing the diaphragm shape?</td>
<td></td>
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<tr>
<td></td>
<td>What hypotheses are formulated by students regarding the shape of the diaphragm in a spectroscope?</td>
<td></td>
</tr>
<tr>
<td>FS11</td>
<td>After changing the shape of the diaphragm, what do you conclude about its role in the functioning of a spectroscope?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>How do students recognize the role of the diaphragm after the test of an hypothesis? Do students identify the grating as he only responsible for diffraction?</td>
<td></td>
</tr>
<tr>
<td>FS12</td>
<td>What do you expect to observe removing the grating?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>What hypotheses are formulated by students regarding the role of the grating in a spectroscope?</td>
<td></td>
</tr>
<tr>
<td>FS13</td>
<td>After removing the grating, what do you conclude about its role in the functioning of a spectroscope?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Do students recognize the role of the grating after the test of an hypothesis? Do students identify the grating as he only responsible for diffraction?</td>
<td></td>
</tr>
<tr>
<td>FS14</td>
<td>What do you expect to observe using only the grating?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>What hypotheses are formulated by students regarding the modification of the spectroscope, in particular using only the grating? Do students identify the grating as the main part of a spectroscope, i.e. the part producing the spectrum?</td>
<td></td>
</tr>
<tr>
<td>FS15</td>
<td>Which is the role of the diaphragm through which light passes?</td>
<td>Which role students attribute to the diaphragm in a spectroscope?</td>
</tr>
<tr>
<td>------</td>
<td>---------------------------------------------------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>FS16</td>
<td>Which is the role of the grating in the experimental setup?</td>
<td>Which role students attribute to the grating in a spectroscope? How its role is described?</td>
</tr>
</tbody>
</table>

Question F2_a has iteratively modified to F2_b and F2_c implementing also the request of a drawing since students' answer were ambiguous and their pattern of reasoning concerning the effect of illuminating a diffraction grating with a monochromatic source did not emerged. Question FS6_b is the best way to pose that kind of question, since in answers to questions FS6_a and FS6_c students mainly limit themselves in declaring that "without rating no spectra is observed", "the role of the grating is to produce the spectrum".
### 5.4.10 Light emission process

Table 5.14: *Light emission process: detailed research questions.*

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP1_a</td>
<td>Observing through an optical goniometer lines of different colors are present. How do you justify their presence?</td>
<td>How do students interpret the emission process in the case of observing a discrete spectrum? How do students relate spectra with the emission process? How do students correlate the observed phenomenology to a microscopic interpretation? On which level do students describe the emission process? How is students' creativity activated in searching for an association between the discrete spectrum and the emission process, in particular: recalling notions of chemistry, scholastic ...?</td>
</tr>
<tr>
<td>LP1_b</td>
<td>During the optical goniometer experiment you observed the spectral lines emitted by a certain gas. Explain the process that gives rise to the observed lines, using a graphical representation.</td>
<td></td>
</tr>
<tr>
<td>LP1_c</td>
<td>What does the emitted energies with respect to the emitting system? (describe an interpretative hypothesis regarding the emission process and making use of a sketch).</td>
<td></td>
</tr>
<tr>
<td>LP1_d</td>
<td>Light is an entity carrying energy. What do the emitted energies represent with respect to the emitting system? (describe an interpretative hypothesis regarding the emission process and making use of a sketch).</td>
<td></td>
</tr>
<tr>
<td>LP1_e</td>
<td>Observing the spectrum of light emitted by a gas discharge lamp how do you describe the light emission process?</td>
<td></td>
</tr>
<tr>
<td>LP1_f</td>
<td>Looking at the spectrum of light emitted by a gas discharge lamp how do you describe the light emission process?</td>
<td></td>
</tr>
<tr>
<td>LP2</td>
<td>How do you imagine the process of emission of light by matter? Explain it and identify the critical points to understand.</td>
<td>How do students imagine the process of light emission by matter? How many models emerge? Are different processes quoted or students try to incorporate the phenomenology under a single coherent model?</td>
</tr>
<tr>
<td>LP3</td>
<td>What investigations would you do to test your interpretation, or at least to identify a physics of the process?</td>
<td>How do students suggest tests in order to support the hypotheses made?</td>
</tr>
<tr>
<td>LP4</td>
<td>Describe the process of light emission in energetic terms, even considering specific cases.</td>
<td>How do students describe the light emission process in energetic terms? Which cases are taken as examples? Is the list homogeneous or it regards specific situations?</td>
</tr>
<tr>
<td>LP5</td>
<td>After observing 3 different types of spectra (continuous, discrete, band), how do you imagine the emission process in the 3 cases? Help yourself with a graphical representation.</td>
<td>How do students interpret the emission process in the 3 cases? Is the answer given at descriptive level, interpretative level or functional level? Which models are suggested by students for accounting for the observation of 3 different types of spectra? With what spontaneous ideas/representations is the observed phenomenology correlated to microscopic processes?</td>
</tr>
<tr>
<td>LP6</td>
<td>LED spectra: what assumptions about the emission process are suggested by the observed spectra?</td>
<td>Which hypotheses on the emission process are formulated by students observing a band spectrum? How do students interpret the emission process? Is the answer given at descriptive level, interpretative level or functional level? Which models are suggested by students for accounting for the observation of a band spectra?</td>
</tr>
<tr>
<td>LP7</td>
<td>Flame tests: What interpretation can be made concerning the process determining the emitted light?</td>
<td>Which hypotheses concerning the emission process are suggested by students for accounting for the light emission process of elements in a flame? Do students provide a micro or macro description of the process? How is the process described in the specific case of a burning element in a flame producing colored light?</td>
</tr>
<tr>
<td>LP8</td>
<td>How do you interpret, in energetic terms, a spectrum?</td>
<td>How do students use energy as conceptual referent for describing the emission process? Which kind of connections between the energetic structure of the source and the energies present in a spectrum emerge?</td>
</tr>
</tbody>
</table>

Questions from LP1_a to LP1_f have been modified since in the first versions students tended to focus on the experimental setup (confusing the mechanism that produces colored light inside a source and the mechanism allowing their separation). A major focus on the emitting system was thus systematically put.
### 5.4.11 Bohr’s model

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM1_a</td>
<td>Write down the acting force on an electron in a Bohr orbit. Evaluate then the total energy of the atom. What does it tell us?</td>
<td>How do students interpret the total energy a system can have? Which difficulties emerge in evaluating the total energy of an electron-proton bound system with a classical approach? What difficulties arise in relating the various kinematic and dynamic information to derive the total energy of a hydrogen atom?</td>
</tr>
<tr>
<td>BM1_b</td>
<td>Bohr’s atomic model hypothesizes a hydrogen atom in which an electron makes a circular orbit around a proton thanks to the mutual Coulomb attraction. Write the acting force between proton and electron and, using the laws of dynamics, find the total energy of the system (kinetics + potential). What can you say about the obtained value?</td>
<td></td>
</tr>
<tr>
<td>BM1_c</td>
<td>In Bohr’s atomic model, the centripetal force that holds an electron around a proton in a circular orbit is of the Coulomb type. Write the relationship between the centripetal force and the Coulomb force and use it to derive an expression for the total energy of the system (kinetic + potential) which is a function of the radius alone.</td>
<td></td>
</tr>
<tr>
<td>BM1_d</td>
<td>Considering Bohr’s atomic model, write down the total energy of a hydrogen atom as a function of the radius alone.</td>
<td></td>
</tr>
<tr>
<td>BM2</td>
<td>How do you interpret the expression obtained with respect to the sign (positive or negative)?</td>
<td>How do students attribute meaning to a total negative energy?</td>
</tr>
<tr>
<td>BM3</td>
<td>How do you interpret the expression obtained as a function of the radius?</td>
<td>According to which reasoning students associate higher or lower energies to different orbits? What is the decreasing/increasing of the total energy attributed to?</td>
</tr>
</tbody>
</table>

Students’ were not able to answer to the first version of question BM1 due probably to their habit in being guided when evaluating a physical relation based on given assumptions (in this case Newton’s second law, the expression centripetal force and the Coulomb force). It emerged that students have to be guided in obtaining the total energy of an hydrogen atom in the measure of giving them the mathematical tools and formulae to be put together, as well as to clearly specify the goal of their calculation.
5.4.12 From the spectrum to the energetic structure of source

Table 5.16: From spectrum to energetic structure of source: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS1</td>
<td>Examine the spectrum emitted by a gas discharge lamp and a LED. Make a hypothesis with a sketch of the energy structure of the two emitting systems.</td>
<td>How do students model the energy structure of 2 different light sources according to the observed spectrum? What kind of assumptions/hypotheses drive the reasoning? How do students identify the relationships between the observed spectrum and the energetic structure of the emitting source?</td>
</tr>
<tr>
<td>SS2</td>
<td>You have observed the spectrum of a LED: how do you imagine the energy structure of the emitting system?</td>
<td>How do students model the energy structure of a LED according to the observed spectrum? What kind of assumptions/hypotheses drive the reasoning? How do students identify the relationships between the observed spectrum and the energetic structure of the emitting source?</td>
</tr>
</tbody>
</table>
### 5.4.13 Balmer and Rydberg’s formulae

Table 5.17: Balmer and Rydberg’s formulae: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRI_a</td>
<td>An empirical formula describing the visible emissions was found by J.J. Balmer in 1885: (1/\lambda = RH(1/n_a^2 - 1/n_b^2)) Where (\lambda) represents the wavelength of the lines, (RH) is a constant and (n_a) and (n_b) are two integers. In particular to reproduce the observed emissions (n_a = 2) and (n_b = 3, 4, 5, 6). In 1916 N. Bohr hypothesized that the radiation emitted was the result of energetic variations of the atomic system and that the energy of each emission could be written as (E = hf = hc/\lambda). Using Balmer’s law, write an expression for the energy of the observed emissions in the hydrogen spectrum.</td>
<td>How do students recognize the link between the emitted energy from an atom and the energy of the emitting system from the analysis of an empirical formula containing a difference of two energies? Do students identify the discrete energy values of the emitting system? Do students associate the negative value of the total energy of an hydrogen atom to the sign of its energy levels? Is the association between the energy of the generic energy level and the negative sign, derived from classical considerations, present?</td>
</tr>
<tr>
<td>BRI_b</td>
<td>An empirical formula describing the visible emissions was found by J.J. Balmer in 1885: (E_{ab} = cost(1/n_a^2 - 1/n_b^2)). Where (E_{ab}) represents the energy of a line and (n_a) and (n_b) are two integers. In particular to reproduce the observed emissions (n_a = 2) and (n_b = 3, 4, 5, 6). In 1916 N. Bohr hypothesized that the hydrogen atom could only be found in precise energy states (called &quot;levels&quot;) in which there was no energy emission and that the energy emitted was the result of energy variations between the levels. Using Balmer’s law and Bohr’s hypothesis, write an expression for the energy of the various levels.</td>
<td></td>
</tr>
</tbody>
</table>
BR1_c  An empirical formula describing the visible emissions was found by J.J. Balmer in 1885: \( E_{ab} = cost(1/n_a^2 - 1/n_b^2) \). Where \( E_{ab} \) represents the energy of a line and \( n_a \) and \( n_b \) are two integers. In particular to reproduce the observed emissions \( n_a = 2 \) and \( n_b = 3, 4, 5, 6 \). If the spectral lines represent the energy emitted in the jump between two atomic energy levels (as hypothesized by Bohr in 1916) write an expression for the energy of the \( E_a \) level and the \( E_b \) level.

BR1_d  In light of what we have seen so far, write an expression for the energy of the generic energy level \( E_n \), justifying the answer.

BR1_e  If the spectral lines represent the energy emitted in the jump between two atomic energy levels (as hypothesized by Bohr in 1916) write an expression for the energy of the generic level \( E_n \) in the light of Rydberg’s formula, justifying the answer.

BR2  In 1885 J.J. Balmer realized that it was possible to obtain the different values of the wavelengths present in the hydrogen spectrum by multiplying a constant \( k = 364.6 nm \) respectively for the coefficients 9/5, 4/3, 25/21 and 9/8. He found the general law describing the succession of these coefficients, multiplying the second and fourth coefficients by 4/4. Find it yourself, making any comments.

BR3  In 1889 J. R. Rydberg, working on the objective of finding the link between spectral emissions and atomic structure, found that it was easier to express the position of the lines if in the numerical relations the reciprocal of the wavelength was used. Express Balmer’s law in terms of \( 1/\lambda \) and discuss it in the light of the knowledge that the emitted radiation has energy \( E = hf \). Use the findings to describe the light emission processes.
In 1889 J. Rydberg generalized the formula found by Balmer expressing it in terms of frequency rather than wavelength, obtaining \( f = k'(1/4 - 1/n^2) \), with \( k' \) constant. What is the link between the constant \( k' \) that appears in Rydberg's formula and the constant \( k \) that appears in Balmer's formula?

How do students describe the light emission process? Which kind of mathematical difficulties emerge in passing from a description in terms of wavelengths to a description in terms of energies? How does the obtained formula, in terms of energy, elicit students in describing the emission process?

How can Rydberg's formula be interpreted in the light of the hypothesis of quantization of the energy radiation?

How do students link wavenumber and energy in order to obtain a specific relation in terms of energies? How is the formula describing the energies of the lines interpreted by students? Do students recognize that it is an application of the energy conservation principle? How does the obtained formula, in terms of energy, elicit students in describing the emission process? How many and which advantages of the new formula are noticed?

How can you describe the emission process in the light of Rydberg's law and photoelectric effect?

How can you describe the emission process in the light of Rydberg's law and photoelectric effect?

Find the value of the constant in Balmer's formula.

Which strategies are adopted by students to obtain a numerical constant from a set of data?

Evaluate the values of the first 6 energy levels for hydrogen.

Which kind of mathematical difficulties emerge in evaluating discrete quantities?

At first the Balmer formula was given in terms of wavenumber, then in energy, searching for an interpretation. In the following experimentations, students had to evaluate themselves the relation based on a series of numerical coefficients, generalize it in terms of wavelength and then to convert it in energy. It emerged that the major involvement of students in deriving a formula has the power to strengthen its understanding and usage in foreseeing its applications and consequences.
5.4.14 From lines to level

Table 5.18: From lines to levels: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIN1_a</td>
<td>Two students S1 and S2 observe a spectrum and discuss. S1: The rightmost line has the longest wavelength, which means the highest frequency. That line, therefore, corresponds to the highest energy value and represents the highest energy level of the hydrogen atom. S2: I don’t agree. The energy of an energy level is $hf$ and the frequency is inversely proportional to the wavelength. This means that the rightmost line corresponds to the fundamental level. With which of the two students, if there is one, do you agree? Show your motivation.</td>
<td>How do students associate a single spectral lines with the discrete energy structure of the emitting system? How do students use hypothesis in order to give meaning at the observation of a single spectral lines? Which argumentations students uses to support their hypotheses?</td>
</tr>
<tr>
<td>LIN1_b</td>
<td>Two students S1 and S2 observe a spectrum and discuss. S1: The rightmost (red) line corresponds to the highest energy value in the spectrum and represents the highest energy level of the hydrogen atom. S2: I don’t agree. Red light energy is the lowest of all. This means that the line on the far right corresponds to the fundamental level of the atom, i.e. the one with the lowest energy. Which of the two students do you eventually agree with? Illustrate your reasoning.</td>
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</tr>
</tbody>
</table>
LIN2 The following diagram shows a part of the discrete hydrogen spectrum (increasing wavelength to the right). Draw, in the space below, the diagram of the energy levels of the hydrogen that contains only the minimum number of energy levels necessary to produce the 10 lines shown. Assume that only the lowest energy levels are involved in creating the lines. Call E1 the fundamental level and E2, E3, etc... the excited levels. The spacing between the levels must be qualitatively correct. Explain briefly.

LIN3 The energy level E2 is involved in the formation of one or more lines in the spectrum shown. How many? Highlight this(those) line(s) in the spectrum shown. Explain.

LIN4 Spectrum image: In what relation are the lines of the spectrum and the energy levels of the emitting system?

LIN5_a Spectrum image: What is the minimum number of levels necessary to justify the presence of the lines that are observed? Draw them.

LIN5_b The figure below shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: What is the minimum number of levels necessary to justify the presence of the observed lines? Explain.

LIN6_a The figure shows the emission spectrum of an ionized helium atom. The energy of the lines increases from left to right. What is the structure of the energy levels of the atom? Describe the strategy used to find the levels.

LIN6_b Which hypotheses subtend the model students have regarding the link between spectral emissions and discrete energy levels? With what spontaneous ideas/representations is the observed phenomenology correlated to microscopic processes?

LIN5_b The figure below shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: What is the minimum number of levels necessary to justify the presence of the observed lines? Explain.

LIN6_a The figure shows the emission spectrum of an ionized helium atom. The energy of the lines increases from left to right. What is the structure of the energy levels of the atom? Describe the strategy used to find the levels.

Which strategies are put in practice by students in passing from a discrete spectrum to an energy level diagram? With what spontaneous ideas/representations is the observed phenomenology correlated to microscopic processes?

LIN4 Spectrum image: In what relation are the lines of the spectrum and the energy levels of the emitting system?

LIN5_a Spectrum image: What is the minimum number of levels necessary to justify the presence of the lines that are observed? Draw them.

LIN5_b The figure below shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: What is the minimum number of levels necessary to justify the presence of the observed lines? Explain.

LIN6_a The figure shows the emission spectrum of an ionized helium atom. The energy of the lines increases from left to right. What is the structure of the energy levels of the atom? Describe the strategy used to find the levels.

LIN5_b The figure below shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: What is the minimum number of levels necessary to justify the presence of the observed lines? Explain.

LIN6_a The figure shows the emission spectrum of an ionized helium atom. The energy of the lines increases from left to right. What is the structure of the energy levels of the atom? Describe the strategy used to find the levels.

Which hypotheses subtend the model students have regarding the link between spectral emissions and discrete energy levels? With what spontaneous ideas/representations is the observed phenomenology correlated to microscopic processes?

LIN4 Spectrum image: In what relation are the lines of the spectrum and the energy levels of the emitting system?
LIN6_b The figure below shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: Representing the energy levels that give rise to the spectrum shown in the figure, explaining how to identify them.

LIN7_a Spectrum image: The energy level E2 is involved in the formation of one or more lines in the shown spectrum. Highlight it/them.

LIN7_b The figure shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: The energy level E2 is involved in the formation of one or more lines in the spectrum shown. Highlight which one(s).

LIN8_a Spectrum image: What new lines would be observed if a higher energy level were taken into consideration?

LIN8_b The figure shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right. How many new lines would be observed if a higher energy level were taken into consideration? Indicates the position of the line(s) in the spectrum.

Questions LIN1_a and LIN1_b differ only in the terms in which they are posed: the former take explicitly in account quantities as wavelength and frequency, the latter is addressed only in terms of energy. They have been used according to the specific perspective of the path (W or E). Question from LIN5 to LIN8 are double because it has been realized that students do not assume that they have to consider the first lower energy levels, giving rise to multiple and difficult interpretations, so it emerged the need to specify it in the questions.
### 5.4.15 From levels to lines

Table 5.19: From levels to lines: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEV1</td>
<td>Compare the values of the hydrogen energy levels with the energies of the lines shown. Based on the relationships, describe what happens in the atom when a photon is emitted. What can you say about your answer to the previous question?</td>
<td>How do students make use of a suggested comparison between energy levels values and energy lines values in describing the light emission process?</td>
</tr>
<tr>
<td>LEV2</td>
<td>For the hydrogen atom the energies of the fundamental level and of the E3 level are respectively -13.61 eV and -1.51 eV. Which line(s) can I expect in the spectrum? Calculate the energy(energies).</td>
<td>How do students correlate information from the micro-world to macro-information? Which hypotheses subtend the reasoning?</td>
</tr>
<tr>
<td>LEV3</td>
<td>The following table shows the energies of the energy levels of ionized helium. Represent the spectrum of emission lines due to the indicated energy levels.</td>
<td>Which strategies are put in practice by students in stepping from micro to macro interpretation? Do students recognize the relationship between energy levels value and the energy of the lines?</td>
</tr>
<tr>
<td>LEV4</td>
<td>Sketch the first 4 energy levels of the hydrogen atom and the spectrum that is obtained by considering these levels.</td>
<td></td>
</tr>
<tr>
<td>LEV5_a</td>
<td>Balmer’s formula reproduces the visible emissions of hydrogen. Can it be used to predict other emissions? How? Draw them.</td>
<td>How do students use their model to forecast other evidences? Are the previsions coherent with the adopted model?</td>
</tr>
<tr>
<td>LEV5_b</td>
<td>From the levels identified which other lines can be expect to be seen?</td>
<td></td>
</tr>
<tr>
<td>LEV6</td>
<td>Calculate the energy of the lines expected in the previous question.</td>
<td>How do students evaluate the calculus? Is the calculus coherent with the adopted model?</td>
</tr>
<tr>
<td>LEV7</td>
<td>Given a generic number n of levels, how many lines do you expect to observe? Justify the answer.</td>
<td>How do students generalize the rule linking spectral lines and energy levels? Do students recognize the relationship between energy levels value and the energy of the lines? Which model is used to link spectral lines and discrete energy levels?</td>
</tr>
<tr>
<td>LEV8</td>
<td>Considering the first six energy levels accessible to the hydrogen atom, whose values are shown in the table, how many emissions do you expect to observe? Justify the answer.</td>
<td>How do students step from micro to macro interpretation? Which kind of relationships emerge in linking energy levels value and the energy of the lines?</td>
</tr>
<tr>
<td>LEV9</td>
<td>In light of the considerations made in the previous question, draw the resulting spectrum.</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>How do students step from micro to macro interpretation? Which kind of relationships emerge in linking energy levels value and the energy of the lines? Which conceptual referent are used in describing the spectrum?</td>
<td></td>
</tr>
</tbody>
</table>
### 5.4.16 Levels representation

Table 5.20: Levels representation: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR1</td>
<td>Concentrate now on the energy values of the levels: Calculate the ratios $E_1/En$ (n=2; 3; 4; 5; 6; 7). Do students evaluate the suggested calculation?</td>
<td></td>
</tr>
<tr>
<td>LR2</td>
<td>Based on the obtained results, can you expect a limit to the energy of a bound proton-electron system (hydrogen atom)? How do students identify the limit of the bonding energy from an analytic calculation showing that levels become closer and closer?</td>
<td></td>
</tr>
<tr>
<td>LR3_a</td>
<td>Qualitatively draw the energy levels, justifying their position and their distances. Which conceptual referents are used by students to represent the energy levels? How do students represent a set of energy levels? Which elements are taken into account for representing the levels? How do students interpret an excited state?</td>
<td></td>
</tr>
<tr>
<td>LR3_b</td>
<td>The following table shows the energies of the energy levels of ionized helium. Represent the levels.</td>
<td></td>
</tr>
<tr>
<td>LR3_c</td>
<td>Make a sketch representing the 6 levels.</td>
<td></td>
</tr>
</tbody>
</table>

Questions LR1 and LR2 turned quite unuseful for helping students in representing the energy levels and have been thus abandoned. Giving instead students a set of values of the energy levels allowed to inquiry the employed model (Bohr’s orbits, stacked levels) as well as the way they interpret a set of negative energies, according to where the zero energy level is placed and the extent to which students see in a series of energy levels (with negative energies) directly a discrete spectrum associating one level to one line.
### 5.4.17 Nature of levels

Table 5.21: *Nature of levels: detailed research questions.*

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL1</td>
<td>We call the allowed energy of a system &quot;energy level&quot;. What is the relationship between the energy value of a level (in the case of hydrogen) and the respective order number n?</td>
<td>Do students identify the discrete energy values of the emitting system? Do student associate the negative value of the total energy of an hydrogen atom to the sign of its energy levels? What difficulties emerge in associating an energy value with an energy level?</td>
</tr>
<tr>
<td>NL2</td>
<td>Which level corresponds to the fundamental state of an atom? Illustrate the reasoning.</td>
<td>How do students refer to the fundamental level (the one with lower energy)?</td>
</tr>
<tr>
<td>NL3</td>
<td>What do individual energy levels represent in an atomic model? Consider the hydrogen atom, represent them and explain.</td>
<td>How do students define the discrete energy levels of an emitting system? Which kind of properties are attributed to levels? What are energy levels, from a physical point of view, associated to?</td>
</tr>
<tr>
<td>NL4</td>
<td>The sign of the energy levels of the hydrogen atom is negative: how do you explain this evidence?</td>
<td>How do students interpret, from an energetic point of view, a negative total energy. Do students recognize that it is an application of the energy conservation principle?</td>
</tr>
</tbody>
</table>
### 5.4.18 Information coded in a spectrum

Table 5.22: Information coded in a spectrum: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS1</td>
<td>Alkali metals (group 1 of the periodic table) and some ions (He ++, Li ++) have spectra in which the positions of the lines can be described by formulas very similar to that of Balmer. How do you explain this similarity in terms of atomic structure?</td>
<td>How the models are re-used by students to interpret new situations? Do students recognize the similarities in structure between atomic hydrogen, alkali metals and hydrogenoid atoms resulting in similar spectra?</td>
</tr>
<tr>
<td>IS2_a</td>
<td>What physical information could be derived from the interpretation of an optical spectrum about the light source?</td>
<td>How do students read a spectrum linking the observation with the source? What referent do students read in a spectrum? How do students correlate those referent to the properties of the source? With what spontaneous ideas/representations is the observed phenomenology correlated to microscopic processes?</td>
</tr>
<tr>
<td>IS2_b</td>
<td>What information does an optical spectrum give me about the source? Explain.</td>
<td></td>
</tr>
<tr>
<td>IS2_c</td>
<td>What information does an optical spectrum give me about the emitting process? Explain.</td>
<td></td>
</tr>
<tr>
<td>IS3</td>
<td>What information can be read in a spectrum?</td>
<td>How do students describe a spectrum? What referent do students read in a spectrum? Do students spontaneously relate its properties with the source/process emitting light or they describe only the macroscopic evidences?</td>
</tr>
<tr>
<td>IS4</td>
<td>Different atoms have characteristic spectra. How do you explain this?</td>
<td>How the models are re-used by students to interpret new situations? What are the differences in the spectra attributed to (different energy levels, different ways of interactions, ...)</td>
</tr>
</tbody>
</table>

Questions from IS2_a to IS2_c have been progressively refined to put a major focus on the process causing the observed emission. In the first stages of the experimentations in fact students limited themselves in giving answers uncorelated with the physical process, preferring to enumerate some physical properties of the source (temperature, composition, ...)
### Digital spectra interpretation

Table 5.23: *Digital spectra interpretation: detailed research questions.*

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIG1</td>
<td>After observing the functioning of a digital spectroscope, how do you interpret the observed two-dimensional graph?</td>
<td>How do students gain competences in interpreting an optical spectra using a double representation (spectrum + spectral profile)? What meaning students give to the plotted quantities?</td>
</tr>
<tr>
<td>DIG2_a</td>
<td>Acquire the spectrum of a white LED. Analyze the comparison between this spectrum and those obtained by inserting blue, green, red and yellow filters. Discuss how you would analyze the data in relation to the involved light-matter interaction.</td>
<td>How does a color vs intensity plot help in planning an experiment in which students analyze the phenomena of selective absorption? How do students analyze data in relation to the intensity distribution according to the profile they collected with and without absorption filters?</td>
</tr>
<tr>
<td>DIG2_b</td>
<td>How would you use the data collected with the digital spectrometer to know the absorbance characteristics of a filter?</td>
<td></td>
</tr>
<tr>
<td>DIG3</td>
<td>Employ a digital spectrometer to observe the light emitted by an atomic source and a LED and illustrates the quantitative information that gives you a spectrometer on the light emitted by a source.</td>
<td>How have students to be guided/helped in quantitatively describe a spectrum using a color vs intensity plot?</td>
</tr>
<tr>
<td>DIG4</td>
<td>How do you interpret the fact that different emissions have different intensities?</td>
<td>How are student helped in recognizing the intensity parameter, appreciable only qualitatively be eye, as a descriptor of the physical process emitting light?</td>
</tr>
</tbody>
</table>

Question DIG2_a was changed to DIG2_b in order to evaluate the effect of giving students less operative information about the measure to perform.
5.4.20 LED experiment

Table 5.24: LED experiment: detailed research questions.

<table>
<thead>
<tr>
<th>CODE</th>
<th>QUESTION</th>
<th>DETAILED RESEARCH QUESTION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED1_a</td>
<td>Explore the V-I characteristics regarding LED light emission of different colors. What hypothesis suggests the comparison between the V-I characteristics and the observed spectrum?</td>
<td>Do students point out the important parameter to measure (threshold voltage and energy of the peak in the spectrum)? How do students correlate the two quantities? What is the slope of the interpolating line attributed to? Do students extrapolate from the characteristics the nature of photoelectric effect or, at least, they identify an energy threshold depending on the color? How do students justify the graph in terms of energy?</td>
</tr>
<tr>
<td>LED1_b</td>
<td>What measures would you do to study the relationship between supplied energy and emitted light?</td>
<td></td>
</tr>
<tr>
<td>LED2</td>
<td>A LED emits light when it is powered, that is when it is connected to a potential difference (voltage). Explore the V-I features regarding LED light emission of different colors. What do you conclude about the light emission process?</td>
<td>What properties do students attribute to a LED as a light source? Do students recognize the connection between threshold voltage and energy of the emitted light? Is the modelling phase of the emission process facilitated by experimental exploration? Which hypotheses are suggested concerning the light emission processes?</td>
</tr>
<tr>
<td>LED3</td>
<td>How do you interpret the obtained results?</td>
<td>How do students interpret the results in the light of the energetic nature of a light source? Do students correlate supplied energy and emitted energy?</td>
</tr>
</tbody>
</table>

Question LED1_a was changed to LED1_b in order to evaluate the effect of giving students less operative information about the measure to perform and the relation to obtain, but rather put they simply in front of a problem leaving them free to propose solutions.
Chapter 6

Research with secondary school students: different approaches for a global path

6.1 Design

From an analysis of the most used textbook in Italian secondary school (Amaldi, 2015; Walker, 2016; Halliday et al., 2015; Caforio and Ferilli, 2004) it emerges that topics related to optical spectroscopy are usually addressed after following a pure historical approach after dealing physical optics and addressed the theory of diffraction gratings. Students have thus in mind a wave model for light and they must integrate it in a coherent framework integrating the energy of the light in a quantum model making use of the concept of photon, generally addressed in the following, when treating the photoelectric effect, among other topics related to modern physics, always presented to students from an historical point of view. The nucleus of the section devoted to optical spectroscopy is based upon the semiclassical Bohr’s model whose hypotheses are arbitrary and not-justified. Characteristic of the treatments reported in the school textbooks is to refer to models of the atom or the structure of the matter that are not justified on an experimental basis. Classical concepts of electrodynamics and dynamics as Coulomb’s force, electrostatic potential energy, circular motion and angular momentum are used to build a model accounting for discrete emissions. The limitation is due to the fact that students focus in learning a series of formulae (frequency-energy relation, the generalized Balmer-Rydberg’s formula) upon which they mainly learn to reason algebraically, in order to solve equations for the calculus of different quantities as declared in the textbooks themselves. Students have to be put in conditions to use the mathematical formalism to solve the problems suggested in the textbook. The understanding of the mathematical formalism is an important but not exhaustive part of physics learning, since the risk is the one of being able to apply formulae without the ability of extending the reasoning in different situations (Sherin, 2001; Pospiech et al., 2016). This approach presents a series of limitations:

- optical spectroscopy phenomena are presented uncorrelated with other optical phenomena previously studied;
- it is not clear what kind of model for light has to be adopted;
- generalizability in the case of atoms more complex than hydrogen is challenging;
• macroscopic level in phenomena description is uncorrelated with the microscopic one: electrons jumping from one orbit to another is the most common way for describing the phenomenology.

The intervention with secondary school students was designed aiming at the coherent integration of macroscopic and microscopic models in terms of: (a) founding the concept of the existence of light-matter interaction giving rise to everyday optical phenomena (refraction and the perception of colors); (b) defining a light source as a system able to transform energy; (c) interpreting different colors as different energies based on their energy supply need in colored sources or via their ability to activate reactions; (d) clarifying the origin of spectral lines as a variation of energy of the emitting system; (e) using model-based reasoning closer to a physical way of thinking.

Educational literature analysis performed in Chap. 3 highlighted that the understanding of phenomena related to optical spectroscopy is closely related to models that students hardly integrate in a coherent conceptual framework, even in the transition from school to university. A relevant discussion poses the problem of the opportunity for students to experience a teaching/learning path integrating macro and micro levels in describing phenomena related to the formation of optical spectra. The comprehension of the relationships between involved physical quantities and phenomenology requires the clarification of the relationship between spectral lines, energy levels, wavelength (or frequency) and energy associated to a radiation of a certain color, as well as the functioning mechanism of an artifact producing spectra, in particular the conceptual difference between a diffraction pattern and a discrete spectrum. The learning process, understood as a conceptual knowing of such relationships poses the problem of the clarification of the nature of the quantities themselves and in particular the overcoming of the following critical points:

• existence of different kind of spectra;
• observed light is always the result of an interaction between light and matter;
• interaction between light and matter depend on the energetic structure of matter itself;
• given a certain number of energy levels, in principles, all transitions between couples of levels can occur.

Addressing of a microscopic model for the emission discrete spectra is thus posed in the previous terms, and not in purely descriptive terms of possible mechanisms and/or useful representation for figurative memorization. Involving students in significant scientific practices requires students to understand the logic founding such practices. It is thus important that students learn the role of models in science in terms of: (a) those models are employed; (b) why they are employed or not; (c) which are potentialities and limits of different models of a same system, in order to appreciate how science works and the dynamical nature of the knowledge that science produces.

Physics brings back the description of optical spectra formation to transition between energy levels or atomic orbits or orbitals, interpreting the phenomenology using different models interweaving macroscopic and microscopic levels. Every microscopic model specifies properties and interactions between light and matter assuming a reference theory that can be classical (light seen as a wave and electrons emitting thanks to oscillation), semi-classical (light treated as a wave and emission occurring between discrete energy levels) or quantum (light treated as photons of different energies interacting with matter with a discrete energy structure).
Three different teaching/learning paths have been set up: one focused on light sources (LS), one focused on the phenomenology (PH) and the other one following a more traditional, conceptual/disciplinary approach (CD) have been designed according to two different perspectives: energy (E) and wavelength (W). In the LS approach the path starts with analyzing light sources and the emitted light from a technological, functional and social point of view searching for physical interpretation of the mechanism emitting light; in the PH approach students use a spectroscope, without knowing its functioning, to analyze spectra from different sources, the mechanism of diffraction is analyzed in sequel of the path; in the CD approach, a more traditional sequence of reasoning is implemented, starting from geometrical optics, through the interpretation of color as a physical quantity; the path is thus embedded in a traditional optics course, deepening some crucial aspects as the light matter-interactions. All approaches aim at searching an interpretation for the formation of discrete spectra, thus linking macro-observations with micro-interpretation both from an historical point of view (analyzing the meaning of the Balmer-Rydberg formulae) and through the representation of the phenomenology through the description of the emission process. The two different perspectives regard the nature of light: in an E perspective light is seen as an entity carrying energy depending on its color totally neglecting the wave interpretation, used in the W perspective. In particular, in an E perspective, the interpretation of light as a wave is completely neglected in favor of an energetic interpretation of the emission of radiation that also justifies the spectra. The diffraction is introduced phenomenologically, associating to each color an energy through the hypothesis that justifies the photoelectric effect. In a W perspective to justify the visible emission lines in the hydrogen spectrum, the empirical Balmer coefficients are interpreted, which describe the succession of wavelengths, to then obtain a formula of general validity, expressed in wave number (Rydberg) and with Einstein’s hypothesis of the photoelectric effect, it allows to interpret the lines as energetic jumps.

In Tab.6.1 approaches and perspectives characterizing each path are outlined. Different approaches and perspectives have been implemented to test the effectiveness, limits and reliability of each method. One of the main limitation of this research project relies on the fact that the available time was not enough for finding samples large enough for a proper study of conceptual change processes. Moreover, quantitative analysis could not be undertaken: activities took place in ordinary classes, with a too small sample size and difficulties in controlling all involved students parameters and variables (their scholastic background, their attitude and interest toward physics, etc...). Finally, most formative intervention modules lasted one day, at most few days, so that long-term learning with understanding was not analysed. Eleven out of the fifteen carried-out experiments with secondary school students were analysed in this thesis, selected so that different approaches and perspective are taken into account in order to allow a cross comparison. The choice of the eleven selected experimentations was driven also by the fact that they are the only ones containing a post-test (sometimes coupled with a tutorial or a pre-test). This criterion allow to qualitatively evaluate important learning outcomes in different settings and also the gain in students’ conceptual knowledge comparing pre- and post-tests.

6.2 Context e sample

Overall, the different paths has been experimented in 15 settings with a total 28 classes involving about 560 students (17-19 years old) from last or penultimate year of secondary formation mainly from scientific liceums from the norther region of Italy (Fig. 6.1). Thanks to a tight collaboration between school and university (Buongiorno et al., 2019c) exper-
Table 6.1: Approaches: light sources (LS), phenomenology (PH), conceptual/disciplinary (CD) and perspectives: energy (E), wavelength (W) implemented in the different paths. The ones evidenced in bold are the ones containing a post-test and thus analyzed.

<table>
<thead>
<tr>
<th>INTERVENTION ID</th>
<th>APPROACH</th>
<th>PERSPECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5_3_2017</td>
<td>LS</td>
<td>W</td>
</tr>
<tr>
<td>6_4_2017</td>
<td>LS</td>
<td>W</td>
</tr>
<tr>
<td>7_5_2017</td>
<td>LS</td>
<td>W</td>
</tr>
<tr>
<td>8_6_2017</td>
<td>LS</td>
<td>E</td>
</tr>
<tr>
<td>9_7_2017</td>
<td>PH</td>
<td>E</td>
</tr>
<tr>
<td>10_8_2017</td>
<td>PH</td>
<td>E</td>
</tr>
<tr>
<td>11_9_2017</td>
<td>CD</td>
<td>E</td>
</tr>
<tr>
<td>12_10_2017</td>
<td>CD</td>
<td>E</td>
</tr>
<tr>
<td>14_2_2018</td>
<td>CD</td>
<td>E</td>
</tr>
<tr>
<td>15_3_2018</td>
<td>CD</td>
<td>E</td>
</tr>
<tr>
<td>16_4_2018</td>
<td>PH</td>
<td>W</td>
</tr>
<tr>
<td>17_5_2018</td>
<td>PH</td>
<td>E</td>
</tr>
<tr>
<td>18_7_2018</td>
<td>CD</td>
<td>W</td>
</tr>
<tr>
<td>19_8_2018</td>
<td>PH</td>
<td>W</td>
</tr>
</tbody>
</table>

Figure 6.1: Geographical distribution of secondary school students taking part to the experimentations. Trieste (97), Bolzano (18), Treviso (291), Vittorio Veneto (52), Tolmezzo (11), Pordenone (36), Mogliano Veneto (37). Attendant of Summer School on Modern Physics held in Udine came from all over Italy (31).
implementations have been conducted in different settings (Buongiorno and Michelini, 2019b, 2016b, 2017a): (a) MASTER CLASSES held at University of Udine consisting in 8 or 4 hours of activity in which one or two classes at a time came from their school on the initiative of the reference teacher, who follows the activity and coordinates the collaboration with the university, integrating choices of content, strategies and methods. In the proposed activities, depending on the available time, two or three laboratory activities carried out in groups are integrated: the optical goniometer experiment, the LED experiment and the single slit diffraction measurements with online sensors to phenomenologically obtain the laws of diffraction and then of a diffraction grating. They are always the result of a cooperation with the involved teachers, in order to have comparable groups in terms of general pre-requisites (experimentations 2_2_2016, 5_3_2017, 6_4_2017, 7_5_2017, 8_6_2017, 9_7_2017, 10_8_2017, 11_9_2017, 12_10_2017, 14_2_2018, 15_3_2018, 16_4_2018, 17_5_2018, 18_6_2018 and 19_7_2018 involved students from different scientific lyceums: L. da Vinci in Treviso, M. Flaminio in Vittorio Veneto, G. Solari in Tolmezzo, G. Leopardi-E. Majorana in Pordenone and G. Berto in Mogliano Veneto); (b) IN SCHOOL in which similar activities have been carried out directly in schools always following the requests of the interested teachers (experimentations 12_10_2017 and 19_7_2018 were held in scientific lyceum G. Galilei in Trieste, experimentation 18_6_2018 took place in scientific lyceum specialized in sporting activity G. Toniolo in Bolzano) (c) SUMMER SCHOOL FOR TALENTED STUDENTS: nationally selected students attend 6 days at the University of Udine being involved in experimental activities, lectures and targeted educational paths monitored on various topics concerning modern physics (quantum mechanics, spectroscopy, superconductivity, Franck and Hertz experiment, ...). The spectroscopy activity, with the experimental phase, engages the students for 8 hours. The school offers students in the penultimate year of Italian secondary schools a high-level educational opportunity, aimed at enhancing excellence in the field of modern physics. Topics of strong impact and interest for students are proposed, such as those of the physics of the twentieth century, generally neglected in the teaching practice of schools, through strategies that involve a strong personal involvement of students with the object of study, a necessary condition to guarantee an effective scientific learning and training orientation. Students, in small groups of three to four members, directly carry out experimental activities in the educational laboratory oriented by seminarial activities on the conceptual frameworks of reference (experimentation 11_9_2017 was of this kind).

6.3 Strategies

Students’ reasoning elicited by offered stimuli are monitored through open-ended questionnaire representing the structure of the path (tutorials, see Appendix). The formulation of the questions was designed according to the IBL strategy (see Sect. 1.2.2). In some experimentation additional test-in and out were provided at the beginning and end of the activity. To prevent the students from preparing the answers, they were not advised of the administration of the post-test. To be noticed that in the first experimentations a tutorial and a different post-test have been used; this choice was due to the fact that contents and strategies of the working method were to set up, and it was important to monitor the step-by-step outcomes. In the last experimentations more standard monitoring instruments, as the same test used before and after instruction, have been used (Tab. 5.2).
6.4 Data analysis

Data have been collected in written form; their analysis has been performed qualitatively, operationally classifying the various categories emerged from students' written answers and drawings. Due to the multiplicity of experimentation and addressed aspects, it is here reported the analysis of the answers to the questions related to the key aspects of the path, the most significant for the research selected among the ones outlined in Tab. 5.3, in order to compare the different outcomes according to the different approaches and perspective used. Aspects taken into account are resumed in Tab. 6.2. Some aspects have not been analyzed in deep since students' answers were not fertile for a research data analysis due to their triviality or superficiality, or simply because the majority of students did not answer. The analysis of the students' written answers was conducted with qualitative methods (see Sect. 1.1.4). Each student's answers and drawings have been classified into categories based on research questions. The aspects taken into consideration were not uniquely based on the research questions, decided a-priori, but also on the aspects that emerged from the answers, thus a-posteriori. The categories identified allowed the qualitative interpretation of the data, which is based on the analysis of the occurrences of the mutually exclusive categories identified and on their operational definition based on the students' answers. In order to interpret answers or drawings that are not particularly clear, it has sometimes been necessary to rely on phrases or other clues (even graphics) present in answers to different questions.

Table 6.2: Conceptual steps of the paths taken into account for comparative data analysis.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>Light emission process</td>
</tr>
<tr>
<td>LIN</td>
<td>From lines to level</td>
</tr>
<tr>
<td>LEV</td>
<td>From levels to lines</td>
</tr>
<tr>
<td>LR</td>
<td>Levels representation</td>
</tr>
<tr>
<td>NL</td>
<td>Nature of levels</td>
</tr>
</tbody>
</table>

6.4.1 Light emission process

Different questions addressing the problem of light emission mechanism from matter have been analyzed, in particular those reported in Tab. 6.3. The choice has been made in order to select common question that students answer after having followed paths with different approach and perspective. In some cases it is possible to draw conclusions on students' conceptual change comparing pre- and post-tests, and on the way the posing of a specific question using specific terminology affects students' answers. Guided by qualitative data analysis methods, categories have been individuated and operationally defined according to students' answers (see Tabs. from 6.4 to 6.6).

The operative definitions in Tab. 6.4 allowed to describe students' pattern of reasoning in terms of occurrences in each category (Figs. 6.2, 6.3, 6.4). When possible pre- and post-tests have been compared, otherwise only post-tests have been analyzed.

The operative definitions in Tab. 6.5 allowed to describe students' pattern of reasoning in terms of occurrences in each category (Fig. 6.5). When possible pre- and post-tests have been compared, otherwise only post-tests have been analyzed.

The operative definitions in Tab. 6.6 allowed to describe students' pattern of reasoning in terms of occurrences in each category (Fig. 6.6). When possible pre- and post-tests have been compared, otherwise only post-tests have been analyzed.
Table 6.3: Questions regarding the light emission processes whose answers have been analyzed.

<table>
<thead>
<tr>
<th>LP1_b</th>
<th>During the optical goniometer experiment you observed the spectral lines emitted by a certain gas. Explain the process that gives rise to the observed lines, using a graphical representation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP1_d</td>
<td>Light is an entity carrying energy. What does the emitted energies with respect to the emitting system? (describe an interpretative hypothesis regarding the emission process and making use of a sketch).</td>
</tr>
<tr>
<td>LP4</td>
<td>Describe the process of light emission in energetic terms, even considering specific cases.</td>
</tr>
<tr>
<td>LP5</td>
<td>After observing 3 different types of spectra (continuous, discrete, band), how do you imagine the emission process in the 3 cases? Help yourself with a graphical representation⁴.</td>
</tr>
</tbody>
</table>

Figure 6.2: Qualitative analysis of answers to question LP1_b from post-tests.
Table 6.4: Questions LP1\_b and LP1\_d: Categories and operative definitions.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>STUDENTS’ TYPICAL ANSWERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICRO-BOHR</td>
<td>Light is emitted when an electron in an excited orbit returns to its natural one; it is the energy that an electron releases when returning to its natural orbit; emitted energies represent electron jumps between different orbitals.</td>
</tr>
<tr>
<td>MICRO-LEVELS</td>
<td>Emitted energies represent electrons that lose energy passing from one level to another one; excited electrons in upper energy states are unstable and return to fundamental level emitting energy in the form of light.</td>
</tr>
<tr>
<td>ENERGETIC LEVEL CHANGE</td>
<td>Matter changes its energetic level, emitting energy in the form of light, matter can have different energy levels (or state): when a transition occurs the amount of energy loss is emitted in light; the emitted energies represent the change in energetic levels.</td>
</tr>
<tr>
<td>ENERGETIC PERTURBATION OF MATTER</td>
<td>A radiation is emitted when there is a transformation of internal energy in an entity implying the emission of the radiation itself; if I perturb matter with a certain amount of energy, matter reacts emitting radiation and maybe other products.</td>
</tr>
<tr>
<td>LAMP</td>
<td>A lamp emits energy because it is supplied with other form of energy; light sources transform energy in light.</td>
</tr>
<tr>
<td>MEASURE PROCESS/SEPARATION</td>
<td>A diffraction grating or a prism allow to separate the different energies; diffraction produces the observed lines; light passing through a hole separates into different energies; light as a wave produces dark and bright lines.</td>
</tr>
<tr>
<td>MIX MACRO-MICRO</td>
<td>Light emission from electronic transitions passes through a dispersive elements and produces the observed spectra; electrons de-excite and the emitted energies, thanks to diffraction are separated; a prism separates the frequencies corresponding to each quantum jump.</td>
</tr>
<tr>
<td>TAUTOLOGIC</td>
<td>The emitted energies represent the energy that the source can emit; a light source emits light that propagates through space decreasing its intensity with distance.</td>
</tr>
<tr>
<td>LINES=LEVELS</td>
<td>Lines represent the energetic levels of electrons; emitted light in a discrete spectrum represent the energy state on the matter.</td>
</tr>
</tbody>
</table>
Figure 6.3: **Comparative qualitative analysis of answers to question LP1\_b from pre- and post-tests.**

Figure 6.4: **Comparative qualitative analysis of answers to question LP1\_d from pre- and post-tests.**
Table 6.5: Question LP4: categories and operative definitions.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>STUDENTS’ TYPICAL ANSWERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSCILLATING CHARGE</td>
<td>Matter is composed by atoms that oscillating with a certain energy, emit light; oscillating charges produces emission of light; thermal agitation produces vibrations in charge composing matter that emit light.</td>
</tr>
<tr>
<td>MICRO-BOHR</td>
<td>Excited electron in atoms return to fundamental level; electrons jump from one orbit to another losing energy that we receive as light.</td>
</tr>
<tr>
<td>MICRO-LEVELS</td>
<td>Electrons change their energy state emitting the energy they lose; when one electron changes its energetic level it emits energy in the form of light.</td>
</tr>
<tr>
<td>PHOTON EMISSION</td>
<td>Emitted light is composed by photons of different energies; a photon is emitted; photons carry energy.</td>
</tr>
</tbody>
</table>

Figure 6.5: Comparative qualitative analysis of answers to question LP4 from pre- and post-tests.
Table 6.6: *Question LP5: categories and operative definitions.*

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>STUDENTS’ TYPICAL ANSWERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TYPICAL EMISSION (DESCRIPTION OF SPECTRA)</strong></td>
<td>In the spectrum I read the wavelengths that the source can emit; lamp emits light of different energy typical of hydrogen; lamps emits a particular spectra, the one of the hydrogen.</td>
</tr>
<tr>
<td><strong>PHOTONS FROM QUANTUM JUMPS</strong></td>
<td>Emitted photons due to electronic jumps are emitted</td>
</tr>
<tr>
<td><strong>FUNCTIONAL</strong></td>
<td>Gas is heated from passage of electrons and this produces light, heating hydrogen atoms; supplying hydrogen with energy; an electric current passes through hydrogen, so its electrons, moving, emits light.</td>
</tr>
<tr>
<td><strong>1 ELECTRON FEW LINES</strong></td>
<td>Hydrogen atom contains only one electron, so the effect of its excitation is a single energy line; being hydrogen having only one electron, the spectrum shows few colors.</td>
</tr>
<tr>
<td><strong>ELECTRONS CHANGE ORBITALS</strong></td>
<td>When an electron came close to the nucleus it emits a specific light; electrons change orbital and emit energy.</td>
</tr>
<tr>
<td><strong>ELECTRONS CHANGE ENERGY STATES</strong></td>
<td>Emission of colors corresponding to the energy that an electron loses in changing its energy state; when an electron change its energy it emits light: electron can lose only discrete amount of energy.</td>
</tr>
<tr>
<td><strong>LAMP</strong></td>
<td>Each lamp has a different emitting process: the source emits different wavelengths; according to the source, the emission spectra is different.</td>
</tr>
<tr>
<td><strong>MEASURE PROCESS/SEPARATION</strong></td>
<td>Diffraction produces spectra; As in the case of the double slit, a diffraction grating produces a spectrum.</td>
</tr>
</tbody>
</table>
6.4.2 From lines to level

Three questions addressing the problem of the conceptual connection between an observed spectra and the underlying energetic structure of the emitting system (Tab. 6.7) have been selected to point out the main interpretative models, ways of reasoning and hypotheses made by students enrolled in this conceptual challenge. Emerged categories are reported in Tab. 6.8 and in Figs. 6.10 and 6.12.

![Figure 6.7: Images provided to students for question LIN\_1a,b (top) and LIN6\_b and LIN8\_b (bottom) respectively.](image)

The operative definitions in Tab. 6.8 allowed to describe students’ pattern of reasoning in terms of occurrences in each category (Figs. 6.8 and 6.9). When possible pre- and post-tests have been compared, otherwise only post-tests have been analyzed. As concern this particular question, it has been decided to take into account both student’s answers and the driving motivations subtending the way in which students look at spectra, resulting in a couples of histograms. Questions LIN\_1a and LIN\_1b differs only by the used conceptual referents: the former is posed in terms of frequency and wavelength, the latter is posed directly in terms of energy of each color.

The operative definitions in Fig. 6.10 allowed to describe students’ pattern of reasoning
Table 6.7: Questions regarding the link between a discrete spectra and the energetic structure of matter.

**LIN_1a**  Two students S1 and S2 observe a spectrum (Fig. 6.7 top) and discuss. S1: The rightmost line (red) has the longest wavelength, which means the highest frequency. That line, therefore, corresponds to the highest energy value and represents the highest energy level of the hydrogen atom. S2: I don’t agree. The energy of an energy level is $hf$ and the frequency is inversely proportional to the wavelength. This means that the rightmost line corresponds to the fundamental level. With which of the two students, if there is one, do you agree? Show your motivation.

**LIN_1b**  Two students S1 and S2 observe a spectrum (Fig. 6.7 top) and discuss. S1: The rightmost (red) line corresponds to the highest energy value in the spectrum and represents the highest energy level of the hydrogen atom. S2: I don’t agree. Red light energy is the lowest of all. This means that the line on the far right corresponds to the fundamental level of the atom, ie the one with the lowest energy. Which of the two students do you eventually agree with? Illustrate your reasoning.

**LIN_6b**  The figure below (Fig. 6.7 bottom) shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: Representing the energy levels that give rise to the spectrum shown in the figure, explaining how to identify them.

**LIN_8b**  The figure (Fig. 6.7 bottom) shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right. How many new lines would be observed if a higher energy level were taken into consideration? Indicates the position of the line(s) in the spectrum.
<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>STUDENTS’ TYPICAL ANSWERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E = hf$</td>
<td>Red line is the lower energy state because: has a lower frequency and thus a lower energy; according to Planck’s relation longer wavelengths have lower energies.</td>
</tr>
<tr>
<td>RED HAS GREATER HEATING POWER</td>
<td>Red line is the higher energy state because: in Herschel’s experiment beyond red there is a greater temperature; red is nearer to infra-red so it heats up more than blue.</td>
</tr>
<tr>
<td>RED HAS LESS ENERGY THAN BLUE</td>
<td>Red line is the lower level because: red colors have less energy than blue colors; in the EM spectrum energy decreases from blue to red.</td>
</tr>
<tr>
<td>RED LINE=LESS BOUND STATE</td>
<td>Red line is the lower energy level because: red line correspond to the orbital with lower energy; red line is linked to the orbit with less energy, i.e. the further from the nucleus; moving away from the nucleus, the required energy for the quantum jump is lower and lower.</td>
</tr>
<tr>
<td>RED LINE=LOWER EMISSION OF ENERGY</td>
<td>Red line is not an energy level because: the required energy for the quantum jump is lower; red line is the consequence of a transition between the two closest levels; lines represent energetic jumps.</td>
</tr>
<tr>
<td>RED IS PART OF PURPLE</td>
<td>Red lines is the lower level because: purple is decomposed in its primary colors among which there is the red; the intensity of the red line is lower since it is part of the purple one; purple is the superimposition of red and blue and thus it has the greater energy, the other color are less energetic.</td>
</tr>
<tr>
<td>BALMER SERIES=LEVEL STRUCTURE FOR H</td>
<td>Red line has the highest energy because: the closer the levels are, the higher the energy is; increasing the energy, levels become closer and closer.</td>
</tr>
<tr>
<td>SPECTRA IS A DIFFRACTION PATTERN</td>
<td>Red line has the lower energy because: moving away from the center of the figure, the intensities become fainter; in a single slit diffraction pattern the intensities decrease with the order of the maxima.</td>
</tr>
</tbody>
</table>
Figure 6.8: Qualitative analysis of answers to question LIN_1a,b from post-tests.
Figure 6.9: Qualitative analysis of answers to question LIN_1a,b from post-tests.

Figure 6.10: Question LIN_6b: categories and operative definition using students’ drawings. From left to right: model (A) (transitions occurs only between adjacent levels), model (B) (one line correspond to one level), model (C) (4 levels accounting for every possible transition), model (D) (all transitions must involve the fundamental level), model (E) (three levels for three distinct group of emissions).
in terms of occurrences in each category (Figs. 6.11). Only post-tests have been analyzed. As concern this particular question, it has been decided to take into account both student’s representations of energetic levels and the interpretative models guiding from the observation of spectra to the energetic structure of matter.

The operative definitions in Fig. 6.12 allowed to describe students’ pattern of reasoning in terms of occurrences in each category (Figs. 6.13). Only post-tests have been analyzed taking into account the interpretation of the mechanism according to which spectral lines are formed.

6.4.3 From levels to lines

A significant question inquiring the reasoning students employ in predicting the emission given a set of energy levels is question LEV8 "Considering the first six energy levels accessible to the hydrogen atom, whose values are shown in the table, how many emissions do you expect to observe? Justify the answer."

Students’ answers allow to study the model used by students in predicting the number of discrete emission lines given a set of energy levels, and thus to reconstruct their way of reasoning. This question was submitted during the Summer School for talented students, i.e. the experimentation coded 11_9_2017 both in pre- and post-test. Before the intervention, the spontaneous idea that a single level corresponds to a single emission line is shared by 13/31 students (among which only one does not consider the fundamental level as a level to be taken into account), while the interpretation according to which an emission is the result of a transition between couples of levels is commonly shared by 12/31 students. Among them 8/12 consider all the possible transitions, 3/12 consider only the ones involving the fundamental level and 1/12 considers only transitions occurring between adjacent levels. These interpretative models, which are based on arbitrary hypotheses, are overcome at the end of the educational path, since in the post-test it emerges how all the students adopt the model in which all the possible transitions are considered as the cause of the spectral emissions.

6.4.4 Nature of levels

In experimentation 11_9_2017, i.e. the Summer School for talented students, the question NL3 was posed before and after the intervention: "What do individual energy levels represent in an atomic model?"

Before the intervention, students mainly answer in terms of "spatial location of electron" using as conceptual referents orbits (13/31), orbitals (13/31), space where electron reside (4/31) or distance from the nucleus (1/32). A description in terms of properties of electrons using conceptual referents as their energies (3/31), their excitation state (3/31) or the energy of the orbital in which they are (2/32) are used by a minority of students. Few students define energetic levels indirectly as energy of emitted photons (1/32) or through the observation that a difference in energy between a couple of levels leads to an emission of energy (1/32).

After the intervention students’ answers, monitored with a post-test, show a general shift against a description in spatial terms of the electron, in which space where the electrons reside (4/31), the distance from the nucleus (3/31), the orbits (2/31) or the orbitals (2/31) are used as conceptual referents. Interpretation shift in favor of a description in terms of properties of electrons, through energies (5/31), the orbital energy (1/32), their state of excitation (9/31) or the property of not emitting (4/31), of an indirect description in terms of energy of the emitted photons (1/31), through the observation that an energy
QUESTION LIN6_b (post-test): The figure below shows the emission spectrum of the lowest levels of an atom, starting from the fundamental one. The energy of the lines increases from left to right: Represent the energy levels that give rise to the spectrum shown in the figure, explaining how to identify them.

INTERPRETATIVE MODELS

Figure 6.11: Qualitative analysis of answers to question LIN_6b from post-tests.
Figure 6.12: Question LIN_8b: categories and operative definition using students’ drawings. From top to bottom: model (F) (only one line at greater energy), model (G) (a group of four lines at greater energy extrapolating the previous pattern), model (H) (lines corresponding to all possible jumps), model (I) (one line at greater energy because jump occur at fundamental level).
6.5 Discussion

As concern the light emission process (question LP1_b "During the optical goniometer experiment you observed the spectral lines emitted by a certain gas. Explains the process that gives rise to the observed lines, using a graphical representation") it emerges from the post-tests that samples that followed an approach starting from light sources (LS) (that, it is remembered, starts from an analysis of different light sources from a technological point of view) mainly describe the process emitting light from a macroscopic point of view (category "LAMP"). Samples that followed a path whose perspective was centered on an energetic interpretation of light (E) rather than an interpretation based on its wave nature (W) are more inclined to speak in terms of "ENERGETIC PERTURBATION OF MATTER" or tend to use a description of matter in terms of energy levels rather than in terms of Bohr’s orbit. The typical misunderstanding according to which the "light emission process" is confused with "the process thanks to which lines are visible, i.e. the dispersive mechanism" (category "MEASURE PROCESS/SEPARATION") is overcome in the following experimentation addressing the question in a more clear fashion (see Sect. 5.4.10), in fact when question concerning the light emission process is posed after the one that explicitly focus the attention on the emitting system (question LP1_d "Light is an entity carrying energy. What does the emitted energies with respect to the emitting system? Describe an interpretative hypothesis regarding the emission process and making use of a sketch") the percentage of students focusing on the dispersive mechanism rather than on the emission process itself is lower. It has also been noticed that when following a path centered on the energetic nature of light (E) the answers are mostly given in terms of emitted photons (or photons carrying energy). If the followed approach is the conceptual one (CD) in an (E) perspective a shift is noticed in terms of description from the Bohr model to an energy levels model (in which electrons or matter change levels) or a model in which
light emits energy consequently to an energetic perturbation avoiding macroscopic or tautological description, the description of the dispersive mechanism and the vision according to which the emitted energies are the characteristic energies of the source. Talented students, following a path with an CD approach and an E perspective provides description of light emission on an interpretative level both before and after instruction with a shift from using the Bohr model to a more general models in terms of energy levels. The interpretation in terms of emission of photons becomes prominent after instruction. Question LP5 "After observing 3 different types of spectra (continuous, discrete, band), how do you imagine the emission process in the 3 cases? Help yourself with a graphical representation" stimulates a reasoning in source functional terms in those students that followed a path whose approach is phenomenological (PH, i.e. based on the observation of spectra as a first step): the exploration through the spectroscope promote students in describing in functional terms a source when asked for its emission process, avoiding to refer to the dispersive mechanism and promoting the description of the observed spectra (category "TYPICAL SPECTRA") in terms of energy or wavelength. To go deeper, in this particular path, students who describe spectra when asked to account for the emission process are 16/41 in one experimentation (16_4_2018) and 16/44 in another one (17_5_2018). Their number decrease to 9/41 and 12/44 after instruction evidencing a weak shift towards a microscopic interpretation. It is interesting to note that the first group, following a (W)-perspective persists in describing spectra using wavelengths (8/9 post vs 8/9 pre) and only one student avoids energy as a conceptual referent after instruction (1/9 post vs 2/10), while the second group following an (E)-perspective considerably changes the conceptual referents: energy (10/12 post vs 6/16 pre) in favor of wavelength (2/12 post vs 10/16 pre). When asked to describe the emission process (question LP5) Following a (CD) approach, i.e. framed within the wider context of optics, with a (W) perspective students focus their attention on the macroscopic process of light emission and propagation, the dispersive mechanism and the description of spectra in terms of wavelength, energy or color avoiding to attempt of giving a microscopic interpretation, and basing their description on the macroscopic phenomenology, typical of optics.

As concern the conceptual model linking discrete emissions to the energy levels, the analysis of the answers given to questions LIN1_a and LIN1_b reveals that both the approach (LS, PH, CD) and the perspectives (E, W) are indifferent to gain a conceptual understanding of the proposed situation: if different energies are associated to different colors, a great percentage of students, even after the instruction, persist in identifying the reddest line in a spectrum with the lower "energy level".

As concern the representation of levels even if the path has an (E) perspective aiming at a description of matter in terms of energy states, even after instruction students persist in using the semiclassical Bohr model used in the path only to justify the negative value of the energy levels. Nevertheless it emerges the change of perspective concerns a description of energy levels in favor of a more general vision in terms of characteristic energies rather in terms of a more limited spatial description "by orbits", conditioned by the previous schooling.
Chapter 7

Research with freshmen in biotechnology

7.1 Introduction

University introductory physics courses in life-science areas degrees face the problem of making students able to apply physics concepts in the different contexts of the specific professionalizing field of study (McDermott and Shaffer, 1992; McDermott et al., 2006). Unfortunately introductory physics is often taught in the same ways in different degrees and the teaching doesn’t take into account the specific context since an effective learning has to be contextualized. Physics concepts are often built upon few fundamental mathematically formulated principles (Meredith and Redish, 2013). Teaching physics to life-science areas students requires far more than simplifying a course and adding in a few superficial applications. It is necessary to point out and improve the methodological and cultural elements, the interpretative instruments and the competences which are the founding elements of the specific degree. As a matter of fact some very general aspect of physics culture are not shared by life-sciences colleagues. Topics that physicists view as “canonical” and consider important for all students are quite different from topics that biologists view as important for understanding and doing modern biology, as for instance random motion, diffusion, microstate thermodynamics, and fluid flow (Brewe et al., 2013; Redish, 2014). Moreover, the work of life-sciences professionals has changed dramatically in the last decades, but the education of those professionals has not: simple academic knowledge is not enough for competence demanding. Revising contents, instruments and methodologies is the central focus of the emerging need for university teaching innovation in order to address the above mentioned aspects, in particular (Michelini and Stefanel, 2016):

- To re-design the way in which physics is offered and approached, so that its role can be recognized in the specific subject matter characterizing the degree, individuating specific applications of physics in the specific professional field (Meredith and Redish, 2013; Cummings et al., 2004; Hoskinson et al., 2014; O’Shea et al., 2013);

- To offer instruments and methods building a physics competence in different fields (Hoskinson et al., 2013);

- To individuate strategies able to produce an active role of students in learning physics and to give them the opportunity for an appropriation of the applied physics methodologies (Hoskinson et al., 2013).
Learning is context-based as a wide literature evidenced (Brewe et al., 2013). General criteria are proposed for adopt innovative curriculum models (Watkins, 2012; Manthey and Brewe, 2013; Donovan, 2013; Thompson et al., 2013) to help students develop reasoning strategies that move beyond traditional disciplinary boundaries. The problem of the relevant contents that have to be integrated in the curriculum has also been discussed as a research question (Redish, 2014) though the problem does not regard contents only, but also the point of discussing methodological tools as: competencies in taking measures, in data analysis techniques and in processes analysis (Michelini and Stefanel, 2016; Redish and Hammer, 2009). For university teaching/learning innovation, the treatment of topics linking models knowledge and experimental data is a fertile field in order for life science-area students to gain specific skills and promote their conceptual change in the introductory physics courses. The work of teaching introductory physics for freshmen in biotechnology goes in the direction of giving an integrated contribution, stressing the importance to include experimental lab, interactive lectures and high students engagement.

7.2 Design

Focusing on those points, a design-based research formative intervention module on the specific topic of optical spectroscopy has been integrated in introductory physics curriculum for biotechnology students at Udine University (IT) (Buongiorno and Michelini, 2019a, 2018). In fact, one relevant topic for biotechnology students formation is optical spectroscopy, since it is an essential prerequisite to carry out qualitative and quantitative analysis of dispersed particles throughout the bulk of a fluid (suspensions), analysis of samples using fluorescence, or to infer molecular structures (Nelson and Cox, 2009). Despite its importance, very often this topic is not integrated in an organic way in introductory physics curricula, preferring to be addressed in the chemistry courses, or never addressed at all, despite it represents a fertile link between knowledge of models and experimental data on an interpretative plan from a physical point of view. This analysis technique offers an important disciplinary contribution on the epistemological plan of physics, since absorption and emission of quantized radiation are fundamental concepts, representing some of the main investigative tools based on light-matter interaction. Optical spectroscopy represents a context in which to address the role of energy in physical analysis, a validation instrument of interpretative models through indirect measures and a way to interpret a code in order to get information on the changes and the states of a physical system. Moreover it is a methodological context in which tools and methods connecting theory and experiment in physics are prominent, allowing students to gain experience concerning the specific ways of investigation in physics. Moreover, the role of the experimental lab is undervalued, since students do not experience the role of the addressed concepts which are, in the end, analysis techniques. The characteristic of the two intervention modules on optical spectroscopy are here discussed together with the students learning outcomes.

7.3 The first experimentation (a.y. 2015/16)

7.3.1 Sample, context and research questions

The activity (coded 1_1_2016) (Buongiorno, 2017; Buongiorno and Michelini, 2016b) involved a group (N=56) of freshmen in biotechnology, overcoming the selection test among 200 applicants, from Udine University (IT) in the academic year 2015/16. They were attending a 3 CTS introductory physics course integrated with 10 hours of laboratory
activities. The research described here was carried out in the framework of this specific course. Propedeutical issues concerning the activity (geometrical and physical optics, with special attention to optical diffraction in order to account for the characteristics of a light pattern caused by a diffraction grating, different kind of light sources, discrete and continuous spectra highlighting the existence of a discrete energy structure in order to account for atomic spectra) have been treated in 6 hours. 2 hours were devoted to the laboratory activity with submitted tutorial, and 2 hours were devoted to the post-test. Before the laboratory, students attended an introductory chemistry course, dealing in particular with the following topics: atoms and molecules, the structure of the hydrogen atom, orbitals and quantum numbers.

In PER, a specific aspect is taken into account in the context of a wider thematic. In particular, in this research the aspect under investigation is the conceptual link between spectral lines and discrete energy levels in the context of optical spectroscopy. The present study aims to give answer to the following research questions:

RQ1) Which role do students assign to the slit and to the diffraction grating in the experimental setup?

RQ2) Which models are mainly used by students in order to describe the emission of light from an atom?

RQ3) Which kind of reasonings and representations are used by students for the relationships between spectral lines and energy levels of the emitting systems?

7.3.2 Instruments and methods

The proposed laboratory was based on the experiment of the optical goniometer (see Sect. 5.2.1).

Data were collected by means of a tutorial (A_16_TUTORIAL) and a post-test (B_16_TESTOUT). No pre-test was used. The tutorial, based on the one developed in (Ivanjek et al., 2015b), consisting of 9 open-ended questions, was submitted individually to the students asking them to argue their answers. The tutorial, conceived as an instrument of investigation rather than a support to the activity itself, was used after the experiment and students’ answer were collected at the end of the whole activity. It made use of IBL strategies and it was organized in stimulus-questions and in-context step-by-step analysis of interpretative aspects. The focus was set on the relationships between spectral lines energies and energy levels in the special case of the hydrogen atom, on the concept according to which the highest energy level in the atom is zero, on the fact that energy levels become closer together as the energy increases and on the relationship between the smallest and largest possible energies of the emitted light which correspond, respectively, to the smallest and greatest possible energy differences among levels, in order to collect students’ reasonings. Interviews concerning the issues addressed in the tutorial were carried out during the laboratory activity. The post-test, delayed about 2 months, has been submitted individually to N=45 students in the context of the final exam of the course. The post-test recalls the issues addressed in the tutorial, using 7 different open-ended key questions: it probes students ability to associate any given spectral line with the transition between two specific energy levels and to sketch a qualitative energy level diagram from a given discrete spectrum.

Data collected were analyzed by qualitative methods with operative definition of the different categories, identified a-priori from the research literature and a-posteriori from the
specific sample’s outcomes, in order to identify the number of non-mutually exclusive aspects present in the argumentation in every answer, the various types of aspect noticed and the conceptual referents underlying the interpretative models. Graphical representations used by students in order to explain their argumentations were analyzed and correlated with written answers.

7.3.3 Data analysis and discussion

Tutorial

Here we report the analysis of the answers to four most significant questions posed in the tutorial (numbered 3, 4, 5, 8). In question 3 (what is the shape of every line caused from?) half of the sample (26/56) answer that the shape of every line is due to the shape of the slit, while a significant fraction (22/56) states that the shape of the lines resemble the shape of the incisions on the grating. A little minority (5/56) argue that lines must be narrow in order to represent different specific energies.

Question 4 is particularly significant in order to analyze the different perspectives under which students interpret a discrete spectrum: the optical spectrum of the hydrogen is shown to students. They are asked to comment on a dialog between two students: the former states that red line in the spectrum corresponds to the higher energy level of the atom, since it has, among all, the grater wavelength; the latter states that the red line corresponds to the lower energy level (fundamental level) of the atom, since it has the lowest energy. Categories of students’ answers are reported in Tab. 7.1. From the analysis of the answers it emerges that a third of the sample (17/56) states, with high confidence, that every line in a spectrum is the outcome of a transition between two levels: these students disagree with both affirmations offered by the tutorial. A quarter of the sample (14/56), on the other hand, expresses, explicitly or implicitly, the idea that a single line corresponds to a single energy level. This denotes the tendency of associating a single emission to a single energy level. In particular, red line, the one with the lowest energy, dearly corresponding to the smallest energy transition, was seen as equivalent to the fundamental level from the half of the sample (27/56), probably due to the trivial interpretation of the formula linking energy and wavelength \( E = h \cdot c/\lambda \) that could represent a formal ritual (Viennot, 2006). In fact this relation refers to the energy of the various emissions, and not to the energy of the levels, but only a little minority of the sample (3 students) states explicitly that, while 2 students state explicitly that the relation refers both to spectral lines and/or levels. A minority of the sample (20/56) disagree with the affirmation that red line corresponds to the fundamental level, arguing that it corresponds to the smallest energy transition. From the analysis of students’ answers different outcomes emerge: the problem of distinguishing the energies of the levels and the energies of the lines, the issue of giving sense to the two representations, as well as the need to discuss the formal relations in order to avoid them to become rituals that affect the interpretative reasonings.

In the following question (question 5) students are asked to compare the five energy values of the different emission lines with the values of the seven lowest energy levels for hydrogen in order to find a relationship between the two entities. On the basis of the relationship, they are asked to describe what happens to an atom when a photon is emitted. After doing that, students are asked to review their answers to the dialogue in the previous question. Despite this experience should help students recognize their tendency to make the common error of associating a single emission line with a single energy level and help them strengthen their understanding of the correct reasoning, half of the sample (28/56) simply describe the emission process and only 22 students analyze the given numerical
Table 7.1: Students’ answers to the second question of the tutorial: "Does red line correspond to the fundamental level because it has, among all, the lowest energy?".

<table>
<thead>
<tr>
<th>Statement</th>
<th>“An observed line corresponds to an energy level.”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agree (A)/Disagree (D) with examples of argumentations</td>
<td>14/56 (A) “Spectral lines represent levels with increasing energy.”; “Line 5 is the one with the highest frequency, thus it is not a fundamental level.”</td>
</tr>
<tr>
<td></td>
<td>17/56 (D) “Every line corresponds to the energy difference between an energy level and level 2.”; “Lines represent a jump between two levels and non a single level.”</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statement</th>
<th>“Red line is the fundamental level.”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agree (A)/Disagree (D) with examples of argumentations</td>
<td>27/56 (A) “Frequency is inversely proportional to $\lambda$, according to $E = h \cdot f = h \cdot c/\lambda$. So red line has lower energy than the violet one, in other words it is closer to the nucleus. We can say that, among all, red line is the fundamental level.”</td>
</tr>
<tr>
<td></td>
<td>20/56 (D) “In the spectrum I cannot identify the fundamental level because the color I see represents an energy difference, thus a jump between levels.”; “The atom in the fundamental level doesn’t emit and the lines represent a $\Delta E$.”</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statement</th>
<th>“$E = h \cdot c/\lambda$ refers to levels.”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agree (A)/Disagree (D) with examples of argumentations</td>
<td>2/56 (A) “Relation between energy and frequency is $E = h \cdot f$, moreover, $c = \lambda \cdot f$ so frequency and wavelength are inversely proportional. Red corresponds to a greater wavelength and thus to lower frequency and energy, so it corresponds to the fundamental level of the hydrogen atom.”</td>
</tr>
<tr>
<td></td>
<td>3/56 (D) “$E = h \cdot f$ refers to the energy of the radiation, so the red line is the one with lower energy.”; “The energy of a single photon is $E = h \cdot f$. “</td>
</tr>
</tbody>
</table>

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values. Out of them, 14 students use the numerical values in order to argue their reasonings concerning the process, 5 students use the numerical values as a starting point to describe the emission process, and 3 students simply analyze the numerical values without mentioning the emission process. Students who analyze the numerical values of the energy levels and of the emission lines adopt different approaches: 13 students describe only a particular set of energetic values, 9 of them focus the attention on the energy of the emission lines underlyng the relationship between energy and wavelength leading to the conclusion that the fundamental level is the one with lower wavelength, while 4 of them focus their attention on the energetic values of the levels. 9 students compare the two sets of energies, but only 4 of them notice that the energy of an emission lines can be evaluated as a difference between two energy levels, while 5 students consider the two sets as representative of the same quantity. Working through this task, 9 students explicitly confirm their previous answer: 6 of them arguing that the red line in the spectrum represents the fundamental level, without recognizing that one of the students is incorrectly associating each emission line with a single atomic energy level; 3 of them arguing that a single line is the result of a specific transition. 3 students deny their previous answer stating that it is not true that red line corresponds to the fundamental level, because negative values exist, doesn’t matter if they are referred to levels. It emerges that the majority of students starts from an idealized model rather than starting from the critical analysis of data provided: they adapt the data to their description without using them as a starting point. 10 students state that the energy of the emitted radiation corresponds to a difference between energy levels, without correlations with the provided numerical values. The emission process is often described in qualitative way in terms of energetic jump of the electron (24/56) that gives back the absorbed energy (13/56), or in terms of energetic variation of the atom (17/56).

In question 8, students are asked to sketch the energy levels for the hydrogen atom, observing their positions and relative distances. Data show that more than half of the students answering this question (29) use the classical representation that resembles the Bohr model, making use of orbits (figure 7.1a). 17 students sketch levels distributed horizontally or vertically (figure 7.1b, c). 4 students make use of different representations at the same time, in particular 2 students couple an orbit-scheme with an energy level-scheme (figure 7.1d), while 2 students couple an orbit-scheme with a sort of histogram (figure 7.1e). Among students who use the Bohr representation, it emerges that 14 of them draw levels in number of 7, as the ones previously shown, only 1 student draws 6 levels (figure 7.1f) and 2 students draw 5 levels (figure 7.1g) in order to justify the five lines in the spectrum. 2 students draw transition between levels without any link to the observed spectrum, while 2 students quote the resulting spectrum (figure 7.1h). Among students who use a level-scheme, the majority of them draws 7 levels, while the remaining draws an arbitrary number of levels, or a number with no link to the number of observed lines.

A spontaneous idea emerges: a single emission line is directly linked to an energy level of the emitting system. This representation, so common among university students, is a common feature of the first interpretations of atomic optical spectra in the history of physics, since scientists used to associate a single emission with a single harmonic oscillation in the atom.

Post-test

In the post-test students are shown a portion of the emission spectrum of atomic hydrogen in which 6 lines are present. The lines are grouped in three series, which is what is expected
Figure 7.1: Tutorial: graphical representations of the energy levels.

to see if only the four lowest energy levels are involved: the fundamental one and the first three exited levels.

Here we report the analysis of the answers to the first six questions of the post-test.

Students’ answers to question 1, ”How are the lines in the spectrum and the energy levels of the emitting system related?”, fall into three main categories: a third (15/45) of the sample states that a line in the spectrum corresponds to a single energy level (examples of students’ argumentations are ”The relation between spectral lines and energy levels is expressed by Planck’s formula: \( E = h \cdot f = h \cdot c/\lambda \).”; ”Every line in the spectrum corresponds to a specific energy level of the considered system.”); 10/45 students state that a single emission line corresponds to a difference in energy between two levels (”Lines correspond to a jump between an energy level and another one: when this happens, radiation is emitted.”; ”Electron in high energy levels is unstable and tends to return to the level with lower energy, so it emits a photon whose energy is equal to the energy difference between the two levels.”), a minority of the sample (4/45) relates the number of series to the number of energy levels (”The first line represents the source, the second two lines represent the wavelengths of the first level, and the last three ones represent the wavelengths of the second level.”).

In the question 2, students are asked to identify the minimum number of energy levels required to produce the part of the spectrum shown, making a sketch of them. 8/45 students draw levels in number of 6, directly associating an emission line to an energy level, 6/45 students draw 7 levels associating a line to a level, adding the fundamental one, 5/45 students draw 3 levels, counting the number of series, 3/45 students draw 7 levels, counting the number of intervals in the spectrum, 10/45 students draw 3 levels with no justification and 2/45 students draw 4 levels in order to account correctly for the 6 emission lines observed (figure 7.2). The majority of the sample make use of the ”Bohr orbit representation” (25/45) rather than a ”level representation” (13/45).

Post-test question 3 states: ”The energy level \( E_2 \) (the first excited level) is involved in the formation of one, or more than one, line(s) in the spectrum. Show the line(s) involving level \( E_2 \).” A third of the sample (14/45) identify the second two lines starting from the left: this may be caused by the interpretation that a group of lines corresponds to a level, or by the interpretation that the involved level is considered only as the final level. 8/45 students identify the second line starting from the lower energy part of the spectrum, associating a single line with a single energy level. Various other answers are present, but hardly
Figure 7.2: Post-test: graphical representations of the energy levels.

interpretable. A single student identifies correctly the three lines whose transitions involve level \( E_2 \) (figure 7.3).

In question 4 students are asked how many new lines would be formed if the next higher energy level were taken into account. They are also asked to indicate the position(s) of the added line(s) in the spectrum. Student’s answers to this question fall into three main categories (figure 7.4): 12/45 draw a single higher energy line at in the right portion of the spectrum (figure 7.4a); 5/45 students expect 4 lines at higher energy (figure 7.4b) and 1/45 student give the correct answer in terms of transitions, though he does not represent the lines in the spectrum.

Question 5 states: "For atomic hydrogen, the energies of the fundamental level \( E_1 \) and \( E_3 \) are respectively \(-13.61\, \text{eV}\) and \(-1.51\, \text{eV}\). Which line(s) is (are) possible to predict in the spectrum? Evaluate its/their energy/energies.". Instead of evaluating the difference between the two given energy levels, 11/45 students associates directly a wavelength to the given two energies, according to the ritual \( E = h \cdot c/\lambda \) while 12/45 students perform unclear calculations involving differences between couples of values, highlighting the lack of conceptual understanding.

The tendency to associate a single emission line to a single energy level is more prominent in the post-test than in the tutorial, due to the fact that no suggestion concerning energy levels values was provided to students: they could only rely on the observed spectrum.

In question 6 students are asked what they expect to observe if the grating is removed. The majority of the sample (32/45), focusing on the descriptive plan, states that the lines will no longer be visible, due to the fact that the grating’s function is to separate the different wavelength. 6/45 students say that lines are always visible, in fact the grating’s role is to make a discrete spectrum more definite, while 5/45 students, focusing on the interpretative plan, state that diffraction will no longer occurs.
Figure 7.3: Post-test: lines involving energy level $E_2$. Student's answers.

Figure 7.4: Post-test: position(s) of the line(s) formed taking into account a higher energy level. Student's answers.
7.3.4 Results

A research-based intervention module on optical spectroscopy for freshmen in biotechnology was designed in order to gain competence on students' learning processes using a tutorial in a laboratorial context, and a post-test.

The specific roles of the diffraction grating and the slit (RQ1) require a particular additional discussion for half of the students who look at the diffraction grating as responsible for the shape of the spectral lines. More than 10% of students expects to observe spectral lines also when removing the grating. These evidence seem to be correlated to the great conceptual change involved in the explanation of the existing difference between a diffraction pattern and a discrete spectrum. Qualitative plan prevails in students' description of the emission of light from an atom: students quote energy changes but when they are provided energy values for levels and lines, they do not correlate the two sets by means of the simple relationship existing between them. It seems that the formal relationship between energy levels and spectral lines have to be specifically addressed (RQ2). Concerning the reasonings and representations used in order to describe the relationship between the two different referents (RQ3) it emerges that the term "energy level" is misused: spectral lines of higher energy are quoted as greater "energy levels". Explicitly, sometimes single lines are related to single levels. This result offers us students’ way of thinking when we correlate it with other outcomes already outlined in literature (Ivanjek et al., 2015a,b; Savall-Alemany et al., 2016) concerning students’ perspective in which the fundamental level has zero energy and it is involved in every transition. Despite an explicit qualitative comparison between lines and levels energies was offered to students in the tutorial, the problem of the conceptual link between the two referents appears in the post-test as a lack of functional understanding of the topic.

Findings of the study here presented suggest the need of devoting more time and attention to the phenomenological exploration and discussion of hypothesis at the base of the experimental work in order to gain a deeper conceptual understanding of every component of the setup. The surprising lack of spontaneous use of simple mathematical operations linked to the processes under analysis, also when all the elements are provided to students, suggests working in gaining ownership with modalities in which it is possible to obtain information from the relationship between spectral lines and energy levels. This is particularly important in the conceptual distinction between continuous and discrete spectra.

7.4 The second experimentation (a.y. 2016/17)

7.4.1 Sample, context and research questions

In a DBR approach contents, methods and monitoring instruments underwent a revision after the first experimentation giving birth to the second one (coded 3_1_2017). The conceptual steps of the path used for secondary school students allowed to calibrate the learning path for freshmen in biotechnology. In the a.y. 2015/16 a research-based intervention module on optical spectroscopy for freshmen in biotechnology at Udine University (IT) (see Par. 7.3) was set up which is the first step of the DBR. In the academic year 2016/17, introductory physics for biotechnology in Udine University (IT) was a 3-CTS course (out of a total of 180 during 3 years) offered during the first semester of the first year; 10 hours out of a total of 40 were devoted to lab activities. The module on optical spectroscopy covered 12+2 hours divided in 4 parts. The sample here considered consists of 49 students attending in the a.y. 2016/17 the first year of biotechnology course.
They were selected at the beginning of the academic year by means of a selection test with the same criteria at national level out of 200 applicants. The sample had no relevant knowledge concerning specific aspects of optical spectroscopy before the instruction.

Part A of the module on optical spectroscopy is part of the one on optics, treating light sources, propagation processes and light matter interaction. The approach to light sources is from a technological point of view: the characteristics of natural and artificial sources are addressed. Mechanisms for producing colored light and dispersion phenomenon complete the analysis of propagation processes, in which diffraction is explored from phenomenological point of view in laboratory, deriving the characteristics laws. Students experience the equivalent role of a prism and a diffraction grating for white light dispersion. Huygens-Fresnel principle founds the interpretation of one slit and grating diffraction. In the historical framework of the Balmer and Rydberg rules, spectra emerge as identity card of elements. The phenomenological laws of the emissivity of Kirchhoff, Wien and Stefan-Boltzmann introduce the Planck interpretation of emission. Limited role is attributed to the Bohr atomic model, which evolve in the energy level model by means of the idea of photon introduced as interpretation of the photoelectric effect. The interpretative role of energy levels assume relevance in examples on how to bridge between spectra and energy levels.

4 hours were then devoted to the laboratory activity (part B), carried out in 3-students group sessions, based on the experiments on diffraction from a single slit and of the optical goniometer.

In this research, we focused on the study of the reasoning connected with the conceptual knots emerged in the literature and on the conceptual relations with laboratorial aspects. In particular, the focus is on the following research questions:

RQ1) How do students relate the laboratorial activity on optical spectroscopy with the emission process?

RQ2) Which kind of reasoning students employ in order to relate energy levels in atoms and spectral lines?

RQ3) How do students evidence the conceptual roles of the grating and the diaphragm in an experimental setup to perform spectroscopic measures?

### 7.4.2 Instruments and methods

In the part of the research described here, students’ learning outcomes and the effectiveness of the approach have been evaluated using a post-test (D_17_TESTOUT), consisting in 10 open-ended questions, inspired by the work described in (Ivanjek et al., 2015b) addressing the main learning knots emerged in the literature, as for example the ability to sketch an energy level diagram knowing the energy values and the ability to predict the expected discrete spectrum. The main open-ended key questions in the post-test addressed the
following problems: Q1: the explanation of the process responsible of the formation of spectral lines; Q2 and Q3 the role of diffraction grating and of the window/diaphragm in the spectrometer; Q4: discussion between students of the information coded in a spectrum; Q5: the representation of energy levels and of the relative spectra, having energy value of an atomic system; Q6: having a specific spectrum: Q6.1: the energy level responsible of a given spectrum; Q6.2 the relative energy level representation; Q6.3 the evidence of one of energy level (E2) involved; Q6.4: the new lines added when an higher energy level is present. Explanations were explicitly requested. The post-test was in the context of students' final examination and took place about 45 days after the module on optical spectroscopy. It lasted 2 hours and all topics covered during the course were addressed. In order to answer the research questions, students' answers in the post-test have been analyzed.

7.4.3 Data analysis and discussion
The explanations of the process responsible for the formation of spectral lines (Q1) are of 4 main non-mutually exclusive categories (Fig. 7.5 left), corresponding to the different levels of analysis: a) atomic processes responsible for the emission (32/49); b) description of the experiment in functional terms (Fig. 7.5 right) (26/49); c) assertion that the gas inside the lamp is responsible for the emission (8/49) or d) the phenomenon of diffraction as responsible for the formation of the spectrum (7/49). In category a) the description of the de-excitation through an energy-level model (Fig. 7.5 center) is often implemented (21/49) with the analogous process of excitation via heating (10/49), electric discharge (6/49) or light absorption (5/49). Students' reasoning refer to 3 different models of emission: a) "the energy of a line correspond to the difference in energy between two levels" (19/49); b) "what is absorbed is re-emitted" (19/49); "all transitions occur to the fundamental level" (7/49). Different causes for the emission are quoted by students: "light is divided in various atomic levels" (2/49); "the electron becomes free" (1/49) or "the emitted colors are those which cannot be absorbed by the gas" (1/49). Despite the majority of students spontaneously adopt energy-levels model in order to account for the emission process, completing it with various interpretation about excitation processes, the need of discussing in detail the relationship between spectral lines and transitions emerges. The specific issues of clarifying that transitions that do not involve the fundamental level are present have also to be addressed specifically as well as the need of linking emission conditions and the employed model. Concerning the role of diffraction, and in particular the prevision of what

Figure 7.5: Describing the process producing spectral lines (left), a sketch showing the energy-level model (center) and a drawing representing the formation of spectral lines through a functional representation of the apparatus (right).

they expect to observe if the grating is removed (Q2.1 and Q2.2) 6 categories emerge from
students' answers: a) separation of colors no longer occurs so, correctly, "only the color of the original light could be seen" (33/49); b) "diffraction/interference no longer occurs" (12/49); c) "lines are better separated" (12/49); d) "the color of the source can be seen at every angle" (3/49); e) "a continuous spectrum appears" (3/49); f) "a single-slit diffraction pattern appears" (2/49). The need of discussing the effects of light diffraction from single or multiple slits both with monochromatic and polychromatic light emerges, justifying the correct dispersive role of the grating in the diffraction phenomenon. The shape of the spectra with respect to the shape of the entrance window/diaphragm is addressed in Q3. Students state that the shape of the lines is due to the vertical engraving on the grating (26/49), to the shape of the slit through which light passes (16/49) or to the shape of the source (3/49). Various other interpretations are present, regarding mostly geometrical alignment, source-grating distance or the presence of lenses (6/49). A single student states that lines have always to be mono-dimensional since they represent a single energy or a single wavelength. The roles of the entrance window and of the grating turns to be controversial: those aspects (Q2.2 and Q3) seems to be purely technical, indeed they address physical aspects since they play a conceptual role in students’ reasoning concerning the formation and modification of a spectrum. A specific IBL explorative path is particularly useful in this case to offer students the opportunity to gain awareness of the functional role of each part of the apparatus from a physical point of view.

Question Q4 allows to analyze the different perspectives students employ when reading the information coded in a discrete spectrum: they are asked to comment on a dialog between two students: the former states that red line in the spectrum of hydrogen corresponds to the higher energy level of the atom, since it has, among all, the greatest wavelength; the latter states that the red line corresponds to the lower energy level (ground level) of the atom, since it has the lowest energy. From the analysis of the answers it emerges that about one third of the sample (18/49) states that every line in a spectrum is the outcome of a transition between two levels: those students disagree with both affirmations offered in the question. On the other hand, a significant percentage of students (7/49) expresses, explicitly or implicitly, the idea that a single line corresponds to a single energy level. The tendency of associating a single emission to a single energy level emerge. In particular, the red line, the one with the lowest energy, clearly corresponding to the smallest energy transition, was seen as equivalent to the ground level by more than half of the sample (29/49), probably due to the trivial interpretation of the formula linking energy and wavelength ($E = hc/\lambda$) that could represent a formal ritual (Viennot, 2006). In fact this relation refers to the energy of the various emissions, and not to the energy of the levels, but only a little minority of the sample (6/49) states explicitly that, while a little number of students (3/49) state explicitly that the relation refers both to spectral lines and/or levels. A minority of the sample (14/49) disagrees with the affirmation that the red line corresponds to the ground level, arguing that it corresponds to the smallest energy transition. In arguing the answer to this question, students make use of different reasoning: an energy level has an energy that can be evaluated by the formula $E = hc/\lambda$ (27/49), the energy of a single line can be evaluated knowing the difference between the energy of two levels (17/49), the transitions involving the ground level has the lowest energy (3/49) or the greatest energy (3/49), the binding energy of the ground level is the greatest (3/49), the emitted energy is due to the electron's velocity (1/49). The concept that in the fundamental level no emission can occur is also pointed out by 1 student. The need of addressing the conceptual difference between spectral lines and atomic levels emerges also in those answers.

In question Q5, students are asked to represent the levels and the resulting line spectra knowing the energy values of a specific atomic system; in particular the values of the
energy of the first 5 levels, starting from the ground level, of ionized helium were given to
students. All students use a representation in terms of stacked energetic levels rather than
an orbit-model representation (used only by one student) differently from the previous
experimentation with biotechnology freshmen that make large use of the representation
using Bohr orbits, since no prominent role were given to level rather than to orbits, using a
classical historical approach in the module of optical spectroscopy [28]. The fundamental
level is located at the bottom (34/49) or at the top (10/49) of the level representation.
The prevalent strategy adopted to students in order to draw the resulting spectra was
to count the number of different transitions that could occur, resulting in 10 lines in the
spectrum (22/49, Fig. 7.6 top). A different number of expected lines emerge from the
other answers: 5 lines, indicating a 1:1 correspondence between lines and levels (15/49,
Fig. 7.6 bottom), 4 lines, in which only transitions involving the ground level are taken into
account (3/49), 4 lines corresponding to transitions only between adjacent levels (2/49), 7
lines corresponding to transitions between adjacent levels and to the ground level (1/49).
Other minor expectations, with no explanation, are present: 8 lines (1 student), 9 lines (1
student) and n lines for the nth level (1 student).

Figure 7.6: Drawing the spectrum knowing the energetic levels. One line for every
transition (top) and one line for a single energy level (bottom).

The reverse problem is addressed in Q6.1: given a discrete spectrum, consisting in
3 series of 1, 2 and 3 lines respectively, students are asked to identify the number of
levels that can account for the observed lines. Students motivate their answers evidencing
different ways of reasoning: each line is a possible transition between any pair of levels,
thus identifying the correct number of levels involved (28/49), each line is a transition
between two adjacent levels (5/49), all transitions end to the ground level (4/49), each line
represents a level (4/49, one student adds the fundamental level), a series of lines (lines
grouped together in the spectrum) is interpreted as originating from one single level (3/49),
the ground level is not taken into account (2/49). The analysis of the discrete spectrum in
order to elicit students’ ways of reasoning in order to represent the involved atomic levels
is addressed in Q6.2. The main representation used is the diagram with stacked levels
(34/49), followed by a sort of histogram (3/49) or an orbit-model representation (2/49).
The main strategies of solutions are the following: iterative arrangements of the levels
in order to obtain distances between pairs of level corresponding to the observed lines
(15/49), analysis from the lowest energetic line to the most energetic lines (or vice-versa)
(8/49), adopting the hypothesis that levels become closer (8/49), reconstructing the level
structure considering lines energies as distances between adjacent levels (3/49), or between
a level and the ground level (3/49), making use of the Ritz’ combination principle (3/49),
association between a single line with a single level (1/49) or association between one level
and a series of lines (1/49).

The individuation of the four transitions involving a specific level, E2, addressed in
question Q6.3, is correctly performed by half of the sample (25/49), while a minority (4/49) individuate only two lines associated with the specific level (the two for which the level is the final one, or the two for which the level is the initial one). Few students make the association between a single line with the specific level (3/49) or the second series of lines (3/49). The main argument is based on the individuation of all transitions involving the specific level (both initial and final level) (22/49). The idea that transition can occur only between adjacent levels is present (3/49), as well as the interpretation according to which a series correspond to a single level (2/49) or the idea that every transition involves the fundamental level (1/49).

Question Q6.4 considers the effect on a given spectrum of considering one more energetic level to the atomic structure. Different ways of reasoning emerge: about half of the sample (26/49) correctly identify the number of new lines appearing on the spectrum, while a single new line appears for a minority of the students (7/49) according to the 1:1 correspondence between number of lines and levels (4/49), taking into account only those transitions involving adjacent levels (2/49) or the ground level (1/49). Other types of responses are present: 2 new lines (3/49), 3 new lines (1/49), various new lines (1/49) without providing an explanation.

7.4.4 Results

Students do not show difficulties in describing the emission process on a qualitative plan (though completeness of the description and the language employed require specific attention); in particular more than half of the sample uses the energy-levels model as a conceptual referent. It seems to be an important achieving the gaining of autonomy in activity in which students build an energy-level model from the interpretation of a discrete spectrum. A methodological approach in which familiarity with the characteristics of the phenomena occurs mostly with qualitative and quantitative exploration in laboratorial activities seems to be fertile, as well as a specific request of interpretation of the involved processes rather than the canonical frontal lesson.

Comparing to the previous phase of experimentation of the formative intervention module on optical spectroscopy in which the informative role of the interpretative theories was prominent, the relevance given to explorative activities in laboratory and to the autonomous interpretation of the specific phenomenology led to a significant improvement, in particular in overcoming atomic model based on a spatial representation through orbits, of purely historical value, in favor of functionally efficient models in terms of more general energy levels to bridge the gap between atomic spectra and atomic structure with a gain of interpretative potentialities from about one third of the students. In the same time, issues to be specifically addressed emerged: connecting equations to physical meaning and integrating multiple representations, in particular distinguishing and giving sense to the energies of the levels and the energies of the lines as well as the need to discuss in depth the formal relations. The more problematic aspects for about one tenth of students regards the concepts of transitions in order to build an energy-level model from the observation of a discrete spectra: often, reasoning is based on arbitrary assumptions that the ground level is involved in every transition or that transitions occurs only between adjacent levels. A small percentage of students seems to assume that a single line is referred to a single energy level. The same students quote energy changes when describing qualitatively the emission process, but when they are provided a quantitative analysis, they do not correlate lines and levels by means of the simple relationship existing between them. The specific roles of the diffraction grating and the slit require a particular additional discussion for half of the students who look at the engraving on the diffraction grating as responsible.
for the vertical shape of the spectral lines. More than a fifth of the students expects to observe spectral lines also when removing the grating (as if lines are always present) or a continuous spectrum when removing the grating (as if it is responsible for the nature of a discrete spectrum). Several different interpretations on the role of the slit and of the diffraction grating suggest a careful work on explorative plan with Inquiry-Based Learning methodologies where the functional role and the physical meaning of the different parts can be explored gradually. Dispersion process from a grating also require a gradual explorative path of the diffraction from 1, 2 or n slits to the relative interpretation in order to distinguish between an energy distribution in a spectrum and an intensity distribution of a diffraction pattern.

A focus is needed on the formal relations in order to avoid them to become rituals that affect the interpretative reasoning. As pointed out in (Meredith and Redish, 2013) in fact, life-science areas students, on average, are less fond of mathematics and less adept at using it than engineering and physical-science students. They are reasonably comfortable with using equations to plug and chug and get numbers but are less familiar with using them to tell stories about and gain insight into the world.

This research-based innovation will address the point of increasing the level of integration of physics in the biotechnological area, with particular emphasis on ways to improve students' competencies in the use of formal reasoning and modeling abilities.

7.5 The third experimentation (a.y. 2017/18)

7.5.1 Sample, context and research questions

A third and last experimentation was conducted in the academic year 2017/18. CTS for the introductory physics course, offered during the first semester of the first year, increased to 4 (out of a total of 180 CTS during 3 years) due to the increasing in laboratorial activities. Sample consisted in 60 students selected at the beginning of the academic year by means of a selection test with the same criteria at national level out of 200 applicants. Only 49 took part in the experimentation. The module on optical spectroscopy covered 10+2 hours (5 hours lecturing part + post-test, 4 hours laboratory, 1 hour problem solving activity, 2 hours final exam). The lecturing part focused on the topics emerged as fundamental in the previous experimentations: the phenomenology of light diffraction, different sources of light, physical meaning of the emission/absorption of light in terms of energy, interpretation of discrete and continuous spectra, energetic atomic structure of atoms and quantized emission/absorption of radiation. Experimental activities increased with respect to the previous experimentations; in a total of 4 hours students, divided in group of 3-4 performed 4 experiments: analysis of a single-slit diffraction pattern with a light sensor connected to the PC to obtain experimentally the relation between positions of maxima and their order, analysis of LED (see Sect. 5.8) and gas-discharge lamps spectra (see Sect. 5.2.1) and analysis of absorption spectra using a digital spectroscope (see Chap. 4).

Research questions have been refined:

RQ1) How does lab activity contribute in students awareness of the emission process?

RQ2) How do students relate spectral lines and atomic energy levels and vice-versa?

RQ3) How to build a module on optical spectroscopy for biotechnology freshmen taking into account their needs?
<table>
<thead>
<tr>
<th>CONTENT</th>
<th>MOTIVATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light sources</td>
<td>Different mechanisms for producing light exist.</td>
</tr>
<tr>
<td>Propagation of light and light/matter interaction</td>
<td>Focus on the energetic nature of light, accounting also for macroscopic observation (i.e. Snell’s law).</td>
</tr>
<tr>
<td>Diffraction</td>
<td>Experimental achievement of a mechanism able to separate light according to its color.</td>
</tr>
<tr>
<td>Diffraction grating as a dispersive element</td>
<td>The diffraction grating allows a better separation of colors and allows precise measures</td>
</tr>
<tr>
<td>Spectra as identifier of elements</td>
<td>Spectra are related to the specific light source and account for the existence of atoms.</td>
</tr>
<tr>
<td>No role is attributed to the Bohr atomic model</td>
<td>Focus on of a more general energy level model.</td>
</tr>
<tr>
<td>Interpretation of the photoelectric effect</td>
<td>Introduce the idea of quantized radiation</td>
</tr>
<tr>
<td>Analysis of the Balmer and Rydberg’s empirical formulae in terms of energy</td>
<td>The interpretative role of energy levels assume relevance in examples on how to bridge between spectra and energy levels</td>
</tr>
</tbody>
</table>
7.5.2 Instruments and methods

The same pre- and post-test (N_18_TESTIN and N_18_TESTOUT) have been submitted to students before the intervention module and immediately after it. In the final exam 4 open-ended questions concerning spectroscopy were present among the other topics addressed in the course. Pre- and post-tests consisted in 7 open-ended questions addressing the main learning knots emerged in the literature, as for example the ability to sketch an energy level diagram knowing the energy values and the ability to predict the expected discrete spectrum from a series of energy levels.

7.5.3 Data analysis and discussion

The classical discussion between two students, the question addressed in the previous experimentations (question LIN_1b) has been posed, avoiding every reference to wavelengths or frequencies of colors, but referring only to their energy. Students’ answers in pre- and post-tests have been compared (Fig. 7.7 top) jointly with the supporting interpretative models (Fig. 7.7 bottom). To be noticed that, after the intervention the percentage of students associating a single line with a single energy level decreases considerably in favor of a vision in which a line in a spectrum does not represent an atomic level but rather a change between two energy levels. A percentage of students that continue to associate the redder line to the lower energy levels however persist. Concerning the motivations that drive the answers, the oversimplified law according to which longer wavelengths correspond to greater energy for supporting the answer that the redder line has the lowest energy is almost abandoned in favor of a description in energetic terms of the emission process.

![Figure 7.7: Question LIN_1b: Does the reddest line in the spectrum correspond to the lowest energy level? (top) Justify your answer (bottom).](image-url)
When students are asked to sketch a set of energy levels (Fig. 7.8) it is observed that the main shift occurs in describing it through a more global energy level diagram, rather than using orbits, abstract and unjustified 2-dimensional graphics representation or even the spectra itself.

Figure 7.8: *Question LR_3b: The following table shows the energies of the energy levels of ionized helium. Represent the levels.*

A brief comment concerning the final examination: according to Fig. 7.9 in which the normalized scores, based on the correctness/uncorrectness of the reasoning and the performed calculations (in order to assign a numerical grade to each student) for every numerical exercise is shown, it is clear that the exercises concerning optical spectroscopy turned out to be quite successful. A major difficulty emerge in the question in which students are asked to step from macro to micro (interpret a spectra in terms of a set of correctly-spaced energy levels).

Figure 7.9: *Average score for exercises proposed to students in the final examination. Questions concerning optical spectroscopy are highlighted in red.*
7.6 Some conclusive remarks

Laboratorial activities on optical diffraction are essential in order to understand diffraction grating’s role in the detection of optical spectra. The explicit request of paying attention to grating and slit’s roles (that previous works showed to be critical concerning lines’ shape) turned out to be sufficient to gain more awareness.

Several alternative models accounting for the formation of spectral lines are initially present, and the module allows to obtain a correct interpretation of optical spectra.

After 3 years of experimentation, students’ needs in order to have a coherent frame which contents are integrated in an introductory physics course emerged: the importance of theoretical, experimental and problem-solving activities turned out to be essential. Two approaches (through a wave model or through a photon model for light centered on its energetic properties) ending with an analysis of Balmer and Rydberg’s works from an historical point of view are possible, allowing the analysis of important methodological elements in the foundation of students’ physical knowledge.
Chapter 8

Research with pupils

8.1 Introduction and design

The study on the foundation of scientific concepts in children (Duschl et al., 2007) evidenced how they begin their scholastic formation with a broad knowledge of the natural world, showing the ability to engage in complex reasoning. In contrast with the common opinion that children's reasoning is concrete, not-causal, not-logical, not-relational, research showed that their way of thinking is surprisingly sophisticated. This constitutes a solid basis for learning scientific concepts, such as model-related reasoning, interpretation of experiments, relations between theory and empirical evidence. However, many key ideas and ways of thinking typical of science are difficult if not impossible to achieve without educational support to be implemented through strategies promoting the pupils' involvement in exploring ideas and problems significant for them. Adults play thus a central role in promoting children's curiosity by directing their attention, structuring their experiences, supporting their learning attempts, and regulating the level of complexity and difficulty of information (Duschl et al., 2007, p.337). When educational approaches used in basic schools do not consider pupils endowed with the skills necessary to engage in a scientific activity, the building of a conceptual understanding is hardly obtained; on the contrary, curricula are often based on outdated knowledge about cognitive development that is not taken into account in teaching design for primary pupils. Pupils can mobilize substantial intellectual resources in the scientific learning challenge; in particular, early epistemological beliefs can serve as a basis for developing an understanding of how scientific knowledge is constructed. Pupils are, in fact, able to take into account ideas and interpretations concerning empirical evidence. As a consequence, children can understand some aspects of the nature of knowledge, such as its degree of uncertainty and the relative reliability of the information conveyed to them. Pupils can be thus involved in educational activities comprising scientific practices relatively complex since the beginning of their schooling programme (Duschl et al., 2007, p.87). This could promote the interest and a positive approach towards science, physics in particular, contributing in preventing the disaffection found in older students (Rocard, 2007). For all these reasons, scientific education is very useful, starting from kindergarten and primary school, as an integrated and not marginal part of basic education, together with the first experiences of observation and representation of the surrounding world. To activate the learning process, an educational approach based on specific angles of attack is needed (Michelini, 2007). It is therefore important to explore the ideas and representations with which pupils interpret the light emission mechanism from observations, at a microscopic level, representing a purpose of the research illustrated in this thesis.
In this specific case, the educational intervention is proposed as a preliminary exploration to answer the following research questions:

RQ1) How do pupils relate spontaneous ideas/representations on the observed phenomenology with microscopic processes?

RQ2) What microscopic processes do emerge in interpreting colored light/spectra formation?

RQ3) How do pupils use the models to interpret new situations?

The educational intervention was carried out during the informal learning context (see Sect. 1.2.5) of the interactive GEI exhibition (see Sect. 1.2.6) understood both as an effective environment to encourage the qualitative and quantitative exploration of physical phenomena in the areas of mechanics, thermodynamics, electricity, magnetism by students from 6 to 15 years, both as a powerful research tool to investigate spontaneous reasoning and mental models used by pupils and young students to interpret the observed phenomenologies. CLOE activities (see Sect. 1.2.6) are learning contexts based on pupil’s active investigation, carried out within the GEI exhibition. The methodology used implies that children, by exploring physical phenomena in person, construct the necessary elements for the acquisition and production of new knowledge through their direct involvement both in operational terms and in terms of discussion and learning. Within the CLOE activities the production of hypotheses of the learning subject is divided into elementary conceptual steps starting from the need to interpret a specific phenomenological situation. The material of the exhibition, which pupils can manipulate, includes different light sources, colored filters, simple spectrometers, plexiglass prisms, everything built with easily available elements, in order to promote the reproducibility of the activity also in the classes.

8.2 Light sources: a neglected topic

It is quite common in primary and lower secondary schools to deal with optics and phenomena related to light and color. When this happens, the focus is mainly on two areas characterizing the study of light phenomena: the propagation of light and its interaction with objects. As far as propagation phenomena are concerned, light is mainly treated using the geometric ray model, often confused with the description of optical paths of light beams. The rectilinear propagation of light rays is a convincing description of how light propagates in space: the classic darkroom experiments, the projected shadows or the beam of light that passes through - for example - a box filled with smoke allow observation of the phenomenon and validate the model. Instead, the interaction of light with objects concerns more phenomena, also generally treated, at primary school level, such as: reflection, diffusion and refraction. They are used for qualitative interpretation at the base of different evidences such as color perception, image formation and light intensity variation. However, the knowledge and interpretation of the light propagation phenomenology does not exhaust the entire spectrum of areas that characterize the study of optics: knowing how light propagates does not provide any information on the mechanisms underlying its production and its interaction with the matter. A complete picture of what includes the study of luminous phenomena must therefore also include the analysis of light sources and the mechanisms by which light is emitted and which justify its characteristics (Fig. 8.1), aspects that are of fundamental importance on technological, scientific and socio-cultural plans. The connection between the properties of the emitted light by a source and the
The study of luminous phenomena includes three areas: the generation of light (light sources), its propagation (for example through a ray model) and its interaction with objects.

emission mechanisms underlying it offers the pupils not only the opportunity to refine the interpretative model about the nature of light, but also the possibility of extending this knowledge in everyday contexts different from the scholastic one. The study of light sources therefore offers the possibility of facing the problem of the connection between formal and everyday knowledge which, in general, implies the recognition of the socially situated nature of all forms of knowledge and the awareness of how theoretical knowledge can be transformed in active knowledge (Michelini, 2004b). Starting from some key concepts, such as the energetic interpretation of light, encourages learners to use the founding ideas to identify in a critical way connections that cannot be distinguished with observation alone. However, the educational feasibility of this implementation in the study of optical phenomena is not obvious, because it involves the understanding of several aspects: how does the light emission mechanism occur? How is a color associated with a specific energy? How does this allow us to know the matter and its characteristics and what does the spectrum of the emitted light represent? Optical spectroscopy is thus proposed as a tool for analyzing the light emitted by the sources starting from informal observations of a ludic type within the GEI exhibition in CLOE laboratories.

8.3 Context and sample

The 2016 edition of the GEI exhibition was the first to host the optical spectroscopy section, developed as a CLOE activity. The exhibition saw the participation of a heterogeneous group of participants: 153 children from kindergarten, 800 primary school children (5 first classes, 6 second classes, 7 third classes, 13 fourth classes, 15 fifth classes) and 321 students from lower secondary school (4 first classes, 4 second classes, 8 third classes) as well as the involvement of 92 perspective primary teachers enrolled in primary science education course as part of their training university and 6 researchers in physics education, members of the URDF as scientific supervisors. The spectroscopy section saw the participation of a kindergarten class, a first class and a fourth class of primary school, a first class, a second class and two third grades of the lower secondary school. The activities, lasting one hour each, were conducted in different shifts, depending on the age of the participants involved and were conducted by a researcher of the URDF or by pairs of perspective primary teachers. In the latter case, the six students involved in their training as lecturers were given the freedom to organize the teaching intervention by choosing appropriate strategies
and methods, making use only of some parts of the path made available to them.

The adopted strategies included interactive stimuli and demonstrative proposals, cooperative discussions, Rogersian type interviews and the production of drawings and written answers posed as problems in the form of an interpretative challenge played on a playful level. Experimental situations were in fact accompanied by stimulus questions that aimed at producing interpretative answers to phenomenology, rather than their simple description. To explore the spontaneous ideas and the language used by children and students as regards light emission phenomena, a path was proposed in a context that was as close as possible to a daily situation; therefore the activities were conducted in an informal context where pupils and students can explore and experiment with different situations realized with common material, comparing each other and with the researcher without the restrictions imposed by a school context. With the aim of offering children and students a specific learning environment in which they can explore the physical phenomenology linked to the production and nature of light, and to investigate the way in which they develop interpretative skills to explain situations and artifacts from results of different phenomenological explorations, the specific activities have therefore been included in a CLOE activity, thus producing a didactic path suitable for both primary school children and lower secondary school students.

8.4 The educational path for pupils

The entire CLOE activity (Buongiorno and Michelini, 2016a) is based on the analysis of the existing relationships between a light source and the characteristics of the light emitted, ending with a coherent energetic interpretation of the phenomenology in terms of spectroscopic observations. The main proposed situation was therefore the one relating the nature of the different light sources with the light they emit. The presence of an energy exchange between the emitting system and the emitted light is at the base of the energetic interpretation of colors, whose energy is associated with the ability to penetrate the illuminated bodies rather than to heat them.

The exploratory path is developed through the following points: analysis of the different light sources (artifacts) from the constructive point of view, characterization of the different lights emitted, energy interpretation of colors, decomposition of light and relations between spectrum and emitting system. The path is further subdivided into 23 conceptual microsteps, each corresponding to an experiment or exploration.

The aim of the path is to allow pupils to transform the concepts that emerge in their representations into coherent interpretative structures and to observe to what extent and with what modalities and difficulties the process takes place. After a brief introduction that recalls the spontaneous ideas about the nature, the propagation and interaction of light with matter thanks to a laser pointer that illuminates opaque materials of different colors, reflective and transparent objects, the path begins with a discussion that focuses on the common sense ideas of pupils related to some aspects of daily life concerning the different known light sources, in particular their structure and their functioning. In this way a first resonance is created between some important aspects of phenomenology and it is offered to those who participate in the activity the possibility of observing and describing the different light sources present, common artifacts in everyday life (Fig. 8.2). The different light sources are classified from different points of view: technological, constructive, economic, and based on their operating principle. The attention is then focused on the light emitted: the pupils turn on the different prepared sources and describe the characteristics of the light observed. The need to use criteria to describe the characteristics of different lights leads
them to use two fundamental parameters: color and intensity. We discuss with them and look for examples of colored lights: the blue flame of the kitchen gas, the orange-red flame of a bonfire lead us to think that there are natural sources of colored lights. Flame tests of different salts of different elements (copper, lithium, strontium, calcium, sodium) confirms and consolidates the idea that the colors of the emitted light characterize the different substances. Other ways to produce colored lights are discussed and it is demonstrated that a colored filter in front of a light bulb is a way to do it. A further reflection develops with the observation that the light heats up (for example approaching a hand to a lit lamp) and that it is therefore able to transport energy. The question of how energy transported by light is linked to color and intensity is faced in a qualitative way by analyzing the color and intensity of an incandescent bulb powered by increasing voltage, linked to the supplied energy (Fig. 8.3). The emitted light, as the electric energy supplied to the bulb increases, is initially red, then orange and finally white. It is observed that if the electric energy that the light bulb receives is used to emit light, it is reasonable to think that the red light carries less energy than the white one. The issue of how associate a specific energy to a specific color is addressed with a simple experiment conducted with different colored LEDs: those devices emit light that is almost monochromatic. To turn on a LED it is necessary to supply it with a minimum quantity of electric energy (threshold energy). This is achieved by gradually increasing the supply voltage, variable thanks to a potentiometer, and easily measurable with a simple voltmeter. In particular, there is a relationship between the
color of the light emitted by an LED and the threshold energy required to produce the light emission (Fig. 8.4). The conclusion is represented by the evidence that the blue color has a greater energy than the red color, contrary to what is suggested by the common sense, which associates the energy to the increase in temperature or to the hot / cold sensation. The greater energy of a specific color, therefore, is not tied to its ability to heat, but more correctly to its ability to penetrate into illuminated bodies (ultraviolet radiation is more energetic than infrared radiation). The issue of the energy associated with white light is posed in problematic terms in this stage of the path: the peculiar nature of white light emerges from the observation that it produces all the other colors when it interacts with transparent objects, such as crystals or a prism, but this observation provides no evidence of the nature of white light as a composition of all observed colors: in fact, a transparent prism can have either the property of separating white light, or transforming it into the various colors observed. This interpretative doubt is left to pupils who imagine designing an experiment that makes it possible to decide between these two interpretations of phenomenology. The classical experiment of the Newton disk provides only a suggestion that white light can already be formed from all colors: the decisive experiment for the confirmation of this hypothesis is implemented by using a second prism to obtain the initial white light. The participants are protagonists of this confirmation, since they are themselves to find the right geometric combination that allows to regain a beam of white light using two prisms and a torch (Fig. 8.5). The recognition that white light is composed of multiple colors (to which physical energy is attributed) is a fundamental phase of the path: after using the prism, other mechanisms or artifacts capable of breaking down light are explored. Colored figures are produced in many familiar cases, even when the light does not interact with transparent objects (an oil stain, a CD, a holographic print, the jagged edges of the leaves on trees ...). These observations allow to recognize that the structure of some objects allows us to separate light and that the perceived colors change according to the angle under which the object is observed. The diffraction grating and the diffraction phenomenon are presented in qualitative terms. A simple tool that uses this principle is the spectroscope, which allows the analysis of the light emitted by the different sources (Fig. 8.6). Pupils thus have the opportunity to analyze the lights previously observed and to describe them further in terms of the colors they contain. The proposed path provides for the discussion of the type of spectra observed and their characteristics: this allows us to classify the spectra in continuous and discrete and to associate the former with the sources that, to produce light, use the glow of a solid material (incandescent lamp) or very dense (Sun), and the second to sources that use a gas (fluorescent lamp). These characteristics do not change if spectroscopes with different grating pitch are used: by changing the lattice (using a fragment of DVD rather than a CD) it is possible to obtain

<table>
<thead>
<tr>
<th>COLORE DEL LED</th>
<th>TENSIONE MINIMA (VOLT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSSO</td>
<td>1,6</td>
</tr>
<tr>
<td>GIALLO</td>
<td>1,7</td>
</tr>
<tr>
<td>VERDE</td>
<td>1,9</td>
</tr>
<tr>
<td>BLU</td>
<td>2,6</td>
</tr>
</tbody>
</table>

Figure 8.4: Different colored LEDs have different minimum threshold voltages: this is related to the activation energy of the process, which depends on the emitted color.
8.5 Discussion

The described path offers kindergarten children and primary and lower secondary school pupils the opportunity to deal with aspects related to the nature of light, such as its chromatic composition and the mechanisms underlying its decomposition, to reflect on the energetic nature of color and to identify the different characteristics of optical spectra. It addresses, on the one hand, the technological characteristics of the artifacts used, including several lamps and a simple spectroscopic, and on the other, the methodological part that concerns the physics of the processes analyzed, in particular the role of energy and the link between it and colored emissions. In the path design phase, the experiment that allows a specific activation energy to be associated with colored LEDs was considered rather challenging from a conceptual point of view, since the association between activation energy and voltage could not be taken for granted. Despite this, it proved to be one of the most effective steps on the path, as it stimulated the active involvement of most of the pupils.
and their ability to work and discuss in groups. In the light of the interventions carried out, even the passage in which the pupils had to find the right geometric combination to regain white light using two prisms proved to be very involving, as well as the exploration through the spectrosopes of the various light sources that turned out to be not only the most appreciated activity but also the one that mostly involved the accompanying teachers. The feasibility of a didactic proposal is linked to the learning outcomes, not in summative terms, but rather in terms of learning processes: a sheet was prepared for the students during the activity in which they were asked questions, urging them to use mainly the graphic language in order to gather their ideas about the different concepts faced during the intervention.

In particular, they were asked to design and illustrate the processes of light emission, the coloring of the light through filters, the composition of white light and the results of the experiment conducted with LEDs. From a qualitative analysis of data, some results going beyond the simple verification of the effectiveness of the intervention emerge: in particular it is interesting to note how the question "What do you expect to observe, imagining to become so small as to enter inside a beam of white light?" primary school children report drawings in which they represent the rainbow, the process of breaking down light or the presence of spectra, giving evidence of the appropriation of the idea that white light is made up of colored components and that spectroscopy is a technique used to separate these components and identify the characteristics of the light emitted. The association between colors and energies also emerges in the responses that the children provide in interpreting the results of the LED experiment, in which colors are ordered based on how much energy they "consume", "carry" or "have". Further data collection campaigns will allow to redesign and improve the working methods with respect to this first phase of the structuring process of the didactic proposal, while the contents of the course seem to be sufficiently complete for the considered school level.

It is thus necessary, on one side, to study how conceptual knots can be addressed and, on the other side, to refound the traditional teaching approach. Scientific education has to be started very soon, together with the first experiences of observation and representation of the surrounding world, in kindergarten and primary school, as an integral part of basic education (Michelini, 2004a). Choosing when and how to establish relationships with everyday experience through specific exploratory experiences represents a challenge to be made coherent in the curriculum in a vertical perspective, proposing motivating activities of analysis, justified by the great formalization children skills (Cobal and Michelini, 2002; Cibin et al., 2003; Fischer, 2005) in contrast with the current fragmentated situation offered in terms of fields of experiences, occasional responses to children’s curiosities, stories and integration of elements of scientific education in games.
Chapter 9

Transferability of the proposals

The need to set up teaching methods taking into account the students’ learning processes requires teachers to integrate the knowledge of the contents (on the planes of quantity, quality, organization, structure, conceptual base) and pedagogical knowledge (understood as learning processes, teaching tools and methods, learning difficulties and alternative conceptions of students). The growing awareness of the centrality of the teacher’s role in fostering learning processes led physics education researchers to focus attention on the way in which knowledge of disciplinary contents, integrated with pedagogical knowledge (PCK, see Sect. 1.2.4) (Shulman, 1986, 1987) can become specific professional competence.

In this framework, an activity carried out with secondary school teachers in the disciplinary area of modern physics and in particular on the topic of optical spectroscopy has been designed and conducted in tight cooperation with the involved teachers aiming at promoting the integration of the Content Knowledge and the Pedagogical Knowledge. This research activity is described in this chapter.

9.1 Introduction

In-service secondary school teacher formation in Italy is mainly due to self-training during school activities (Luzzato, 1999; Pugliese Jona et al., 1999; Dutto, 2001; Bonetta et al., 2002; Dutto et al., 2003a,b) and, despite a law dating back to year 1990 (Law 341/90) expects initial university teacher formation, only in 1999 pre-service teacher education effectively started.

The problem of the specific disciplinary formation of secondary school teachers arises from the fact that they have a degree obtained after four years at university, resulting in good disciplinary formation, but without professional formation. Younger teachers can rely on pre-service educational programs which is a bi-annual (S.S.I.S., 1999-2009) or annual (T.F.A., 2011-2015) post-degree master consisting in 30% an tro/psico/pedagogical areas, 30% educational labs for analysis of didactical planning and review of class intervention and 40% apprenticeship with final thesis. The employment process took usually place through procedures ascertaining mainly cultural preparation and transmission capacities (Dutto et al., 2003b). Sometimes teachers attended fragmentary actions in their in-service training, but for the main part they formed their professionalism through direct experience in the class (Luzzato, 1999; Dutto, 2001). Despite in 2016 a law makes mandatory professional development of in-service secondary school teachers, very often the total responsibility of their training is continued to be attributed to schools, resulting in a poor organic unity of the activities. Most teacher thus continue to be self-trained on the basis of their willingness.

Researches concerning pre- and in-service secondary school teacher formation on scien-
scientific topics evidenced formative needs on methodological and disciplinary plans (Michelini, 1997; Pugliese Jona et al., 1999). In-service formation has to be able to face specific educative and formative problems: the nature and role of interaction between contents and the organization of the educational activity, the managing of curricula, of the learning processes, of the methods of innovation and of the overcoming of the conceptual knots (Dutto et al., 2003a; Michelini and Schiavi, 2001).

The intuitive dimension drives teachers in developing a useful sensitivity for the choice of strategies and methods to be adopted, according to their experiences, and very often it remains their only reference for educational choices. Proposals coming from didactical tradition, scholastic publishing, dispersed and differentiated forms of in-service training are mostly disorienting because of their fragmented setting regarding contents, methods, duration and offers (Dutto et al., 2003a,b) and lead teachers to think that it is necessary to adapt their approach to a consolidate praxis relying on textbooks or on the experience of older teachers (Eraut, 1994).

The re-qualification of teachers of the profession of the teacher cannot be satisfied with theoretical notions (Anderson, 1995), but it has to be contextualized. The situated dimension of contextualized analysis, of experimentation and of implementation in context of educational proposals allows the development of the reflection in professional practice, which is an indispensable condition to master innovation (Woolnough, 2001).

Regarding modern physics topics, recent reforms (Law 107/2015) re-designed secondary school curriculum introducing modern physics, with the possibility for a new final exam in the school year 2016/17 in which, for the first time, physics could be a predominant part. Secondary school physics teachers have a degree in math, phys, engineering, resulting in a not-homogeneous good disciplinary formation, accompanying the aforementioned problems regarding the specific professional competences.

New teaching profession is composed by an articulate set of disciplinary, technical, pedagogical, social and organizational competences (Michelini, 2001; Michelini et al., 2002) and PER has to contribute to in-service teacher formation, since research represents the most effective instrument for teachers involvement in their formation, integrated with didactical commitment. Experiences of collaboration with professionals in educative and didactical research is therefore an important condition for the joining of research and professional practice (Dutto et al., 2003b) that turns to be a mixture of pure, applied and action research.

9.2 The IDIFO6 project and the MQ_P course peculiarities

Since 1996, PERU coordinates IDIFO (Innovazione Didattica In Fisica e Orientamento - Didactical Innovation In Physics and Guidance) project with 20 Italian universities involved. A master offering 198 CTS on modern physics topics for in-service teacher education and 2, 12 and 60-CTS educational modular paths, both in frontal lessons and in e-learning making use of a specific web platform, allow the choice for a personal profile formation. The offer of IDIFO6 project allowed to respond positively to the request of 25 physics secondary school teachers asking for specific training on modern physics from a network of three scientific schools from Veneto, one of the biggest Italian region, proposing them a specific course named MQ_P (Buongiorno et al., 2019b). Teachers requested this specific training, moved by their responsible engagement, in order to best accomplish their mission in the formation of the new generations of students.

Teacher formation model in MQ_P course employed integrates phases of study, critical reflections and actions, sharing with the researchers discussions of problematic issues and
proposals of intervention in a school setting. Contents and methods of in-service teacher education involved the educational reconstruction of fundamental disciplinary contents, analysis of alternative teaching paths, formal deepening of content structures and problem solving activities together with the planning of teaching interventions.

Three phases were planned corresponding to three specific formative models for teachers (Michelini et al., 2013):

(A) Metacultural: an organic and coherent research-based path on a specific topic is proposed to teachers. During this phase, time is dedicated to discussion of disciplinary contents, educational choices, methods and instruments with respect to the rationale of the path;

(B) Experiential: teachers play the role of students, testing materials, exercises, lab activities;

(C) Situated: teachers choose and design a customized formative intervention module (4 to 12 hours) to be experimented in their classes (addressing specific crucial aspects and/or the whole path).

At the end of the course, every participant revised individually the contents addressed and two rubrics guided the planning of the teaching intervention, demanding them to point out the founding cores and the conceptual knots together with a conceptual map, the proposed activities and the sequence of stimulus question for at last one topic among the ones addressed. The outcomes of the various experimentations have been shared with our research group, allowing the monitoring both of the work done by the teachers in designing a didactical proposal on modern physics, and of the learning outcomes of the students involved.

9.3 Contents and settings

The structure of MQ_P course addressed the following topics:

- Analysis of guidelines for innovation in curriculum on modern physics;

- Educational proposals on photoelectric effect, wave optics, optical spectroscopy and Bohr’s interpretation;

- Focus on crucial experiments interpretation: discussion of those experiments which interpretation founds the physics of quanta interpretational proposal in the passage from classic physics to quantum mechanics (Compton and photoelectric effect, Bertozzi’s experiment on relativistic energy of electrons);

- Laboratorial activities on measurement of the ratio e/m (electric charge and mass of the electron), Franck and Hertz experiment, optical polarization and Malus’ law, measure of the speed of light, measurements of atomic spectra wavelengths and energies;

- From structured to open problem solving (Maloney, 2001) on Compton effect, photoelectric effect, de Broglie wavelength, Heisenberg’s uncertainty principle and spectroscopy (derivation of energy level structure from discrete spectra and prevision of spectral line formation in different physical conditions).
25 Italian physics secondary school teachers from three different scientific high schools attended MQ_P course. 12/25 teachers attended only (A) and/or (B) phases in order to grasp the main issue concerning educational approach; 13/25 teachers attended all the phases, and among them, 8 teachers conducted an experimentation in their classes on the designed education proposals.

9.4 Educational materials

In order to monitor teachers’ project, two rubrics were used. Those rubrics, widely used in teacher education, allow a synthetic and reliable analysis of the projects in order to compare the different types of rationale used:

S1 (Sheet 1): fundamental/pivotal concepts of the proposals and expected learning difficulties;

S2 (Sheet 2): key questions according to a direction in developing the addressed topics and relative conceptual map, rationale and structure of the proposal.

Educational material provided to teachers was a collection of research-based problem solving exercises on optical spectroscopy, in particular concerning the way in which is possible to infer the energy level model from an experimental spectra and vice-versa.

9.5 Data analysis

Teachers’ production consisted in two kinds of educational projects: 8/13 specific on optical spectroscopy and 5/13 general on modern physics.

The structure of the proposals on optical spectroscopy was conducted first qualitatively, identifying the contents, organized subsequently according to the rubric shown in Fig. 9.1 and then qualitatively, coding each project according to the structure of the addressed contents. A graph allows to see the whole structure of each proposal (Fig. 9.2). Other graphs are thus constructed in a way in which it is possible to identify, for each content, the number of teacher that included that topic in the proposal and the position of that topic in the proposal (Fig. 9.3). Representation regards the number and the position of the addressed contents, but does not provide any information concerning duration and importance given to each content.

Five teachers who did not specifically address optical spectroscopy designed a more general proposal to modern physics topics, addressing contents categorized in Fig. 9.4 divided in the categories "crucial experiments", "key aspects of quantum physics", "interpretative hypothesis", "properties of a massless particle", "electromagnetic waves and spectra" and "case studies". Since no organic path emerged from the educational proposals on modern physics, the analysis was conducted qualitatively accounting only for the frequencies of the included contents. The more frequently included crucial experiments (Fig. 9.5a) are the photoelectric effect, specifically addressed in the MQ_P course, the Compton effect and the black body spectrum. The Frank-Hertz experiment, despite its importance, is included in the proposal only by one teacher. Every teacher quotes at least two crucial experiments and only one quotes them all. The majority of the involved teachers includes crucial theoretical aspects of quantum physics (Fig. 9.5b) quoting at least two aspects, the most addressed one is de Broglie’s contribution to the interpretation of the wave nature of matter. Only one teacher does not consider important to integrate any of those aspects in the proposal. A bigger importance is given to the interpretative hypothesis or models
Figure 9.1: Rubric for the analysis of contents included by teachers in the designed educational projects on optical spectroscopy. In the very last cell, the code color for each thematic area is shown in order to interpret the graph shown in Fig. 9.2.

Figure 9.2: Structure of the eight designed educational proposals on optical spectroscopy. Each line represents a teacher’s proposals, divided into included topics, as reported in the rubric of Fig. 9.1.
Figure 9.3: For every addressed topic (vertical axes) it is possible to observe the number of teachers who included it in the project (horizontal axes) and its position in the sequence of the educational proposals, according to the color code (or the equivalent numbers). For example, topic A2 is included by seven teachers: three of them placed it in first position, three in second position and only one teacher placed it in the third position.
accounting for the different phenomenology as Bohr, Einstein or Plank's hypothesis (Fig. 9.5c): every teacher quotes at least one of those aspects and one of them quotes them all. The analysis of relativistic dynamic is taken into account only from three teachers, addressing concepts like energy, velocity and momentum for a photon, while the other two do not believe to be an important part of the proposal. Two teachers begin the educational proposal on modern physics addressing the electromagnetic spectrum and the wave nature of light using the Maxwell’s equations. Three teachers include specific case studies and applications as the tunneling effect and the potential well phenomenology for a massive particle in the middle or at the end of the proposal.

<table>
<thead>
<tr>
<th>A. Crucial experiments</th>
<th>D. Properties of a massless particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 - photoelectric effect</td>
<td>D1 - energy</td>
</tr>
<tr>
<td>A2 - Compton effect</td>
<td>D2 - speed</td>
</tr>
<tr>
<td>A3 - Franck and Hertz experiment</td>
<td>D3 - momentum</td>
</tr>
<tr>
<td>A4 - black body spectrum</td>
<td></td>
</tr>
<tr>
<td>A5 - Devisson and Germer experiment</td>
<td></td>
</tr>
<tr>
<td>A6 - Atomic spectra</td>
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</table>

<table>
<thead>
<tr>
<th>B. Key aspects of quantum physics</th>
<th>E. EM waves + spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 - de Broglie wavelength</td>
<td>E1 - Maxwell equation</td>
</tr>
<tr>
<td>B2 - Schrodinger equation</td>
<td>E2 - EM spectra</td>
</tr>
<tr>
<td>B3 - Heisenberg’s uncertainty principle</td>
<td></td>
</tr>
<tr>
<td>B4 - quantized energy exchanges</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Interpretative hypothesis</th>
<th>F. Case studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 - Planck’s hypothesis</td>
<td>F1 - tunneling</td>
</tr>
<tr>
<td>C2 - Einstein's photoelectric effect interpretation</td>
<td>F2 - potential well</td>
</tr>
<tr>
<td>C3 - Bohr’s model</td>
<td></td>
</tr>
<tr>
<td>C4 - Balmer’s formula</td>
<td></td>
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<tr>
<td>C5 - energy level model</td>
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</tr>
</tbody>
</table>

Figure 9.4: Rubric for the analysis of contents included by teachers in the designed educational projects on modern physics.

9.6 Discussion

The emission mechanism is one of the most quoted argument in the proposal on optical spectroscopy. In the proposal structure, it is placed at the beginning, usually at the first, second or third place; this is quite surprisingly since, in our educational path, it is presented as an arrival point of a sequence of reasoning and not presented directly to students. Technological aspects are included by 5 teachers: this is not a natural setting, since generally applicative aspects are addressed at the end of a standard lessons. Probably this peculiar characteristic is due to our setting, in which technological aspects of different light sources are used as an approach. A general tendency of focusing on light sources and emitted light characteristics at the beginning is clearly recognizable. Only in one case the characteristics of the emitted light come before the sources, and in this peculiar case, because characterization of the emitted light is given a big importance. Analysis of incandescent emission occupy an equally relevant position in teachers’ proposals and it is placed immediately after approaches to phenomena, sometimes alone, sometimes accompanied from an insight of the characterization of a light source as a system transforming energy. Flame tests is a content teachers believe important to be addressed, even if in different moment during the proposal. Composite nature of white light is another of the topic that teachers
Figure 9.5: Some addressed contents in modern physics proposals. On the vertical axes the number of teacher is reported.

consider important to be addressed, not immediately, but after clarifying that light is an entity carrying energy rather than an electromagnetic radiation and/or the discussion on the energetic nature of colors, which is another topic mainly included in the initial phase, as the characterization of light sources by color and intensity of the emitted light. No one of the formal constructs is addressed before entering into the discussion on the nature of colors, white light peculiar characteristics or the nature of light and its description in energetic terms. In particular, among the main addressed constructs, Bohr’s model, Kirchhoff’s laws, Planck’s hypothesis, Wien’s law and Balmer’s formula emerge, ordered with respect to their frequencies. Only in one case, formal aspects are addressed using the classical atomic model, at the beginning of the proposal. In structuring the proposals, the majority of the teachers deserve to Balmer’s formula and Planck’s hypothesis the final positions. Very few teachers reserve Ritz’ combination principle usually at the end, despite its utility in interpreting spectra. Concerning the position of spectra in the rationale, their continuous or discrete nature or their peculiarity in characterizing elements occupy the first positions only in few proposals: teachers address the phenomenological exploration together with the analysis of the formal aspects. The majority of the proposals addresses the role of spectra in characterizing elements in the middle or at the end of their proposals. As expected, the majority of teachers address the energy level model in the final part of their proposals, as well as the interpretation of spectra as tracers of energetic exchanges. The link between levels and lines is addressed by the majority of the teachers, but the reverse and more difficult task to derive levels from a discrete spectrum is addressed by few of them. Optical spectroscopy proposed as a bridge between classical and modern physics deserve attention and insight, generally in the final part of the proposals. Dispersion phenomena is immediately subsequent to the analysis of the characteristics of the emitted light, followed by an exploration with spectroscopes. Formal constructs are always addressed in the following, except when an insight into the role of diffraction grating and slit is addressed, which is not a common aspect. Five teachers’ main approach to modern physics is based upon the analysis of the crucial experiments leading to the revising of clas-
sical physics principles, in particular in the light of Planck and Einstein’s hypothesis and only in one case with the analysis of the quantization of the energetic exchanges coming before these themes. Bohr’s model follows a review of the different aspects of quantum physics, and only in one case optical spectroscopy is used as a bridge for the analysis of the quantized nature of light and the emission processes. Wave nature of matter and Heisenberg’s principles are generally addressed subsequently. To be noticed that in one case the rationale of the optical spectroscopy proposal is quoted: the coherence of a path thus influences also teachers who want to address more general issues. Elements are embedded in the proposals without any justification in a more organic rationale and the design appears to be an effort of treating, via story-telling approach, every characterization of key aspects, crucial elements and typical cases of modern physics, with a coherence given mainly from the perspective of addressing every topic rather than of an organic interpretation of the phenomena: rather than build an organic frame for quantum theory, teachers adopt approaches in which fragmented peculiar elements of the theory are shown to students. A need of supporting teachers in inserting the interpretative perspective on disciplinary plan emerges, in order to overcome the narrative one for the identification of the relevant elements.

To conclude this part of dissertation, it has to be noticed that a considerable number of secondary school teachers in Italy aims at improving modalities to teach modern physics in the school. Physics Education Research Unit (PERU) from University of Udine was therefore asked to contribute to in-service teachers’ professional development on this topic.

In this chapter both modalities according to which a specific course, MQ_P, was addressed and some formative outcomes are described in detail. MQ_P was requested by a group of serious and motivated secondary school teachers asking for guidelines for the innovation in the curriculum, including crucial aspects of physics of quanta and relative experiments, to be addressed. Particular attention was paid to single aspects’ critical analysis and to educational setting of problem solving and laboratory activities. In implementing the request we inserted a more organic part addressing a specific educational proposal on optical spectroscopy, whose organic unity was re-elaborated to teachers according to designing rubrics requesting the detection of both educational goals and key questions linked to activities in an organic educational proposal. The accurate writing of the educational projects disappointed the expectations regarding the organic unity in favor of a careful detection of the educational goals that, for teachers, represent the reference pattern of the main innovative aspects of the transition between classical and modern physics. Interpretative, modeling and formal aspects are addressed in conceptual rather than in disciplinary terms for a multiplicity of non-organic interpretations. Applicative contexts, as the case of the potential well and the tunneling effect, are rarely addressed. Addressing and organization of proposals on optical spectroscopy turned out to be quite complete and significant, since they result to be highly fertilized from the presentation and discussion of our educational proposal, which was re-elaborated in different ways maintaining, at the same time, a coherent structure.

Needs to deepen conceptual knots that physics education research (PER) is pointing out concerning modern physics and optical spectroscopy remain evident, in particular the conceptual role of every part of an apparatus performing spectroscopic measures and the relative physics is underestimated, the need to separate macroscopic and microscopic plans, the emission mechanisms and the nature of the radiation needs to be specifically addressed.

Class experimentation performed by five teachers, designing the optical spectroscopy proposal, ended with the administration of exercises, evaluated only in terms of correct/incorrect answers without analyzing learning trajectories of the students.
Conclusions

The research described in this thesis focuses on the educational reconstruction (see MER, Sect. 1.1.2) in a vertical perspective of the topic of spectroscopy in the optical band. The research project, of the type design-based (see DBR, Sect. 1.1.3) developed a teaching/learning (T/L) path on the specific topic. Experimentations of methodologies and innovative materials to promote different schooling grades students' learning have been integrated with secondary school teachers formation activities focusing on the pedagogical content knowledge (see PCK, Sect. 1.2.4) of the specific contents. The vertical perspective allowed to keep under control the coherent and unitary vision of the physical content to be adapted to the cognitive structures of different-aged students.

The goal of the research was to clarify teaching/learning elements concerning the topic of optical spectroscopy; with this in mind, theoretical frameworks disciplinary knowledge and empirical data have been used as a support to the educational design. In these terms, challenges arising from the design of a path to be used in real educational settings (school, university) have been faced. From this point of view, the research described in this thesis provides an emblematic case of how design can contribute to reduce the gap between theory and educational practice, which is, moreover, one of the considered key aspect in a DBR approach.

The research has been organized according to the main different stages outlined by DBR: (a) preliminary analysis; (b) design, experimentation, evaluation and revision; (c) building an educational knowledge on the topic in terms of a path. DBR approach intertwines disciplinary reflections, the in-context research on the interactions between teaching/learning processes and the development of a piece of scholastic curriculum, allowing to answer to the research questions through a systematic link between educational theory and practice, reinforcing both coherence and flexibility of the design process.

a) Preliminary analysis: the educational design started from a disciplinary, historical and epistemological analysis (see Sect. 2.1 and Chap. 2) as well as from a study of the research literature on the topic (see Sects 3.1, 3.2 and 3.3). The disciplinary analysis pointed out as founding content cores: the nature of light as an entity carrying energy, in particular the evidence that different colors have different energies; the justification, on physical bases, of phenomenological laws, as the Snell's or Balmer's ones to achieve a significant integration between macro and micro perspective regarding propagation of light and its interaction with matter; the transfer of energy as conceptual referent to interpret light-matter interaction phenomena; the characterization of a light source as a system transforming energy from one type to radiant; the evidence that each light source can be uniquely described by a set of energy levels leading to the formation of a characteristic spectrum; the properties of certain objects to decompose light rather than transform it. From the study of the research literature several points emerged: the validity of the laboratorial approach to optical spectroscopy that allows to found the concepts starting from the phenomenology;
the need to directly address the link between discrete light emission and discrete structure of matter; the need to face the microscopic interpretation to correlate and clarify relationships between physical properties of involved entities (as energy, wavelength, frequency) and processes involving them. Key elements that helps students in overcoming learning difficulties are: energy of light as conceptual referent to interpret spectra, as well as the link between emissions and structure of matter; the interpretation of color as a result of an interaction; the description of the structure of matter in terms of energy levels/band avoiding the Bohr’s model; the analysis of diffraction phenomena and the exploration leading to the laws describing the light pattern produced by a diffraction grating in order to distinguish a diffraction pattern from a spectrum. These aspects have been taken into account because they are often presented both at school and at university in the form of mathematical relationships between involved quantities (for example the law describing the change in direction of a light ray in refraction phenomena, the laws describing a monochromatic diffraction pattern, the rules for evaluating wavelengths in the hydrogen spectra, etc...) that students formally manipulate, without gaining a deep and coherent conceptual understanding, even on the microscopic level of the underlying physical contents.

b) Design, experimentation, evaluation and revision cycles: Based on the identified aspects in the preliminary analysis phase, activities have been designed. In this stage, obviously empirical, of the research the following aspects have been taken into account: students’ reasoning strategies both in formal and informal contexts where the planned activities have been experimented; teacher teaching strategies. Depending on the different needs and scenarios of the research, qualitative analysis methods have been adopted for analyzing collected data. These data come from the worksheets compiled by the students (prior, during and after instruction), from teachers’ developed projects and from direct observations of the T/L processes and their discussion. Data analysis provided elements and guidelines for the evaluation of the learning processes and activities, for the strategies to be adopted (see Par. 1.2) as well as the teaching support materials, in particular the structuring of the learning path in terms of sequence of addressed concepts. This working method allowed confirmation/disconfirmation of the preliminary hypotheses and the formulation of new ones, resulting in the activation of a new cycle of planning, experimentation, evaluation and revision. The evaluation of the results of the performed experiments in terms of comparison between the expected and obtained learning results, concerning students, and in terms of transforming disciplinary knowledge into pedagogical competence, concerning teachers, allowed to consolidate the use of experiments, simulations and strategies as tools that effectively support the adopted approaches.

c) The T/L path: the path (see Par. 5.1) was designed in order to promote the conceptual understanding of the phenomenology of light emission from matter, in particular focusing on emission from gases causing a discrete spectra, and of the laws of optical spectroscopy, introducing innovative elements as for example the integration with the wider framework of optics starting from the phenomenology. Despite the approach adopted in the research described in this thesis is focused on the microscopic model in terms of abstract entities as for example energy levels and photons, the phenomenological plan plays a central role: both students and teachers need to be personally involved in experimental activities to elicit the reasoning. Traditionally, students and teachers live an experiment as verification of known laws and, for this reason, they consider quantitative experiments to be more significant. They see the
experiment as a controlled reproduction of a phenomenon performed to determine correlations between quantities. To overcome this limiting vision it was decided to include in the path of qualitative experiments that stimulate reasoning on physical concepts analyzing the phenomenology and searching for interpretations. The approach based on the phenomenology facilitates the reasoning at microscopic level, in particular:

- Snell law's interpreted as phenomenon of light-matter interaction seen on light propagation plan;
- The mechanism of vision interpreted as a phenomenon of light-matter interaction;
- Chromatic composition of light through the experiment of the double prism;
- Association between color and energy through the LED experiment (correlation with the energy peak in the spectrum and the threshold voltage);
- Quantum interpretation of light analyzing phenomena of photoelectric and fluorescent emission;
- Existence of atoms through the evidence peculiar emission spectra;
- Balmer and Rydberg's law as a relation between emitted energy of light and variation of energy of the emitting system;
- Analysis of the same object illuminated with different lights, correlate the colors of various object with a specific light-matter interaction;
- The evidence of light as an entity carrying energy through the analysis of the various effect produced by illumination;
- The description of a light source as a system transforming energy through the analysis of different light sources.

Students gradually overcome the descriptive level starting to formulate hypotheses and producing explanations based on the interpretations of observed phenomena in physical terms, not merely deducing the observations from the theory. In introducing the microscopic model for the emission of light, the concept of model as a representation of observed reality and its connection with the empirical domain of validity was emphasized. This approach presents initial difficulties for students who are led to give explanations based on their spontaneous conceptions or pre-existing knowledge rather than to reason about the physical processes of the observed system. Concerning this aspects, avoiding the Bohr's model (describing only the structure of the hydrogen atoms in terms of orbits) in favor a more general description of matter in terms of energy states allow a more general interpretation of the phenomenology enlarging the area of applicability of the involved processes.

To conclude, the educational reconstruction of the disciplinary contents (according to the MER framework) integrated with the PCK approach for teacher training, turned out to be a useful reference framework for developing a research aimed at producing educational knowledge in terms of a conceptual path on optical spectroscopy with DBR methods. The description of the design process represents a research product that can guide future studies aimed at designing educational paths. Results of the research provide a first validation of the educational design illustrated in this thesis in terms of learning strategies and teacher training. Teachers involved in the laboratories were able to directly verify the educational validity of the path and at the same time make use of it in order to consolidate an overall view of the phenomena linked to the interpretation of optical spectra based on microscopic
physical models, realizing a significant growth of the knowledge of the disciplinary content but also of pedagogical competence.

The experimented educational paths follow three main approaches: based on light sources (LS), phenomenological (PH) and conceptual-disciplinary (CD) with two different perspectives: light as a wave (W) or light as an entity carrying energy (E) (Par. 6.1). Results of the experiments performed with secondary school students (Chap. 6) show that students's reasoning are oriented to a vision of light in terms of photons and the description of the phenomenology of the light emission process as an energetic phenomena is promoted if the (E) perspective is adopted. This perspective also help students in using a more general representation of the energetic structure of matter in terms of energy levels with respect to a semi-classical representation using Bohr's orbits. An approach based on (LS) promotes a description of the process emitting light in functional terms, while a (PH) approach leads students to reason in terms of characteristic spectra rather than on microscopic interpretations. The conceptual knot on the connection between spectral lines and energy levels is partially overcome using an (E) perspective since the role of the energy conservation principle is mainly adopted. Nevertheless it remains evident how the transition from energy levels to spectra lines is an easier conceptual challenge for students with respect to the reconstruction on the energy structure of an emitting system. This specific aspect has to (and can) be addressed from two different angles of attack: one is the numerical one (through the analysis of Balmer/Rydb erg formula) and the other one is using the representation of a spectrum as an energy distribution searching for interpretations.

The educational proposal on optical spectroscopy presented here contributes to building the identity of the physicist in the students, implementing some historical aspects related to the history of spectroscopy in supporting of the concepts addressed and contributing to the educational reconstruction. The role of the history of physics in the path has been manifold and differentiated, in terms of problematic issues, such as Newton's reasoning on the nature of white light, of experiences narrated to consolidate the role of spectra in the analysis of substances by flame tests, of role assignment to the experimental data to pose the problem of the interpretation of the mechanisms that emit light, of problem solving for the search for interpretations in the empirical formulas of Balmer and Rydberg. The historical approach helps students to overcome the main learning knots that emerged in the literature, in particular the conceptual link between discrete emissions and quantized energy levels. Interpretative tools, such as lines as energy differences as suggested by the Balmer-Rydb erg formula, rather than light understood in the general sense of radiation rather than photons or waves are used by students to interpret optical spectra and related emission mechanisms at the origin (GRQ1). Experiments help in recognizing the energetic nature of colors (LED experiment, see Sect. 5.8) and the distinction between energy related to colors and energy related to intensity (SPETTROGRAFO, see Chap. 4).

The SPETTROGRAFO system has been implemented in two educational paths: in the last experimentation with university freshmen in biotechnology in the context of the introductory physics course laboratory and in the last six experimentations with secondary school students. Results show an increment in students' involvement evidencing the central role, for the learning of optical spectroscopy, of experiments in which students have a prsonal role in designing, performing and independently exploring the different involved aspects concerning both the spectra analysis, the process of measurement and the interpretation of emission and absorption processes. The SPETTROGRAFO system, thanks to its capability of showing in real time how does a spectrum change when light is absorbed is a valid instruments to stress the dependence from the energy of light in phenomena involving light-matter interaction. Exploration with spectroscopes and the optical goniometer
experiment (see Sect. 5.2.1) turned out to be useful in identifying the roles of the different part of a spectrooscope or a more sophisticated apparatus performing spectroscopic measurements, in particular the role of the slit as a simple diaphragm accounting for the sharp shape of the lines turns out to be clarified thanks to the suggestions according to which students are stimulated in changing its shape (GRQ2). The evidence that students persist in identifying the reddest line in a spectrum with the lower energy level could be related to the misunderstanding of the term "level" or "state" since students, even if recognize the need for energetic transitions to obtain a discrete spectra, assign to the colors an "energy level" or "energy state" according to the energy that color carries. It emerges the need to distinguish between the energetic state of the source and the energetic state of the emitted light: from one side there are the properties of the emitted light, from the other one the energetic properties of the emitting system. This is one of the motivation according to which deriving the energetic structure of the emitting system turns out to be more difficult with respect to obtain a discrete spectrum from an energy levels structure. Other two evidences support this major difficulty: one is that a spectrum is seen as a diffraction pattern and students do not recognize the need to obtain whatsoever energy levels diagram (in this case the energy of the lines is linked to their intensity), the other one is that for a certain discrete spectra different energy levels diagrams are possible according to the adopted hypothesis, and strategies are missing. Students who followed a path in an (E) perspective, differently from others, tend to use less the formula $E = hf$ to justify the lower energy of the redder line but rather they focus on the energetic properties such as its heating power, or referring to previous knowledge, as for example that red has lower energy than blue. The reverse challenge, i.e. the passage from micro to macro (from levels to spectra) results an easier task for students even if some unjustified hypotheses persist (transitions to the fundamental level or transitions between adjacent levels). A fertile way to overcoming this difficulties, as data show, is addressing the path in an (E) perspective since concepts as the energy conservation principle is more contextualized and thus most easily applicable. The difficulty of interpreting a spectra (an energy distribution in space) as a diffraction pattern (an intensity distribution in space) arise in those students who did not face an IBL approach for deriving the law or the diffraction phenomena (experimentations 16_4_2018 and 17_5_2018), underlying the importance of this step in the path (GRQ3).

Since the prerequisites of the different secondary school classes in which the various experimentations have been conducted were homogeneous (involved students have already studied geometrical optics and some qualitative treatment concerning optical discrete spectra from gases) the strategic angle of attack according to which the three areas of optics have been used as a starting point for accounting for light-matter interactions from an energetic point of view turned out to be effective in the measure students interpret the light emission processes in energetic terms. This is also true for older students, even if they already studied the wave model for light. Younger pupils benefit of this approach, starting from the optical phenomena of light propagation, heating due to light and light sources, since they represent familiar contexts that allow the development of reasoning based on the idea that light carries energy and that different energies correspond to different colors (SRQ1). Conceptual knots evidenced in the literature concerning the formation of the spectral lines are overcome in every approach (LS, PH and CD) even if the CD approach turned out to be useful in helping students to describe light emission in terms of microscopic models rather than from a macroscopic point of view or making use of explanations that take into account mainly the dispersive mechanisms or the technological implementation of the light source. Open problems regard the hypothesis at the basis of the formation of spectral lines, in particular the arbitrary assumption that transitions can occur only to the
fundamental level or only to adjacent levels. An implementation based on the quantum selection rules can help in rigorously identify both the allowed transitions and the different transition probabilities (SRQ2, SRQ3). To gain a coherent comprehension on macro/micro scales concerning phenomena related to optical spectroscopy, it is necessary to point out that the macroscopic evidence of the recorded spectral lines is intimately linked with the microscopic structure of the emitting element in the case of gaseous elements. To this scope flame tests represent a fertile context to stress the point that both hydrogenoid atoms and alkali metals show in their spectra regularities similar to the ones in the hydrogen spectra. Students are aware of the dependence of the emitted light from the emitting system, but the difficulties arise when students are asked to justify the differences in the observed spectra. The need to point out that microscopic systems can be described by their total energy has to emerge as well as the need to describe the interaction processes. The semiclassical Bohr’s atomic model helps in justifying the negative energies values of the atomic levels, that students tend to find difficult to understand. The discreteness of the energy levels in atoms is made by taking advantage of the analogy with the energy levels of a macroscopic object (a chair) in a gravitational field. The mathematical formalism justifying the band structure is avoided, but the interpretative conceptual tools, as the observation of the continuous but incomplete spectra of a LED and the evidence that a monoenergetic emission is caused by a transition between two monoenergetic levels are provided. Despite this, students, on average and independently from the followed approach or perspective, struggle in describing the microscopic processes accounting for continuous but incomplete spectra of the light emitted by a LED, show poor commitment in extending to the energy bands the energy levels model. The use of Bohr’s model brings a series of conceptual difficulties, firstly the tendency of students of speaking of electrons jumping between orbits or between levels; the more general discussion in terms of "atoms gaining/losing energy" is mainly used by students that followed a CD approach. In some cases the emission is associated only to excited electrons/atoms neglecting the de-excitation process, in other cases the phase of excitation of the microscopic system is neglected in favour of the description of how the system de-excites itself (SRQ4). The atomic models used by students to describe the emission of radiation are mainly divided into the "Bohr's orbits" typology, probably a recollection of school environments and widely used for its immediate applicability and intuitiveness, and in the most abstract and general typology of the "energy levels". Quantitative references are often absent and the students maintain themselves on a qualitative level. The need for a more detailed clarification regarding the profound conceptual differences between the two models emerges; for this purpose it is necessary to introduce in the path the treatment and interpretation of atomic spectra different from those characteristic of the hydrogen atom or of hydrogenoid atoms, in which the correspondence between orbits and levels is direct (SRQ5).

This research work on vertical learning path as concern optical spectroscopy from primary pupils to university freshmen represents an attempt to address, from a research point of view, the main learning knots, evidenced by the literature and emerged during the research itself, inside a coherent learning path, and not as a series of de-contextualized learning interventions. An innovative experimented approach is based on energy as an angle of attack. The key concept founding the bases of the three experimented approaches is the reading of a spectrum as a graph in terms of energy emitted by matter and interpreted as energetic changes in the emission system. The building of the formalization of this aspect by means experimental investigations searching for interpretations (the LED experiment) or by means of analysis of mathematical relations (the analysis of the Balmer-Rydberg formulae) are the key aspects of development of the proposed learning paths. Regarding
the research with secondary school students a big work was devoted to the construction of a representation by means of energy levels rather than orbits; this effort turned out to be useful to represent quantitatively the energetic properties of light sources avoiding misleading interpretations valid only in special cases, based on ad-hoc hypotheses. The interpretation of colors from an energetic point of view help this purposes, in particular in distinguishing discrete colored emissions and discrete energy levels. The educational approach with pupils aimed at providing them elements to build explanatory models based on experimental observation without the introduction of surrogate model.

Results shows that integrating observation and experimental activities, stimulating the reasoning on microscopic level, allows students to play an active role in the learning process and to use a scientific model in developing scientific ideas and explanations. The results of this research, according to a widely shared approach, support the validity of IBL strategies in physics teaching. The educational approach that justifies the microscopic model starting from phenomenology can also be extended to other specific scientific contents as a support to the planning of educational paths and/or training activities for science teachers aiming at promoting the transition from traditional teaching to a innovative teaching able to face the challenges that learning poses.
Appendix A

Monitoring instruments

In this appendix the monitoring instruments (tutorials, tests in and tests out) used in the various experimentations, according to Tab. 5.2 are reported.
A_16_TUTORIAL

i) Concentrati sul ruolo che ha il reticolo di diffrazione nel setup sperimentale del
goniometro ottico e rispondi alle seguenti domande motivando le risposte:

i.1) Come giustifichi la presenza di righe di diverso colore?

i.2) Se la sorgente fosse monocromatica, cosa ti aspetteresti di osservare?

i.3) Cosa fa sì che le righe abbiano quella forma?

ii) In un goniometro ottico, una lampada a idrogeno (l’elemento più semplice esistente)
è posta di fronte ad una fenditura e un collimatore; un reticolo di diffrazione si trova
tra l’uscita del collimatore e un sistema ottico di osservazione. Si osserva, al primo
ordine, da un lato rispetto al centro del reticolo, la serie di righe mostrate.

Considera la seguente discussione:

Studente 1: “La riga all’estrema destra ha la lunghezza d’onda maggiore, il che si-
ignifica la maggior frequenza. Quella riga, quindi, corrisponde al più alto valore di
energia e rappresenta il livello energetico più alto dell’atomo di idrogeno.”

Studente 2: “Non sono d’accordo. L’energia di un livello energetico vale $hf$ e la
frequenza è inversamente proporzionale alla lunghezza d’onda. Questo significa che
la riga all’estrema destra corrisponde al livello fondamentale.”

Con quale dei due studenti, se ce n’è uno, sei d’accordo? Illustra la tua motivazione.

iii) Confronta i valori dei livelli energetici dell’idrogeno (allegati) con le energie delle
righe mostrate precedentemente (allegate). Sulla base delle relazioni, descrivi cosa
avviene nell’atomo quando un fotone è emesso. Cosa puoi dire della tua risposta data
alla domanda ii)?

iv) Concentrati ora sui valori di energia dei livelli.

iv.1) Calcola i rapporti $E_{1}/E_{n} \ (n = 2, 3, 4, 5, 6, 7)$.

iv.2) Sulla base dei risultati ottenuti, puoi aspettarti che esista un limite all’energia
di un sistema legato protone-electrone (atomo di idrogeno)?

iv.3) Disegna qualitativamente i livelli energetici, giustificando la loro posizione e le
loro distanze.

iv.4) Le righe spettrali si estendono all’infinito a sinistra e destra dello spettro (anche
se non le vediamo)?
ALLEGATI

<table>
<thead>
<tr>
<th>Livello</th>
<th>Energia (eV)</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>$E_2$</td>
<td>-3.40</td>
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<tr>
<td>$E_3$</td>
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<tr>
<td>$E_4$</td>
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</tr>
<tr>
<td>$E_5$</td>
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<tr>
<td>$E_6$</td>
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</tr>
<tr>
<td>$E_7$</td>
<td>-0.28</td>
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</table>

Tabella 1: Energie dei livelli più bassi dell’atomo di idrogeno.

<table>
<thead>
<tr>
<th>Riga</th>
<th>$\lambda$ (µm)</th>
<th>Energia (eV)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3.12</td>
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<tr>
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<td>4</td>
<td>0.49</td>
<td>2.55</td>
</tr>
<tr>
<td>5</td>
<td>0.66</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Tabella 2: Lunghezze d’onda delle righe osservate e relativa energia.

La relazione tra l’energia di un fotone e la sua lunghezza d’onda è la seguente:

$$E = h \cdot f = \frac{h \cdot c}{\lambda} = \frac{1.24}{\lambda (\mu m)} eV$$

Con $h$ costante di Planck e $c$ velocità della luce.
1) In che relazione sono le righe dello spettro e i livelli energetici del sistema emittente?

2) Qual è il numero minimo di livelli necessari per giustificare la presenza delle righe che si osservano? Disegnarli.

3) Il livello energetico E₂ è coinvolto nella formazione di una o più righe nello spettro mostrato. Evidenziala/le.

4) Quali nuove righe si osserverebbero se si prendesse in considerazione un livello energetico superiore?


6) Cosa si osserverebbe se dall’apparato sperimentale venisse rimosso il reticolo?

7) Cosa si vedrebbe nell’intervallo angolare 0°-180° del goniometro di laboratorio se usassi una lampada a incandescenza?
C_16_TUTORIAL

i) Osservando attraverso un goniometro ottico si osservano righe di vari colori. Come giustifichi la loro presenza?

ii) In un goniometro ottico, una lampada a idrogeno (l’elemento più semplice esistente) è posta di fronte ad una fenditura e un collimatore; un reticolo di diffrazione si trova tra l’uscita del collimatore e un sistema ottico di osservazione. Si osserva, al primo ordine, da un lato rispetto al centro del reticolo, la serie di righe mostrate.

Considera la seguente discussione:
Studente 1: “La riga all’estrema destra ha la lunghezza d’onda maggiore, il che significa la maggior frequenza. Quella riga, quindi, corrisponde al più alto valore di energia e rappresenta il livello energetico più alto dell’atomo di idrogeno.”
Studente 2: “Non sono d’accordo. L’energia di un livello energetico vale $hf$ e la frequenza è inversamente proporzionale alla lunghezza d’onda. Questo significa che la riga all’estrema destra corrisponde al livello fondamentale.”

Con quale dei due studenti, se ce n’è uno, sei d’accordo? Illustra la tua motivazione.

iii) Confronta i valori dei livelli energetici dell’idrogeno (allegati) con le energie delle righe mostrate precedentemente (allegate). Sulla base delle relazioni, descrivi cosa avviene nell’atomo quando un fotone è emesso. Cosa puoi dire della tua risposta data alla domanda ii)?

iv) Concentrati ora sui valori di energia dei livelli.

iv.1) Calcola i rapporti $E_1/E_n$ ($n = 2, 3, 4, 5, 6, 7$). Noti qualche tipo di regolarità?
iv.2) Sulla base dei risultati ottenuti, puoi aspettarti che esista un limite all’energia di un sistema legato protone-elettrone (atomo di idrogeno)?
iv.3) Disegna qualitativamente i livelli energetici, giustificando la loro posizione e le loro distanze.
iv.4) Le righe spettrali si estendono all’infinito a sinistra e destra dello spettro (anche se non le vediamo)?

v) Il diagramma seguente mostra una parte dello spettro discreto a righe dell’idrogeno (lunghezza d’onda crescente verso destra).

Disegna, nello spazio sottostante, il diagramma dei livelli energetici dell’idrogeno che contenga solamente il minimo numero di livelli energetici necessari per produrre le
10 righe mostrate. Assumi che solamente i livelli energetici più bassi sono coinvolti nella creazione delle righe. Chiama $E_1$ il livello fondamentale ed $E_2$, $E_3$, ecc... i livelli eccitati. La spaziatura tra i livelli deve essere qualitativamente corretta. Spiega brevemente.

![Diagramma con scala di energia da 0 eV](attachment:diagram.png)

ALLEGATI

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Tabella 1: Energie dei livelli più bassi dell’atomo di idrogeno.

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</tbody>
</table>

Tabella 2: Lunghezze d’onda delle righe osservate e relativa energia.

La relazione tra l’energia $E$ di un fotone, la sua frequenza $f$ e la sua lunghezza d’onda $\lambda$ è la seguente:

$$E = h \cdot f = \frac{h \cdot c}{\lambda} = \frac{1.24}{\lambda(\mu m)} eV$$

Con $h$ costante di Planck e $c$ velocità della luce.
D1) EMISIONI SPETTRALI. Durante l'esperimento del goniometro ottico hai osservato le righe spettrali emesse da un certo gas. Spiega il processo di emissione che dà luogo alle righe osservate, avvalendoti di una rappresentazione grafica (3).

<table>
<thead>
<tr>
<th>SPIEGAZIONE</th>
<th>DISEGNO</th>
</tr>
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<tbody>
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</table>

D2) RUOLO RETICOLO O PRISMA IN SPETTROSCOPIA. Gli apparati per effettuare misure di spettroscopia ottica sono costituiti da una fenditura e da un prisma o da un reticolo di diffrazione, attraverso i quali si osserva la sorgente in esame.

2.1) Spiegare il ruolo del prisma ovvero del reticolo (2).

2.2) Cosa si osserverebbe se venisse rimosso il reticolo nel goniometro ottico? Spiegare ed illustrare, aiutandosi con un disegno. (1)

D3) LA FORMA DELLO SPETTRO. Con una lampada a scarica di gas e l'apparato del goniometro ottico usato in laboratorio si osservano immagini spettrali a forma di righe. È possibile ottenere immagini spettrali di altra forma con la stessa lampada a scarica di gas? In che modo? (2)

D4) DISCUSSIONE SULLO SPETTRO DELL'ATOMO DI IDROGENO. La figura seguente mostra lo spettro visibile dell'atomo di idrogeno:

![Fig.1: Spettro dell'atomo di idrogeno nella regione del visibile](attachment:image.jpg)

Considera la seguente discussione:

*Studente 1*: "La riga all'estrema destra ha la lunghezza d'onda maggiore, il che significa la maggior frequenza. Quella riga, quindi, corrisponde al più alto valore di energia nello spettro e rappresenta il livello energetico più alto dell'atomo di idrogeno."
Studente 2: "Non sono d'accordo. L'energia della luce emessa vale hf e la frequenza è inversamente proporzionale alla lunghezza d'onda. Questo significa che la linea all'estrema destra corrisponde al livello fondamentale dell'atomo, ossia quello con minore energia."

Quale studente ha ragione? Illustrare la risposta (3).

D5) LO SPETTRO DELL'ELIO IONIZZATO. La seguente tabella riporta le energie dei livelli energetici dell'elio ionizzato.

<table>
<thead>
<tr>
<th>ENERGIE DEI LIVELLI (eV)</th>
<th>Rappresentazione dei livelli energetici</th>
</tr>
</thead>
<tbody>
<tr>
<td>-54.44</td>
<td></td>
</tr>
<tr>
<td>-13.60</td>
<td></td>
</tr>
<tr>
<td>-6.04</td>
<td></td>
</tr>
<tr>
<td>-3.40</td>
<td></td>
</tr>
<tr>
<td>-2.16</td>
<td></td>
</tr>
</tbody>
</table>

Rappresentare lo spettro di righe di emissione dovuto ai livelli energetici indicati (4)

D6) DALLO SPETTRO AI LIVELLI ENERGETICI. Nella figura sottostante è riportato lo spettro di emissione dei livelli più bassi di un atomo, a partire da quello fondamentale. L'energia delle righe aumenta da sinistra a destra.

6.1) Qual è il numero minimo di livelli necessari per giustificare la presenza delle righe che si osservano? (spiegare) (2)
6.2) Rappresentare i livelli energetici che danno luogo allo spettro mostrato in figura, spiegando come si individuano. (3)
6.3) Il livello energetico E2 è coinvolto nella formazione di una o più righe nello spettro mostrato. Evidenziare quali (1).
6.4) Quante nuove righe si osserverebbero se si prendesse in considerazione un livello energetico superiore? Indica la posizione della/e riga/righe nello spettro. (2)
E_17_TUTORIAL

SORGENTI
1. Indicare tre sorgenti di luce di natura diversa

2. Quali principali tipi di sorgenti possiamo individuare?

3. Quali sono i principali meccanismi di funzionamento delle sorgenti (quali processi fisici conosci che producono luce)?

4. Riflettiamo su cosa chiamiamo sorgente di luce: che cosa caratterizza una sorgente di luce?

LA LUCE EMESSA DALLE SORGENTI
5. Che colore ha la luce emessa dalle varie sorgenti?

6. Possiamo dire che ci sono sorgenti che emettono luce colorata? Quali ad esempio: fare 3 esempi

7. Il bianco è da considerare un colore della luce?
   ESPERIMENTO: Il prisma riceve luce bianca e restituisce luce di colori distribuiti secondo un preciso ordine: quello dell’arcobaleno.
   Cosa fa il prisma: separa o trasforma la luce? Illustra un esperimento che permetta di decidere?

8. SINTESI. I principali modi per produrre luce colorata sono i seguenti:

9. Potrebbe avere una struttura anche la luce che appare di un solo colore? Per rispondere devo disperdere il fascio che vedo di un solo colore il più possibile, mandandolo in un prisma oppure utilizzando altre modalità di dispersione.
10. Girovagando con spettroscopi e occhialini a reticolo, scopro che:

CLASSIFICO LE SORGENTI in base allo spettro

11. FACCiamo i calcoli

F_17_TESTOUT

D0) Indicare uguaglianze e differenze tra gli spettri di emissione di una lampadina a filamento, di una lampada a scarica di gas e di un led, giustificando le principali differenze.

D1) Durante l'esperimento del goniometro ottico hai osservato le righe spettrali emesse da un certo gas. Spiega il processo di emissione che dà luogo alle righe osservate, avvalendoti di una rappresentazione grafica.

<table>
<thead>
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<th>SPIEGAZIONE</th>
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<tbody>
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<td></td>
<td></td>
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</table>

D2) Gli apparati per effettuare misure di spettroscopia ottica sono costituiti da una fenditura e da un prisma o da una fenditura ed un reticolo di diffrazione, attraverso i quali si osserva la sorgente in esame. Spiegare il ruolo del prisma ovvero del reticolo.
D3) Illustrare, aiutandosi con un disegno, cosa si osserverebbe tramite il goniometro ottico se venisse rimosso il reticolo. Spiegare la risposta.

D4) Con una lampada a scarica di gas e l’apparato del goniometro ottico usato in laboratorio si osservano immagini spettrali a forma di righe. È possibile ottenere immagini spettrali di altra forma con la stessa lampada a scarica di gas? In che modo?

D5) La figura seguente mostra lo spettro visibile dell'atomo di idrogeno:

![Fig.1: Spettro dell'atomo di idrogeno nella regione del visibile](image)

Considera la seguente discussione:

**Studente 1:** "La riga all'estrema destra ha la lunghezza d'onda maggiore, il che significa la maggior frequenza. Quella riga, quindi, corrisponde al più alto valore di energia nello spettro e rappresenta il livello energetico più alto dell'atomo di idrogeno."

**Studente 2:** "Non sono d'accordo. L'energia della luce emessa vale hf e la frequenza è inversamente proporzionale alla lunghezza d'onda. Questo significa che la linea all'estrema destra corrisponde al livello fondamentale dell'atomo, ossia quello con minore energia."

Con quale dei due studenti sei eventualmente d'accordo? Illustra il tuo ragionamento.
D6) Confronta i valori dei livelli energetici dell'idrogeno riportati in Tab.1 con le energie delle righe mostrate nello spettro di Fig.1 i cui valori energetici sono in Tab.2. In base a tale confronto descrivi cosa avviene nell'atomo quando un fotone è emesso.

<table>
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<td>E3</td>
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<td>E4</td>
<td>-0.85</td>
</tr>
<tr>
<td>E5</td>
<td>-0.54</td>
</tr>
<tr>
<td>E6</td>
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</tr>
<tr>
<td>E7</td>
<td>-0.28</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Emissione spettrale</th>
<th>E (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.12</td>
</tr>
<tr>
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<td>4</td>
<td>2.55</td>
</tr>
<tr>
<td>5</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Tab.1: Energie dei livelli più bassi dell'atomo di idrogeno.  
Tab.2: Energia delle emissioni osservate nello spettro

Commenta / rivedi la tua risposta alla domanda precedente

D7) La seguente tabella riporta le energie dei livelli energetici dell’elio ionizzato

<table>
<thead>
<tr>
<th>ENERGIE DEI LIVELLI (eV)</th>
<th>Rappresentazione dei livelli energetici</th>
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<td>-3,40</td>
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<td>-2,16</td>
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</tbody>
</table>

Rappresentare lo spettro di righe di emissione dovuto ai livelli energetici indicati
D8) Nella figura sottostante è riportato lo spettro di emissione dei livelli più bassi di un atomo, a partire da quello fondamentale. L'energia delle righe aumenta da sinistra a destra. Qual è il numero minimo di livelli necessari per giustificare la presenza delle righe che si osservano? (spiegare)

![Fig.2: Spettro dell'atomo di idrogeno](image)

D9) Rappresentare i livelli energetici che danno luogo allo spettro mostrato in figura, spiegando come si individuano.

D10) Il livello energetico E2 è coinvolto nella formazione di una o più righe nello spettro mostrato. Evidenziare quali.

D11) Quante nuove righe si osserverebbero se si prendesse in considerazione un livello energetico superiore? Indica la posizione della/e riga/righe nello spettro.

D12) Esamino lo spettro emesso da una lampada a scarica di gas e di un led. Fare un’ipotesi con uno schizzo della struttura energetica dei due sistemi emittenti.
SORGENTI
1. Indicare tre sorgenti di luce di natura diversa

2. Quali principali tipi di sorgenti possiamo individuare?

3. Quali sono i principali meccanismi di funzionamento delle sorgenti (quali processi fisici conosci che producono luce)?

4. Riflettiamo su cosa chiamiamo sorgente di luce: che cosa caratterizza una sorgente di luce?

LA LUCE EMESSA DALLE SORGENTI
5. Che colore ha la luce emessa dalle varie sorgenti?
6. Possiamo dire che ci sono sorgenti che emettono luce colorata? Quali ad esempio: fare 3 esempi

7. Il bianco è da considerare un colore della luce?
   ESPERIMENTO: Il prisma riceve luce bianca e restituisce luce di colori distribuiti secondo un preciso ordine: quello dell’arcobaleno.
   Cosa fa il prisma: separa o trasforma la luce? Illustra un esperimento che permetta di decidere.

8. SINTESI. I principali modi per produrre luce colorata sono i seguenti:

9. Potrebbe avere una struttura anche la luce che appare di un solo colore? Per rispondere devo disperdere il fascio che vedo di un solo colore il più possibile, mandandolo in un prisma oppure utilizzando altre modalità di dispersione.
10. Girovagando con spettroscopi e occhialini a reticolo, scopro che:

CLASSIFICO LE SORGENTI in base allo spettro

UN MODELLO PER L'EMISSIONE DELLA LUCE

11. Il modello atomico di Bohr ipotizza un atomo di idrogeno in cui un elettrone compie un'orbita circolare intorno a un protone in virtù della reciproca attrazione coulombiana. Scrivi la forza agente tra protone ed elettrone e, utilizzando le leggi della dinamica, trova l'energia totale del sistema (cinetica + potenziale). Cosa puoi dire del valore ottenuto?

12. L'atomo più semplice è quello dell'idrogeno. Il suo spettro ottico è illustrato in figura ed è stato il primo ad essere studiato.

Una formula empirica che descrive le emissioni visibili è stata trovata da J.J. Balmer nel 1885:

$$\frac{1}{\lambda_{ab}} = R_H \left( \frac{1}{n_a^2} - \frac{1}{n_b^2} \right)$$

Dove \(\lambda\) rappresenta la lunghezza d'onda delle righe, \(R_H\) è una costante e \(n_a\) ed \(n_b\) sono due numeri interi. In particolare per riprodurre le emissioni osservate deve essere \(n_b=2\) e \(n_a=3,4,5,6\).

Nel 1916 N. Bohr ha ipotizzato che la radiazione emessa fosse il risultato di variazioni energetiche del sistema atomico e che l'energia di ogni emissione si possa scrivere come \(E=hf=hc/\lambda\). Utilizzando la legge di Balmer scrivi un'espressione per l'energia delle emissioni osservate nello spettro dell'idrogeno.
13. Chiamiamo "livello energetico" l'energia permessa di un sistema. Che relazione c'è tra il valore in energia di un livello (nel caso dell'idrogeno) e il rispettivo numero d'ordine $n$?

14. Disegna i primi 4 livelli energetici dell'atomo di idrogeno e lo spettro che si ottiene considerando questi livelli.

15. La formula di Balmer riproduce le emissioni visibili dell'idrogeno. È possibile utilizzarla per prevedere altre emissioni? In che modo? Disegnarle.

16. I metalli alcalini (gruppo 1 della tavola periodica) e alcuni ioni (He+, Li++) hanno spettri in cui le posizioni delle righe possono essere descritte da formule molto simili a quella di Balmer. Come ti spieghi questo similitudine in termini di struttura atomica?
H_17_TUTORIAL

SORGENTI

1. Indicare tre sorgenti di luce di natura diversa

2. Quali principali tipi di sorgenti possiamo individuare?

3. Quali sono i principali meccanismi di funzionamento delle sorgenti (quali processi fisici conosci che producono luce)?

4. Riflettiamo su cosa chiamiamo sorgente di luce: che cosa caratterizza una sorgente di luce?

LA LUCE EMESSA DALLE SORGENTI

5. Che colore ha la luce emessa dalle varie sorgenti?

6. Possiamo dire che ci sono sorgenti che emettono luce colorata? Quali ad esempio: fare 3 esempi

7. Il bianco è da considerare un colore della luce?

ESPERIMENTO: Il prisma riceve luce bianca e restituisce luce di colori distribuiti secondo un preciso ordine: quello dell’arcobaleno.

Cosa fa il prisma: separa o trasforma la luce? Illustra un esperimento che permetta di decidere.

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CLASSIFICO LE SORGENTI in base allo spettro

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\[ E_{ab} = \text{cost} \cdot \left( \frac{1}{n_a^2} - \frac{1}{n_b^2} \right) \]

Dove \( E_{ab} \) rappresenta l’energia di una riga e \( n_a \) ed \( n_b \) sono due numeri interi. In particolare per riprodurre le emissioni osservate deve essere \( n_a=2 \) e \( n_b=3,4,5,6 \). 

Nel 1916 N. Bohr ipotizzò che l'atomo di idrogeno potesse trovarsi solo in precisi stati energetici (chiamati "livelli") in cui non vi era emissione di energia e che l'energia emessa fosse il risultato di variazioni energetiche tra i livelli. Utilizzando la legge di Balmer e l’ipotesi di Bohr, scrivi un’espressione per l’energia dei vari livelli.
13. Chiamiamo "livello energetico" l'energia permessa di un sistema. Che relazione c'è tra il valore in energia di un livello (nel caso dell'idrogeno) e il rispettivo numero d'ordine n?

14. Disegna i primi 4 livelli energetici dell'atomo di idrogeno e lo spettro che si ottiene considerando questi livelli.

15. La formula di Balmer riproduce le emissioni visibili dell'idrogeno. È possibile utilizzarla per prevedere altre emissioni? In che modo? Disegnarle.

16. I metalli alcalini (gruppo 1 della tavola periodica) e alcuni ioni (He+, Li++) hanno spettri in cui le posizioni delle righe possono essere descritte da formule molto simili a quella di Balmer. Come ti spieghi questo similitudine in termini di struttura atomica?
D0) Indicare uguaglianze e differenze tra gli spettri di emissione di una lampadina a filamento, di una lampada a scarica di gas e di un led, giustificando le principali differenze.

D1) Durante l'esperimento del goniometro ottico hai osservato le righe spettrali emesse da un certo gas. Spiega il processo di emissione che dà luogo alle righe osservate, avvalendoti di una rappresentazione grafica.

D2) Gli apparati per effettuare misure di spettroscopia ottica sono costituiti da una fenditura e da un prisma o da una fenditura ed un reticolo di diffrazione, attraverso i quali si osserva la sorgente in esame. Spiegare il ruolo del prisma ovvero del reticolo.

D3) Illustrare, aiutandosi con un disegno, cosa si osserverebbe tramite il goniometro ottico se venisse rimosso il reticolo. Spiegare la risposta.
D4) Con una lampada a scarica di gas e l’apparato del goniometro ottico usato in laboratorio si osservano immagini spettrali a forma di righe. È possibile ottenere immagini spettrali di altra forma con la stessa lampada a scarica di gas? In che modo?

D5) La figura seguente mostra lo spettro visibile dell'atomo di idrogeno:

![Fig.1: Spettro dell'atomo di idrogeno nella regione del visibile](image)

Considera la seguente discussione:

**Studente 1**: "La riga all'estrema destra (rossa) corrisponde al più alto valore di energia nello spettro e rappresenta il livello energetico più alto dell'atomo di idrogeno."

**Studente 2**: "Non sono d'accordo. L'energia della luce rossa è la minore tra tutte. Questo significa che la riga all'estrema destra corrisponde al livello fondamentale dell'atomo, ossia quello con minore energia."

Con quale dei due studenti sei eventualmente d'accordo? Illustra il tuo ragionamento.
D6) Confronta i valori dei livelli energetici dell'idrogeno riportati in Tab.1 con le energie delle righe mostrate nello spettro di Fig.1 i cui valori energetici sono in Tab.2. In base a tale confronto descrivi cosa avviene nell'atomo quando un fotone è emesso.

<table>
<thead>
<tr>
<th>Livello</th>
<th>E (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>-13.61</td>
</tr>
<tr>
<td>E2</td>
<td>-3.40</td>
</tr>
<tr>
<td>E3</td>
<td>-1.51</td>
</tr>
<tr>
<td>E4</td>
<td>-0.85</td>
</tr>
<tr>
<td>E5</td>
<td>-0.54</td>
</tr>
<tr>
<td>E6</td>
<td>-0.38</td>
</tr>
<tr>
<td>E7</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emissione spettrale</th>
<th>E (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td></td>
<td>3</td>
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<td></td>
<td>4</td>
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<tr>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

**Tab.1:** Energie dei livelli più bassi dell'atomo di idrogeno.  
**Tab.2:** Energia delle emissioni osservate nello spettro

Commenta / rivedi la tua risposta alla domanda precedente

D7) La seguente tabella riporta le energie dei livelli energetici dell’elio ionizzato. Disegna i livelli.

<table>
<thead>
<tr>
<th>ENERGIE DEI LIVELLI (eV)</th>
<th>Rappresentazione dei livelli energetici</th>
</tr>
</thead>
<tbody>
<tr>
<td>-54.44</td>
<td></td>
</tr>
<tr>
<td>-13.60</td>
<td></td>
</tr>
<tr>
<td>-6.04</td>
<td></td>
</tr>
<tr>
<td>-3.40</td>
<td></td>
</tr>
<tr>
<td>-2.16</td>
<td></td>
</tr>
</tbody>
</table>

Rappresentare lo spettro di righe di emissione dovuto ai livelli energetici indicati

D8) Nella figura sottostante è riportato lo spettro di emissione dei livelli più bassi di un atomo di idrogeno, a partire da quello fondamentale. L'energia delle righe aumenta da sinistra a destra. Qual è il numero minimo di livelli necessari per giustificare la presenza delle righe che si osservano? (spiegare)
D9) Rappresentare i livelli energetici che danno luogo allo spettro mostrato in figura, spiegando come si individuano.

D10) Il livello energetico E2 è coinvolto nella formazione di una o più righe nello spettro mostrato. Evidenziare quali.

D11) Quante nuove righe si osserverebbero se si prendesse in considerazione un livello energetico superiore? Indica la posizione della/e riga/righe nello spettro.

D12) Esamino lo spettro emesso da una lampada a scarica di gas e di un led. Fare un’ipotesi con uno schizzo della struttura energetica dei due sistemi emittenti.
J_17_TUTORIAL

LE SORGENTI DI LUCE

1) Dopo aver osservato le luci emesse da sorgenti diverse (lampada a incandescenza, lampada a fluorescenza, LED, lampada a idrogeno...) descrivile sottolineando uguaglianze e differenze.

2) Elenca altre sorgenti di luce conosciute.

3) Rifletti su cosa chiamiamo sorgente di luce: che cosa caratterizza una sorgente di luce?

4) Dopo aver osservato la luce emessa da varie sorgenti tramite lo spettroscopio, descrivi cosa hai osservato.

LO SPETTROSCOPIO

5) Osserva la struttura dello spettroscopio e spiega il suo funzionamento.

6) Esplora e descrivi il ruolo di ogni componente dello spettroscopio (apertura, reticolo di diffrazione, tubo).
7) Esplora le sorgenti di luce con gli occhialini a reticolo:

8a) Che differenze noti rispetto all'esplorazione con lo spettroscopio?

8b) Qual è la forma delle immagini che osservi?

8c) Quale elemento produce la forma dello spettro?

LA DIFFRAZIONE

8) Dopo aver osservato la fenomenologia della diffrazione da singola fenditura e da un reticolo, descrivi il ruolo della diffrazione come meccanismo dispersivo e confrontalo con la dispersione da un prisma.

UN MODELLO PER L'EMISSIONE DELLA LUCE

9) Il modello atomico di Bohr ipotizza un atomo di idrogeno in cui un elettrone compie un'orbita circolare intorno a un protone in virtù della reciproca attrazione coulombiana. Scrivi la forza agente tra protone ed elettrone e, utilizzando le leggi della dinamica, trova l'energia totale del sistema (cinetica + potenziale). Cosa puoi dire del valore ottenuto?

10) L'atomo più semplice è quello dell'idrogeno. Il suo spettro ottico è illustrato in figura ed è stato il primo ad essere studiato.
Una formula empirica che descrive le emissioni visibili è stata trovata da J.J. Balmer nel 1885:

\[ E_{ab} = \text{cost} \cdot \left( \frac{1}{n_a^2} - \frac{1}{n_b^2} \right) \]

Dove \( E_{ab} \) rappresenta l'energia di una riga e \( n_a \) ed \( n_b \) sono due numeri interi. In particolare per riprodurre le emissioni osservate deve essere \( n_a = 2 \) e \( n_b = 3, 4, 5, 6 \).

Nel 1916 N. Bohr ipotizzò che l'atomo di idrogeno potesse trovarsi solo in precisi stati energetici (chiamati "livelli") in cui non vi era emissione di energia e che l'energia emessa fosse il risultato di variazioni energetiche tra i livelli. Utilizzando la legge di Balmer e l'ipotesi di Bohr, scrivi un'espressione per l'energia dei vari livelli.

11) Chiamiamo "livello energetico" l'energia permessa di un sistema. Che relazione c'è tra il valore in energia di un livello (nel caso dell'idrogeno) e il rispettivo numero d'ordine \( n \)?

12) Disegna i primi 4 livelli energetici dell'atomo di idrogeno e lo spettro che si ottiene considerando questi livelli.


14) I metalli alcalini (gruppo 1 della tavola periodica) e alcuni ioni (He\(^+\), Li\(^++\)) hanno spettri in cui le posizioni delle righe possono essere descritte da formule molto simili a quella di Balmer. Come ti spieghi questo similitudine in termini di struttura atomica?
K_17_TUTORIAL

LE SORGENTI DI LUCE

1) Dopo aver osservato le luci emesse da sorgenti diverse (lampada a incandescenza, lampada a fluorescenza, LED, lampada a idrogeno...) descrivile sottolineando uguaglianze e differenze.

2) Elenca altre sorgenti di luce conosciute.

3) Rifletti su cosa chiamiamo sorgente di luce: che cosa caratterizza una sorgente di luce?

4) Dopo aver osservato la luce emessa da varie sorgenti tramite lo spettroscopio a tubo, descrivi ciò che hai visto.

LO SPETTROSCOPIO

5) Osserva la struttura dello spettroscopio a tubo e spiega il suo funzionamento.

6) Esplora e descrivi il ruolo di ogni componente dello spettroscopio (apertura, reticolo di diffrazione, tubo).
7) Esplora le sorgenti di luce con gli occhialini a reticolo:

8a) Che differenze noti rispetto all'esplorazione con lo spettroscopio?

8b) Qual è la forma delle immagini che osservi?

8c) Quale elemento produce la forma dello spettro?

LA DIFFRAZIONE

8) Dopo aver osservato la fenomenologia della diffrazione da singola fenditura e da un reticolo, descrivi il ruolo della diffrazione come meccanismo dispersivo e confrontalo con la dispersione da un prisma.

UN MODELLO PER L'EMISSIONE DELLA LUCE

9) Nel modello atomico di Bohr, la forza centripeta che tiene in orbita circolare un elettrone intorno a un protone è di tipo coulombiano. Scrivi la relazione tra forza centripeta e forza coulombiana e utilizzala per ricavare un'espressione per l'energia totale del sistema (cinetica + potenziale) che sia funzione del solo raggio.
10) Come interpreti l'espressione ottenuta rispetto al segno (positivo o negativo)?

11) Come interpreti l'espressione ottenuta in funzione del raggio?

12) L'atomo più semplice è quello dell'idrogeno. Il suo spettro ottico è illustrato in figura ed è stato il primo ad essere studiato.

Una formula empirica che descrive le emissioni visibili è stata trovata da J.J. Balmer nel 1885:

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Dove \( E_{ab} \) rappresenta l'energia di una riga e \( n_a \) ed \( n_b \) sono due numeri interi. In particolare per riprodurre le emissioni osservate deve essere \( n_a=2 \) e \( n_b=3,4,5,6 \).

Se le righe spettrali rappresentano l'energia emessa nel salto tra due livelli energetici atomici (come ipotizzato da Bohr nel 1916) scrivi un'espressione per l'energia del livello \( E_a \) e del livello \( E_b \).

13) Trova la costante nella formula di Balmer.

14) Calcola il valore dei primi 6 livelli energetici dell'atomo di idrogeno.

<table>
<thead>
<tr>
<th>( n )</th>
<th>( E_n ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
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<td>2</td>
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<td>3</td>
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<td>5</td>
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<tr>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

15) Fai un grafico che rappresenta i 6 livelli.
16) Dai livelli individuati quali altre righe si possono prevedere?

17) Calcolare l'energia delle righe previste alla domanda 22).

18) Dato un generico numero \( n \) di livelli, quante righe ti aspetti di osservare? Giustifica la risposta.


![Spettro di emissione](image-url)

20) Hai osservato lo spettro di un LED: come immagini la struttura energetica del sistema emittente?
1. Abbiamo intorno a noi sorgenti di luce molto diverse tra loro. Come caratterizzeresti dal punto di vista fisico una sorgente di luce?

2. Osserva la luce emessa da sorgenti diverse e descrivine le caratteristiche.

3. Quali grandezze fisiche caratterizzano le luci emesse dalle varie sorgenti?

4. Osserva le luci emesse dalle diverse sorgenti con gli occhialini a reticolo. Individua uguaglianze e differenze e riporta le tue osservazioni dettagliate.

5. Osserva le luci emesse dalle diverse sorgenti con lo spettroscopio. Illustrane le diverse caratteristiche peculiari.

6. Cosa prevedi di osservare cambiando la forma dell’apertura?

7. Cosa prevedi di osservare rimuovendo il reticolo?

8. Che cosa prevedi di osservare utilizzando solo il reticolo?

9. Illustra quello che ritieni essere il ruolo di ciascuna delle seguenti componenti di uno spettroscopio:

<table>
<thead>
<tr>
<th>FENDITURA</th>
<th>TUBO</th>
<th>RETICOLO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

11. Che indagini faresti per mettere alla prova la tua interpretazione, o almeno per individuare una fisica del processo?


13. Descrivi il processo di emissione della luce in termini energetici, anche considerando casi specifici.


15. Il colore è una grandezza fisica? Spiegare.

16. Spiega il processo (o i processi) con cui si ottiene luce colorata.

17. Lo spettro ottico (in banda visibile) dell’idrogeno è illustrato nella figura seguente. In un modello ondulatorio della luce, le lunghezze d’onda λ delle righe sono rispettivamente: 656.3nm (rosso), 486.1nm (azzurro), 434.1nm (blu), 410.2nm (violetto).

Spettro visibile dell’atomo di idrogeno
Nel 1885 J.J. Balmer si accorse che era possibile ottenere i diversi valori delle lunghezze d’onda presenti nello spettro dell’idrogeno moltiplicando una costante k=364.6nm rispettivamente per i coefficienti 9/5, 4/3, 25/21 e 9/8. Trovò la legge generale che descriveva la successione di tali coefficienti, moltiplicando il secondo e il quarto coefficiente per 4/4. Trovala anche tu, facendo eventuali commenti.

18. Nel 1889 J. R. Rydberg, lavorando all’obiettivo di trovare il legame tra emissioni spettrali e struttura atomica, aveva trovato che era più semplice esprimere la posizione delle righe se nelle relazioni numeriche si utilizzava il reciproco della lunghezza d’onda. Esprimi la legge di Balmer in termini di $\frac{1}{\lambda}$ e discutila alla luce della conoscenza che la radiazione emessa ha energia $E=nh\nu$ (con $h$ costante di Planck e $\nu$ frequenza della radiazione in un modello ondulatorio). Utilizza quanto ricavato per descrivere i processi di emissione luminosa.

19. Alla luce di quanto visto finora, scrivi un’espressione per l’energia del generico livello energetico $E_n$, giustificando la risposta.


22. Considerando i primi sei livelli energetici accessibili all’atomo di idrogeno, i cui valori sono indicati in tabella, quante emissioni ti aspetti di osservare? Giustifica la risposta.

<table>
<thead>
<tr>
<th>n</th>
<th>$E_n$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-13.61</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
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</tr>
<tr>
<td>5</td>
<td>-0.54</td>
</tr>
<tr>
<td>6</td>
<td>-0.38</td>
</tr>
</tbody>
</table>

23. Alla luce delle considerazioni fatte nella domanda precedente, disegna lo spettro risultante.

24. Quali informazioni fisiche si ricavano dall’interpretazione di uno spettro ottico a proposito della sorgente luminosa?
M_17_TUTORIAL

PROPAGAZIONE DELLA LUCE E INTERAZIONE LUCE/MATERIA

1) Quali sono i principali fenomeni legati alla propagazione della luce? Elencali.

2) Ritieni che l'elenco emerso sia omogeneo nei suoi contenuti? Rifletti e spiega.

3) Considera, in particolare il fenomeno della rifrazione e quello della trasmissione: quali caratteristiche hanno in comune? Quali sono le differenze?

4) Si possono identificare diversi piani riguardo i fenomeni di propagazione della luce? Spiega.

5) Rifletti in merito al caso della luce che attraversa un corpo trasparente secondo due prospettive diverse:

<table>
<thead>
<tr>
<th>Prospettiva 1</th>
<th>Prospettiva 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legge di Snell</td>
<td>Come ti spieghi il cambio di velocità?</td>
</tr>
<tr>
<td></td>
<td>Quali grandezze fisiche sono coinvolte nel processo?</td>
</tr>
</tbody>
</table>

SORGENTI DI LUCE

6) Spiega ed esemplifica i criteri in base ai quali si possono classificare le diverse sorgenti di luce.
7) Rifletti su cosa chiamiamo "sorgente di luce": che cosa caratterizza una sorgente di luce? Spiega.

**LA LUCE EMESSA DALLE SORGENTI**

8) Osserva la luce emessa da sorgenti diverse e descrivine le caratteristiche.

9) Quali grandezze fisiche utilizzeresti per caratterizzare le luci emesse dalle varie sorgenti?

10) Dopo aver osservato la luce emessa dalle varie sorgenti con lo spettroscopio descrivi ciò che hai visto.

11) Osserva la struttura dello spettroscopio e illustra quello che ritieni sia il suo funzionamento, descrivendo il ruolo di ogni componente (apertura, reticolo, tubo).

12) Che cosa prevedi di osservare cambiando la forma dell'apertura?

13) Dopo aver cambiato la forma dell'apertura, cosa concludi in merito al suo ruolo nella costruzione di uno spettroscopio?

14) Che cosa prevedi di osservare togliendo il reticolo?

15) Dopo aver rimosso il reticolo, cosa concludi in merito al suo ruolo nella costruzione di uno spettroscopio?
16) Che cosa prevedi di osservare senza fenditura né tubo (utilizzando solo il reticolo)?

17) Osserva le diverse sorgenti con gli occhialini a reticolo. Per ciascuna di esse individua uguaglianze e differenze rispetto all'osservazione condotta con lo spettroscopio. Riporta le tue osservazioni dettagliate e le conclusioni.
LE PROVE ALLA FIAMMA

1) Composti diversi alla fiamma producono luci di colore diverso. Quali associazioni si possono fare tra il colore della fiamma e gli elementi dei composti?

2) Quale interpretazione si può fare del processo che determina la luce emessa?

I COLORI DELLA LUCE

3) Per caratterizzare con una grandezza fisica il colore della luce ne studio l’interazione con la materia. Illumino con luci di colori diversi uno stesso sistema e ne studio il guadagno in energia interna. Per fare ciò uso la stessa lampada e filtri di diverso colore per produrre luci di colore diverso che illuminano una stessa massa d’acqua. Cosa emerge dall’analisi dei dati ottenuti? (spiegare).

4) Alla luce dei risultati dell'esperimento, quale associazione si può fare tra colore della luce ed energia trasportata?

LA LUCE BIANCA

5) In nessuno spettro compare il colore bianco; in particolare un prisma riceve luce bianca e restituisce luci di colori diversi distribuiti in un preciso ordine. Immaginare ed illustrare un esperimento che permetta di decidere se il prisma opera una trasformazione o una scomposizione della luce.

6) La luce bianca presenta una struttura cromatica intrinseca. In che modo è possibile esplorare se ciò vale anche per le luci colorate?

FENOMENOLOGIA DELLA DIFFRAZIONE DA SINGOLA FENDITURA E DA RETICOLO

7) Come cambia la figura di diffrazione al cambiare del colore della luce?
8) Come cambia una figura di diffrazione dello stesso colore avvicinando la fenditura allo schermo?

9) Come cambia la figura di diffrazione al cambiare dell’ampiezza di fenditura?

10) Nell’ipotesi ondulatoria della luce, come si scrive la condizione di minimo di intensità luminosa nella diffrazione sullo schermo? (spiegare).

11) Nell’ipotesi ondulatoria della luce, come si scrive la condizione di massimo di intensità luminosa nella diffrazione sullo schermo? (spiegare).

12) Nel caso di due fenditure, come si determina la posizione dei massimi di diffrazione? (spiegare e scrivere la relazione formale).

13) Nel caso di reticolo, come si determina la posizione dei massimi di diffrazione? (spiegare e scrivere la relazione formale).

14) Dopo aver osservato la fenomenologia della diffrazione da singola fenditura e da un reticolo, descrivere il ruolo della diffrazione come meccanismo dispersivo e confrontarlo con la dispersione da un prisma.

15) Quali differenze e analogie ci sono utilizzando gli occhialini e gli spettroscopi a tubo?
ESPLORAZIONE FENOMENOLOGICA CON SPETTROSCOPIO DIGITALE

16) Dopo aver osservato il funzionamento di uno spettroscopio digitale, come si interpreta il grafico bidimensionale osservato?

17) Illustrare cosa è rappresentato in uno spettro ottico e come si produce ciò che si osserva.
UN MODELLO PER L'EMISSIONE DELLA LUCE

1) L'atomo più semplice è quello dell'idrogeno, composto da un protone ed un elettrone. Il suo spettro ottico è illustrato in figura ed è stato il primo ad essere stato studiato.

![Spettro ottico dell'idrogeno](image)

Le lunghezze d'onda delle righe visibili sono rispettivamente, da sinistra a destra: 656.3 nm (rosso), 481.1 nm (azzurro), 434.1 nm (blu), 410.2 nm (violetto).

Nel 1885 J.J. Balmer nota come questi quattro valori possano essere calcolati moltiplicando una costante $k$ rispettivamente per i seguenti coefficienti: 9/5, 4/3, 25/21, 9/8.

Calcolare il valore della costante $k$ spiegando il ragionamento.

2) Un'interessante osservazione può essere fatta moltiplicando il secondo e il quarto coefficiente per 4/4, in modo da ottenere la serie di coefficienti:

3) In che modo sono sistematicamente legati il numeratore e il denominatore di ogni coefficiente? Scrivere la legge generale ed eventuali commenti.

4) Nel 1889 J. Rydberg generalizza la formula trovata da Balmer esprimendola in termini di frequenza piuttosto che di lunghezza d'onda, ottenendo $f=k'*(1/4-1/m^2)$ s$^{-1}$, con $k'$ costante. Qual è il legame tra la costante $k'$ che compare nella formula di Rydberg e la costante $k$ che compare nella formula di Balmer?

5) Come si può interpretare la formula di Rydberg alla luce dell'ipotesi di quantizzazione dell'energia della radiazione?

6) Nel modello atomico di Bohr, la forza centripeta che tiene in orbita circolare un elettrone intorno a un protone è di tipo coulombiano. Scrivere la relazione tra forza centripeta e forza coulombiana e utilizzarla per ricavare un'espressione per l'energia totale del sistema (cinetica + potenziale) che sia funzione del solo raggio.
7) Come si interpreta l'espressione ottenuta rispetto al segno (positivo o negativo)?

8) Come si interpreta l'espressione ottenuta in funzione del raggio?

9) Se le righe spettrali rappresentano l'energia emessa nel salto tra due livelli energetici atomici (come ipotizzato da Bohr nel 1916) scrivere un'espressione per l'energia del generico livello En alla luce della formula di Rydberg, giustificando la risposta.

10) Sapendo che \( h \cdot k' = 13.61 \text{ eV} \), calcolare il valore dei primi 6 livelli energetici dell'atomo di idrogeno.

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</table>

11) Rappresentare graficamente i 6 livelli. Quali osservazioni si possono fare sul loro andamento?

12) Dai livelli individuati quante altre righe si possono prevedere? Giustificare la risposta.
13) Calcolare l'energia delle righe previste alla domanda 11) e disegnare lo spettro risultante. Quali osservazioni si possono fare sulla disposizione delle righe?

14) Dato un generico numero \( n \) di livelli, quante righe ci si aspetta di osservare? Giustificare la risposta.


16) Dopo aver osservato lo spettro di un LED, quali struttura energetica è possibile immaginare per tale sistema emittente?
1) Qual è il ruolo dell’apertura attraverso cui passa la luce?

2) Qual è il ruolo del reticolo nel setup sperimentale?

3) Se la sorgente fosse monocromatica cosa ti aspetteresti di osservare?

<table>
<thead>
<tr>
<th>Risposta</th>
<th>Rappresentazione grafica</th>
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</table>

4) Che cosa rappresentano le energie emesse rispetto al sistema emittente?

<table>
<thead>
<tr>
<th>Illustrare un'ipotesi interpretativa in merito al processo di emissione</th>
<th>Rappresentazione grafica</th>
</tr>
</thead>
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</table>

5) Nell’esperimento si sono osservate le seguenti righe e due studenti discutono.

![Spectrum Image]

Studente 1. La riga 5 corrisponde ad una maggiore energia e quindi rappresenta il livello energetico più alto dell’atomo di idrogeno.

Studente 2. Non sono d’accordo. L’energia della riga 5 è la più bassa tra tutte e quindi corrisponde al livello fondamentale.

Con quale studente sei d’accordo? Discuti le due risposte.
6) Durante l'esperimento del goniometro ottico hai osservato le righe spettrali emesse da un certo gas. Spiega il processo di emissione che da luogo alle righe osservate, avvalendoti di una rappresentazione grafica.

7) La seguente tabella riporta le energie dei livelli energetici dell'elio ionizzato. Rappresenta i livelli.

<table>
<thead>
<tr>
<th>ENERGIE DEI LIVELLI (eV)</th>
<th>Rappresentazione dei livelli energetici</th>
</tr>
</thead>
<tbody>
<tr>
<td>-54,44</td>
<td></td>
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<td>-13,60</td>
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<td>-6,04</td>
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<td>-2,16</td>
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</tbody>
</table>
O_18_TESTIN-TESTOUT

1) La luce è un ente che trasporta energia. Che cosa rappresentano le energie emesse da una sorgente luminosa?

<table>
<thead>
<tr>
<th>Descrivere un'ipotesi interpretativa in merito al processo di emissione</th>
<th>Rappresentazione grafica</th>
</tr>
</thead>
</table>

2) Osservando una sorgente luminosa con uno spettroscopio si sono osservate le seguenti righe e due studenti discutono.

Studente 1. La riga 5 corrisponde ad una maggiore energia e quindi rappresenta il livello energetico più alto del sistema emittente.

Studente 2. Non sono d'accordo. L'energia della riga 5 è la più bassa tra tutte e quindi corrisponde al livello energetico più basso.

Con quale studente sei d'accordo? Giustifica la tua risposta.
3) Con uno spettroscopio osservi una sorgente di luce e vedi uno spettro a righe, come quello della figura precedente. Spiega il processo di emissione che da luogo alle righe osservate, avvalendoti di una rappresentazione grafica.

4) La seguente tabella riporta le energie dei livelli energetici di uno specifico sistema emittente (un atomo di elio ionizzato). Rappresenta i livelli.

<table>
<thead>
<tr>
<th>ENERGIE DEI LIVELLI (eV)</th>
<th>Rappresentazione dei livelli energetici</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-3,40</td>
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<td>-2,16</td>
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</tr>
</tbody>
</table>
P_18_TESTIN-TESTOUT

1. Se illumino un oggetto, esso si riscalda. Come giustifichi questo fatto?

2. Da quali caratteristiche della luce ti aspetti che dipenda il riscaldamento? Giustifica la risposta.

3. Osserva la luce emessa da diverse sorgenti (A- lampada a incandescenza, B - LED, C - lampada a scarica di gas) con uno spettroscopio. Quali uguaglianze/differenze noti nei diversi spettri?

4. Dopo aver osservato 3 tipi diversi di spettri, come immagini il processo di emissione nei 3 casi? Aiutati con una rappresentazione grafica.

   LAMPADA A INCANDESCENZA

   LED

   LAMPADA A SCARICA DI GAS

5. Osservo con uno spettroscopio la luce viola emessa da una sorgente. Come ti immagini lo spettro?

6. Come interpreti, in termini energetici, uno spettro?
7. Osservando una sorgente luminosa con uno spettroscopio si sono osservate le seguenti righe e due studenti discutono.

Studente 1. "La riga 5 corrisponde ad una maggiore energia e quindi rappresenta lo stato energetico più alto del sistema emittente."
Studente 2. "Non sono d'accordo. L'energia della riga 5 è la più bassa tra tutte e quindi corrisponde allo stato energetico più basso della sorgente."
Con quale studente sei d'accordo? Giustifica la tua risposta.

8. La seguente tabella riporta le energie degli stati energetici di uno specifico sistema emittente (un atomo di elio ionizzato). Rappresenta gli stati.

<table>
<thead>
<tr>
<th>Energie degli stati (eV)</th>
<th>Rappresentazione degli stati energetici</th>
</tr>
</thead>
<tbody>
<tr>
<td>-54,44</td>
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<td>-3,40</td>
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<tr>
<td>-2,16</td>
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</tbody>
</table>
Q_18_TUTORIAL

A) Introduzione

1. Considera l'interazione luce-materia: individua i principali fenomeni e descrivi come si spiegano.

2. Quali grandezze fisiche descrivono l'interazione luce-materia? Spiega con esempi.


4. Quando illumino un corpo, esso si scalda. Che ipotesi attiva questo fatto?

5. Il riscaldamento del corpo è l'unico effetto causato dall'averlo illuminato?

6. Quali grandezze fisiche caratterizzano la luce emessa dalle sorgenti?

7. Esplora con lo spettroscopio la luce emessa da diverse sorgenti. Che ti pi di spettri hai rivelato?

8. Lo spettroscopio come artefatto: come è costituito e come funziona.

9. Qual è il ruolo del reticolo?

B) La diffrazione

10. Quali sono i parametri da cui dipende la figura di diffrazione da singola fenditura?
11. Basandoti sui seguenti dati campione (Allegato), progetta un esperimento che permetta di ricavare le leggi del fenomeno.

12. Un reticolo è composto da molte fenditure estremamente ravvicinate. Quali caratteristiche peculiari ha la figura di diffrazione ottenuta e qual è la legge che la regola?

C) Esperimento: spettri di LED
13. Osservo con uno spettroscopio a reticolo alcune sorgenti LED. Quali sono le caratteristiche dello spettro?

14. Quali ipotesi in merito al processo di emissione ti suggerisce lo spettro che osservi?

15. Esplora le caratteristiche I-V in merito all'emissione di luce LED di colori diversi. Che ipotesi suggerisce il confronto tra le caratteristiche I-V e lo spettro osservato?

16. Dopo aver osservato lo spettro della luce emessa da un LED e condotto le misure, fai un’ipotesi sulla struttura energetica di tale sistema emittente, aiutandoti con un disegno e giustificando la risposta.

D) Esperimento: spettrometro digitale
17. Osservando lo spettro della luce emessa da una lampada a scarica di gas come descrivi il processo di emissione luminosa?
18. Acquisisci lo spettro di un LED bianco. Analizza il confronto tra tale spettro e quelli ottenuti infrapponendo filtri di colore blu, verde, rosso e giallo. Discuti come analizzeresti i dati in relazione all'interazione luce-materia interessata.
<table>
<thead>
<tr>
<th>Pos (mm)</th>
<th>Intensity</th>
<th>Pos (mm)</th>
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R_18_TESTOUT

1. Considera l'interazione luce-materia: come spieghi i processi fisici coinvolti?

2. Discuti un fenomeno di interazione luce-materia che produce luce colorata e spiegalo.

3. Quali grandezze fisiche caratterizzano la luce emessa dalle sorgenti?

4. Illuminare un corpo lo scalda: come lo spieghi?

5. Il riscaldamento di un corpo è l'unico effetto che si ottiene quando lo si illumina? Spiega.


7. Quali sono i ruoli delle diverse parti di uno spettroscopio?


10. Il segno dei livelli energetici dell'atomo di idrogeno è negativo: come spieghi questo fatto?
11. La seguente tabella riporta le energie dei livelli energetici di uno specifico sistema emittente (un atomo di elio ionizzato). Disegna i livelli e quali emissioni ti aspetti di osservare.

<table>
<thead>
<tr>
<th>Energia (eV)</th>
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<tbody>
<tr>
<td>-54,44</td>
</tr>
<tr>
<td>-13,60</td>
</tr>
<tr>
<td>-6,04</td>
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<td>-3,40</td>
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<td>-2,16</td>
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</tbody>
</table>

12. Osservando una sorgente luminosa con uno spettroscopio, due studenti osservano le seguenti righe e discutono.

Studente 1: "La riga 5 corrisponde ad una maggiore energia e quindi rappresenta lo stato energetico più alto del sistema emittente"

Studente 2. "Non sono d'accordo. L'energia della riga 5 è la più bassa tra tutte e quindi corrisponde allo stato energetico più basso della sorgente."

Con quale dei due studenti sei d'accordo? Giustifica la tua risposta.

LA DIFFRAZIONE DA SINGOLA FENDITURA (Test di ingresso)

1. Quali sono i parametri da cui dipende la figura di diffrazione da singola fenditura? Per rispondere immagina di progettare un esperimento: quali grandezze fissi e/o modifichi nell'apparato? Spiega il ruolo di ciascun parametro e fai una previsione su cosa cambia al variare di ogni parametro.

<table>
<thead>
<tr>
<th>Parametri</th>
<th>Previsione</th>
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</table>

2. Basandoti sui dati campione allegato, progetta un'analisi che permetta di ricavare le leggi del fenomeno.

3. Alla luce delle analisi condotte, prevedi come cambia la distribuzione di luminosità al variare del colore della luce utilizzata.

4. La luce bianca viene divisa nei colori di cui è composta se fatta passare attraverso un prisma. Il fenomeno della diffrazione può essere utilizzato per scomporla allo stesso modo? Spiega.
LA DIFFRAZIONE DA DOPPIA FENDITURA E DA RETICOLO
5. Nel caso in cui siano presenti 2 fenditure, indica di quali parametri bisogna tener conto.

6. Come illustri l'effetto di scomposizione della luce da parte di un reticolo di diffrazione?

<table>
<thead>
<tr>
<th>Rappresentazione</th>
<th>Descrizione</th>
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</table>

LO SPETTROSCOPIO E L'OSSERVAZIONE DI SPETTRI
7. Lo spettroscopio come artefatto: descrivilo e utilizzalo per osservare le luci emesse da varie sorgenti.

8. Indicare e descrivere i tipi di spettri mostrati.
D = 1 m  
\( \lambda = 635 \text{ nm} \)  
a = 0.12 mm

Con D=distanza fenditura-schermo, \( \lambda \)=lunghezza d'onda della luce utilizzata, a=ampiezza di fenditura.

<table>
<thead>
<tr>
<th>Pos (mm)</th>
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DIFFRAZIONE DELLA LUCE & SPETTROSCOPIA OTTICA

L'ANALISI QUANTITATIVA DEGLI SPETTRI

1. Uno spettro fornisce informazioni quantitative circa le luci emesse da diverse sorgenti. Caratterizza quantitativamente gli spettri sotto riportati in termini di lunghezze d'onda.

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<tr>
<th>SORGENTE</th>
<th>DESCRIZIONE QUANTITATIVA</th>
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<td>Laser rosso</td>
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</tr>
<tr>
<td>Idrogeno</td>
<td></td>
</tr>
<tr>
<td>Elio</td>
<td></td>
</tr>
<tr>
<td>Litio</td>
<td></td>
</tr>
<tr>
<td>LED rosso</td>
<td></td>
</tr>
<tr>
<td>LED blu</td>
<td></td>
</tr>
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<td>Sole</td>
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</table>
2. Lo spettro in banda visibile dell'idrogeno è caratterizzato da quattro righe di lunghezza d'onda \( \lambda_1 = 656.3 \text{nm} \) (rosso), \( \lambda_2 = 486.1 \text{nm} \) (azzurro), \( \lambda_3 = 434.1 \text{nm} \) (blu) e \( \lambda_4 = 410.2 \text{nm} \) (violetto). Nel 1885 J.J. Balmer si accorse che valeva la relazione \( \lambda_n = k \cdot c_n \) con \( k = 364.6 \text{nm} \) e i coefficienti \( c_n \) sotto riportati. In questo modo trovò la legge generale che descriveva la successione di tali coefficienti, moltiplicando il secondo e il quarto coefficiente per \( 4/4 \). Trovala anche tu, facendo eventuali commenti.

<table>
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<th>( n )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
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<tbody>
<tr>
<td>( c_n )</td>
<td>9/5</td>
<td>4/3</td>
<td>25/21</td>
<td>9/8</td>
</tr>
</tbody>
</table>

3. Quali informazioni si possono leggere in uno spettro?

**L'INTERPRETAZIONE DEL PROCESSO DI EMISSIONE**


5. Considera altri fenomeni di interazione luce-materia: illuminando un oggetto esso si riscalda; la luce impressiona le pellicole fotografiche ed è in grado di abbronzare la pelle; la luce attiva fenomeni di fluorescenza o di fosforescenza. Come spieghi questi fenomeni?

6. Quali parametri fisici caratterizzano la luce emessa da una sorgente?

7. Decidi di inviare della luce su un materiale per riscaldarlo: su quali parametri della luce agiresti e in che modo, per ottenere un riscaldamento maggiore?

8. I raggi infrarossi (IR) scaldano. Se utilizzi luce IR di maggiore intensità, ottieni un maggiore riscaldamento o altri tipi di effetti? Spiega.

9. Illuminando un corpo con raggi X, non ottengo riscaldamento. Come giustifichi questo fatto?
10. Analizza la formula di Balmer alla luce dell'interpretazione dell'effetto fotoelettrico per scrivere la legge del processo di emissione in termini energetici.

11. Come puoi descrivere il processo di emissione alla luce della legge di Rydberg e dell'effetto fotoelettrico?

12. Utilizza uno spettrometro digitale per osservare la luce emessa da una sorgente atomica e da un led ed illustra le informazioni quantitative che ti da uno spettrometro sulla luce emessa da una sorgente.

13. Come utilizzeresti i dati presi con lo spettrometro per conoscere le caratteristiche di assorbanza di un filtro?
DIFFRAZIONE DELLA LUCE & SPETTROSCOPIA OTTICA

GLI SPETTRI CODIFICANO INFORMAZIONI SULLA STRUTTURA DELLA MATERIA

1. In quali modi è possibile ottenere luce colorata? Spiega i meccanismi fisici.

2. Composti diversi alla fiamma producono luci di colore diverso. Quale interpretazione si può fare del processo che determina la luce emessa?

3. Atomi diversi presentano spettri caratteristici. Come ti spieghi questo fatto?

4. Osservando lo spettro della luce emessa da una lampada a scarica di gas come descrivi il processo di emissione luminosa?

5. Come interpreti il fatto che emissioni diverse abbiano diverse intensità?
DIFFRAZIONE DELLA LUCE & SPETTROSCOPIA OTTICA

L'ESPERIMENTO DEL LED E LA CARATTERIZZAZIONE DI UNA SORGENTE DI LUCE

1. Un LED emette luce quando viene alimentato, cioè quando viene collegato ad una differenza di potenziale (tensione). Esplora le caratteristiche V-I in merito all'emissione di luce LED di colori diversi. Cosa concludi in merito al processo di emissione luminosa?

2. Quali misure faresti per studiare la relazione tra energia fornita e luce emessa?

3. Come interpreti i risultati ottenuti?

4. Dopo aver osservato lo spettro della luce emessa da un LED fai un'ipotesi sulla struttura energetica di tale sistema emittente, aiutandoti con un disegno e giustificando la risposta.

5. Come caratterizzi dal punto di vista fisico una sorgente di luce?
Bibliography


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