An Educational Path on Optical Spectroscopy as a Bridge from Classical to Modern Physics to Overcome Conceptual Knots

Daniele Buongiorno, Marisa Michelini
buongiornodaniele@gmail.com

Abstract

Optical spectroscopy is a conceptual referent linking classical and modern physics which provides experiments on the atomic structure and light-matter interaction. Its disciplinary relevance, as well as its importance on the cultural and social levels is widely recognized but few efforts have been made to integrate those aspects in education. Our Physics Education Research Unit from Udine University (Italy) designed an educational method on optical spectroscopy for secondary school students to directly involve them in experimental and interpretative tasks which allow them to highlight the link between energy level in atoms and luminous emission. In the theoretical framework of the Model of Educational Reconstruction, the educational approach involves an analysis of the main conceptual knots on the basis of a significant - if not vast - literature concerning the interpretation of optical spectra. By means of design-based research methods, we designed several intervention modules in which interpretative issues related to the analysis of simple optical spectra from different sources are highlighted using inquiry-based learning strategies. Learning outcomes were monitored by means of empirical research using pre/post-tests and tutorials.

Keywords: Physics education research, optical spectroscopy, educational reconstruction, design-based research

Introduction and Research Perspective

Nowadays modern physics is recognized as indispensable in all European secondary school curricula, but there are still problems concerning which strategies to be employed (Michelini et al., 2014). Optical spectroscopy is a context that provides an experimental basis for the atomic structure of matter and modern quantum theory. Moreover it provides a significant methodological example of how physics makes use of indirect measures of energy in order to obtain information and validate models. Focused experimental activities that can be carried out with simple and cheap spectroscopes allow us to highlight the link between atomic energy levels and corresponding luminous emissions.

The Physics Education Research Unit of Udine University is designing an educational path on optical spectroscopy for secondary school students, which directly involves them in experimental studies and interpretations related to microscopic phenomena involving light-matter interaction.

From a research perspective, the design of an educational path starts with the analysis of the known conceptual knots, and a study of Physics Education Research (PER) literature on optical spectroscopy, despite it not being very wide, has shown that the main learning difficulties concern the conceptual link between discrete emissions and energy levels in atoms and the experimental conditions under which a discrete spectrum rather than a continuous one can be observed. Secondary school and university students tend to associate the energy of a single emission line with the energy of a single energy level, rather than to the difference between couples of levels (Rebello et al., 1998; Zollman et al., 2002). In introductive astronomy courses, where spectroscopy plays a key role, difficulties emerge in describing the process of luminous emission from atoms (Bardar et al., 2006). The problem of the conceptual link between spectral emissions and energy levels has also emerged in studies conducted by university students (Korhasan & Wang, 2016; Ivanjek, 2012; Ivanjek et al., 2015).

The same research shows that students are not aware of the experimental conditions necessary to produce a spectrum. Other researches (Savall-Alemany et al., 2016) have also shown that secondary and tertiary level students, as well as secondary school teachers do not have a clear idea of the quantum model for atoms, nor of the quantum model for light, so they struggle to predict the way these models interact in emission and absorption processes. Evidence has emerged to prove the existence of spontaneous models concerning the formation of discrete spectra and of their links with the quantized structure of atoms. Those models have to be overcome in order to reach a scientific view of the topic (Gilbert et al., 1998).

In the theoretical framework of the Model of Educational Reconstruction (MER) (Duit et al., 2005; Duit et al., 2012) by means of Design-Based Research (DBR) methods (DBR Collective, 2003; Collins et al., 2004; Van der Akker et al., 2006; Anderson & Shattuck, 2012) the educational approach to optical spectroscopy necessitates a reconstruction of the contents from an educational point of view, an analysis of the main conceptual knots and the main interpretative problems that have emerged from the history of physics and the design of conceptual micro-steps, in which active learning strategies make it possible to overcome any conceptual knots.

An educational proposal for secondary school students on optical spectroscopy will be presented with the aim of overcoming the conceptual knots evidenced in literature with an organic path integrating experimental activities. The proposal has been put into practice in different contexts: masterclasses, CLOE (Conceptual Lab of Operative Exploration) and a summer school for gifted students. All experiments occurred within the parameters establish by the IDIFO6 project[1] of the national project PLS (Progetto Lauree Scientifiche - Scientific Degree Project).

Learning outcomes and difficulties that resulted from the experiments will be discussed, in particular: i) which microscopic models spontaneously emerged; ii) the spontaneous ideas regarding the conceptual link between spectral lines and energy levels; iii) the operational difficulties.

The Educational Path

An educational approach concentrated on the common sense ideas of students as a necessary condition in order to activate the learning process (Viennot, 2003). We thus began the learning path with explorative activities and identifications of the different ways through which students correlate macroscopic observations (spectral emissions) and microscopic interpretations (matter energy structure). The first insight concerns the classification of optical phenomena in three big thematic areas: production, propagation and interaction of light with matter. An insight on the difference between refraction and transmission of light stimulates an analysis of the two points of view upon which those two apparently similar phenomena are viewed: while refraction is a macroscopic phenomenological description of the light path across the interface between two mediums with different indexes of refraction, a study of the transmission processes requires a deeper analysis, in particular from an energetic point of view. In our perspective, an energetic interpretation of the processes regarding the production of light and its interaction with matter becomes immediate: we thus choose to use energy, rather than wavelength or frequency as a conceptual referent for the interpretation of optical spectra. Recognize and classify light sources represent a valid context to reinforce the idea that production of light is an energetic process, in which light is recognized as an entity carrying energy, emitted as a result of an energetic transformation inside the source. Natural and

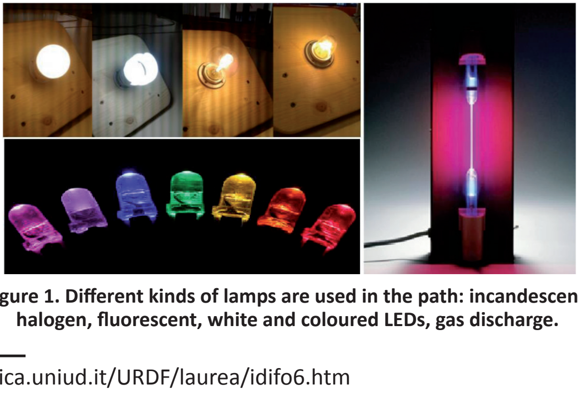

Figure 1. Different kinds of lamps are used in the path: incandescent, halogen, fluorescent, white and coloured LEDs, gas discharge.

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[1] http://www.fisica.uniud.it/URDF/laurea/idifo6.htm

artificial light sources are analyzed both from a structural and functional point of view (figure 1).

The presence of an energy exchange between a light emitting system and emitted light is at the basis of a first interpretation of the emission processes, in which the colour of the light is also analyzed, particularly in the specific case of an incandescent emission in which both the colour of the light and its intensity change with varying the power. The use of simple and cheap spectroscopes allows us to characterize a source according to the specific spectrum and continuous, discrete and band spectra can also be analyzed. The role of each spectroscope part is analyzed with the artefact method (Bartolini Bussi & Mariotti, 1999) in order to highlight each functional role of every spectroscope component (figure 2).

Figure 2. A simple spectroscope: the grating and slit are evidenced.

Monochromatic diffraction phenomena are experimentally analyzed with a digital acquisition of light intensity as a function of the position (Gervasio & Michelini, 2009) starting from single slit and ending with the analysis of the diffraction pattern produced by a grating. This analysis allows to assign to diffraction the role of a dispersive mechanism able to highlight the chromatic structure of light, as in the case of a prism (figure 3). In some experimentations, the analysis of the diffraction pattern took place with IBL strategy (Michelini & Stefanel, 2015).

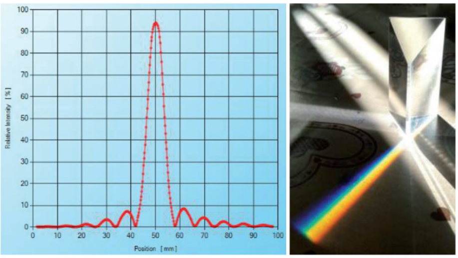

Figure 3. Different dispervive phenomena (diffraction, left and dispersion, right) are used to highlight the chromatic structure of light.

An analysis of the Balmer series for hydrogen is used to search for regularities in the observed spectrum (figure 4). Students are thus encouraged to think independently when reconstructing the historical development of ideas: the coefficients obtained by Balmer make it possible to read the experiment results in which the first four visible lines in the hydrogen spectrum can be obtained with the general empirical formula $\lambda_n = k \cdot \left(\frac{n^2}{n^2-4}\right)$ (Hindmarsh, 1967), that is can be modified to obtain a more general and interpretable reading, in terms of wave-numbers: $\frac{1}{\lambda_n} = k' \cdot \left(\frac{1}{4} - \frac{1}{n^2}\right)$, as Rydberg did (Hindmarsh, 1967).

Figure 4. The first four lines in the optical spectrum of hydrogen.

The reading in energy terms suggests how energy of a specific luminous emission is caused by an energy variation at a microscopic level in the emitting system. Using the energy level model, the key aspect of the negative binding energy can be addressed. The history of physics supporting the addressed concepts has an essential role here. The discrete nature of light is discussed interpreting Einstein's hypothesis for the photoelectric effect. The energy level model for atoms rather than the Bohr model - which makes use of orbits - guides students to face emission and absorption of radiation in terms of energy, which also allows students to make general reflections about light emissions from LEDs.

Context, Sample and Methodology

The path has been experimented with 208 students aged between 17 and 18 from scientific lyceums. There were three contexts in which the experiments were conducted:

- **Masterclass**: involved students participating in an 8-hour long activity at university. Classes are led by the teacher who follows the activity and coordinates with the university, integrating content, strategies and methods during lectures at school.
- **CLOE** (Conceptual Laboratory of Operative Exploration): this activity has the same nature and setting of a masterclass, the only difference being that students are engaged in an activity that only lasts for 4 hours.
- **Summer school on modern physics**: a national selection allows a number of students to participate in a 6-day intensive activity at university which includes lectures, experiments and a focused educational path on different aspects of modern physics i.e.quantum mechanics, superconductivity, Franck-Hertz experiment etc... The spectroscopy part requires a total of 8 hours.

Masterclasses and CLOE activities involved different secondary schools from Veneto, one of the biggest regions of Italy. In the path, depending on the availability of time, two or three laboratorial activities were performed in groups: the optical goniometer experiment, the LED-ruler experiment and on-line diffraction measures from a single slit.

- **The optical goniometer experiment**. Involves the observation of discrete spectra at various orders produced by the interaction of the light emitted by a discharge lamp with a diffraction grating. The goniometer (figure 5) allows for the measurement of angles corresponding to various emissions. It is thus possible to evaluate the wavelength of a specific emission, using the grating formula ($d \cdot \sin\theta = m \cdot \lambda$) and to convert this quantity in an associated energy ($E = \frac{h \cdot c}{\lambda}$)[2] according to Einstein's interpretations of the photoelectric effect.

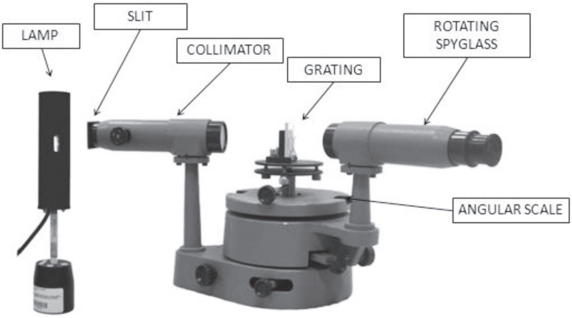

Figure 5. The optical goniometer experiment: emitted light from the lamp is collimated in order to make its direction of incidence perpendiculaly through the grating. Different chromatic components thus are angularly resolved and the rotating spyglass together with the angular scale allows to measure the corresponding angles.

- **The LED-ruler experiment**. It is assembled with low-cost materials and it allows one to observe the spectrum of the light emitted from a LED and to evaluate the energy corresponding to the dominant colour: observing the LED through diffraction toy glasses makes it possible to observe its spectrum projected along a ruler and, with a simple trigonometric calculus, its diffraction angle and thus, the corresponding colour energy can be is calculated (figure 6). This quantity is put into relation with the triggering voltage of the LED. Thanks to these two experiments, students can observe and analyze different kind of spectra: a discrete as well as a continuous peaked one.

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[2] In the relation $d \cdot \sin\theta = m \cdot \lambda$, d is grating's pitch, θ is the diffraction angle, with respect to the optical axis, of a particular wavelength λ in a particular order m. In the relation $E = \frac{h \cdot c}{\lambda}$, , h is Planck's constant and c the speed of light.

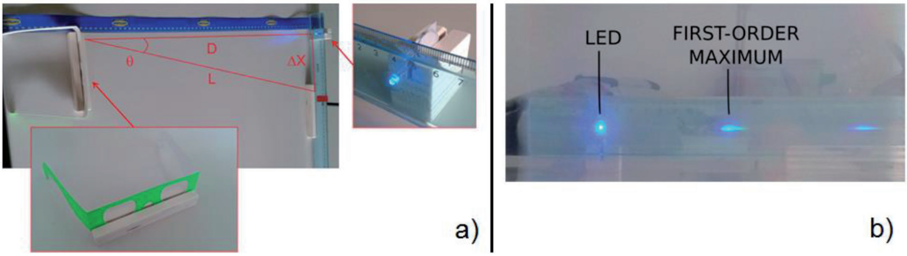

Figure 6. Low-cost experimental setup for observing the spectra of the light emitted from a LED and measuring the diffraction angle corresponding to the peak emission (a). observing through the grating the spectrum appears projected along the ruler (b).

- **On-line diffraction measurements**. A single slit diffraction phenomenon is explored with the aid of a patented sensor (Gervasio & Michelini, 2009) allowing one to obtain a digitalized graph in which intensity is plotted against position along the screen. The analysis of the graph enables one to obtain the diffraction laws.

The same conceptual core and rationale of the path characterized the different interventions; only the specific didactical trajectories revealed differences in the order of the stimuli problems submitted to students through Inquiry-Based Learning strategies (Abd-El Khalick et al., 2004; Mc Dermott et al., 2000). Contents addressed in all experiment, as well as their sequence, were revised every time, as recommended by a DBR approach (table 1).

Table 1. Structures of the different paths. Every column refers to a different experimentation (M: masterclass, C: CLOE, SS: summer school), while numbers refer to the sequence of the addressed contents in every path.

CONTENTS	M(a)	M(b)	M(c)	C(a)	C(b)	M(d)	SS
Light sources	1	1	1	1	2	2	1
Light emitted from sources	2	2	2	2	1	1	2
Diffraction	-	-	-	4	5	5	5
IBL path on diffraction	4	4	4	-	-	-	-
Exploration with spectroscopes	5	5	5	5	3	4	3
Structure of a spectroscope	6	6	6	6	4	5	4
Coloured light structure	3	3	3	3	-	3	7
Planck’s hypothesis and Bohr’s model	7	9	9	9	8	9	9
Total energy of an H atom	8	7	7	7	6	7	6
From coefficient to Balmer’s formula	-	-	-	-	-	-	8
Balmer-Rydberg’s formula (1/λ)	-	8	8	-	-	-	-
Balmer-Rydberg’s formula (energy)	-	-	-	8	7	8	10
Black body emission formalism	-	-	-	-	-	-	9
Drawings of levels and prevision of emissions	-	10	10	10	9	10	11
From discrete spectra to levels	-	-	-	-	-	11	12

Table 2. The path has been experimented on different contexts, with different samples of students and using different monitoring instruments. In a DBR approach, the path underwent variations in the content and structure, as highlighted in the last column.

Date	Experimentation	N. students	Pre-test	Tutorial	Post-test	Path version
Jan, 1, 2017	M(a)	43	No	Yes	Yes	1
Feb, 1, 2017	M(b)	33	Yes	Yes	Yes	2
Feb, 2, 2017	M(c)	35	Yes	Yes	Yes	2
Feb, 13, 2017	C(a)	22	No	Yes	Yes	3
Feb, 14, 2017	C(b)	32	No	Yes	Yes	4
Mar, 10, 2017	M(d)	11	No	Yes	Yes	5
Jun, 28, 2017	SS	32	Yes	No	Yes	6

With regards to masterclasses and CLOE, different monitoring instruments were used:every student completed a guided tutorial (i.e. a worksheet with the same structure of the proposed path) with post-tests and, in some cases even pre-tests were conducted. The test-out was completed by students in their classes and the outcomes were discussed with the all teachers involved as a collaboration between school and University. The post-test was structured in 13 questions (table 3)

Table 3. Requests in the post-test.

Questions	Requests
D1	Point out similarities and differences among various observed spectra and justify.
D2	Explain the emission process causing the observed emission lines
D3-D5	Describe the role of the grating and the slit
D6-D7	Describe the light emission process from an atom comparing the energies of the emitted radiation and those of the levels
D8	Draw a spectrum knowing the energetic structure of the levels
D9-D12	Draw the energy level structure given a discrete spectrum
D13	Sketch the energy structure of a LED and a gas discharge lamp given their emission spectra

Concerning the summer school, the same test was used as a pre-test and a post-test and all were completed by students at the beginning and at the end of the activity.

Data Analysis

The analysis of students' written answers was conducted with qualitative methods: written answers and drawings were classified in categories which were chosen a-priori, based on the research questions and the aspects that emerged from the students' answers. Each category is operationally defined according to students' expressions. The identified categories allowed data qualitative interpretations based on the emergent frequencies. In order to interpret ambiguous answers or drawings, it was sometimes mandatory to rely on clues present in answers or drawings of different questions.

Here we report some results that emerged from data analysis concerning answers 47 students gave to the most significant questions of the post-test of the experiment "Masterclass(c)"and the answers 32 students gave to a significant question in the pre- and post-test of the experiment that was conducted in the summer school for gifted students.

Masterclass(c) experimentation: Post-test

With respect to the D1 question "Point out similarities and differences between light spectra from a incandescent lamp, a gas-discharge lamp and an LED, and justifying your answers" 38/47 answers were limited to describing spectra in terms of colours and/or present discontinuities, making analogies with the colours in a rainbow. 6/47 students interpreted a continuous spectrum as a consequence of thermal agitation (2/47) or to incandescence (2/47) and a discrete spectrum as a consequence of the nature of the emitting gas (1/47) or energetic jumps at atomic levels (1/47).

Question D2, referring to the experiment of the optical goniometer, asked to explain the process accounting for the observation of spectral lines, with the aid of a sketch. 23/47 students described the experiment in functional terms, eventually quoting diffraction as the mechanism responsible for the division of the colours. 8/47 students, on the other hand, interpreted the presence of different coloured lines in terms of the microscopic process causing the emission in terms of transitions between orbits (5/47) or levels (3/47). 6/47 students use both a microscopic interpretation of light emission and a macroscopic description of the measurements apparatus. It emerged that the Bohr orbit model, which is used to describe jumps between orbits and/or indirectly used to account for the idea that an electron is localizable, is a conceptual referent for many students.

Questions D3-D5 test for the functional role of the slit and of the grating in accounting for the formation of a spectrum: 21/47 students believe that the shape of the slit is responsible for the shape of the lines, while, on the other hand, 11/47 students believe that it is the engraving on the grating that is responsible for it. Only a single student referred to the sharpness of the lines as a fundamental conceptual referent in a description of a discrete spectrum without taking into consideration that fact that lines can be differently shaped, according to the employed setup. A specific IBL explorative path was particularly useful in this case since it offered students the opportunity to gain awareness of the functional role of every part of a spectroscope.

Issue related to the representation of the energy structure of the emitting system and the relative spectrum was addressed in question D8: the values of the first five energy levels of an ionized helium atom were shown to students who were then asked to represent them graphically and to sketch out the spectrum they expected to observe. 8/47 students employed “orbits” as conceptual referents, while 18/47 employed stacked “levels” as a more general representation, avoiding the use of the spatial representation of an atom (figure 7).Three models emerged that accounted for the formation of spectral lines with respect to the energetic structure of the emitting system (figure 8): a) a 1:1 correspondence between a line and a level (25/47), b) n close lines associated with nth level (4/47) and (c) all possible transitions (1/47).

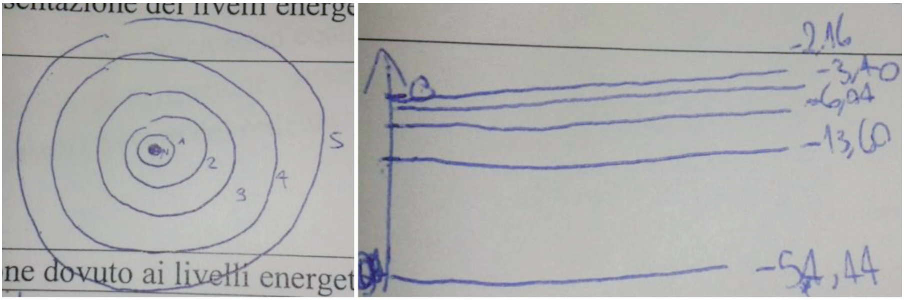

Figure 7. Models for atomic energy levels: orbits (left) and levels stacked with respect to an energy scale (right).

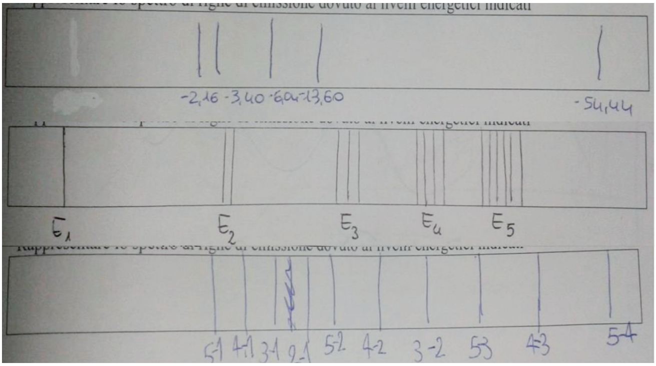

Figure 8. Given 5 levels, students expect 5 emissions in the spectrum (top), n close lines associated with nth level (centre) or all possible transitions (bottom).

Summer school experimentation: Pre- and post-tests

Answers to two significant questions of pre- and post-tests are analyzed and discussed below. The two questions were:
D1 "What do single energy levels represent in an atomic model?"
D2 "Considering that the first six energy levels of the hydrogen atom (values provided) how many emissions are expected? Justify your answer and draw the spectrum."

Answers to question D1 in the pre-test were given prevalently in terms of spatial localization of electrons in atoms, using orbits as conceptual referents (12/32), space where electrons can be found (4/32), orbitals (2/32) or distances from the nucleus (1/32), rather than in energy terms, using as conceptual referents electron energies (3/5), their exciting state (3/32) or the energy of the orbital (2/32). A minority of students indirectly defined energy levels as the energy of emitted photons (1/32) or observed that the difference between the energy of two levels corresponds to the emitted energy (1/32). After the intervention, students' answers, monitored with the post-test, showed a general trend against describing the electron in spatial terms, using conceptual referents as the space where electrons can be found (4/31), distance from the nucleus (3/31), orbits (2/31) or orbitals (2/31), in favour of descriptions in terms of properties of electrons in excitation state (9/31), energy (5/31), the property of not being able to emit radiation (4/31) or the energy of the orbital (1/31). A definition of energy levels is given in terms of characteristic energy of the system (6/31), in terms of an indirect definition relating the energy of the emitted energy to a difference between a couple of energy levels (5/31) or in terms of the energy of the emitted photons (1/32). It emerged that the perspective regarding the descriptions of energy levels in terms of spatial description using orbits rather than in terms of characteristics energies of the emitting system (i.e. the energy levels) was probably conditioned by what students had been taught previously at school.

Answers to question D2 allowed students to investigate the model they employed to foresee emissions in a discrete spectrum with only information regarding the energy values of the energy levels. Before the intervention, the spontaneous idea that a single level corresponds to a single emission line was quite prevalent (13/32). Out of those students, not one of them considered the fundamental level as an energy level. The interpretation according to which a single emission line is the outcome of a transition between a couple of levels was shared by 12/32 students (8 of whom considered all the transitions, 3 students considered only the ones involving the fundamental level and 1 student considered only transitions involving adjacent levels). Those interpretative models, based upon an arbitrary basis, were overcome by the end of the intervention, since it emerged from the post-test that all students adopted the model according to which all transitions were taken into account to justify the discrete emission in a spectrum.

Conclusions

A proposal for an educational path on optical spectroscopy for secondary school students, experimented in different contexts, has been presented and described together with some learning outcomes. The educational path has been designed in a DBR context in the theoretical framework of the MER. Qualitative analysis of students' written answers allowed to assign significance to data collected in order to obtain indications concerning the usefulness of the propose activities. Questions posed to students turned out to be fertile in the spontaneous production of models describing the energetic structure of matter accounting for discrete spectra, stimulating students in moving from a descriptive to an interpretative level, developing their functional reasoning. The proposed experimental activities enriched the activities, and the employed strategies can be implemented in a conceptual path, since starting from observations it is possible to find the interpretative basis of microscopic processes described by modern physics.

Optical spectroscopy is a fertile context in different areas: regarding the new guidelines concerning modern physics topics in scholastic curriculum, as a disciplinary deepening from optics to modern physics (i.e. in a vertical perspective linking different grades of instructions), as a transversal topic, thanks to the numerous application in chemistry, biology, astrophysics and art, which have a motivational and orienting role, as a context in which energy is used to describe light-matter interaction, and as a methodological and epistemic basis of physics, since indirect measures based on energy are used to validate models.

The aforementioned activities represent a fertile context for a collaboration between school and University, and the experimented path turned out to be a basis for the overcoming of some conceptual knots i.e. the role of a spectroscope in generating and detecting spectra, the difference between a diffraction pattern (which is an intensity distribution) and a spectrum (which is an energy distribution), difficulties related to linking spectral lines and energy levels, that can be caused by erroneous models of how spectral emissions are generated. The conceptual link between energy levels of a physical system (its states) and the orbits of the electrons, whose existence is out of discussion remains an ongoing problem: the need for a clarifying step regarding the deep conceptual differences between the various representations and the various models emerged from the results. It is thus necessary, consider in the path not only the specific case of the hydrogen atom, in which the correspondence between orbits and levels is direct, and thus misleading, but also more general cases, as for example atoms with many electrons.

Thanks to a DBR approach, it is possible to point out the best strategies to design the setting up of effective educational interventions, in particular, a methodological approach in which qualitative and quantitative explorations of phenomena are performed seems to be fertile, as well as specific activities in which students are asked to interpret the involved processes.

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Bio-notes

Daniele Buongiorno holds a Bachelor’s degree in Physics (2011, University of RomaTre, Roma, IT) and a post-graduate degree in Physics (specialization in Astrophysics, 2015, University of RomaTre, Roma, IT). He is a third-year PhD student in Physics Education at the University of Udine (IT), within the Department of Mathematics, IT and Physics, and the Physics Education Research Unit. His research field addresses the educational significance of optical spectroscopy. His main interests include the interpretation of links between spectral lines and discrete energy levels, students’ interpretative models and strategies, and the role of processes and apparatuses which can lead to the formation of a vertical educational path from primary pupils to university.

Professor Marisa Michelini is Full Professor in Physics Education at Udine University, where she is rector delegate for Didactic Innovation. She manages the Research Unit in Physics Education. She is president of the International Research Group in Physics Education (GIREP), director of the Italian University Consortium on Education and Guidance, committee member of the Multimedia Physics Teaching and Learning, board member of the EPS-PED division and honorary member of the Italian Association for Physics Teaching. She founded the Centre for Research in Education, the Lab Centre for Physics Education, the Centre for Guidance, the Research Unit in Physics Education. She has published extensively in her field of expertise.