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An inquiry-based learning path to introduce modern physics in high-school

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Abstract. Although Modern Physics (MP) is a scientific field of increasingly interest, due to its mathematical and conceptual difficulty, it was not generally taught in Italian high-schools. Recently, in order to reduce the gap between school curricula and modern technology, the Ministry of Education promoted the inclusion of MP in Italian secondary schools. MP hot topics produce interest and enthusiasm in learners at all ages, but to address this topic in high school in an effective way it is necessary to translate complex theories and highly-advanced experiments into an understandable language appreciated by students. In this contribution, we discuss an inquiry-driven learning sequence suitable to introduce MP, that we experienced, as pilot study, with a sample of about 40 students attending the last year of the scientific high school "Benedetto Croce" of Palermo in the school year 2015/2016. Our results suggest that an inquiry-based learning path, composed by three phases (frontal lessons + inquiry-based laboratorial activity + cooperative work), can constitute a successfully teaching approach to effectively engage students into an active learning of the MP, provided the teacher has a crucial role in facilitating the knowledge, activating the questioning process and supporting a valuable reasoned exploration.

1. Introduction

The importance of teaching Modern Physics (MP) in secondary school isn't just connected to its cultural relevance. In fact, this surprising and charming branch of Physics, builds a new way of thinking and seeing the world. MP is not only an ensemble of calculation rules to reproduce experimental data; its objective is to develop new technologies that have a ubiquitous presence in everyday life. Moreover, MP offers the possibility of building concepts and interpretative hypothesis, which haven't their counterparts in classical area. Because of this, the Italian Ministry of Education recently decided to include it in the curricula of secondary school. However, some problematic aspects and obstacles to overcome arise both in the teaching and in the learning of the MP (Persano Adorno *et al.* 2017). In the last decades, physics educators proposed many teaching strategies to better address this issue. There are several important studies focused on the learning and teaching MP at secondary school and senior/junior college levels (Kroemer 1994, Styer 1996, Petri & Niedderer 1998, Johnson *et al.* 1998, Ireson 2000, Taber 2004, Persano Adorno & Pizzolato 2015). Many researchers concluded that both teaching and learning MP are hard because it contains abstract ideas, requires strong mathematical tools, and deals with complicated operations. In secondary school environments, most problems deal with the teaching strategies adopted for MP and conceptual difficulties (Kroemer 1994, Ireson 2000, Muller & Wiesner 2001, Olsen 2002, Etkina 2010).

To effectively introduce MP at the high-school level, teachers need to translate complex theories and highly-advanced experiments into an understandable language appreciated by students. Furthermore, it is increasingly necessary that educators change their attitude towards this discipline, renouncing a too transmissive teaching method. Another relevant problem in the teaching/learning of MP is related to the low level of textbooks, very often unsuitable for the learners; although they introduce new concepts in a simple way, they appear too much detailed about particular aspects. The textbooks look as encyclopedias, built as university manuals. Finally, the choice of arguments without taking account of psychological maturation of students, the excessive overexposure of MP topics on Internet, the underestimation of historical and philosophical aspects of the discipline, are all elements limiting the acquisition of skills by students.

In order to present MP, the teacher can make operational choices between different educational approaches: (i) a *Technological* approach, based on main applications of MP: laser, diodes, sheet of graphene, etc.; (ii) a *Philosophical* approach, mainly based on the interpretation of MP and on its meaning for the worldview; (iii) a *Historical* approach, based on the dealing with the problems of classical physics solved by MP, (iv) an *Experimental* approach, based on performing experiments in the labs in cooperative learning; (v) an *Inquiry* approach, based on survey scientific approach through an active exploration process, or a suitable combination of them.

On the basis of our teaching experience, we believe that the analysis of the phenomenology, the implementation of experimental activities, the modelling and the use of data representation languages, the contextualization of theoretical concepts in the world where we live, are important elements to facilitate the building of learning of MP. In the following we present and discuss an inquiry-driven learning sequence suitable to introduce MP, experienced by students attending the last year of the lyceum “Benedetto Croce” of Palermo. We show that an inquiry-based learning path, composed by three phases (frontal lessons + inquiry-based laboratorial activity + cooperative work), can constitute a successfully teaching approach to effectively engage students into an active learning of the MP, provided the teacher has a crucial role in facilitating the knowledge, activating the questioning process and supporting a valuable reasoned exploration.

2. A brief introduction to an inquiry-based activity

The purpose of an inquiry-based process is to make learners able to analyze a problem, to run and develop a plan of studies and exploration activities, to build speculations, by making a distinction between possible alternatives, to search for information, to build models, to discuss and compare them in a context of peers (Herron 1971, Bybee 1993, McDermott 1996, National Research Council 2000, Llewellyn 2002, Banchi & Bell 2008). The Inquiry-based approach also allows to relate existing knowledge and new experiences, to change preconceived ideas and conceptual design, and to build new knowledge. In particular, students involved in an inquiry-based learning activity, collect data to develop explanations of scientific phenomena they study. They give a particular importance to the experimental evidence, using it as a starting point to build explanations on the behavior of natural phenomena; they build models designed to answer scientific questions and, doing it, build high-level skills; they discuss and communicate, in a context of peers, their models of explanations, developing critical review skills, crucial in their future life.

The teachers play the delicate role of planning a scientific inquiry program for their students by selecting approaches able to strengthen the understanding in students, choosing contents and contexts that create interests. They facilitate the learning, focusing on the scientific inquiry, organizing working groups, challenging the students to accept and share responsibilities related to their learning, identifying the differences among students and promoting these. They activate continuous assessment strategies of their teaching and student learning, steadily checking the understanding, directing the self-assessment, improving the teaching practice. The teachers design the learning environments, define the working times, identify useful resources outside of school and endeavor to make these resources available to students. Educators promote in their classes the development of scientific communities dedicated to learning, highlighting different ideas, skills and experiences of learners and facilitating a fruitful collaboration among students. Fig. 1 shows the different phases of an Inquiry-based learning cycle.

Fig. 1. Inquiry-based learning cycle (http://www.creativeinquiryteacher.com/?page_id=6)

There are various levels of inquiry in science education – the initial level where the teacher directs every aspect, to the highest level where the student holds the control and needs the intellectual and practical skills to become investigator, acting as a researcher (Banchi & Bell 2008). Through the series of different levels of inquiry, the student becomes more able to carry out his/her own independent inquiry, and the assistance of the teacher becomes different, less instructive, but more enabling and flexible.

3. Activity description

Our sample of students attending the last year of a scientific high-school actively participated to a cooperative learning on the fundamental concepts of MP and was involved in a laboratorial activity concerning the Franck-Hertz and the photoelectric effect experiments within an inquiry-based learning environment, with different level of teacher guidance.

Indeed, before the beginning of the laboratorial work, we randomly split up our sample in two groups composed by about 20 students:

Group 1 faced the experimental activity in a ***Guided-Inquiry*** learning environment (Banchi & Bell 2008). In this situation, it is expected that the students plan and conduct the experiment, with little guidance from the teacher and with a limited laboratory preparation. The research problem to be solved is given by the teacher, but the students have the responsibility to design and conduct the work, by collecting data and building models.

Group 2 faced the laboratorial work within a ***Structured-Inquiry*** environment (Banchi & Bell 2008). In this level of Inquiry, the question and the detailed procedure for the utilization of the labs are provided by the teacher. However, the students, working in small groups, generate an explanation supported by the collected data by themselves in the lab. They are responsible for uncovering the answer. The teacher acts as a knowledge facilitator, providing support or materials.

The whole activity, lasting about 15-20 hours, consisted of following three phases:

Frontal lessons, mainly based on video-projection and use of multimedia material, tests and oral discussion;

1. Execution of experiments at the Modern Physics Laboratory at the Department of Physics and Chemistry of the Palermo University;
2. Cooperative work in the classroom, which included the data analysis and the conclusive discussion.

In these phases, great importance was done to implement peer discussions in order to favour problem-solving among students.

Phase 1

During the first phase of the learning path, the students of both groups were introduced by the educators into the physical problem to address in the Franck-Hertz and in the Photoelectric effect experiments. In this phase, all students actively participated to the discussion with questions focused on the limits of classical physics, on the Bohr model and on the Einstein explanation. This phase lasted 4 hours for both groups.

Fig. 2. A view of the frontal lesson (*Phase 1*) at the scientific high school “B. Croce” of Palermo

Phase 2

Before the **laboratorial activity**, at the Modern Physics Laboratory, the students were invited to follow the educators’ instructions for what concerns the procedure to perform, in order to get to the necessary physical conditions for the data collection. Fig. 3 shows the experimental facilities available at the Laboratory for both the experiences.

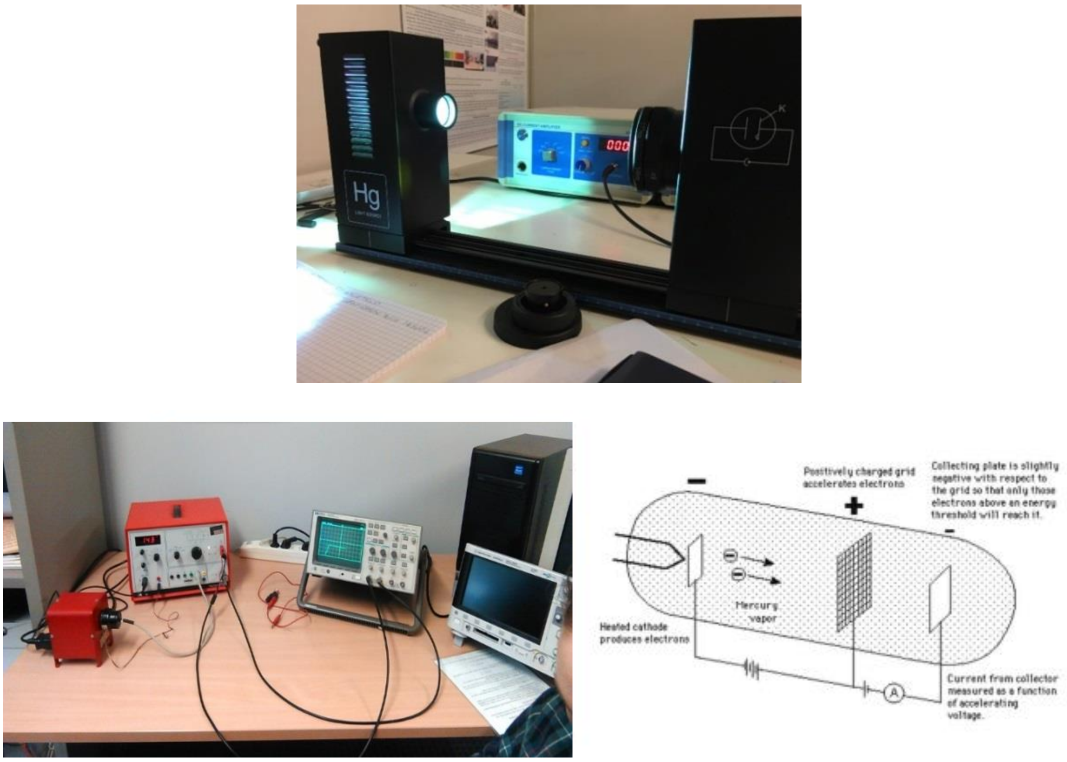

Fig. 3. (top): Experimental set-up for the Photoelectric effect; (bottom): Experimental set-up for the Franck-Hertz experiment (left) and schematic representation of the mercury-filled F-H tube (right)

Group 1

Group 1 was firstly invited to carry out the Photoelectric Effect experiment. The teacher, showed the tool use and proposed the research question: "Where and why the classical physics fails in the data explication?". In order to answer to this question, the students had to develop hypotheses, collect data and draw conclusions based on the recorded data.

The first afternoon (three hours) in the laboratory were critical. Students belonging to this group seemed quite bewildered and stuck on a stance. In this phase, the teacher tried, by using more questions, to stimulate and encourage them to go forward (Persano Adorno & Pizzolato 2015). For example, despite students well knew that they were dealing with a photodiode, in accordance with their previous knowledge, they tried to verify the first Ohm's law.

In order to put an end to the sense of failure experienced by students of group 1 when working at this level, during the second afternoon (three hours) spent in the laboratory, the teachers decided to actively participate to the experiment conduction, illustrated the procedure and the method and provided the results and their explanation, lowering the level of the Inquiry approach towards a Confirmation Inquiry environment (Banchi & Bell 2008). Despite of the students' diligence on performing the scheduled measurements and on collecting the data, they encountered many difficulties to generate their own explanations.

Group 2

After a more detailed instruction on the question and on the utilization of the experimental tools, students of group 2 were asked to work in groups and to perform scientific investigations, by collecting data and building possible explanations. The active participation of the teachers to the discussion, as peers, activated student scientific inquiry through the onset of an effective questioning on what was observed and measured.

Students used the logbooks to annotate the followed procedure, the difficulties encountered throughout the activity and the changes they made during the inquiry process. The students of this group spent ten hours in the lab successfully carrying out both the experiences.

Fig. 4. Students carrying out the Photoelectric effect

Fig. 5. Students carrying out the Franck-Hertz experiment

Phase 3

The **cooperative work** was carried out in the classroom, lasting four-five hours. Students of both groups were invited to write a scientific report on the experience done and on acquired/reinforced concepts.

In particular, students of **Group 2** built the models and performed the calculations, drawing the graphs for both the experiences. By starting from the data collected during the Franck-Hertz experiment, they were able to find an experimental confirmation of the Bohr's postulates, asserting that atoms can absorb energy only in quantum portions. During the cooperative discussion in the classroom they argued that in this experiment, electrons are accelerated and pass through mercury vapor, where they lose energy by inelastic scattering in quantized steps as they excite mercury atoms from the ground state to an excited state. By measuring the distance between the peaks in the I-V curve, they found that the excitation energy is E_{exc} ~ 5eV, in very good agreement with the real value of the difference in energy between the two levels in mercury ($\Delta E = 4.9$ eV).

For what concerns the photoelectric effect, the students belonging to Group 2 carried out the best fit of the data collected (V_{stop}-vs-ν) in order to calculate the value of the Planck's constant. During this relevant phase of the cooperative work, the students learned the significance of linear regression of the experimental data and how to calculate the error bars. They obtained the very reasonable value: $h = (6.51 \pm 0.25)10^{-34}$ Js.

Unfortunately, both for sake of time and for lack of interest, students belonging to **Group 1** did not carry out the Franck-Hertz experiment; for what concerns the photoelectric effect, they did not find the relationship between the potential stop and the frequency values and limited themselves to write a report, without data analysis and calculation of the Planck's constant.

Fig. 6. Cooperative work (*Phase 3*) of students in the classroom

4. Discussion and conclusion

Information about the students belonging to both groups affective development and motivation to learn was achieved by means of structured interviews based on the Intrinsic Motivation Inventory, with specific items adapted to our study (McAuley *et al.* 1991, Ryan & Deci 2000, Jang *et al.* 2016). To quantify the student satisfaction, we used a five-point Likert scale: 5: Very much; 4: Somewhat; 3: Undecided; 2: Not really; 1: Not at all.

Table 1. Mean student outcomes on a five-point Likert scale

Questions (interest-enjoyment dimension; perceived competence dimension)	**Confirmation Inquiry Group 1**	**Structured Inquiry Group 2**
I enjoyed this learning experience	2.9	4.5
I am satisfied with my performance at this experience	2.1	4.4
After this learning experience, I feel pretty competent	1.8	3.9
I understood better the topic	1.5	4.5

As evidenced also by the answers to the interviews, the students of **Group 1** were not able to cope the sense of responsibility of which were been charged and, during the laboratorial learning activity, their attitude was passive and unmotivated. The sense of failure generated frustration in the students, making them consider the laboratorial work "a waste of time" (Quintana *et al.* 2005).

Otherwise, the laboratorial learning sequence followed by students of **Group 2** enhanced their outcomes in terms of motivation, interest, reflective participation, critical observation and discovery learning. The learners have enthusiastically realized a video testifying the whole activity. Moreover, some students of Group 2, discussed this activity at their final graduation exam.

In conclusion, the objective of the learning path here described was not to add extra contents to those delivered during regular classes, but try to modify the student conceptions on MP. Indeed, in previous years we noticed that traditional lectures and discussions, culminating in the resolution of some exercises, many times did not encompass quantum concepts that remain unclear.

The close synergy between high school and university educators represented a positive experience, as well as the laboratorial work. On the basis of (i) the answers to structured interviews, (ii) the marks obtained at the final examination, our results suggest that an inquiry-based learning path, composed by three phases (frontal lessons + inquiry-based laboratorial activity + cooperative work), can constitute a successfully teaching approach to effectively engage students into an active learning of the MP, provided the teacher has a crucial role in facilitating the knowledge, activating the questioning process and supporting a valuable reasoned exploration.

Inquiry-based learning environments with lower teacher guidance, helpful to stimulate higher reasoning skills, particularly in university context (Pizzolato *et al.* 2014), sometimes may produce negative feelings due, for example, to run into mistakes or achieve unexpected results, especially in high-school students.

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