UNIVERSITÀ DEGLI STUDI DI PADOVA

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# Development of a teaching-learning sequence on quantum physics for the Italian secondary school

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# Abstract

In the past 15 years, quantum physics has been included in most secondary school standards, including the Italian ones, but still in a rather marginal way. The conceptual complexity of quantum physics is often a hurdle for students as well as for teachers; as a consequence, most teachers and textbooks opt for narrative/historical approaches which, however, are not sufficient to grasp the deepest conceptual aspects of quantum physics, nor to deal with its technological applications. For instance, the introduction of probability, uncertainty, and superposition, which are essential for understanding quantum physics, is highly non-trivial. These concepts are counter intuitive and conflict with the classical world view that is familiar to most students. A radical change in thinking is needed and ways to instigate conceptual change should be investigated. Quantum physics has been an important part of university physics and engineering education for a long time, but the often abstract and mathematical teaching practices used have been in dispute for several years. Currently, more emphasis is placed upon visualization and conceptual understanding. A conceptual approach to quantum physics allows to introduce quantum physics at an earlier stage, and therefore it has become part of the secondary school curriculum in many countries.

This thesis work consists of the development and test of a research-based teaching-learning sequence (TLS) based on the study of relevant literature in physics education research and on a survey conducted with secondary school teachers. More specifically, the work developed during the thesis includes:

1. A review of the literature on the teaching and learning of quantum physics, with particular reference to the proposals developed in the Italian context.

2. A survey with a group of secondary school physics teachers aimed at understanding the needs and difficulties of teaching quantum physics.

3. On the basis of the literature and of the results of the survey, we developed a teaching-learning sequence (TLS) on quantum physics for the fifth year of the Italian "liceo scientifico".

4. The TLS was then tested in a real classroom context.

The first chapter introduces the results of the review of the literature on the teaching and learning of quantum physics, the second one discusses the typical students' learning difficulties and learning process theories. The third chapter shows an overview of the proposals developed by different Italian research groups in physics education.

In the fourth chapter the research design and methods are discussed. We focus on the introduction of the learning activities with particular reference to the tutorial proposed on the photoelectric effect. The analysis of the results obtained from the surveys and the activities done by the students is shown in the fifth chapter.

# *Index*

# *1. Secondary school curricula*

## *1.1 Overview of international curricula*

On the basis of the Agenda for the modernization of Europe's higher education systems, starting from 2005 many nations have decided to include Physics of the 20th century in secondary school curricula.

In international research in physics education, the importance of investing in this area of knowledge has been underlined for years, planning didactic courses that pose fascinating conceptual challenges to students, and show how physics is a discipline in continuous evolution, whose knowledge allows to explain the functioning of modern technological applications and where there is opportunity for comparison between different points of view.

Because the inclusion of quantum physics in national curricula is rather new in most countries, it is interesting to compare quantum physics curricula from these countries. Staderman et al. [2019] collected and analyzed official curriculum documents from fifteen countries to identify key items present in most curricula. The countries investigated are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Portugal, Spain, Sweden, and the United Kingdom.

Their inventory (shown in Table 1 and 2) identifies a shared current core curriculum of quantum physics which contains the following seven main categories: discrete atomic energy levels, interactions between light and matter, wave-particle duality, de Broglie wavelength, technical applications, Heisenberg's uncertainty principle, and the probabilistic nature of quantum physics.

The items that are mentioned in the majority of the countries (Q3 to Q9, see tables for the enumeration) define the international current quantum physics core curriculum on the secondary level. The curriculum items Q10 to Q17 only occur in a few documents. The topics are diverse and can be seen as extensions of the core curriculum as in the next figure.

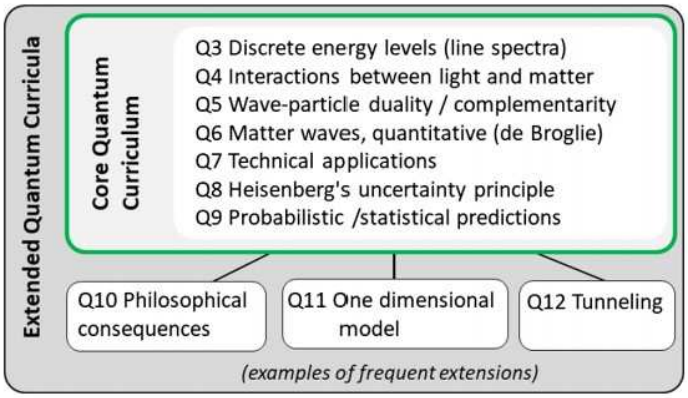



Figure 1. International core curriculum and extensions.

Staderman et al. found that the content focus of the secondary school quantum physics curricula lies primarily in the fundamental principles and the phenomena and applications. All of the seven content items from the core curriculum belong to these two categories. Consequently, high school students from most countries will mainly get to know fundamental principles and phenomena and applications of quantum physics in an advanced physics course. The extra content from advanced physics courses stems from the other three categories. Figure 2 shows how the extra items of different curriculum documents can be categorized: The IB diploma program and the Scottish advanced higher physics course focus on the wave function and other mathematical representations; the Netherlands and Sweden have additional items from the atomic theory in their extra content; most German states have extra items from all three categories. In contrast, the extra items of Norway and Italy focus solely on philosophical aspects. Also the Belgian and the Austrian curriculum documents contain philosophical consequences, but in both countries, they are only mentioned as an optional suggestion.

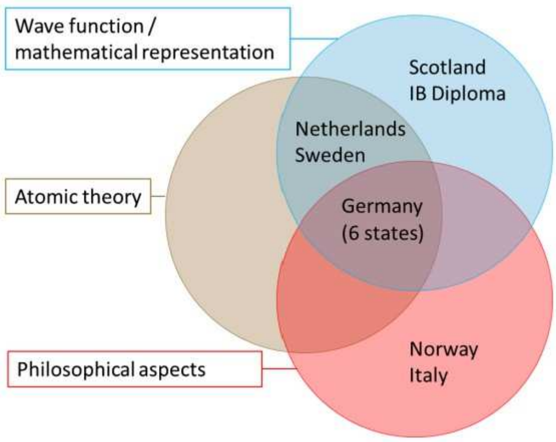



Figure 2. Different national curriculum documents grouped according to the thematic focus of extensional quantum physics items.

They also found differences in the focus of the listed topics of certain countries, which indicate different views on teaching quantum physics. For instance, challenging items like quantum physics interpretations or epistemological aspects of quantum physics are taught only in a few countries. Although research suggests that epistemological aspects help students to comprehend novel quantum physics concepts, many countries do not explicitly include these in the curriculum.

Staderman et al. conclude that in contrast to research results quantum physics is taught in upper secondary schools in many countries now, and there is a common core curriculum. However, in light of physics education research, the current core curriculum might not necessarily be the best way of introducing quantum physics on a conceptual level. At the moment, the most common approach is quasihistorical with elements from traditional university quantum mechanics courses. It is unrealistic to expect surprising curriculum innovations in most countries, because developing and changing national standards is generally a complex and slow process which often involves different stakeholders.

| Country | Implementation year of curriculum/syllabus | Name or abbreviation of the physics course | Exam: Written leaving exam, centrally set | Exam: Written leaving exam, locally set | Exam: Oral examination possible | Q1 Black body radiation | Q2 Bohr atomic model | Q3 Discrete energy levels (line spectra) | Q4 Interactions between light and matter | Q5 Wave-particle duality / complementarity | Q6 Matter waves, quantitative (de Broglie) | Q7 Technical applications (SEM, LED, laser) | Q8 Heisenberg's uncertainty principle | Q9 Probabilistic /statistical predictions | Q10 Philos. consequences / interpretations | Q11 One dimensional model / potential well | Q12 Tunneling | Q13 Atomic orbital model | Q14 Exclusion principle / periodic table | Q15 Entanglement | Q16 Schrödinger equation | Q17 Calculations of detection probability | N1 Working with hypothesis | N2 The role of scientific models | N3 Tentativeness | N4 Controversies in science | N5 Creativity in science | N6 History of science |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Canada (Ontario) | 2009 | 4U | | | | | | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | ○ | | ○ | ○ | ○ | ○ |
| Australia (National) | 2016 | 4U | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Spain | 2015 | F2 | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | ○ | ○ | ○ | ○ | | |
| Austria | 2014 | Ph | | ● | ● | | □ | ■ | □ | ■ | ■ | □ | ■ | ■ | □ | | | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Belgium (Flemish community) | 2015 | K | | ● | ● | | □ | □ | □ | □ | □ | □ | □ | □ | □ | | | | | | | | | | | | | |
| | | F | | ● | ● | | | | | | | | | | | | | | | | | | ○ | ○ | | ○ | | ○ |
| Germany (Rhineland Palatina) | 1998 | L | | ● | ● | | □ | ■ | ■ | ■ | ■ | □ | ■ | ■ | □ | □ | □ | □ | ■ | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| | | G | | ● | ● | | □ | ■ | ■ | ■ | ■ | | □ | ■ | □ | | | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Sweden | 2011 | 3 | | ● | ● | | | | | | | ■ | ■ | | | ■ | ■ | | ■ | | ■ | | | | | | | |
| | | 2 | ● | ● | ● | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | ○ | ○ | ○ | ○ | | |
| Portugal | 2003 | Fi | ● | ● | | ■ | | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | ○ | ○ | ○ | | | ○ |
| Italy (Liceo Scientifico) | 2010 | Fi | ●* | ●* | ● | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | | | | | | | | ○ | ○ | ○ | ○ | | ○ |
| France | 2012 | Fi | ● | | ● | | | ■ | | ■ | ■ | ■ | | ■ | | | | | | | | | ○ | ○ | | ○ | | ○ |
| Germany (Bavaria) | 2011 | Ph | ● | | ● | | | ■ | ■ | ▲ | ▲ | ■ | ■ | ▲ | | ■ | ■ | ■ | ■ | | ■ | | ○ | ○ | ○ | ○ | ○ | ○ |
| Germany (Saxony) | 2012 | L | ● | | ● | | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | | ■ | | ■ | | | ○ | ○ | ○ | ○ | ○ | ○ |
| | | G | ● | | ● | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Germany (Hesse) | 2016 | L | ● | | ● | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | □ | | ■ | | □ | ■ | ○ | ○ | ○ | ○ | ○ | ○ |
| | | G | ● | | ● | | ■ | ■ | ■ | ■ | ■ | | □ | ■ | □ | | | □ | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Germany (NRW) | 2014 | L | ● | | ● | | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | | | | | | ■ | ○ | ○ | ○ | ○ | | ○ |
| | | G | ● | | ● | | | | ■ | ■ | ■ | | | ■ | | | | | | | | | ○ | ○ | ○ | ○ | | ○ |
| Germany (Lower Saxony) | 2017 | E | ● | | ● | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | | ■ | | ■ | ○ | ○ | ○ | ○ | ○ | ○ |
| | | G | ● | | ● | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Germany (Baden-Württemberg) | 2016 | 4 | ● | | ● | | | | ■ | ■ | ■ | | ■ | ■ | | | | | | | | | ○ | ○ | ○ | ○ | | ○ |
| | | 2 | | | ● | | | | ■ | ■ | ■ | | | ■ | | | | | | | | | ○ | ○ | ○ | ○ | | ○ |
| Finland | 2016 | 7 | ● | | ● | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | |
| | | 1 | ● | | ● | | | | | | | | | | | | | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Norway | 2006 | 2 | ● | | ● | | | | ■ | ■ | | ■ | ■ | | ■ | | | | | ■ | | | ○ | ○ | ○ | ○ | ○ | ○ |
| | | 1 | | | ● | ■ | ■ | ■ | | | | | | | | | | | | | | | ○ | ○ | | ○ | ○ | |
| Denmark | 2008 | stx A | ● | | ● | | | ■ | | ■ | | □ | | | | | | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Intern. Baccalaureate | 2016 | HL | ● | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | | | | | | ○ | ○ | ○ | ○ | ○ | ○ |
| Netherlands | 2016 | na | ● | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | | | | | ○ | ○ | | ○ | | |
| UK (Scotland) | 2015 | HA | ● | | | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | | ■ | | | | | | ○ | | ○ | ○ | | ○ |
| UK (England ) | 2016 | A | ● | | | ■ | | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | ○ | ○ | ○ | ○ | | ○ |

[a]Legend: Exam: ● common exam for this course; ●* possible exam form, rarely applied (see country-specific information in Appendix B).
[b]QP items: ▲ in compulsory physics course grade 10, age 15-16; ■ in advanced physic course grade 11–13; age 17–19; □ optional for teachers in advanced physic course.
[c]NOS items: ○ mentioned in the curriculum of this physics course.

Table 1. The table, from Staderman, shows an overview of the quantum physics topics covered in upper secondary school curriculum documents.

| Content item mentioned in the curriculum document | | Countries/15 |
|---|---|---|
| Q1 | Blackbody radiation | (9) |
| Q2 | Bohr atomic model | (13) |
| Q3 | Discrete energy levels (line spectra) | 15 |
| Q4 | Interactions between light and matter | 13 |
| Q5 | Wave-particle duality or complementarity | 15 |
| Q6 | Matter waves, quantitative (de Broglie) | 12 |
| Q7 | Technical applications | 13 |
| Q8 | Heisenberg's uncertainty principle | 9 |
| Q9 | Probabilistic or statistical predictions | 8 |
| Q10 | Philosophical consequences or interpretations | 5 |
| Q11 | One-dimensional model or potential well | 3 |
| Q12 | Tunneling | 4 |
| Q13 | Atomic orbital model | 1 |
| Q14 | Exclusion principle or periodic table | 2 |
| Q15 | Entanglement | 2 |
| Q16 | Schrödinger equation | 2 |
| Q17 | Calculations of detection probability | 1 |

Table 2. The table shows the frequency of quantum physics curriculum items for different countries.

## *1.2 The Italian "Liceo Scientifico"*

The teaching methodologies of quantum physics in upper secondary school are a long-debated didactic problem, which has become particularly urgent in Italy with the introduction of the Reform of physics programs for scientific high schools [DM 2010]. The change in ministerial programs is primarily attributable to the need to update school topics so that they can cover currently socially relevant issues and questions. The purpose of high school courses (Italian "Licei") is in fact to:

"Provide the student with the cultural and methodological tools to understand in depth the reality, to follow the development of scientific and technological research and to identify the interactions between the different forms of knowledge [...]" (Art. 2 "Revisione dell'assetto ordinamentale, organizzativo e didattico dei licei", 2008)

Through the Gelmini Reform, starting from 2010/2011 school year, emphasis to the knowledge developed in the twentieth century has increased in Liceo Scientifico curricola. Among the topics to be addressed on physics of the twentieth century in scientific high schools, it also includes the introduction of some concepts of quantum physics, which are essential for understanding recent scientific developments and modern technological applications.

For all the other non-scientific high schools, the indications are still vague and only present an invitation to deal with these topics: "It is desirable that the student will be able to deal with twentieth-century physics, related to the microcosm and / or to the macrocosm, focusing on the problems that historically have led to the new concepts of space and time, mass and energy" [DM, 2010].

For the fifth year of the scientific high school, the Ministerial Decree of 7 October 2010, n.211 ("Indicazioni Nazionali"), states:

*"Lo studente completerà lo studio dell'elettromagnetismo con l'induzione magnetica e le sue applicazioni, per giungere, privilegiando gli aspetti concettuali, alla sintesi costituita dalle equazioni di Maxwell. Lo studente affronterà anche lo studio delle onde elettromagnetiche, della loro produzione e propagazione, dei loro effetti e delle loro applicazioni nelle varie bande di frequenza. Il percorso didattico comprenderà le conoscenze sviluppate nel XX secolo relative al microcosmo e al macrocosmo, accostando le problematiche che storicamente hanno portato ai nuovi concetti di spazio e tempo, massa ed energia. L'insegnante dovrà prestare attenzione a utilizzare un formalismo matematico accessibile agli studenti, ponendo sempre in evidenza i concetti fondanti. Lo studio della teoria della relatività ristretta di Einstein porterà lo studente a confrontarsi con la simultaneità degli eventi, la dilatazione dei tempi e la contrazione delle lunghezze; l'aver affrontato l'equivalenza massa-energia gli permetterà di sviluppare un'interpretazione energetica dei fenomeni nucleari*

*(radioattività, fissione, fusione). L'affermarsi del modello del quanto di luce potrà essere introdotto attraverso lo studio della radiazione termica e dell'ipotesi di Planck (affrontati anche solo in modo qualitativo), e sarà sviluppato da un lato con lo studio dell'effetto fotoelettrico e della sua interpretazione da parte di Einstein, e dall'altro lato con la discussione delle teorie e dei risultati sperimentali che evidenziano la presenza di livelli energetici discreti nell'atomo. L'evidenza sperimentale della natura ondulatoria della materia, postulata da De Broglie, ed il principio di indeterminazione potrebbero concludere il percorso in modo significativo. La dimensione sperimentale potrà essere ulteriormente approfondita con attività da svolgersi non solo nel laboratorio didattico della scuola, ma anche presso laboratori di Università ed enti di ricerca, aderendo anche a progetti di orientamento. In quest'ambito, lo studente potrà approfondire tematiche di suo interesse, accostandosi alle scoperte più recenti della fisica (per esempio nel campo dell'astrofisica e della cosmologia, o nel campo della fisica delle particelle) o approfondendo i rapporti tra scienza e tecnologia (per esempio la tematica dell'energia nucleare, per acquisire i termini scientifici utili ad accostare criticamente il dibattito attuale, o dei semiconduttori, per comprendere le tecnologie più attuali anche in relazione a ricadute sul problema delle risorse energetiche, o delle micro- e nanotecnologie per lo sviluppo di nuovi materiali)."*

*["The student will complete the study of electromagnetism with magnetic induction, its applications and the conceptual aspects such as the synthesis consisting of Maxwell's equations. The student will also deal with the study of electromagnetic waves, their production and propagation, their effects and their applications in the various frequency bands. The educational path will include the knowledge developed in the twentieth century relating to the microcosm and the macrocosm, bringing together the issues that historically have led to the new concepts of space and time, mass and energy. The teacher must pay attention to using a mathematical formalism accessible to students, always highlighting the founding concepts. The study of Einstein's special theory of relativity will lead the student to deal with the simultaneity of events, the dilation of times and the contraction of lengths; the mass-energy equivalence will allow him to develop an energetic interpretation of nuclear phenomena (radioactivity, fission, fusion). The model of the quantum of light can be introduced through the study of thermal radiation and Planck's hypothesis (also addressed at a qualitative level), and will be developed on the one hand with the study of the photoelectric effect and its interpretation by Einstein, and on the other hand with the discussion of the theories and experimental results that highlight the presence of discrete energy levels in the atom. The experimental evidence of the wave nature of matter, postulated by De Broglie, and the uncertainty principle could conclude the path in a significant way. The experimental dimension can be further investigated with activities to be carried out not only in the school's teaching laboratory, but also in university laboratories and research*

*institutions, also by joining orientation projects. In this context, the student will be able to deepen topics of interest, approaching the most recent discoveries in physics (for example in the field of astrophysics and cosmology, or in the field of particle physics) or deepening the relationship between science and technology (for example the issue of nuclear energy, to acquire the scientific terms useful to critically approach the current debate, or of semiconductors, to understand the most current technologies also in relation to repercussions on the problem of energy resources, or of micro- and nanotechnologies for the development of new materials)."]*

In addition, the Reference framework for Physics test in the final exam ("Esame di Stato") of Scientific High Schools, indicates in more detail what students should know and be able to do at the end of the Scientific High School (protocollo 13577 del 15 dicembre 2015):

| | |
|---|---|
| TEACHING UNIT | Quantum Physics |
| PREREQUISITES | • The Rutherford experiment and atomic model<br>• Atomic spectra<br>• Interference and diffraction (waves, optics)<br>• Discovery of the electron<br>• Classic collisions |
| ESSENTIAL CONTENTS | • Blackbody emission and Planck's hypothesis<br>• Lenard's experiment and Einstein's explanation of the photoelectric effect<br>• Compton effect<br>• Bohr model of the atom and interpretation of the atomic spectra<br>• The Franck - Hertz experiment<br>• De Broglie wavelength<br>• Wave-particle dualism. Limits of validity of the classic description<br>• Diffraction / Interference of electrons<br>• The uncertainty principle |
| CONTENT-RELATED SKILLS | • Illustrate the black body model and interpret the emission curve using the Planck's law of distribution<br>• Apply the laws of Stefan-Boltzmann and Wien and recognize their phenomenological nature<br>• Apply the Einstein equation of the photoelectric effect for solving exercises<br>• Illustrate and apply the Compton effect law<br>• Discuss wave-body dualism<br>• Calculate the frequencies emitted in the transitions between different levels of the Bohr atom<br>• Calculate the wavelength of a particle and compare it with the wavelength of a macroscopic object<br>• Describe the quantization condition of the Bohr atom using the De Broglie relation<br>• Calculate the quantum uncertainty on the position / momentum of a particle<br>• Analyze particle interference and diffraction experiments, also illustrating formally how they can be interpreted starting from the De Broglie relation on the basis of the superposition principle |
| SECTORIAL SKILLS | • Knowing how to show, by referring to specific experiments, the limits of the classical paradigm of explanation and interpretation of phenomena and being able to argue the need for a quantum vision<br>• Knowing how to recognize the role of quantum physics in real situations and in technological applications<br>• Be able to understand and argue popular and scientific critical texts dealing with the topic of quantum physics |

The field covered by twentieth century physics is very wide and it was chosen to give space in particular to the fundamental theories of relativity and quantum physics. At the secondary school level there is not the possibility of going into the details of these theories. The aim in introducing these topics is to provide the basis for understanding the profound cultural modifications that they have entailed and the physical principles on which is based most of today's technology.

# *2. Results in quantum physics education research*

## *2.1 Learning difficulties*

The teaching of Quantum Physics presents multiple intrinsic difficulties that mainly live in the necessary condition of changing the way of thinking, reasoning and imagining reality [Besson, Malgieri 2018]. The main learning difficulties are therefore linked to the contrast that arises between the ideas and methods of the classical and quantum world. In fact, quantum phenomena cannot be traced back to something already known in classical physics and it is often impossible to create a faithful representation of them without making distorting simplifications, which can lead to erroneous conceptions.

Because of the differences between the conceptual nature of quantum mechanics and classical physics, research on testing teaching strategies for introductory quantum mechanics is needed [Krijtenburg-Lewerissa 2017]. For the development of effective teaching strategies, it is important to know what difficulties students have with quantum mechanics. Therefore, this section gives an overview of findings about students learning difficulties which are divided into three quantum topics: wave-particle duality, wave function and atoms.

### *2.1.1 Wave-particle duality*

The fact that tiny entities show both particle and wave behavior is called wave-particle duality. This behavior conflicts with prior, classical interpretation of waves and particles. Quantum mechanics does not describe an electron's path, only the probability of finding it at a certain location. Students sometimes falsely considered this wave behavior to be a cloud of smeared charge and several secondary and undergraduate students considered the wave behavior of electrons to be a pilot wave, which forces the electron into a sinusoidal path [Müller and Wiesner 2002].

Students' difficulties about phenomena involving wave-particle duality are now discussed.

The **double slit experiment** is used to illustrate the wavelike behavior of photons, electrons and other small objects. Understanding of the double slit experiment depends in part on the students' understanding of the wave and particle behavior of quantum objects. If students see photons as classical particles with definite trajectories, this influences their comprehension of this experiment.

This can be seen by the fact that some secondary students considered photons to deflect at the slit edges and move in straight lines towards the screen. Another common problem depends on incomplete understanding of the de Broglie wavelength. Students do not always understand the influence of velocity and mass on wavelength and the influence of wavelength on the interference pattern.

The **uncertainty principle** states that there are certain properties that cannot simultaneously be well defined. Four categories of depictions of the Heisenberg uncertainty principle are observed: (i) uncertainty is erroneously described as a measurement error due to external effects, (ii) uncertainty is wrongly described as a measurement error due to error of the instrument, (iii) uncertainty is falsely thought to be caused by measurement disturbance, and (iv) uncertainty is correctly seen as an intrinsic property of quantum systems.

The explanation “measurement **disturbs** the system” is associated with the idea that each particle has definite values for both position and momentum, but these definite values cannot be determined because measurement of a particle’s position alters the value of its momentum. This is a particularly common misconception because the “gamma ray microscope” explanation from Heisenberg can be interpreted to support it. This idea is rendered untenable through tests of Bell’s theorem in 1972 from Freedman and Clauser. This misconception exemplifies the misconception that quantum mechanics involves a measurement uncertainty whereas in fact it involves indeterminacy.

The **photoelectric effect** is the phenomenon by which materials can emit electrons when irradiated by light of sufficiently high frequency. This effect is used to show the particle-like behavior of light. Some students confuse the photoelectric effect with ionization and certain students have difficulty with fully understanding how light and electrons interact. Students who use the wave model wrongly described the energy transfer in terms of vibrations, which were caused by wavefronts bumping the metal. These students believe that an increase in light intensity would lead to an increase in the number of wave fronts. Some undergraduate students wrongly think that light reacts chemically with an electron, and others incorrectly believe that the intensity of light could influence if electrons were ejected or not.

From this review of students' difficulties in phenomena and experiments involving wave-particle duality, three clusters of quantum objects description raised:

1) *Classical description*, in which students describe quantum objects exclusively as particles or waves;

2) *mixed description*, in which students see that wave and particle behavior coexist, but still describe single quantum objects in classical terms;

3) *quasi quantum description (semiclassical description)*, in which students understand that quantum objects can behave both as particles and waves, but they still have difficulty describing events in a nondeterministic way.

The next table resumes the students' interpretations, for each phenomena discussed, divided into these three clusters of description.

TABLE. *Students' description about wave-particle duality organized into three categories ranging from classical to quantum thinking.*

| | Classical description | Mixed description | Quasiquantum description |
|---|---|---|---|
| Photons or electrons | Electrons or photons are depicted as classical particles | Electrons and photons follow a definite sinusoidal path | Electrons are smeared clouds of charge |
| | Electrons or photons have definite trajectories | Electrons are either a particle or a wave depending on other factors | Electrons or photons are waves and particles simultaneously |
| | Light always behaves like a wave | Equations of properties of light also apply to electrons | |
| Double slit experiment | Light has no momentum | There is no relation between momentum and de Broglie wavelength | There is no relation between momentum and interference pattern |
| | Photons and electrons deflect at a slit and subsequently move in a straight line | No interference pattern appears with single photons and electrons | |
| Uncertainty principle | Uncertainty is due to external effects, measurement errors or measurement disturbance | | |
| Photoelectric effect | Energy is transmitted by wave fronts, more wave fronts cause more energy | Light collides with electrons | |
| | The intensity of light influences the energy transferred to a single electron | | |

### *2.1.2 Atoms*

The **quantum atomic model** describes the probability of observing the electron at a certain position, but it does not describe a temporal trajectory of an electron inside the atom. Research shows that secondary and undergraduate students rely on various atom models and can develop hybrid models consisting of combinations of different models [Petri 1998].

Ke et al. [2005] divided the different atomic models into three different stages: (1) An early, planetary, quantum model, in which the electron orbits in a circle of constant radius, (2) a transitional model, in which the electron moves along a sinusoidal path, and (3) a probabilistic model, in which the position of the electron is uncertain.

In the majority of articles emerges that secondary and lower undergraduate students have difficulty in giving up Bohr's planetary atomic model. Kalkanis et al. [2005] ascribed this to many students believing that scientific content they learned previously is scientifically correct and models are sometimes seen as replicas of reality believing that electrons are localized around the atom and moving around elliptical orbits. McKagan et al. [2008] claim that the solution is in comparing and contrasting different models, but also reported that students have difficulty understanding the reasons for the development of new atom models.

To explain atomic spectra, current atomic models include energy levels. These energy levels cannot be arbitrary, but they have certain, specified values. These quantized energy levels can only be explained by considering them as bound wave functions and taking into account boundary conditions. Taber [2005] observed that several secondary students did not understand the necessity of introducing quantization, because they did not see the planetary model as insufficient. Some students also had difficulty in forming an adequate concept of orbitals and confused orbitals with planetary orbits or concentric shells.

### *2.1.3 Wave functions*

Wave functions represent the state of particles. The wave function $\psi$ is not a physical wave, but a mathematical construct which contains all information of a system and predicts how particles will behave given a specific potential. $|\psi|^2$ can be interpreted as the probability density. Similar to wave-particle duality, undergraduate students often describe the wave function as a sinusoidal particle path. Misconceptions about **wave functions** can be divided into the two categories observed by Singh et al. [2006]: (i) misunderstanding due to overgeneralizations of prior concepts ("classical metaphors cause misconceptions and promote misplaced classical thinking"), and (ii) difficulty distinguishing between closely related concepts, which results in a mix up of energy, wave functions, and probability. These authors noticed that many undergraduate students are likely to have difficulties in understanding the meaning of potential well graphs and see potential wells as external objects. Other students mix up wave functions and energy levels.

Wave functions are not limited to classically permitted regions, they can extend past classical boundaries. This effect causes particles to have a probability of existing at positions that are classically impossible. An important result thereof is the phenomenon called **tunneling**. Misunderstanding of probability is an obstacle to the appropriate understanding of scattering and tunneling. Many students have difficulty distinguishing between energy and probability, which is due in part to diagrams which mix wave functions and energy levels.

As regarding high school students, an attempt to go beyond a purely qualitative explanation of the concept of wave function was proposed by the Udine research group through the phenomenon of light polarization and by the Pavia research group through a proposal on Feynman path method which are discussed in chapter 3.

## *2.2 Learning process theories*

A learning theory describes how students receive, process, and retain knowledge during learning. We now discuss the main elements and results and methods from the theories taken into account in the development of the teaching learning sequence.

### *2.2.1 The concept of appropriation*

Appropriation is a term whose semantic extension in the social sciences is rather vast. In science education “appropriation” is usually intended with a positive connotation, as a process in which the learner internalizes the acquired content, incorporates it into his own discourse, and is then able to use it in a personal way, expressing it with a language and terms not uncritically retrieved from external authorities, for interacting with others.

Recently, Levrini and co-workers [2015] have attempted to define the term more precisely, to operationalize it, providing criteria, or “markers” which could be used to check whether a process of appropriation, for a particular learner, had or had not occurred. In doing so, and referring specifically to the case of appropriation in young students such as those in high school, Levrini and co-workers expand the scope of the term, by arguing that appropriation can be seen as the process by which disciplinary content becomes so relevant to the individual, to be chosen as an element in the construction of his personal narrative of the self. Life stories [McAdams 2001] are psychosocial constructions, coauthored by the person himself or herself and the cultural context within which that person's life is embedded and given meaning. As such, individual life stories reflect cultural values and norms. Life stories are intelligible within a particular cultural frame, and yet they also differentiate one person from the next.

Operatively verifying whether appropriation has successfully occurred in individual students requires letting them speak freely about the content, possibly in the absence of the teacher, and with less constraints than usual in search of revelatory signs of connections between the disciplinary content acquired, and the student’s individual narrative of the self. Once identified, such elements are organized in profiles, describing how the student’s discourse seems to be organized around his/her idiosyncratic terms, expressions, or his/her thesis. Levrini and co-workers checked whether a “signature” idea clearly emerges from the student’s profile and data, which respects five operational markers:

1) it is authentic, in the sense that it is recognizable as personal, and it is verbalized using terms and expressions which are not borrowed from external authorities, such as the teacher or the textbook.

2) It is grounded in the discipline, in the sense that it respects the disciplinary norms of physics, and it used by the student for coordinating the physical content in a way which is meaningful to him, and scientifically valid.

3) It is thick, meaning that it is grounded in, and inseparable from, the students' epistemological discourse.

4) It is non incidental: it does not appear only in one isolated episode (for example, in the interview only), but it can be traced in different classroom activities.

5) It is bearer of social relations: the idea identifies a role or position of the student within the class community, and conversely, the development of the idea is not separable from the overall dynamics of the class.

In their work the definitions of a set of guidelines for learning environments designed to foster appropriation and of a set of operative markers for verifying the successful occurrence of appropriation in students can be found. Concerning the construction of learning environments, Levrini and co-workers identify the three following criteria:

1) Longitudinality expresses the idea that the learning of physics is a continuous process of widening and refining acquired knowledge, which must be globally coherent. The connections with models, phenomena and theories previously studied must be systematically presented, and, from the point of view of language, if some terms or concepts change in meaning in the passage from one theory to another, the differences and analogies must be explicitly discussed.

2) Multi-dimensionality is intended as the requirement that the physical content is analyzed and compared according to different dimensions; thus, not only from a conceptual, experimental, and formal point of view, but also considering their philosophical-epistemological implications.

3) Multi-perspectivenes means that the content is analyzed under two different perspectives which are both internal to the boundaries of the discipline, i.e. two different physical perspectives or approaches. For example, in the context of their study on thermodynamics the authors systematically compared the macroscopic and microscopic approaches.

The design of a learning environment respecting such criteria is not a trivial task; it involves producing teaching materials which are relevant from a cultural, and not only scientific, point of view; and introducing activities, such as open discussions concerning different perspectives or epistemological views, which challenge the authoritative image of science, in which a unique point of view is legitimate.

### *2.2.2 Conceptual change*

Some authors have considered the problem of teaching quantum physics from the perspective of the so called "conceptual change" [Kalkanis 2003]. Its basic principles are summarized in the dissatisfaction-intelligibility-plausibility-fruitfulness model by Posner and co-workers [1982]:

- Dissatisfaction: the learner must first realize that his existing conceptions cannot explain the new evidence at hand, and that a radical change is necessary. This result will not be achieved with a single anomaly but with a whole range of problems which are unsolvable with the old approach.
- Intelligibility: for a learner to accept and accommodate a new conception, he must find it intelligible. The model should make sense to him, and he should be able to explain that concept to other students. Initially, analogies and metaphors can help making the new model intelligible.
- Plausibility: the new conception must be plausible for it to be accommodated; it must not appear to be only an ad hoc construction made to deal with anomalous evidence but must also be consistent with the previous model on facts that it could explain.
- Fruitfulness: the learner must find that the new model has the potential to be extended to other incidences and open up new areas of inquiry.

Posner, in his conceptual change model, argues that the learning of science can involve the replacement of persistent, theory-like erroneous conceptions which are called misconceptions.

In contrast, Vosniadou in her approach to conceptual change [2012] argues that a global restructuring, meant as a complete replacement of a theoretical structure with another seldom occurs in instruction. More often, the initial framework theory and the one which is being acquired through instruction may coexist in the mind of the learner for a long time, forming a dynamical system in constant development. During the process of acquiring information incompatible with the pre-existing framework, the learner may develop internal inconsistencies, and reorganize his knowledge in "synthetic" conceptions or models, which are forms of *hybridization* between the two frameworks. Thus, a misconception is more often an inconsistency arising from the conflict between the initial and acquired frameworks, and in this sense is in itself a form of hybridization.

Vosniadou's framework theory approach could be relevant in student instruction on quantum physics. It is observed several cases of students spontaneously producing hybrid, synthetic models as seen in previous chapter. Vosniadou and co-workers provide several suggestions for designing learning environments able to promote successful conceptual change from the perspective of framework theories which directly influence the design of teaching-learning sequence:

1) Explain, rather than replace. Instruction should not simply tell learners that their existing ideas are wrong and should be replaced, but focus on explaining how the new framework can be consistent with their initial models and explanations;

2) Facilitate meta-conceptual awareness, try to make students explicitly aware of the structure of their initial explanatory frameworks. Give students time for discussing their conceptions, and the possible sources of conflict with the new model. Make the conceptual structure of the new theory transparent highlighting those ontological categories that must be created from the beginning;

3) Carefully consider the order in which the material is presented; try to predict at what points in the learning process contradictions may be produced, synthetic conceptions may be formed, and develop strategies to counter them.

# 3. Italian approaches in teaching quantum physics

The picture that emerges from the literature on the choices of approach and didactic strategy adopted in the teaching and learning proposals of quantum mechanics is extremely diversified.

In research literature, among the possible **approaches** to the teaching of quantum physics, three main ones can be identified: historical, logical-philosophical and phenomenological.

The **historical** approach that underlies the National Indications is the most traditional and widespread in textbooks (for example: Amaldi, "L'Amaldi per I licei scientifici"; Halliday, Resnick & Walker "Fundamentals of Physics"). Quantum physics is constructed as a result of extensions of classical mechanics, considering the phenomenological contexts, which historically have constituted an interpretative problem for classical physics. The problem of black body radiation, the photoelectric effect, the Compton effect and the Bohr atom are analyzed in order to introduce the Heisemberg's uncertainty principle and the complementarity principle formulated by Bohr. This approach is limited to a discursive explanation of the subject. It could cause a disconnected understanding formed by fragments of information, often linked to each other only by the chronological order of their discoveries. From research in teaching it has been observed that a problematic consequence of this conceptual fragmentation is that students, in their effort to fill the gaps between information fragments, tend to assign classical properties to quantum systems. Despite its problems, this approach offers ideas for reflecting on the epistemological nature of the discipline and its methodological rules, which risk being implicit in using other approaches.

The second **logical-philosophical** approach starts from today's structure of quantum theory, that is from the axiomatic structure of quantum physics. This approach, similar to the university one, is based on the belief that it is "impossible to understand quantum physics without possessing its mathematical structures" [Pospiech 1999]. Although mathematical formalism cannot be fully developed in high school, Pospiech, in her works, claims that it is possible to successfully understand the main ideas of quantum physics starting from spin, which has no classical analogues, and from Pauli's matrices. By introducing the spin, it is possible to get to the superposition principle and to the other elements of the axiomatic structure, without going through semi-classical representations. The mathematical tools used by Pospiech's are the Pauli matrices, i.e. 2x2 matrices. The use of these matrices provides a formal basis to explain the outcomes of experiments such as that of Stern and Gerlach.

The formalism used has the advantage that, at least in its basic aspects (the use of a function), it is also known to secondary school students. Any attempt, however, to overcome a first qualitative or semi-qualitative level, even for the simplest aspects, comes up against difficulties with formalism that are hard for high school students to overcome. This is essentially the reason why the proposals with analogue settings did not have real use in the school until the broad usage of the PC.

The third, **phenomenological**, approach introduces the concepts of quantum physics starting from the phenomenological analysis of experimental situations, subsequently highlighting the role of the formalism that describes them. An example of this approach is that proposed by the research group of Udine [Michelini 2014]. In their work, the phenomenology of light polarization is analyzed through experiments with polaroid filters and crystals of birefringent materials. Through the formulation of interpretative hypotheses, which requires students to actively participate in the development of the learning sequence, the properties of the photon are gradually identified, arriving at the formulation of the superposition principle and the impossibility of attributing a trajectory to the quantum object. A second experiment linked to the phenomenological approach is that proposed by Malgieri, from the University of Pavia [Malgieri 2015]. The approach is based on the Feynman path method and makes use of the contribution of interactive simulations that allow exploration and investigation activities otherwise difficult to be performed. Feynman's approach allows students to express in a clear and understandable way what happens when problematic aspects of quantum physics arise such as the impossibility of assigning a defined trajectory to the quantum object or the problem of measurement, helping them to build mental models consistent.

The approach outlined by the National Indications can be described as a **pseudo-historical and qualitative approach**, which focuses almost exclusively on the quantum theory of the early twentieth century. This approach has been widely criticized by research in physics education at an international level as it requires students to give up concepts and categories of thought in classical physics, without providing them with new tools to understand the new interpretation of phenomena offered by quantum physics. As described, the result of this approach is the permanence in students of concepts and categories of thought that are deeply rooted in a classic way of interpreting quantum phenomena. The ministerial indications, however, leave freedom for teachers to introduce quantum physics insights into the school curriculum or to choose different approaches from the one reported.

## 3.1 Feynman path method – Pavia group

The Pavia group proposes to immediately present some experimental tests, also available online in interactive versions in remote virtual laboratories, which have led to the introduction and consolidation of the photon concept. The order followed by this presentation is not historical, with the aim of preventing the student from developing erroneous alternative conceptions and hybrid mental models.

It begins with tests of the existence of the photon and description of the main properties ($E = h\nu$, $p = h\nu/c$) by photoelectric effect (1905), Compton effect (1920) and double slit experiments. In the latter, interference fringes constituted by the accumulation in time of single luminous points follow evidence of light as composed of quanta. This reconciles the students' misconception that the fringes are due to interaction between two or more photons because they are shown to pass "one at a time". The group also focus on the indivisibility of the photon through the Grangier Roger Aspect experiment (1986) in order to prevent students from building a model whereby the photon interferes with itself by physically dividing into parts. Aspect's experiment was the first quantum mechanics experiment to demonstrate the violation of Bell's inequalities. Its result allowed for further validation of the quantum entanglement and locality principles. Nowadays, quantum physics' violation of Bell's inequalities has been clearly established: the violation of Bell's inequalities is also used for some quantum cryptography protocols, in which a spy's presence is detected when Bell's inequalities cease to be violated.

It is also noted that, by associating a probabilistic law with the behavior of the quantum object, it is possible to reconstruct the wave behavior in a statistical sense through the law of large numbers as proposed also by E. Fabri [1988]. Light is therefore interpreted as composed of discrete objects but not of classical particles.

An experiment that reinforces the concepts introduced with that of the double slit is the Mach-Zender experiment with single photons which shows the contradiction between quantum and classical rules for the calculation of probabilities. The only way to interpret the results of Mach-Zender experiment is the use of quantum rules for the calculation of probabilities as the modulus squared amplitude. Classical probability calculus, i.e. simple sum of probabilities to go through one slit or the other, fails.

The need for a new theoretical arrangement that interprets these experiments and provides a description of the light which takes into account all of these aspects was then introduced by using the Feynman model.

This is a mathematical model of the quantum object that should not be associated with an ontological value, as paths and vectors cannot be associated with elements of reality. This approach introduces the necessity of an in-depth discussion on the meaning of the models in physics.

The first application of the model discusses the experiment of the two slits with one photon at a time. The usual interpretation of the experiment is recovered through the law of large numbers: if a large number of photons are sent against the screen, they will accumulate in areas where the probability of detection is greater. The Mach-Zehnder experiment is therefore explained by introducing a new rule for the photon reflection: phase shift of the pigreco phasor when a path involves a reflection on a metal surface or a mirror or by a medium with a reflection index lower than one with a higher refractive index. This law can be justified with an analogy to mechanical waves theoretically starting from Fresnel equations which students should know from the fourth year of school.

This method also extends to massive particles starting from experimental evidence (interference and diffraction with single electrons, neutrons and fullerene molecules) introducing De Broglie's concept of wavelength.

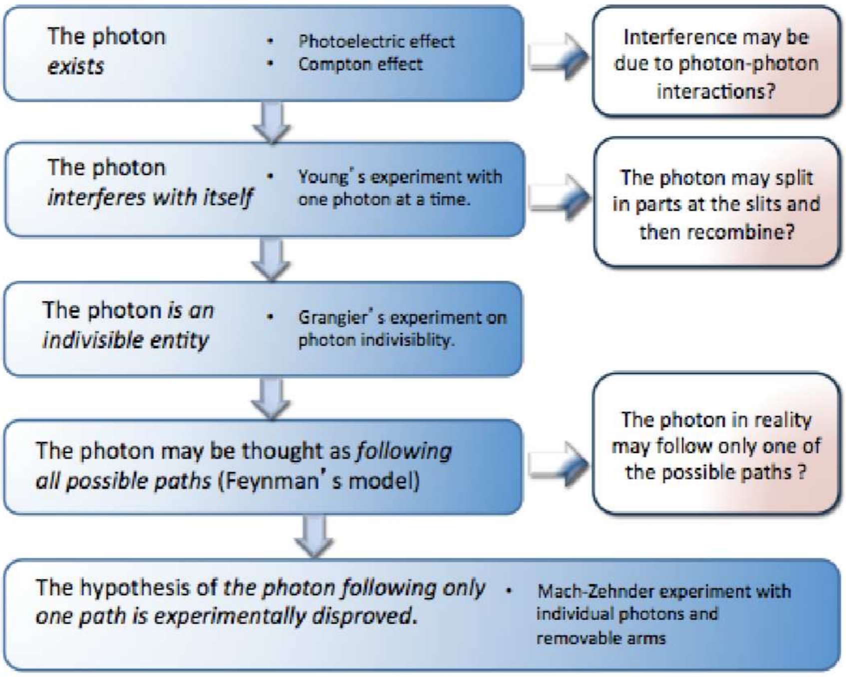
The uncertainty principle is introduced starting from the diffraction from a variable opening slit. The width of the slit is seen as the uncertainty on the x position of the photon while the width of the diffraction figure can be connected to the uncertainty on the component in x of the momentum.

The concept of wave-particle dualism is introduced from the beginning in the discussion on the calculation of the probability of events in physics. The concept of complementarity has to be introduced, that is, the incompatibility between the possibility of detecting, for the same quantum object and in the same experiment, wave-like aspects and corpuscular-type aspects. By corpuscular-type aspects we mean an aspect that allows an interpretation of the behavior in terms of trajectories such as the various possible paths followed to get to the detector.

The Mach-Zehnder experiment is therefore modified by introducing an intermediate which-way detector. It is shown that the dualism from the point of view of the paths is expressed as follows: quantum objects are always detected as localized entities but their probability of detection is given by the rule of quantum probability which is responsible for the emergence of interference phenomena.

If in an experimental apparatus the possible paths or processes are made distinguishable with the addition of a new detector then the distinct paths in this way do not lead to the same experimental result, having different effects on these apparatuses, and therefore do not interfere. The rule to be used then is that of classical probability and interference phenomena are lost. This theme brings with it insights on the role of detectors in classical physics models compared to that in quantum physics models (where they occupy a place within the model) and reflections on overcoming the wave-particle dualism by introducing an idea of "quantum object" or "quanton" (as also seen in Lévy-Leblond [2003]).

The following scheme resumes the order followed by the group in introducing photons and their quantum properties together with some questions which the experiments proposed aim to answer:




The group makes use of simulations created through Geogebra software which are also useful for showing examples of classical limits.

Therefore, Feynman's path method is seen as an *algorithm* that allows to face quantum physics mathematical difficulties in a way feasible by secondary school's students, an adequate *language* for expressing the most arduous and deep concepts and the *visualisation* of processes through a graphical representation of the mathematical model.

Simulations could give students the wrong impression that quantum objects retain classical features, such as trajectories, which could be a decisive factor in leading them to inconsistent conceptions. In order to avoid this, the attempt was to follow a "source-to-detector' philosophy, so as to focus students' attention on the emission and detection events and the paths between them, rather than on the quantum object itself, which was never directly represented. Therefore, what could seem a handhold for visualizing quantum description, considered to be a point of strength of Feynman's approach, has been revealed in some cases to be leading to misconceptions about the quantum behavior itself.

According to the results of a test of the effectiveness of this approach performed on 14 high school students [Malgieri 2017], the sum over paths approach may be effective in overcoming some of the educational difficulties in the teaching of basic concepts of quantum physics. Feynman's approach offers a natural functional model of wave particle duality, which helps students build consistent, detailed, and integrated mental models. A majority of high school students are able to construct at least a partially integrated view of different quantum phenomena and experiments concerning wave particle duality and which way measurements, and 9 students out of 14 use the sum over paths approach to provide a fully consistent explanation of the two slit experiment with one electron at a time. The incidence of deterministic and hybrid conceptions of wave particle duality is limited in our data, and in particular the difficulty reported in the literature, consisting in believing that possible paths correspond to trajectories followed by the quantum object with a certain probability, was limited to one case only in our sample, presumably thanks to proper sequence planning.

The authors recognize the cognitive limits of considering this a mere method and choose to follow further guidelines in order to "facilitate meta-conceptual awareness […] and explicitly highlight [to students] those ontological categories that must be created anew" [Malgieri 2015]. The idea is to accompany the ontological shift of quantum objects through a step-by-step refinement process which is made, mostly, through the analysis of modern quantum optics experiments so as to outline step by step the photons' quantum ontology.

In this context, the student's *ontological shift* occurs in the case in which he lays the foundations for the explanation of the system not in terms of individual objects present in it and with well-defined physical properties but in the identification of the possible paths between source and detector. Then the student should focus on the phases associated with the path that allow him to calculate the probabilities of detection. In cases where this shift does not occur, spontaneous theories are created from students such as the fact that the phasor represents an intrinsic rotary movement of the particle [Malgieri 2017].

Favorable aspects of this approach are the following:

i) the way of calculating the quantum transition amplitude is easily understood by the student, since it is based on the classical notion of trajectory.

ii) this didactic approach immediately introduces the concept of quantum indeterminism, since the amplitude of transition allows to determine only the probability of the associated event.

## *3.2 Polarization of light – Udine group*

The Udine group proposes the construction of theoretical framework in a specific physical context such as the polarization of light, whence to acquire basic concepts by representing them in iconographic and mathematical form and then generalizing them to arbitrary quantities and systems, with appropriate examples [Michelini 2014].

According to the authors, a descriptive introduction to quantum physics is acceptable in terms of dissemination purposes but appears unsatisfactory in terms of teaching. It is necessary to produce awareness of the assumptions of the new physics and offer some indication of the formalism adopted in it (formalism assumes an almost conceptual role in quantum mechanics).

The wave approach is a rigorous way to approach the new mechanics but requires mathematical skills absent in secondary education, involves a too long learning process and does not take into account the potential of the vector formalism which is at the foundation of the new mechanics.

Therefore, in order to explain central aspects of quantum physics such as overlap, uncertainty and entanglement in the simplest possible way, avoiding complicated mathematical constructs, the authors propose a simple example of quantum physics: the polarization of light. The photons, linearly polarized, are described as particles that move in real space while the theoretical description of the phenomenon makes use of two-dimensional vectors in an abstract space.

Simple phenomenological experiences are proposed on the linear polarization properties of the light which is assumed to be constituted, in suitable low intensity conditions of the beams considered, by indivisible quantities of energy (photons). Through the theoretical and practical use of a laser light beam that affects polarizing filters and birefringent crystals, the student is introduced to the fundamental concepts of the quantum world.

The Malus's law, if applied to individual photons interacting with a polaroid filter, allows the introduction of quantum indeterminism about the results of polarization measurements, which are generally stochastic.

Therefore the characteristics of the proposal are:

i) Explore the polarization of light from an experimental, conceptual and formal point of view.

ii) Discuss simple ideal experiments of interaction of single photons with polaroids and birefringent crystals (calcite crystals).

iii) Describe in quantum terms in a two-dimensional vector space the polarization state of light (and spin).

In particular:

- The interpretation and consequences of the overlapping principle are illustrated considering beams with polarizations along arbitrary directions impinging on birefringent crystals.

- The concept of non-commutative observables is shown by having the light beams engraved on polarizers in succession, aligned along non-coincident directions, and observing how the properties possessed by photons are modified.

- The evolution of the state of a photon in time is illustrated by the rotation without attenuation of its polarization direction and the collapse evolution of the state vector is shown by photons passing through a polarizer.

- It is also possible to recover a simplified version of the quantum formalism of states and linear operators in a Hilbert space of dimension two. This gives the student the opportunity to perform simple algebraic calculations to obtain the probability distribution of outcomes of polarization measurements.

- The phenomenology of linear polarization of light is shown in interaction with filters and crystals which can be easily found and used to organize experimental activities of low cost for students.

Polarization phenomena, and in particular the way in which polarization states can combine with each other, present tight analogies with the way in which quantum states do combine in general, and thus allow to show the key principles of the formalism in a simple and direct way [Ghirardi 1997]. This simplicity also constitutes the limit of the proposal which cannot deal with the more general case of Hilbert spaces in infinite dimensions and therefore the properties of non-limited operators (such as position and impulse).

By limiting itself to the degrees of freedom of polarization, the proposal is not able to treat physically interesting cases such as the determination of the energy levels of a physical system or the probability distribution associated with the measurement outcomes of the position or impulse observable.

The proposal has been tested with more than 250 high school students from 2004 to 2014 and it has been observed that the initial conceptions of the students are mainly deterministic and local and the process of evolution towards quantum conceptions takes place through a global multiple levels restructuring. A not marginal part of students have difficulties to abandon the classical idea of pre-existing properties to be able to do a prevision (40%). The majority of students was able to discuss and explicit consequences of a quantum phenomenon only when they had the possibility to use formalism to describe it (70%).

## *3.3 Pars destruens and pars construens – Bologna group*

The core idea developed by the group was to join up a destructive part belonging to the "old quantum physics" (the pars destruens) with a constructive framework (pars construens) by using the quantum double-slit experiment as an epistemological, experimental and conceptual junction. As suggested by Feynman, in fact, this experiment touches the very core of quantum physics, leading to face directly with some contradictions and interpretative limits of classical paradigms. The pars destruens revolves around the four fundamental phenomena related to the "old quantum theory" and foreseen in the "Indicazioni Nazionali": black body, photoelectric effect, Compton effect and Bohr's atomic model, in order to foster the discrete-continuous debate.

The path begins with the study of the black body: it starts with a discussion on the historical context, which reveals how this argument arises from the industrial need to develop increasingly efficient bulbs. Hence the need to build a model of ideal absorber and emitter called black body (elaborated by Kirchhoff). In discussion of the black body, it is suggested to put students in the conditions of understanding how the problem is a border problem between electromagnetism, thermodynamics and optics and to insist on how Planck's resonator model is the result of a rich process that has seen, even historically, the intertwining of evidence phenomenological, empirical laws, mathematical models and analogies. After discussion on the laws of Stefan-Boltzmann and Wien, the contribution of Planck, underlining how its distribution was first proposed as a pure mathematical model and, then, has been interpreted on the basis of the physical model of the resonators. Considering the situation in which the cavity is in equilibrium (its temperature is constant) and thinking of the cavity walls as made up of linear oscillators, the Planck model allows to model the process of interaction between the radiation inside the cavity and the resonators themselves and to find the spectral distribution such as that which maximizes the entropy function. The crucial point is that, in order to have agreement between the experimental data and the theoretical data, the process must be discrete, that is, the energy exchanged between resonators and radiation must occur in discrete packets. This discretization is mathematically expressed by the presence of the natural constant h, in the formula that expresses the energy exchanged between radiation and oscillator.

The photoelectric effect and the Compton effect are treated following a more traditional path, in which they start from the analysis of the experimental evidence, the unexplainable effects are presented with classical physics and they get the hypotheses of Einstein and Compton respectively. The fundamental difference of the Compton effect with respect to the photoelectric effect lies in having to deal with an electron that is no longer linked to the crystalline structure. The process, therefore, does not require to consider the binding energy. The step forward in the modeling made by the Compton effect is therefore the possibility of treating the radiation-matter interaction as a collision between two bodies, both free and therefore as if it occurred in an isolated system, which makes it possible to use the simple mathematical treatment based on conservation of energy and momentum. The Compton effect traditionally completes the path that leads from Einstein's quantum of light to the construction of the photon concept.

The junction part has the role of leading students towards the pars construens by presenting the first steps that led to the search for a new comprehensive theoretical framework that could account for all those phenomena that challenged and put in crisis the classical paradigms.

The topics covered in this second part concern indeterminacy, complementarity and the double slit experiment. The indeterminacy is shown to highlight some features of the quantum description of the world: the introduction of a non-epistemic type of probability, the need to renounce a causal principle of classical type and the concept of trajectory, the introduction of the concept that a quantum object has no properties defined by a single value and that there are pairs of conjugated quantities. In particular, the purpose of the treatment of indeterminacy, is that to argue, as Lévy-Leblond, that "While for classical entities, the physical properties take on unique and determined numerical values, for quantons they are characterized by numerical spectra, extended sets of numerical value." To give a qualitative idea of the concept of conjugate variables, it is proposed to students a metaphor taken from a well known text by Brian Greene: the metaphor of the Chinese menu.

It was also considered the discussion of the mental experiment of the γ-ray microscope. It is indeed still present in many textbooks and represents the main topic used to introduce indeterminacy. The group, therefore decided to treat it, to show its potential and limits. Heisenberg, in devising the thought experiment, chooses an "operationist" approach where position and momentum have meaning only if defined by the procedures needed to measure them. The analysis of Heisenberg's thought experiment highlights the problem of measurement but, on the other hand, it introduces the so-called "disturbance interpretation" of uncertainty, no longer accepted today.

For this reason, the presentation on indeterminacy continues with the debate between Bohr and Heisenberg on the origin of indeterminacy (also through excerpts or short videos taken from Frayn's "Copenhagen", 2009). In the debate Bohr disputes to Heisenberg the disturbing interpretation and says that uncertainty is the consequence of the wave-particle dualism, considered by Bohr the true theoretical basis for the construction of the new quantum formalism.

Regarding the double slit experiment and as well as for the pars construens, the path use what has been developed for the PLS ("Piano lauree scientifiche") course and, therefore, the materials developed by CNR-IMM of Bologna. These materials, in addition to describe and explain the experiment in its mental version, illustrate in detail also its practical realization which was first achieved in 1976 by three university researchers from Bologna.

From the experiment of single electron interference, shown to the students through slides and audio-visual materials, it is possible to underline the contradictions and interpretative limits of classical mechanics that require the development of a new logic, able of overcoming inconsistencies. To show how to overcome wave-particle dualism, the group suggests the use of metaphors, such as those of the cylinder and platypus, presented in Lévy-Leblond.

The purpose of the third and final part (pars construens) is to build a new language able to explain the logic of quantum interpretation. As far as pars construens is concerned, the group focused on Stern-Gerlach experiments, so as to build a constructive framework not linked to classical-like properties and to avoid any semi-classical misconception. The researchers decided to focus the construction of the genuine interpretative apparatus on something new, as the spin of Ag atom.

The proposal has been tested in three classes between December 2014 and May 2015 with a total of 31 hours spent in lessons, tests and activities. The group found that the proximity to the end of the school year and to the "Esame di Stato" had two negative effects: students had less time to spend to the study of quantum physics and most of the students were not willing to make the intellectual effort required by the last part of the path. The results of the experimentation showed that the problematization helped the more confident students to understand the concepts of the path, but at the same time led several students to reject the concluding arguments of the path considered too complex. Using the observation tools designed for the assessment the group identified the critical points of the path proposed:

i) the need to fix the path, reducing its complexity and problems or by modifying some particularly difficult points (indeterminacy and the superposition principle).
ii) the need to investigate the causes that lead a student not to accept the theory and how non-acceptance is linked to appropriation.
iii) the need to plan moments of collective discussion in order to favor accountability (the "collective activities in which students play different roles such as the "philosopher", the "mathematician". In this way it will be possible to show students how knowledge admits many roles e is not linked only to disciplinary skills").

## 3.4 Coupled harmonic oscillators – Rome group

The proposal of the research group of the University of Rome [Giannelli 2003] consists of a didactic approach to MQ obtained through the study of simple classical mechanical models (such as a system of coupled harmonic oscillators) which present very close formal analogies with the formalism of states and operators in Hilbert spaces.

More in detail, considering a finite system of coupled harmonic oscillators, it is possible to introduce the following concepts to the student:

i) the superposition principle since the linear combination of arbitrary motion solutions is still a solution of the motion equations.

ii) the concept of orthonormal basis since the normal modes of oscillation of the system constitute a basis in the vector space of the solutions of the equations of motion and are orthogonal and normalized with respect to a suitable scalar product and associated norm.

iii) the concept of dynamic evolution that preserves the vector norm.

iv) the possibility of representing the classic observables by means of suitable linear operators.

v) the concept of discretization of certain classic quantities following the imposition of boundary conditions.

These concepts, obtained from the study of such a simple classical physical system, are subsequently reformulated in a quantum framework and accompanied by the interpretative postulates proper to its orthodox formulation. The advantages of this discussion is in the possibility of facilitating the study of quantum formalism if the student had previously familiarized himself with the rudiments of linear algebra in a simplified context. However, the operation of overlapping states in MQ has an interpretation that is not analogous to the classical world and which is linked to the genuinely stochastic nature of the results of the measurement processes of quantum observables. The same quantum indeterminism must be assumed without experimental reasons, finding no justification in the study of a classical linear system where the laws of evolution and forecasts are strictly deterministic. In summary, the existence of mere formal analogies in such different branches of physics could mislead the student from understanding that the characteristic features of quantum mechanics derive from an interpretation of his formalism that is irreducibly non-classical.

# *4. Development of the teaching learning sequence*

In this chapter we introduce the survey conducted with secondary school physics teachers and the research design of a teaching learning sequence for introducing quantum physics at the secondary school level.

The development and test of the proposed research-based teaching-learning sequence (TLS) is based not only on the study of relevant literature in physics education research shown in the previous chapters but also on a survey conducted with secondary school teachers.

The survey with a sample of 6 secondary school physics teachers is aimed at understanding the needs and difficulties of teaching quantum physics in the school practice. This survey is conducted with a semi-structured interview. To our knowledge, in the Italian panorama of educational research similar surveys has been performed only by the physics education research group at the University of Udine [Michelini 2014] which proposed a questionnaire to a group of teachers during the IDIFO master. In the next paragraph we introduce the design of the interviews.

On the basis of the literature and of the results of the survey, we then developed a teaching-learning sequence (TLS) on quantum physics for the fifth year of the Italian "liceo scientifico" which was then tested in a real classroom context.

The activity plan tested went through three main steps. An initial discussion with students on the concepts of model and experiment in physics in particular about light and microscopic particles and their properties. The aim is to gather the initial conceptions of the students about these concepts and the students had to resume the observations they made divided in groups of three in a table we designed. These steps follow the model of Vosniadou for conceptual change explained in chapter 2.2.

The table aims to facilitate in the the students their meta-conceptual awareness, so that they are explicitly aware of the structure of their initial explanatory frameworks. The students have some time for discussing their conceptions, and for recognizing the possible sources of conflict with the new model.

The main source of conflict between their explanatory framework and the quantum physics theory is chosen to be the photoelectric effect. As later explained, this experiment is not only one of the topics that has to be taught during the last year of Licei scientifici, but it also provides the opportunity to discuss an experiment that requires a global view of different physics topics which students have studied. It also can be easily tested in a secondary school laboratory and allows to carry out an experimental measurement of Planck's constant, central to quantum physics. The method used here is the design of a tutorial to be done by the students at home divided in groups and then discussed in class through and active discussion led by the teacher when students could face the main results of the experiment and why they conflict with the classical model of light. A presentation of other historically important experiments via online simulators follows with the aim of reinforcing these observations.

The last step consists in returning to think on the question posed at the first point with the aim of reorganizing the students' foreknowledge by presenting a synthesis that in our case follows the idea of “quanton” presented by Lévy-Leblond [2003] and used also by Bologna group, as discussed in chapter 3.3. Their preconceptions make students focus on the failure of classical physics and creates the idea of incompleteness and strangeness of modern physics. Our aim is now to help student to synthetize their observations and reasonings in a quantum description of the nature of the particles. This quantum description should not invoke contradictions such as wave-particle duality in order to avoid semiclassical descriptions as found in literature (chapter 2.1). Therefore, we describe microscopic entities by introducing the concept of "quanton" with this aim.

At the end of the educational path, we proposed informal interviews to the students, keeping them divided into the groups with which they work during the tutorial on the photoelectric effect. These interviews aim to verify not only the final conceptions of the students on the nature of quantons but we also want to evaluate the effectiveness of the TLS in order to understand the elements that students claim have helped them most in understanding.

## *4.1 Analysis of the needs of secondary school teachers*

The interview to be proposed to teachers of the scientific high schools in the region is aimed at learning about the school situation regarding the quantum physics module. The knowledge of the current state and the opinions of teachers helps to outline a TLS that is as feasible as possible in a fifth class of Italian scientific high schools and therefore not the result of a mere academic work.

For this purpose, it is advisable to carefully determine the questions that will constitute the interview which was then carried out through teleconference interviews with six teachers from different schools located in different cities (Padua, Vicenza, Rovigo, Este (PD), Bassano del Grappa (VI)), coming from academic backgrounds in both physics and mathematics studies and with large differences in years of teaching experience (from 3 to 30 years).

Based on the typical responses of the teachers and the didactic issues which they highlight, it will be possible in the future to create a closed-ended questionnaire which therefore has the characteristics to be spread and filled out by a wider audience of teachers.

In Italy, the research group in Physics Education of the university of Udine [Michelini 2014] proposed a questionnaire to some teachers during the IDIFO master. However, this questionnaire was proposed in the middle of the master, with the risk that it may have influenced some of the answers given by the teachers. It received feedbacks from 6 teachers and a qualitative analysis of the responses provided was applied. Divided into two parts, the second is of interest for our purposes and consists of three questions:

- Why to teach quantum physics?
- Basic concepts that cannot be renounced in a didactic proposal in QM. Explain the reasons for the choices.
- Which aspects to privilege (formal, historical, logical, conceptual, applicative)?

Starting from the answers, the group reports that, with regard to the motivations for teaching QM in secondary school, the central point cited by all teachers is the "cultural value of QM", the fact of being one of the "fundamental theories of modern physics”, necessary to“ explain all microscopic phenomena ”. In prevalence (4/6) it is also added that: “it is interesting because it introduces absolutely new and counterintuitive ideas with respect to classical physics and common sense”; "Provides a new vision of nature fundamentally different from that provided by classical physics". All the teachers indicated the superposition principle as an indispensable basic concept: “The superposition principle is essential to understand the superimposed states, and therefore the need for a probabilistic description”. In four cases, indeterminism or the uncertainty principle are also included, because it provides a new vision of reality. Regarding the last question, some teachers claim: "Here we are dealing with choices that also depend on personal preferences"; "You cannot give a single answer, the choice is up to the teacher". The request for didactic autonomy expressed by the teachers and their personal choices emerge stronger than choices dictated by research references.

### *4.1.1 Protocols of the interview to secondary school teachers*

Returning to the survey we proposed, it is possible to divide it into four parts. The following table shows the semi-structured questions commented on in the adjacent column.

- The first part has as a model the questions proposed by the Udine Group in order to collect the teachers' convictions regarding the motivations for teaching quantum physics in schools, the essential concepts and the aspects to be privileged in a didactic proposal. The importance of quantum physics may emerge in the modern view of the microscopic world, its role as a paradigmatic theory, the role it can play in the construction of theoretical and formal thought or an attention to technological applications. The formative importance of retracing the birth of theory and contributions to the epistemological and philosophical debate may emerge.
- The second part aims to understand how the ideas expressed in the previous part could be declined in the real school experience. Here we consider also the needs of the students which the teachers found during their teaching experience.
- The third part has the aim of investigating the previous knowledge of a typical fifth class of scientific high school on particular topics that the literature indicates may influence the understanding of quantum physics and the ways in which a TLS can take shape.
- In the fourth and last part it ends with some anagraphical and personal information and any additional comment from the teacher.

With this survey we are therefore able to understand the personal ideas of teachers and to know the real school status of this part of physics teaching with particular attention to the difficulties encountered and the needs of teachers, students and their school path near to the “esame di Stato”.

| | |
|---|---|
| **PART 1**: IDEAS ABOUT introducing quantum physics at SECONDARY SCHOOL level | The **goal** is to collect the main opinions and methods about teaching quantum physics. |
| **Q1** What do you think of the introduction of quantum physics in the National Guidelines for the fifth grades of Scientific High Schools? | For example, we expect: "too difficult", "a flight forward", "necessary to introduce concepts of the knowledge of modern physics", "necessary to introduce it for wide technological applications", etc. |
| **Q2** What are the basic topics that you consider indispensable in a didactic proposal in quantum physics? Explain the reasons for the choices. | Focus on topics. |
| **Q3** Which approaches should be favored in teaching these topics? | Focus on approaches. For example, formal, historical, ontological, applicative |
| **PART 2**: HOW QUANTUM PHYSICS IS TAUGHT IN SCHOOL PRACTICE | The **goal** of this part is to understand how the ideas expressed in the previous part could be declined in the school experience. The concern also begins to turn towards the class and the needs of students. |
| **Q4** If you have already taught the quantum physics module in the past in one of your classrooms, how did you organize the teaching? Did you use methods in continuity with the other modules in physics or did you use different tools and methods than usual? Why? What textbook do you use? | For example: lectures, exercises, tutorials, video-lessons, online experiments… Understand if different methods have been implemented than those used for other topics and why. |
| **Q5** What topics did you specifically address and why? | The question is aimed at highlighting any differences with the answers given in Q2. It may be useful to investigate why some topics that are perceived as important in Q2 may not be address in teaching practice. |
| **Q6** How did you check student understanding? Did you encounter any particular difficulties? | Investigate the methods of assessment implemented by teachers. |
| **Q7** How do you assess the results obtained by students on the quantum physics module?<br>Under what conditions do you consider the student to have understood the topics? | Another interesting topic is that of "non-acceptance" (diametrically opposed to "appropriation") by students. It may be useful to discuss whether there have been cases of non-acceptance in quantum physics. |
| **PART 3**: PRIOR KNOWLEDGE OF THE CLASS | The **goal** is to investigate prior knowledge on particular topics that the literature indicates to influence the understanding of quantum physics. |
| **Q8** Regarding your current fifth class:<br><br>a) Did the students deal with probabilities and statistics? In what context?<br><br>b) Did the students face the meaning of model in physics and differences with mathematical models? | |

| | |
|---|---|
| c) How well do students know matrices and vectors and in which applications in physics?<br><br>d) Did the students make use of simulations, laboratories, software or other digital technologies in your lessons, in dealing with modern physics topics? What role do you give to these tools and how are they perceived by your students?<br><br>e) Did the students deal with Rutherford and atomic models, atomic spectra, interference and diffraction (waves, optics), the discovery of the electron (Millikan ...), polarization and polarizing filter? | |
| **PART 4**: PERSONAL DATA AND FURTHER OPINIONS | |
| **Q9**<br>Age<br>University studies<br>Courses or masters attended on topics about teaching quantum physics<br>Discipline(s) teaching<br>Years of teaching | |
| **Q10** Do you have any further comments you would like to give us? | |

It should be noted that question Q4, regarding the textbook in use at school, was included as it emerged, during the interviews themselves, that many teachers explicitly refer to it providing opinions on strengths and weaknesses of the text.

A partial transcript of the teacher answers is reported in the annex D. In the table are reported the main elements emerged from the interviews and we analyze them in detail in the next paragraph 4.1.2.

### 4.1.2 Results of the interviews to the teachers

From the answers to question 9 we get a profile of the sample of the teachers interviewed (2 female and 4 male). The years of experience range from 3 to 30. All of them teach both mathematics and physics. Four of them have got degrees in mathematics and two of them in physics. Four out of six have attended training courses related to physics teaching in the field of quantum physics. Both those who have followed the courses and those who have not followed them complain that the proposals offered by the universities are often limited to an exposition of the contents of quantum physics but not of the teaching methodologies that they consider most useful for them.

Qualitatively analyzing the answers provided by the teachers, we can deduce that in almost all cases, the teachers are positive towards the inclusion of quantum physics in the national guidelines for scientific high schools. With reference to the first question, in almost all cases this positivity is accompanied by some observations which are summarized in the following:

- Lack of time in dealing with the topics of the last year of scientific high school and the coming of the “esame di Stato”. The exam, according to the teachers, sets the need to face the topics included in the Reference Framework in the short time available and to be able to have a spare time to be spent in doing exercises in preparation of the exam by the end of the year. Furthermore, the teachers propose to their students exercises and tests that are similar to the typology of the questions of the “esame di Stato” in order to make the students practice the exam itself. Many also have the perception that the questions presented in the exam for the quantum physics module are trivial applications of a few formulas.
- Discontinuity between the method used in the previous physics modules and the method used for the module in quantum physics. Many teachers expressed the need to have tools that do not make the lesson only discursive. The complexity of mathematics for describing models is a problem, as already discussed. In this case, laboratory activities (or a computer simulation of it) takes on an even more important meaning: it allows the teacher to "demonstrate" the logical steps without resorting to excessive use of mathematics.
- According to many teachers, the textbooks have not yet reached a level of completeness equal to the other modules. It is perceived as a transition phase, in which there are still no well-validated methods and tools to use during their lessons of quantum physics.
- Even the curricular preparation of teachers in some cases constitutes a limit. Some of them complain that they have never dealt with quantum physics subjects at university (those who have studied mathematics). On the contrary, those who know well the topics report a lack of training opportunities offered by universities on the teaching of these topics. The training

courses on quantum physics are about knowledge and not didactic methodologies, as emerged from question 9.

The arguments in favor, and shared by all the teachers, are the observation that students frequently show curiosity towards this module and the opportunity for interdisciplinarity and global vision that it allows. Interdisciplinarity is generally recognized with the chemistry and philosophy course but also with art and history. The global vision of physics that allows derives from a necessary review and deepening of many of the modules addressed previously. For many teachers there is an opportunity to understand how science progresses.

As regards the second question on the topics deemed indispensable, it is noted that these correspond in almost all cases with the topics actually dealt in the school experience, asked in question 5. From this, it may follow that many teachers have mainly adhered to the idea of having to address the topics mentioned in the Reference Framework and proposed by the textbooks. In particular, the prevailing vision is the one of the historical approach (question 3) and the topics are those of the crisis of classical physics up to the Bohr atom. The concept of uncertainty is faced only by some teachers. There are some exceptions of teachers who consider other topics related to particle physics, solid state physics or astrophysics to be important, but the time available is recognized as a limit.

Turning to the method in detail, all the teachers say that there is discontinuity with the remaining modules of physics. The historical approach itself is not used in almost any of the other modules and often even the lack of proof is perceived as a limit. In many cases the laboratory is not proposed and it is recognized that this may be a limit of their preparation that could be overcome if training courses with this theme were proposed by universities (one teacher suggested this explicitly in the last question). The use of images and videos becomes more massive at this stage. The exception is only one teacher who claims to maintain a frequent use of mathematics thanks to probability distributions and their application to describe the orbitals of a hydrogen atom and the identification of the radial maximum.

From question 6 it emerges that evaluation methods also change with this module. While in the other modules the written test is the main assessment strategy, here they make a broader use of the oral interviews, quizzes and open questions assumes a greater presence. In almost all cases, as already highlighted at the beginning of the paragraph, this is a practical consequence due to the "esame di stato" because teachers choose to use assessment methods similar to those students would find during the "esame di stato" in order to train them to the exam. In addition to this motivation, many recognize that a second reason is the risk of proposing, alternatively, exercises that are either too trivial or too difficult for students. In many cases the mathematics that can be proposed is limited to the Planck and De Broglie relations.

In the seventh question the majority of teachers affirm that, although some students may have more interest in the "strangeness" of quantum physics and historical tales, the performance remains on average in line with other topics in physics. Curiosity is identified as a key element to improve attention but, on the other hand, the period next to the “esame di Stato” and university entrance tests and the change of method are a limit on performance.

Regarding question 8:

a) Statistics and probability are, in most cases, considered as complements that often cannot be addressed due to lack of time. Combinatorics and probability are addressed by all teachers although probability distributions, even if their usefulness in physics is recognized, are rarely explained.
b) In many cases it is discussed in the context of thermodynamics, the description of the solar system or atomic models. It is recognized that even the textbooks almost never refer to this concept and to the limits of applicability of the models used.
c) As for vectors, their use changes in the various classes from the definition as an oriented segment to the use of Cartesian components. However, many of the typical topics of linear algebra are not addressed and the scalar and cross products are presented only in relation to their application to the concepts of work and torque. Matrices are used only for solving linear systems.
d) The use of computer programs for data analysis, simulations and the laboratory varies a lot depending on the teacher but also on the interests of the students.
e) The concept of polarization is presented in almost all cases at the end of the electromagnetic waves before tackling special relativity. It is never studied in depth, except for some laboratory experiences.

These topics are often prerequisites in several of the quantum physics teaching proposals, some presented in the previous chapter. However, it can be seen from school practice that only some of these topics are dealt with the details necessary and in some cases they are not addressed due to lack of time.

Table 1 shows a summary of the main topics issued from the interviews. Many of these results have been considered in the design of our teaching learning sequence proposal.

| Question | Main topics that emerged |
|---|---|
| Q1) What do you think of the introduction of quantum physics in the National Guidelines for the fifth grades of Scientific High Schools? | - Positive towards the inclusion of quantum physics in the national guidelines for scientific high schools (6 out of 6)<br>- Lack of time in dealing with the topics of the last year and identification of an important constraint with the "esame di Stato" (5 out of 6)<br>- Textbooks have not yet reached a level of completeness equal to other topics adressed at secondary school level (4 out of 6)<br>- Students frequently show curiosity towards this module (5 out of 6)<br>- Interdisciplinarity and global vision that quantum physics is an opportunity (6 out of 6) |
| Q2) What are the basic topics that you consider indispensable in a didactic proposal in quantum physics? Explain the reasons for the choices. | - Crisis of classical physics up to the Bohr atom as in the Reference Framework (6 out of 6)<br>- Uncertainty (2 out of 6)<br>- Topics from astrophysics of solid state (1 out of 6)<br>- Necessary review and deepening of many of the physics topics addressed previously (6 out of 6) |
| Q3) Which approaches should be favored in teaching these topics? | - Historical approach (6 out of 6) |
| Q4) If you have already taught the quantum physics module in the past in one of your classrooms, how did you organize the teaching? Did you use methods in continuity with the other modules in physics or did you use different tools and methods than usual? Why? What textbook do you use? | - Use of images, videos and apps becomes more massive (5 out of 6)<br>- Less use of mathematics (5 out of 6)<br>- Use of laboratory activities (0 out of 6) |
| Q6) How did you check student understanding? Did you encounter any particular difficulties? | - Students show to be more interested in the narrative part of this topic (5 out of 6)<br>- Student marks are in line with those achieved in previous physics topics (6 out of 6) |
| Q7) How do you assess the results obtained by students on the quantum physics module?<br>Under which conditions do you consider the student to have understood the theory? | - Assessment methods change with this topic (4 out of 6)<br>- Assessment methods are linked to the "esame di Stato" (6 out of 6) |
| Q9) Courses or masters attended on topics about teaching quantum physics. | - Has attended training courses related to physics teaching in the field of quantum physics (4 out of 6)<br>- Complains that the proposals offered by the universities are often limited to an exposition of the contents of quantum physics (6 out of 6) |

Table 1. Main topics issued during the interviews.

## 4.2 Research design and methods

### *4.2.1 Backward design*

The method used to design the teaching learning sequence is the so-called “backward design”. The term "backward design" was introduced by Grant Wiggins and Jay McTighe in their book “Understanding by Design” [2005] to describe a design logic that focuses on the development of deep and lasting "understandings" [Whitehouse 2014].

The authors make a critic to traditional design where the main focus is on activities to be done which they also call “hands on without being minds on”. In fact, according to the authors knowledge is not simply a list of contents. The kwowledge is organized around core concepts or ‘big ideas’ that guide the students’ thinking about the domain (e.g., Newton’s second law of motion); it is “conditionalized” to specify the contexts in which it is applicable; it supports understanding and transfer (to other contexts) rather than only the ability to remember. Learning must be guided by generalized principles in order to be widely applicable. Knowledge learned at the level of rote memory rarely transfers to other contexts; transfer most likely occurs when the learner knows and understands underlying principles that can be applied to problems in new contexts. Learning with understanding is more likely to promote transfer than simply memorizing information from a text or a lecture. Therefore, they propose a design process based on two key ideas:

1. Focus on teaching and evaluating for the understanding of deep, lasting, meaningful key ideas that can be transferred to other contexts, even outside of school (*area of the meanings*);

2. A "backward" logic, in which the planning of activities is done as a last step, after you have reflected on the purposes of teaching (*area of the acquisitions*) and evaluation.

The logic is based on three steps: identify the desired outcomes (“lasting understandings”, knowledge and skills), determine evidence of acceptability (evaluation), plan experiences and education (activities). The idea is similar to “designing by skills”, because it does not start from activities or concepts but from learning goals. These learning goals are wide-ranging and can be itemized becoming specific and measurable. It is a priority to go to the heart of the question: what important understandings is our design aimed at? The word "understanding" is not obvious. In the language of the authors, but also in its etymology, it concerns with the sphere of meanings: they are “deep ideas”, those of high cultural value or founder for the discipline, wide-ranging. It obviously has a link with the concept of competence, even if it is not completely coincident. However, it is a "higher" level of awareness with respect to knowledge and skills. Deep understandings can be seen as the final outcome of the process of “appropriation” discussed before. From the concept of "understanding" we can better understand the three steps of backward design:

Step 1. Identify Desired Results. In Stage 1 we consider the goals. Analyze aims, national, international and school indications, curriculum. There is certainly a greater amount of content than what can be done so a choice has to be made. What deserves to be understood in depth and in a lasting way? What should students know, understand, and be able to do? What big ideas are worthy of understanding and implied in the established goals (e.g., content standards, curriculum objectives)? What “enduring” understandings are desired? What provocative questions are worth pursuing to guide student inquiry into these big ideas? What specific knowledge and skills are targeted in the goals and needed for effective performance?

Step 2. Define evidence of understanding and tools for evaluation. In the second stage we consider evidence of learning. How will we know if students have achieved the desired results and met the content standards? How will we know that students really understand the identified big ideas? What will we accept as evidence of proficiency? The backward design orientation suggests that we think about our design in terms of the collected assessment evidence needed to document and validate that the desired results of Stage 1 have been achieved.

Step 3. Identify specific knowledge and skills, design activities, identify teaching methodologies, materials and resources. With identified results and appropriate evidence of understanding in mind, it is now time to finalize a plan for the learning activities. What will need to be taught and coached, and how should it best be taught, in light of the performance goals? What sequence of activity best suits the desired results? How will we make learning both engaging and effective, given the goals and needed evidence?

At the end of this process, a design template is compiled. It is not a sequence to be strictly followed: on the contrary, going back and forth, reviewing and re-adjusting will be needed. In the final product is important to follow the logic which guides the design of the teaching activities.

We now discuss the design of our teaching learning sequence (TLS) which can be found in its entirety in the Appendix.

### *4.2.2 Design of the teaching learning sequence*

**Step 1: Identify learning outcomes**

In the first part we identify desired results. We are guided by national or institutional standards that specify what students should know and be able to do at the end of scientific secondary school. These standards provide a framework to help us identify teaching and learning priorities and guide our design of curriculum and assessments. In addition to external standards, we mainly consider the needs of our students and those of the teachers as emerged from the interviews. For example, student interests, developmental levels, and previous achievements influence our design as shown in Step 3. The sequence takes into account the need expressed by the interviewed teachers to pay attention to the operational feasibility, also considering the period of the school year that is close to the "esame di Stato". The introduction on models and the topics addressed in the tutorial constitutes also a review of a wide range of subjects which are included in the "esame di Stato" such as electromagnetic waves, electric circuits, elastic collisions, energy balance.

In the next table we show this part of the design template which is divided in goals from national and international standards, the identification of the enduring understandings expressed in terms of skills and knowledge that the student should acquire:

| **Goals from national and international standards** |
|---|
| From the national indications for the scientific high school, in the paragraph on quantum physics we find:<br>"[…] The affirmation of the model of the quantum of light can be introduced through the study of thermal radiation and Planck's hypothesis (also addressed only in a qualitative way), and will be developed with the study of the photoelectric effect and its interpretation by Einstein, and with the discussion of the theories and experimental results that highlight the presence of discrete energy levels in the atom. The experimental evidence of the wave nature of matter, postulated by De Broglie, and the uncertainty principle should conclude the path in a significant way […]".<br><br>These indications are clarified and listed in more detail in the reference framework for the "esame di stato" of scientific high schools which, among the essential contents, include:<br>- The black body emission and the Planck hypothesis;<br>- Lenard's experiment and Einstein's explanation of the photoelectric effect;<br>- The Compton effect;<br>- Bohr model of the atom and interpretation of the atomic spectra; |

- The Franck - Hertz experiment;
- De Broglie wavelength;
- Wave-particle dualism. Limits of validity of the classic description;
- Diffraction / Interference of electrons;
- The uncertainty principle.

These topics are in agreement with learning objectives reported in literature [Knight 2004]:
- to recognize phenomena that cannot be explained by classical physics, thus motivating the need for a new theory;
- to extablish experimental evidence by which we know about the existence of atoms and about their properties;
- to understand the photoelectric effect experiment and its implications;
- to understand the photon model and its application to the photoelectric effect;
- to understand the evidence for matter waves and the de Broglie wavelenght.

Furthermore, these topics agree with the quantum physics courses curricula from fifteen European countries as investigated by Staderman et al. [2019].

We now focus on the enduring understandigs we aim the students will achieve at the end of the learning sequence.

| Area of the meanings |
|---|
| **Enduring understandings** |
| • The concept of model in physics. Limits of applicability: the student must not develop the incorrect feeling that everything he has previously studied in physics is wrong;<br>• Role of the experiments;<br>• Overcoming the wave-particle dualism. Knowing how to argue about the models that describe the behavior and nature of quantons. |

| Area of acquisitions | |
|---|---|
| **Knowledge** | **Skills** |
| Describe Lenard's experiment and discuss Einstein's explanation of the photoelectric effect. | Apply Einstein's model to the photoelectric effect. |
| Describe the black body emission and interpret it using Planck hypothesis. | Illustrate the black body model by interpreting the emission curve on the basis of Planck's distribution law. |
| Define the de Broglie wavelength and explain the reasons why it was introduced. | Discuss the terms wave and particle. |
| Discuss the wave model and the particle model. Know the limits of validity of the classic description. | Calculate the wavelength of a particle and compare it with the wavelength of a macroscopic object. Estimate Planck's constant. |
| Describe diffraction and interference of electrons.<br><br>Discuss the idea of quantons relating it with the wave-particle duality. | Analyze experiments of interference and diffraction with particles, illustrating how they can be interpreted starting from the De Broglie hypothesis. |
| | Discuss, referring to specific experiments, the limits of the classical paradigm of explanation |

| | |
|---|---|
| | and interpretation of phenomena and argue the need for a quantum vision with reference to the specific experiments. |

**Step 2: Evidence of learning**

The second step is the definition of evidence of understanding and the choice of tools for evaluation. In this proposal it was decided to diversify the assessment during the course. This decision is based on two reasons. First, diversification allows for the monitoring of learning over time. It also allows to verify that the learning is authentic and non-incidental in the meaning discussed in the previous chapter (see “The concept of appropriation”).

The evaluation process goes through the following stages:

- An initial moment in which initial conceptions are collected by the students. Student are divided into groups of three and, through a discussion at home, they have to describe their ideas about light, electrons and atoms, illustrating their main properties and which experiments they have studied about them.
- An evaluation of the work done on the tutorial to verify the understanding of the photoelectric experiment and the relationships between the fundamental quantities involved in the phenomenon.
- A written essay after introducing Einstein's quantum model in order to verify if the student has understood the need for a new model to explain the phenomena observed through the photoelectric effect.
- A final informal interview with students divided into the same groups as in the tutorial. In this interview some general questions on the learning path were added in order to evaluate the TLS itself.

**Step 3: Developing learning activities**

In the last step we finalize a plan for the learning activities. The chosen approach is placed between the historical and qualitative approaches with the aim of creating the need for a new model starting from the main experiments of the first years of 1900, paying attention of not using typically semiclassical terms in order not to hinder the conceptual shift of students. This approach is the one which best fits with the requests from the national standards that ask for an introduction of the experiments of the first years of 1900. The large use of images, videos and online simulations is aimed at satisfying the cognitive need of visualization. This need is increased because of the distance learning connected to the sanitary emergency. Furthermore, with distance learning the hours of physics lessons are reduced from three to two per week. The tutorial proposed together with the online simulation of the photoelectric effect allows us to focus on a historically important experiment and replaces a purely formal approach for the presentation of Einstein's quantum model [Besson, pg. 90].

The sequence also takes into account the need expressed by the interviewed teachers to pay attention to the operational feasibility, also considering the period of the school year that is close to the "esame di Stato". The introduction on models and the explanation of the tutorial constitutes also a review of a wide range of topics which will be useful for the "esame di Stato" such as electromagnetic waves, electric circuits, elastic collisions, energy balance. We now describe the plan of activities in our teaching learning proposal.

- *Initial discussion on models in physics*

The teaching learning sequence begins with a discussion on models in physics using as an example the nature of light itself through the historical debate between Newton and Huygens. Through a discussion led by the teacher, the two models historically used to describe the behavior of light are analyzed, especially underlining the contrast, within classical physics, between wave and corpuscular models and the motivations, also recalling simple experiments seen in past school years. The goal is to make students understand how even in classical physics there are more models for describing the same physical entity with each of them explaining some behaviors more effectively than the other. A discussion on the Newton's model of light, as in its "Opticks" 1704, was necessary since students know the Huygens wave model of light but never had the chance to learn how Newton treated light (see Appendix, lesson 1).

For the electron we discussed the experience of Millikan with cathode rays. This discussion gives the opportunity to question how the definition of a physical object can be contextualized within a chosen physical model and to analise what are the properties of a physical object that we measure in a given experiment and how we measure them. In our view, this discussion should favour in students a reflection on what they can see directly with their senses and what properties of an object can be measured from an experiment without “seeing it” (such as in the typical source-detector experiments in quantum physics).

*- Gathering initial students' ideas*

After that, students are divided into groups of three and at home they are asked to discussed and write a synthesis of their ideas about light, electrons and atoms, their main properties of these entities and experiments they recall about them. This is done through the completion of an assigned table where students had to give definition, properties, a representation and a list of linked experiments about the light, the electron and the atom.

*- The photoelectric effect*

We next focus on photoelectric effect which represents the core experiment of the teaching learning sequence. The photoelectric effect is studied through a tutorial to be done at home whose aim is to create a "conflict" with classic ideas through the results of the photoelectric experiment that students carry out using an online simulation . The design of the tutorial is shown in the next chapter 4.3. After that, a revision of the work done on the tutorial and a classroom discussion about the critical points of the photoelectric effect is led by the teacher and the Einstein's photon model is introduced in order to explain the phenomena observed.

*- Relevant experiments of the beginning of the 19th century (black body, double slit with electrons)*

After the correction of the tutorial, we discuss further experiments to show the need for a new model to explain the discussed experiments. The teacher describes experiments such as black body and double slit experiments with electrons which cannot be interpreted correctly in the context of classical physics.

*- Classroom discussion on the role of models in physics: the quanton*

In conclusion, we return to discuss about the definitions proposed at the beginning of the teaching unit. We found that contradicting ideas and wave-particle duality are the main ideas that students learn from popular physics. These ideas make students focus on the failure of classical physics and creates a feeling of incompleteness and strangeness in connection to modern physics. The concept of quantons, proposed by Lévy-Leblond [2003] at a qualitative level, tries to overcome this difficulty . If we describe microscopic entities by introducing the concept of "quanton", there is no need to invoke contradictions and wave-particle duality. With students, the concept of quanton is introduced through the readings from Einstein and Lévy-Leblond as discussed in chapter 4.4.

## 4.3 Tutorial about the Photoelectric Effect

This paragraph together with the following one introduces in more detail the design of the tutorial and the presentation of the concept of “quanton” to students since they represent the most distinctive and innovative parts of the TLS.

During his experiments on electromagnetic radiation (in which he demonstrated that light consists of electromagnetic waves), Hertz noticed a spark between the two metallic balls when a high frequency radiation is incident on it: this is called photoelectric effect. Photoelectric effect is the emission of electrons when electromagnetic radiations with sufficiently high frequency is incident on certain metal surfaces. We call the emitted electrons as photoelectrons and the current they constitute as photocurrent. The phenomenon was first observed in 1880 and explained by Albert Einstein in 1905 using Max Planck's quantum theory of light. As the first experiment which demonstrated the quantum theory of energy levels, photoelectric effect experiment is of great historical importance.

The photoelectric effect is a powerful tool to help students build an understanding of the photon model of light, and to probe their understanding of the photon model. However, literature results found difficulties understanding even the most basic aspects of the photoelectric effect, such as the experimental set-up, experimental results, and implications about the nature of light. Steinberg et al. [1996] identified the following specific student difficulties:

- a belief that V = IR applies to the photoelectric experiment;
- an inability to differentiate between intensity of light (and hence photon flux) and frequency of light (and hence photon energy);
- a belief that a photon is a charged object;
- an inability to give any explanation relating photons to the photoelectric effect.

These difficulties are taken into account in the design of the tutorial.

### *4.3.1 Design of the tutorial*

Basing on these premises, we have developed a tutorial in which the students make use of an interactive simulation. In particular, at the end of the tutorial, students should be able to:

1. correctly predict the results of experiments of the photoelectric effect (e.g., how changing the intensity of light will affect the current and the energy of electrons, how changing the wavelength of light will affect the current and the energy of electrons, how changing the voltage of light will affect the current and the energy of electrons, how changing the material of the target will affect the current and the energy of electrons);

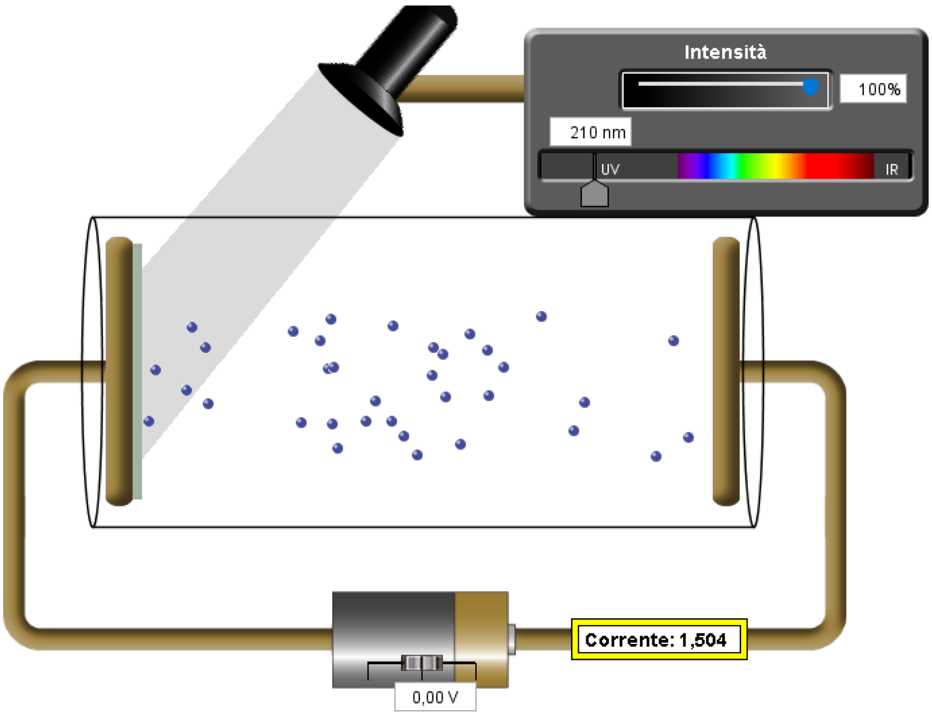
2. describe how these results lead to the photon model of light and which results contrast with the classical interpretation (e.g., argue that only a photon model of light can explain why, when light is shining on the metal but there is no current, increasing the frequency will lead to a current, but increasing the intensity of light or the voltage between the plates will not).

The experiment is proposed to be explored through an interactive simulation since not all the schools have the setup needed in their laboratories and because of the distance learning modalities due to the spread of COVID-19 pandemic. The role of interactive simulations has been studied in depth by educational research, and the general conclusion is that such instruments, especially when used in the context of guided exploration and inquiry activities, can offer significant support to the learning process, and provide relevant educational gains (see Rutten, 2012; Swaak, 2001; Blake, 2007; Fraser, 2006; Podolefsky, 2010). This is particularly true for subjects, such as quantum physics, in which real experimental activities in the laboratory are not easy to realize, at least for advanced problems. The number of researchers who focused on developing computer simulations of quantum phenomena for educational use has been steadily growing in the last 20 years. Several online repositories of educational simulations for quantum mechanics exist: QUVIS of University of St. Andrews; Physlets of the comPADRE group; PhET of University of Colorado; Visual Quantum Mechanics from Kansas State University.

"True" remote laboratories are those in which real, functioning and operational apparatuses are synchronously controlled through the visual interface, and results are displayed precisely as they were obtained in the experimental run that the user has initiated. True remote laboratories are certainly more fascinating for students, but also have the disadvantage that only one user at a time can perform an experimental run. Realistic virtual simulations allow users to visualize apparatuses and obtain realistic experimental results and are alternative or complementary to both real experiments and true remote laboratories. In our case, we use a realistic virtual simulation from PhET (which can be found in https://phet.colorado.edu/en/simulation/legacy/photoelectric).

The tutorial requires an introduction during the frontal lesson which includes an historical presentation of the experiment and an explanation of the experiment set-up: vacuum tube, the circuit and metal cathode, ammeter, battery. There is also a discussion about which quantities can be set up and which ones are measured and about the general functioning of the simulator. First of all, students should provide the classic explanation based on thermal emission, define the concept of extraction work and write the electron energy balance. This review part is also useful as a review of various topics in view of the "esame di Stato" and makes students aware of the complexity and transversality of this experiment in relation to different physics issues.

The tutorial is assigned to students as homework by dividing them into groups of 3 students. The same division into groups was maintained for all activities. The following picture shows a screenshot from the simulator:



The tutorial is shown in the Appendix and we now discuss it. In particular:

- The first section focus on the classical model of light and the concept of thermal emission and questions aim to stimulate students to recall previous knowledge and to make predictions based on it.

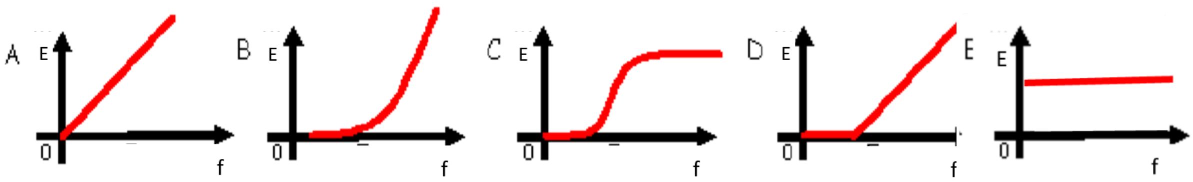
*Refer to the phenomenon of thermal emission from a metal surface.*

*a) What happens to the metal surface when light hits it? How would you represent it with a drawing?*

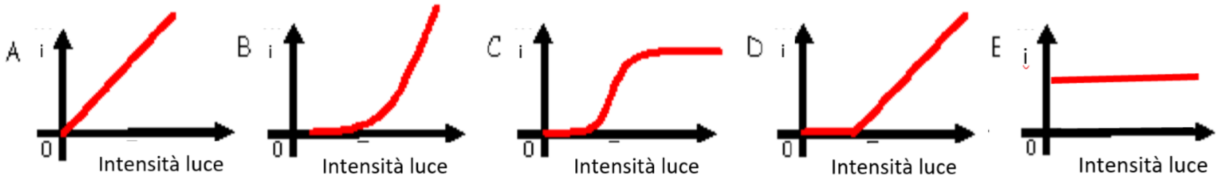
*b) Does the phenomenon of electron emission occur for any value of the light frequency?*

*c) Choose the graph that correctly represents the relationship between the following quantities:*

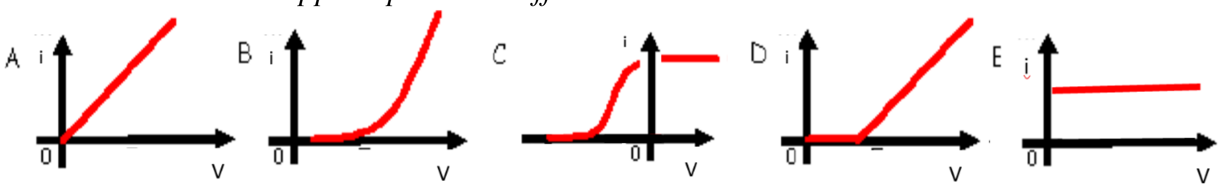
• *Kinetic energy of the emitted electrons and frequency of the incident light*




• *Electric current and intensity of incident light*




• *Electric current and applied potential difference*




The subsequent questions aim at checking if students make correct use of the various features of the simulator.

Then, through a free exploration of the simulator, they are asked to identify the characteristic physical dimension of the experiment which causes the emission of electrons and a current in the circuit.

*Using the two cursors G and H, set the wavelength to 690 nm (corresponding to red) and vary the intensity of the light, then vary the wavelength until you observe the emission of electrons from the metal cathode. Now try adjusting also the potential applied through the slider F.*

*What parameter caused the electron emission to begin? Explain.*

This first step is a qualitative exploration of the experiment and they can notice a first important incongruence between the classical model of thermal emission of light and what they observe as a result of the experiment. Afterwards, students are guided through a more quantitative analysis of the experiment.

- In the "role of the threshold frequency" section, the goal is to understand which physical variable determines the emission of electrons and what is their initial energy once extracted.

They repeat the previous observation for several materials in order to observe the link between the material and the threshold frequency and they recognize that the extraction work is a characteristic of the material. Then, focusing on a single material, they collect data on the energy of the emitted electrons as a function of the frequency of the incident light and they identify a threshold frequency, which cannot be explained in the classical context.

> *Choose a material. Move the slider that adjusts the wavelength to the maximum value and, keeping the light intensity fixed at 100%, start moving it slowly.*
>
> *- What wavelength does the emission starts at?*
>
> *- What happens by decreasing the wavelength again?*
>
> *Repeat the observation for all materials. For each one it derives from the simulation the wavelength at which the emission starts (which is therefore defined as the "threshold" wavelength) and calculate the corresponding frequency (threshold frequency).*
>
> *From now on, focus on just one cathode material, Copper. Plot the Energy of electrons vs. Light frequency you get by setting the light intensity to 100% and moving the slider that adjusts the wavelength.*
>
> *Identify the following on the graph:*
>
> *A - the threshold frequency*
>
> *B - the range of frequencies that determines a kinetic energy of the electrons greater than zero*
>
> *C - the range of frequencies that do not cause electron emission*

- In the section "role of light intensity in the photoelectric effect" the goal is to understand what determines the number of electrons emitted.

> *Adjust the wavelength of the incident light so that it is greater than the previously determined threshold wavelength (therefore frequency lower than the threshold frequency). Now experiment by moving the slider that adjusts the intensity of the light.*
>
> *Are there light intensity values that determine an electric current in the circuit?*
>
> *Adjusts the wavelength of the incident light so that it is lower than the threshold wavelength (therefore frequency greater than the threshold frequency). Now experiment again with the slider which controls the intensity of the light.*
>
> *Does the intensity of the light affect the number of electrons that are emitted?*

*Does the intensity of the light affect the speed with which the electrons are emitted?*

*Draw below the graph Current vs. light intensity you get by setting the wavelength of light to 150 nm and moving the slider which controls the light intensity.*

*How does the intensity of the electric current change in the circuit? Explain why bymaking reference to previous answers.*

- The section "stopping potential difference" aims at exploring the phenomenon in relation to this quantity and to collect some data which then are used to estimate the Planck constant.

*Set the wavelength of the incident light to 150 nm, the intensity of the light to 100% and the value of the potential difference of the battery to zero (it is useful for this point to select the option "show only electrons with higher energy high ").*

*What happens to the motion of the electrons if you move the cursor by setting positive values of the battery potential difference?*

*What happens to the motion of the electrons if you move the cursor by setting negative values of the battery potential difference?*

*Draw below the graph Current vs. battery voltage you get by setting the wavelength of light to 150 nm, the light intensity to 100% and moving the slider that adjusts the value of the potential difference of the battery.*

*Use the graph to find the potential difference that you need to apply to zero the current intensity. This potential difference is the stopping potential difference.*

*Once the found value of the stopping potential difference has been set for the battery, the slider of the light intensity and wavelength of light varies. Does the value of the stopping potential difference change by varying the intensity of the light? And by varying the wavelength?*

At the end of the work student are asked to upload their product and in the following lesson, the main results of the experiment are discussed in order to understand which of the behaviors can be explained classically and which cannot:

- Increasing the light intensity increases the current but not the stopping potential (in contrast with what should occur with thermal emission);
- There is a threshold frequency, or wavelength, that depends on the cathode material (in contrast with the classical expectation);
- Regardless of the light intensity, the current appears instantly with no delay.
- Increasing the intensity of the incident light intensity, the measured photocurrent increases (as expected).

- The stopping voltage does not depend on the light intensity.
- The stopping voltage depends on the frequency of the incident electromagnetic radiation (simple dependence $U_0 = U_0(f) = U_0(1/\lambda)$ was surprising – see the Fig. a).
- No photocurrent can be observed for frequencies less than a given threshold frequency $f_0$ (i.e., wavelengths greater than the corresponding threshold wavelength $\lambda_0$), and this frequency depends only on the material of the photocathode, regardless of the light intensity.
- The saturation photocurrent is determined by the intensity of light. (See the Fig. b).

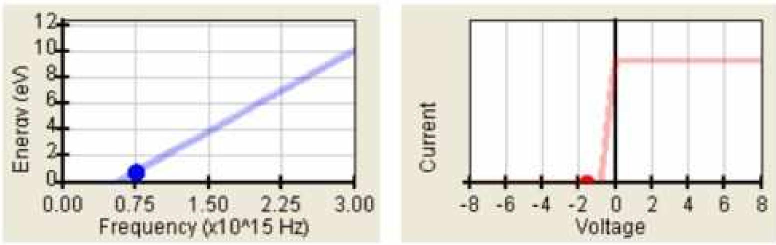



**FIG.: a)** simple dependence kinetic energy of electrons vs. frequency of incident light, **b)** typical current-voltage characteristics.

## *4.4 Wave-particle dualism and the idea of quantons*

Most textbooks and popularization works about quantum physics remain plagued by archaic wordings and formulations. These observations were underlined also by some of the teachers interviewed who says explicitly they try to avoid students to the erroneous belief that everything which has to do with physics before quantum physics is wrong.

Initial formulations of novel conceptions, being still tributary to the old views they are to replace, of necessity are awkward and inappropriate. Any scientific theory, following its inception, then has to undergo a recasting process through which its notions are clarified and its terms improved. An example in point is offered by maxwellian electromagnetism, which, within a few decades, evolved from a mechanistic presentation (dealing with stresses and motions in a material medium, the ether) to a radically novel theory of fields. The question then is that of the reasons for the delays in the recasting process of quantum theory (and much the same remarks could be developed for relativity theory).

“Wave” and “particle” are not things but concepts, and incompatible ones; as such, they cannot characterize the same entity. While it is true that quantum objects may in some cases look like waves, and in other cases like particles, it is truer still that in most situations, particularly the ones explored by the elaborate modern experiments, they resemble neither one nor the other. The situation here is reminiscent of that encountered by the first explorers of Australia, when they discovered strange animals dwelling in brooks.

To stress the meaning of this notion we can examine it from the point of view of the discrete/continuous dichotomy. Quantons show discreteness in that they come in units and can be counted: an atom has an integer number of electrons, and a photographic plate registers the individual impacts of photons. Nevertheless, electrons as well as photons (and all quantons) do show continuous essence as well, since they can be subjected to interferences, superposition, etc. In fact, it should be realised that a physical object must be characterised through the consideration of two discrete/continuous dichotomies; one has to consider separately the question of the number of objects and the question of their extension (spatiotemporal properties). Within classical physics, these two questions merge. Classical particles are discrete under both aspects; they come in discontinuous counts and are discretely localised. Classical fields are continuous under both aspects; they have continuous amplitudes and continuous spatial extensions. But quantons exhibit the original combination of discreteness in number and continuity in extension, as shown by the following table [Lévy-Leblond 2003]:

| | **Number** | **Extension** |
|---|---|---|
| **Particles** | discrete | discrete |
| **Fields** | continuous | continuous |
| **Quantons** | discrete | continuous |

This double nature of quantons is not a contradictory one since discreteness and continuity do not refer to the same notions.

It is possible to understand the two partial classical appearances of quantons; if, in a given experimental set-up, the discrete character of their number is preponderant and the continuous character of their extension secondary, they can be approximately described as particles. Conversely, if, in another experimental set-up, the discrete character of their number is secondary and the continuous character of their extension preponderant, they can be approximately described as waves The latter cases mostly met for macroscopic systems comprising a large number of quantons, which often may be reasonably treated by a continuous description (as, in classical physics, a flow of sand or grain may be assimilated to a fluid). But in most cases, especially in the very sophisticated modern quantum experiments, quantons certainly look neither as waves nor as particles, and must be accounted for through their intrinsic and unique conceptualization

It must be stressed that the continuous nature of quantons is not limited to their spatial localisation; it holds as well for all physical magnitudes associated to space-time, such as speed, momentum, and energy. While for classical entities, the physical properties take on unique and determined numerical values, for quantons they are characterised by numerical spectra, extended sets of numerical values. The possible discretisation of some of these spectra, for instance the energy levels of a bound system, is but a particular case, linked to the spatial confinement of the system (in close analogy with the quantisation of the frequencies of vibrating strings).

#### *4.4.1 Implementation of the idea of quantons in the TLS*

The idea of quantons was introduced in the learning sequence, as final step, through an active classroom discussion led by the teacher. During this discussion we tried to reorganize the initial conceptions gathered from the survey on the initial student ideas and we made use of two readings, the first written by A. Einstein and the second by Lévy-Leblond.

To overcome the contradiction of the wave-particle dualism that can be generated after discussing the various experiments that characterized the physics of the early 19th century (in some the wave property is highlighted in others the corpuscular one) we start with a reading by A. Einstein on the properties of a physical entity and on how to "measure" them. The idea outlines in the extract is that we can distinguish between a wave or a particle (as meant in classical physics) through their “effects” on a detector. The questions proposed to the students are: what does it means that an object behaves like a particle or a wave? How can we apply this approach to a quantum object which cannot be seen by our eyes?

Distinguishability of wave effects and particle effects from A. Einstein (1938), *L’evoluzione della fisica*, p. 41:

*“We observe a wall built on the sea. The sea waves continually hit its surface and retract one after the other to give way to the occurring ones. The wall wears out, that is to say its mass is reduced and we can ask ourselves what is the quantity removed within a certain period of time, let's say a year. Now let's imagine a different process, with which to reduce the mass of the wall to the same extent. We shoot against the wall, splintering it in the places hit by the bullets. The mass of the wall will also decrease with this method and nothing prevents us from imagining that in both cases the reduction could be the same. However, from the appearance of the wall we will always be able to judge which cause has acted, whether the continuous action of the waves or the discontinuous barrage of the bullets. To understand the phenomena we are about to describe, it will be good to keep in mind the difference between sea waves and volleys of bullets. "*

The second reading is an extract of the article “On the nature of Quantons” (2003) by Lévy-Leblond. This reading makes also use of a metaphor which can help students to understand the nature of quantum particles.

*“The fact that the true nature of quantum objects has long been misunderstood is demonstrated by the common description that is still made today in terms of an alleged 'wave-particle dualism'. First of all, it should be pointed out that this formulation is at least ambiguous. Because it can be understood both as if it were saying that a quantum object is at the same time a wave and a particle,*

*or that it is sometimes a wave and sometimes a particle. Neither of these two interpretations actually makes sense. "Wave" and "particle" are not objects but concepts, and mutually incompatible; therefore, they absolutely cannot describe the same entity. While it is true that quantum objects may in some cases resemble waves, and in other cases particles, it is certainly truer than in most situations, particularly those faced by elaborate modern experiments, they resemble neither. The situation described above is reminiscent of that encountered by the first explorers of Australia, when they discovered strange animals that lived in the streams. Seen from the front, these animals showed a duck beak and webbed legs, while, seen from behind, they showed a hairy body and a tail. They were then nicknamed "duck-beaver". It was then discovered that this beaver-duck dualism had a limited validity and that the zoological specificity of this animal deserved a proper name, which became "duckmole". In much the same way we can (and must) then confidently affirm that quantum objects are neither waves nor particles and must be described by a new and specific concept, which certainly deserves a name of its own. The proposal is to call them "quantons".”*

## 4.5 *Experimentation of the TLS in a real classroom*

The teaching learning sequence presented above was tested in a fifth grade of an italian “liceo scientifico” which is the only typology of high school address where the quantum physics module has to be taught. Due to the spread of COVID-19 pandemic, we were not sure whether the developed TLS could be tested in a real classroom. Thanks to the collaboration of Professor Stefania Lippiello we were able to experiment the TLS in one of her classes. As a matter of fact, the teacher was taking part into an in-service teacher training programme named COLLABORA – a Community Of Learners on LABORAtory – work, promoted by the Research Group in Physics and Astronomy Education of Padua, when we started designing the teaching-learning sequence (TLS). During this programme the teacher already had the opportunity to work with the backward design logic. One of the tasks during the training was the development of TLSs using the backward design approach.

The fifth grade classroom was made up of 21 students from the “liceo scientifico” Jacopo da Ponte in Bassano del Grappa (VI) and the lessons took place in distance learning from April to May 2020.

The following diagram shows the actual plan of the lessons carried out in the classroom and at home by the students during the intervention. The materials and tools used during the different meetings are also reported. The lecture notes delivered to the students are listed in the Annex.

| |
|---|
| **Lesson 1 - 24/04/2020** |
| Classroom: Introduction on the concept of model in physics (scientific method) and application to light (file "Introduction"). Use of PhET - University of Colorado [PhET] “bending-light” and “wave-interference” simulators.<br>Homework: Table on initial ideas to be completed at home divided into groups of 3.<br>Materials: files “Metodo sperimentale” and “Luce” in annex C. |
| **Lesson 2 - 28/04/2020** |
| Classroom: Discussion of the homework, discussion about electron discovery, introduction to the photoelectric effect and to the use of the online simulator.<br>Homework: Tutorial with the same division into groups.<br>Materials: file “Elettrone” e “Effetto fotoelettrico” (annex C), simulator and template “Tutorial” (annex B). |
| **Lesson 3 - 05/05/2020** |
| Classroom: Correction of the first part of the tutorial. Discussion on "Fermi estimates": for example, estimate on the speed of electrons to understand if it is necessary to use the relativistic formula for kinetic energy or if the classical formula is sufficient, |

| |
|---|
| Materials: file "Electron speed" in annex C. |
| **Lesson 4 - 09/05/2020** |
| Classroom: Conclusion of the correction of the tutorial.<br>Materials: Tutorial with correct answers. |
| **Lesson 5 - 12/05/2020** |
| Classroom: Einstein's explanation of the photoelectric effect (file "Einstein explanation of the photoelectric effect") linking it to the observations made during the correction of the tutorial.<br>Materials: file “Spiegazione Einstein effetto fotoelettrico” in annex C. |
| **Lesson 6 - 16/05/2020** |
| Classroom: Discussion on blackbody with the aim of providing a historical explanation for the introduction of the formula E = hf by Planck (file “Corpo nero”). Double slit interference with electrons. Use of the blackbody-spectrum simulator and double-slit-simulation for the double slit of PhET.<br>Homework: Essay about the photoelectric effect.<br>Materials: file “Corpo nero” in annex C. |
| **Lesson 7 - 19/05/2020** |
| Classroom: Conclusion and discussion of previous lesson topics and introduction to quantons. |
| **Lesson 8 - 25/05/2020** |
| Classroom: Estimation of the constant h (and meaning of h in analogy with the meaning of c for the theory of relativity) and readings from Einstein and Levy-Leblond on quantons.<br>Materials: Readings from Einstein and Levy-Leblond (chapter 4.4.1). |

# 5. Results

## 5.1 Students' initial conceptions

The following table summarizes the answers returned by the students through the fulfillment of the table assigned to gather their initial conceptions. The students were divided into groups of 3 (the groups are indicated in parentheses). It should be noted that, especially by the more participatory students, the compilation of this table was mainly appreciated for two reasons: the opportunity to create a discussion with classmates and the opportunity to review topics faced in the past or in other disciplines. The latter reason is related to the need, which emerged from the students, to have a global vision of the subject and the opportunity to review the previous topics in view of the "esame di Stato".

| | DEF. & PROPERTIES | REPRESENTATION | LINKED EXPERIMENTS |
|---|---|---|---|
| **Light** | - electromagnetic wave (Maxwell) (G5, G2, G3)<br>- particle (Newton) (G5, G2, G3)<br>- constant speed in vacuum (G5, G2, G7, G1, G6)<br>- frequency and wavelength (G2)<br>- polarization (G1, G3, G6)<br>- color = frequency (G3)<br>- 4 theories: Newton's corpuscular, Huygens' wave, Maxwell's electromagnetic wave and quantum vision (G4) | - photon or electromagnetic wave. Changes according to the situation (G5)<br>- as an electromagnetic wave (G2, G3, G4)<br>- corpuscular or wave (G7)<br>- "it can be represented as a wave according to Huygens' model, as a particle beam according to Newton's model or as a particle (photon or quantum)" (G1)<br>- Representation with a ray model linked to the phenomenon of refraction and reflection (G6) | - Young double slit (G5, G2, G1, G3, G6)<br>- photoelectric effect (G1, G5, G6)<br>- decomposition of light into colors (G1, G2, G4, G5)<br>- exp. by Michelson-Morley (G5, G7)<br>- lenses (G2)<br>- reflection and refraction (G1, G2, G3, G4, G6)<br>- interference (G1, G3)<br>- absorption (G3)<br>- Romer, Fizeau, Foucault and Michelson for speed of light (G1)<br>- Huygens principle (G6)<br>- Compton effect (G1, G6)<br>- Doppler effect (G6) |
| **Electron** | - elementary particle (G5, G4, G6)<br>- mass (G2, G7, G1, G3, G4)<br>- volume (G7)<br>- component of atoms (G5, G6)<br>- negative charge (G5, G2, G7, G3, G4, G6)<br>- orbitals (G2)<br>- wave function (G2) | - particle in traditional models, description of motion and position through wave function (G5)<br>- representation linked to the orbital model of the atom. (G4, G6, G7, G2)<br>- "the classical representation according to the energy levels of the atom: 2 electrons on the first level, and then 8 for each | - beta radiation (G5)<br>- Rutherford experiment (G2, G3)<br>- Crookes, Thomson (cathode ray tube) (G7, G4, G6)<br>- Millikan (G1, G7, G6)<br>- Gold leaf electroscope (G3) |

| | | | |
|---|---|---|---|
| | - Heisenberg principle (G2)<br>- spin 1/2 (G1, G3) | level going up in ascending order" (G1)<br>- "in reality we know that it cannot be represented / seen because it is too fast and constantly moves in the orbital "(G3) | |
| **Atoms** | - Atomic mass (G7, G3)<br>- Atomic number (G3)<br>- mass (G1, G4)<br>- energy (G1)<br>- volume (G7, G1)<br>- neutral charge (G1, G4, G6)<br>- density (G7, G3)<br>- Made up of subatomic particles: e, p, n (G6, G5, G2, G4)<br>- Oxidation number, electronegativity (G7, G3) | - Orbital model, in the past the orbit or Thomson model (G5, G3, G6)<br>- Orbit model (G2, G7)<br>- Orbital model (G2, G3)<br>- Thompson, Rutherford and Bohr model (G1, G4) | - Rutherford experiment (G5, G2, G7, G1, G3, G4, G6)<br>- Bohr atom (G2, G7) |

Discussing light, all students recognize it as an electromagnetic wave (linked to Maxwell equations) and Newton's corpuscular model. These models are both simultaneously present in the students' initial conceptions. In particular, Group 4 indicates 4 definitions: distinguishing Huygens' wave theory from Maxwell's and proposing a "quantum vision" besides the corpuscular model. The listed properties are all in reference to the wave model (frequency, wavelength, polarization). This can be justified considering that Maxwell's wave model is a topic of the same school year, as is Einstein's relativity. Furthermore, although they know Newton's corpuscular hypothesis, they never had the opportunity to study it in detail.

These observations are confirmed by the the mental representations of the students. Light is represented as periodic waves as it is done usually for waves or with "points" in the corpuscular case. We note that the term "particle" and "corpuscle" and also "photon" and "quantum" are used with an equivalent meaning. These terms are now in common use and all students have used them in the chemistry course.

The experiments discussed are all typically addressed during the fourth and fifth years of the scientific high school. We can also observe that few groups mention experiments not yet faced in the physics curriculum such as the photoelectric effect and the Compton effect.

As regards the electron and the atom, the prior knowledge developed in the chemistry course, in the study of the constituents of matter plays some influence. Concepts such as "wave function", "spin", "orbitals" encountered in chemistry (but never deepened and systematized) are present in the list. Therefore, both model of wave and particle are present and coexist and some groups expressed the idea that they should use one or the other according to the situations or according to the "exercises" that are proposed to them. In the case of atoms, all the models that are usually presented during a historical discussion of the evolution of the model of an atom are listed by the groups.

These observations are in agreement with the typical students' pre-knowledge highlighted by the literature in physics education (chapter 2.1) and confirm that the teaching of quantum physics must take care to systematize ideas that students already know, often incomplete if not incorrect. Hence the importance of discussing models and their limits of applicability during the physics course in order not to convey the coexistence of opposing ideas.

## *5.2 Tutorial*

The tutorial, carried out at home by the students divided into groups, was corrected in class through a discussion led by the teacher. Like many of the other activities, the correction of the tutorial was also an appreciated opportunity to discuss other issues faced previously in the physics curriculum, including the concept of measurement and if we we can associate an error to a measurement made through a simulator, or electric circuits and the motion of particles in an electric field.

The homework done by the students have been qualitatively analyzed and we the results below.

Overall, it is possible to state that the work was good for all groups and there are no cases of particular misunderstandings about the operation of the simulator. The following analysis does not discuss errors in the calculations or in the representation of the data.

The first section of the tutorial is useful to verify if the students understood the phenomenon of thermal emission in the classical context and if they are able to make predictions on the photoelectric experiment based on this model. At this point it is observed that there are some difficulties due to the fact that some groups have tried to answer referring on their prior knowledge about the photoelectric effect. Other students, despite having understood the classic model of thermal emission (question 1a) have identified with difficulty the intensity as a threshold quantity for this experiment (incongruent answers in question 1b and 1c). During the discussion in class, while correcting the tutorial, it emerged that these errors are related to the fact that some groups knew, in general terms, the concept of threshold frequency; for other groups the difficulty was related to the understanding and interpretation of the graphs themselves but also to the difficulty, once a model has been chosen, of being consistent with the answers while maintaining the same model. In the first case, despite the exercise asking to predict the result on the basis of classical knowledge, the previous knowledge, albeit fragmentary, of the photoelectric effect prevailed as for Group 4, which justifies: *"The first graph represents the relationship between kinetic energy and frequency, represented by a broken line, which initially coincides with the x axis and then begins to grow with a direct proportionality, this is because a minimum frequency is needed so that the electrons can be extracted from the metal. "* Although in the previous point they stated: *"[in the context of the classical interpretation ...] therefore we expect in the first place the existence of a minimum threshold of light intensity, below which electrons cannot be emitted because the energy would be insufficient, and secondly, as the intensity of the light increases, the number of electrons emitted should also increase. "* This Group, in the graphs, recognizes both a threshold frequency and a threshold intensity by choosing option D for both questions.

In the following questions, the answers are correct for all groups, demonstrating an understanding of the correct use of the simulator and the interpretation of the data available to them.

It should be noted that Group 4, already taken as an example for question 1, in point 4c recognizes a connection between their previous knowledge and what they collect from the simulator. In fact, they are able to explain the trend of the graph by referring to the well-known Planck relation, known to them, $E = h (f - f_0)$.

In point 5 of the tutorial, both in the definitions of point 5a and in the explanation (point 5c), some contradictions emerge which have the same origin as those that emerged in point 1. The definitions of light intensity show how many groups have preferred to rely on a particle model: *"the number of photons that crosses a unitary section in the unit of time."* When trying to justify the trend of the current measured as a function of the set light intensity found in point 5c, all the students recognize their direct proportionality but, as also emerged from the questions asked in classroom, no one was able to justify why current went to zero only for null values of the intensity. In this way, it emerges that the students have the perception that the classic model is unable to correctly justify the overall trend although it is not able to correctly put the question in terms of threshold quantities.

In conclusion, with the last question of the tutorial, students are stimulated to justify the trends found by the experiment. Most of the students during the tutorial became aware of the incompleteness of the model in use and in some cases stating it explicitly: *"Based on the empirically collected data we can establish that the laws taken into account to determine the graphs before the experiment are not complete"* or *"In reality, a minimum threshold of light intensity is not necessary for the current to increase, as long as it is greater than zero"*. The only exception is the group 4, that answered the first question having in mind the previous knowledge on the photoelectric effect and not the classical model, in fact: *"In all three cases the graphs coincide with the prediction made in point 1c, which are therefore have been experimentally verified. "*

## *5.3 Comment on the essays*

After the explanation in class of Einstein's quantum model, the students were given an essay to be done at home with the aim of verifying if students understood the photoelectric experiment and the Einstein explanation.
This task was not mandatory because many of the students were focus on the university entrance tests or on the "esame di Stato". 14 students submitted the essay: 2 students from group 1, 3 students from group 2, 1 student from group 3, 2 students from group 4, 3 students from group 5, 2 students from group 6 and 1 student from group 7.

The essay was semi-structured and the following questions were provided for guiding the presentation:

*Explain the photoelectric effect, through the following points:*

*1. What does the phenomenon consist of? Also briefly describe the instrumental apparatus.*

*2. What did the classical model foresee?*

*3. What did the experiment show instead (what was not explainable through the classical model)?*

*4. How does Einstein explain the phenomenon?*

*5. Derive the energy balance for the thermal emission.*

*6. In what period does this discovery take place? (historical context)*

*7. How does this fit into the changing model of interpreting light?*

*8. Can you derive Planck's constant through this experiment?*

From the correction of the papers, on average, no conceptual errors emerged, demonstrating that the correction of the tutorial in class and the active discussion with the students allowed to correctly resolve the experiment and the differences between Lenard's expectations and the explanation of Einstein. One shou also notice that the essay was performed at home so the students could use the lecture notes for aswering the questions.

An analysis of the answers given by the students shows a correct use of the concept of model and the description of the classic model and the quantum model. The predictions of each model and the results of the experiment are correctly discussed. At this stage, the initial misunderstandings caused by the foreknowledge of some of the typical phenomena and experiments of the early twentieth century, known from other disciplines or from personal readings, appears to be overcomed. Many of the students conclude by saying that both models must be taken into account. This achievement is important for the continuation of the educational path because the student should not think that they can completely replace the wave model with a new particle model but that both models correctly describe some aspects of the same physical entity that we call light. The next logical step is to share the idea that we must consider light (and quantum objects in general) as a new entity that does not exactly correspond either with the corpuscles or with the waves of classical physics but which has properties that typically we attribute to both.

## *5.4 Interview to the students*

At the end of the learning sequence, informal interviews were proposed to the students keeping the same groups used during the activities. Through these interviews we wanted to verify not only the final conceptions of the students on the nature of quantons but also to identified which elements of the TLS were recognized by the students as the most effective in the development of their understanding.

The guiding questions for the semi-structured interview are the following:

*1) Did you find the path interesting / stimulating?*

*2) Thinking about the path taken, which are the concepts that you think to have better understood and, on the contrary, which are the worse?*

*3) What were the teaching methods (tutorials, examples, analogies, simulations, discussions ...) that have been more useful for you?*

*4) Have you ever met any of the topics before? Where / when / in which discipline.*

*5) Still thinking about the path which words would you use to describe quantum objects (quantons)? How are they different from classical objects such as waves and particles?*

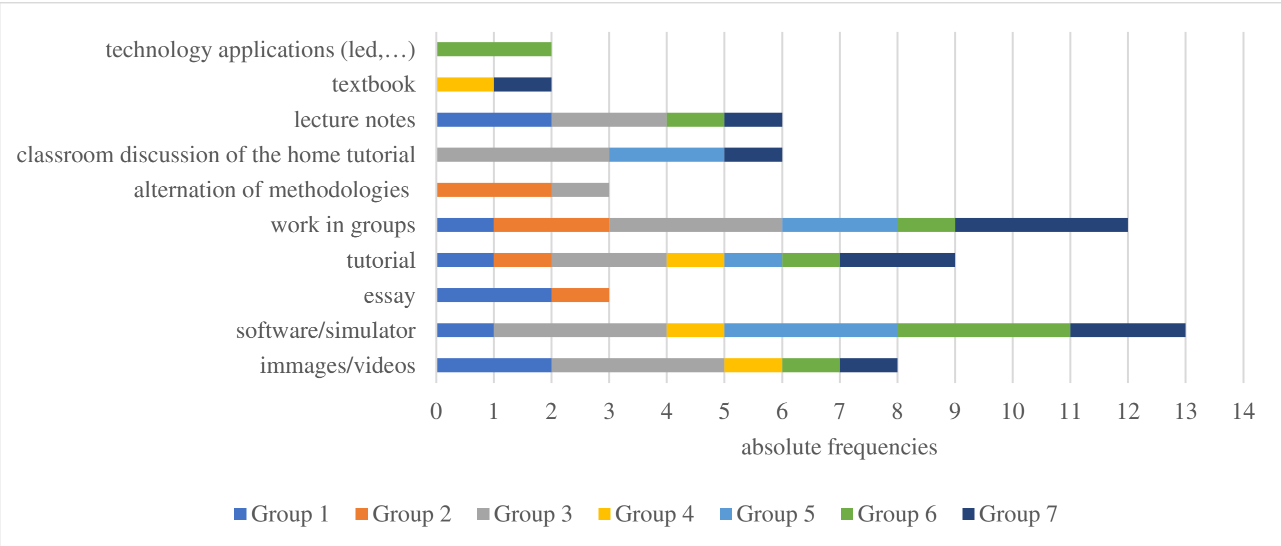
*6) What degree course would you like to enroll in? Have you explored any subject on your own that particularly interested you?*

### *5.4.1 Results of the interviews to the students*

We now discuss the answers to the interviews to the students. The methods deemed most effective for understanding are the simulators used during the lectures in general, the tutorial specifically, and group work. Other tools considered useful were the use of images and videos to "see things", the discussion and correction of the tutorial itself in the classroom and the uploaded lecture notes, including the files listed in the annex C and the recordings of the lessons. Most of the students found interest and therefore were able to keep mental focus from the simulations and the change between the different methodologies (tutorial, discussions, readings, working at home in groups). A synthesis of the answer of the students is presented in graph 1.

The students justify these answers saying that the tutorial and the division into groups allowed them to work personally with the simulator using all the time available to them to make attempts and to discuss between them in groups. Furthermore, most of the students agree with the fact that distance learning modalities make generally more difficult to maintain concentration: alternating explanations with individual work on the simulator and discussion during the group work helped them to maintain a high level of interest and concentration. In particular, 5 students stressed that in distance learning is difficult to stay concentrate during the lecture, and in one case there were also serious problems with home internet connection.

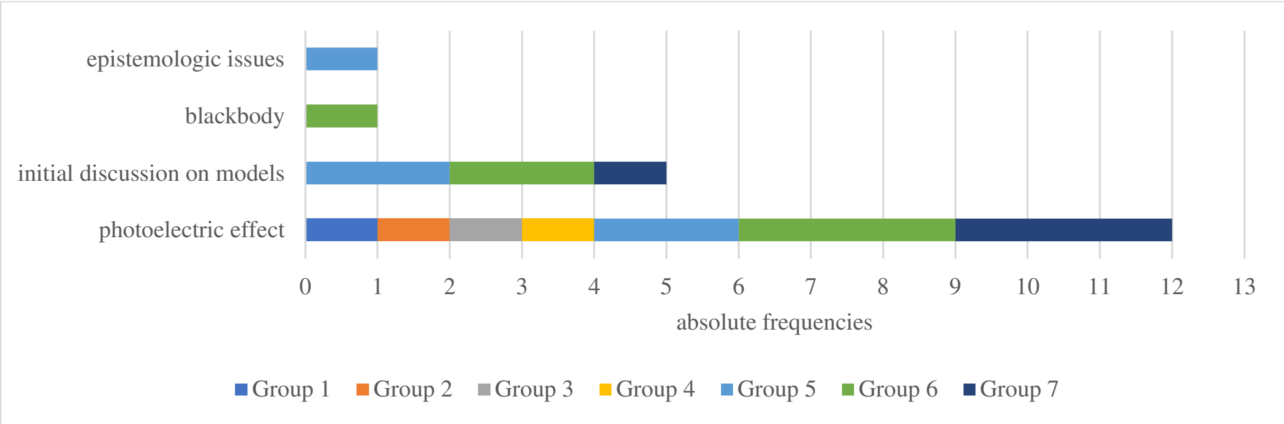
The lecture notes have generally been found useful by students who are used to textbook.



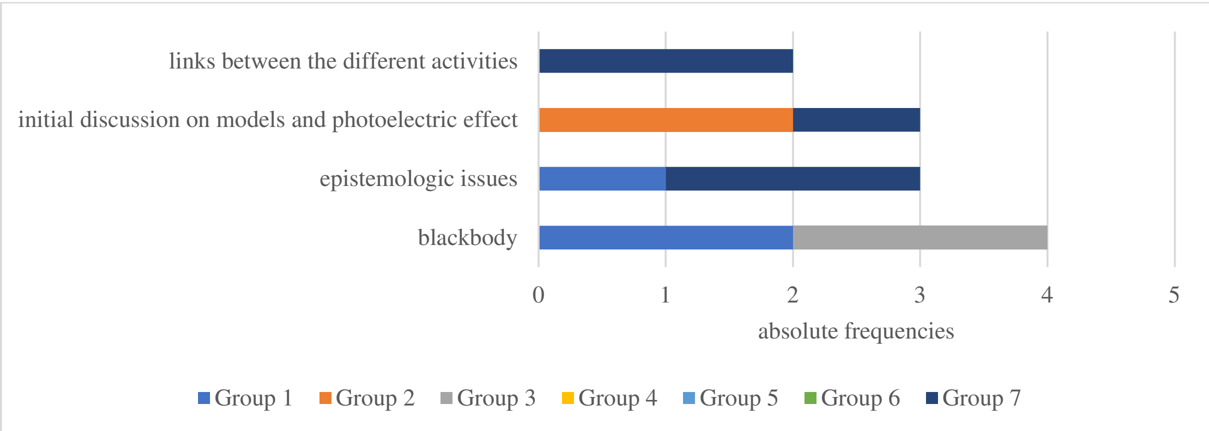

Graph 1. Absolute frequencies of answers to question 3 about which methods students found most useful for understanding the subject.

The most frequent answers to the question about which topics they claim to have understood better are the photoelectric effect and the initial discussion about models. Most of them justify this choice with reasons similar to the ones given in the previous question. The tutorial and the various activities related proposed  helped students to be focused on the topic. Also the opportunities to clarify doubts and to interact were more frequent. The student who claims to have better understood the last part (from black body to the quantons) was a student in the group 5, who was showing interest in the relation between physics and philosophy.

The topic which the majority of the students perceived to be less clear was the black body. For all of them, the main difficulty was understanding the the probability distribution. Only for one student in group 2, the discussion on practical applications (i.e. LEDs) have been useful to clarify it.

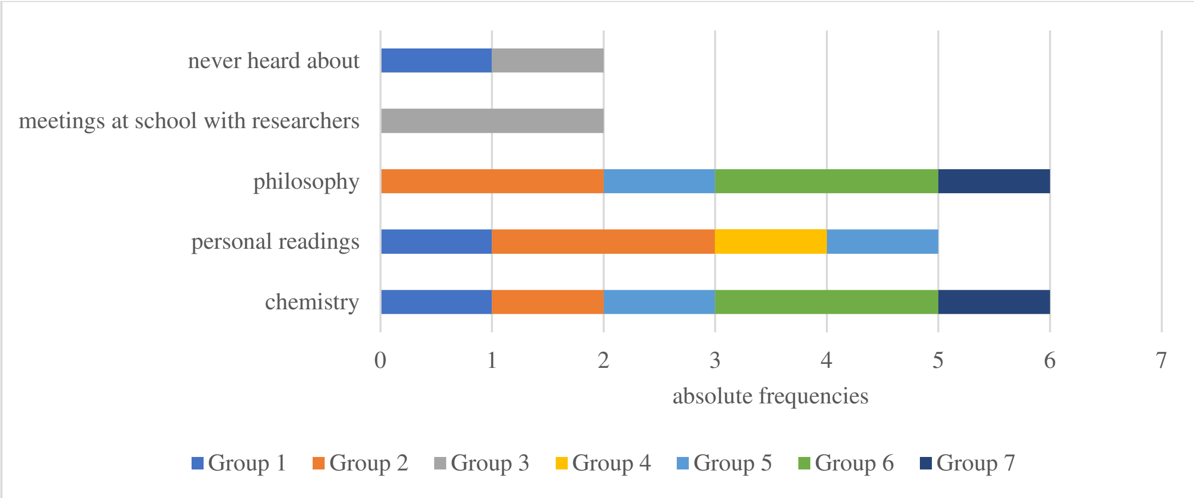



Graph 2. Absolute frequencies of topics that students think to have better understood.



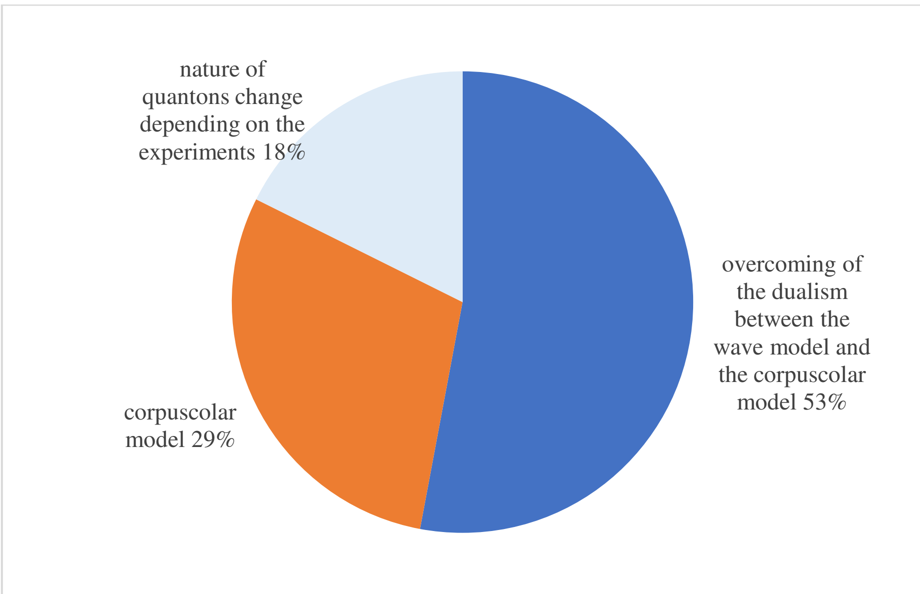

Graph 3. Absolute frequencies of topics that students claim to have worse understood.

Only two students claimed that they have never heard before any of the quantum physics topics covered. Most of the students have met these topics in the study of chemistry, through discussions made in the philosophy course but also in extra-curricular meetings, through documentaries and popular scientific videos. Many of these students also claimed that they have appreciate the lectures and that they have been able to better understand ideas that previously have been perceived as disconnected or abstract and "strange".




Graph 4. Absolute frequencies of answers to question 5 about where the student claim to have already encountered some of the topics discussed during the TLS.

For 11 students out of 21 emerges an overcoming of the dualism between the wave model and the corpuscular model. Some students (4 out of 21), on the other hand, understood the differences between the two models but have a vision linked to the experiment in question, stating that the nature of quantons changes depending on the experiment which they are considering. Finally, for 6 students their final idea of quantons presents characteristics which are typical of the corpuscular model alone.




Graph 5. Results from question 5 about the nature of quantons.

In the first case, the student thinks on the properties of quantons and recognizes that some of these can be described with the elements that we usually associate to classical waves or particles but does not identify them with either of them. In the second case, the student follows a different reasoning based on the experiment in question: although they recognize that quantons have some properties in common with those of particles and waves, in the description of the experiments they identify quantons with one or the other. In the latter case, the student identifies the quanton with the particles and the understanding of the topics is limited to the photoelectric effect.

An example of a typical answer given by a student in the first case is the following (from a student from group 2):

*"I can't really imagine quantons! Electrons and light. I would say the wave and particle models are both valid but one thing that struck me is that physics allows us to describe quantons through a single model which states they have properties that are apparently mutually exclusive and actually coexist in the same entity which we can't see with our eyes. I think technology il very important today and experiments."*

Another example from a discussion between two students of group 5:

Student A*: "it is a bit difficult to give a definition so spontaneously but I could probably describe it with an alternative model to the particle and to the wave that in a certain sense adjusts the properties of these two other models to the quanton."*

Student B*: "I absolutely don't know how to define it but I would know how it manifests itself through experiments or through graphs but if I had to give a definition I would not know."*

Student A*: "I was very struck by the last discussion we had in relation to the quanton, that is, this new way of doing science has somewhat destroyed the mental structures we had created through which we filtered the reality around us. If we filter phenomena using the models we had before or senses such as sight, using the senses that we thought were absolute no longer makes sense and therefore we need to create a kind of new reference system through which to filter the data."*

Student B shows an argument which follows the second case discussed before. Student A, conversely, reaches a higher level of abstraction recognizing the role of the experiments and models on describing the properties of quantons.

Another example of a student of the first case is the following, from group 6:

*"First of all in my opinion we must consider the two aspects of the wave model and corpuscular model and there are some experiments that can be explained with one and others with another but that does not mean that it is either one or the other but something different which shares the properties of a classical particle or wave and highlighted from an experiment or another. We used the metaphor with the duckmole that I found very interesting, that is, something that remains inside you, and that exemplifies what the quanton is in short and therefore it is necessary to give new characteristics to this object that was previously unknown or to which was previously attributed only one of these two characters."*

It is interesting to cite the answer given to this student by a mate:

*"I find fascinating this concept of not being able to see it but at the same time being able to study it because it exists and therefore this has opened up a bit of my vision of myself and, as my mate says, if we rely only on what is in front of our eyes and what can be seen we do not reach the complete fullness of ourselves and this is demonstrated by physics but not only."*

The following student, from group 4, shows some characteristics in between the first and second case since he understands the limits of the classical models of wave and particle but refuses to give a definition of quanton since we still "know too little about it" and "not having practical knowledge in everyday life it is difficult to say whether an hypothesis is right or wrong":

*"In my opinion, too little is still known about the quanton to be able to define it as we can do with a macroscopic body because we have known about the latter since science began. About the quantum objects we can tell how it responds to the various experiments and therefore what are the various models that explain it. I am thinking of CERN experiments with colliding particles. In my opinion we have reached the stage of understanding not so much how it works but what result it gives us. Not having practical knowledge in everyday life it is difficult to say whether an hypothesis is right or wrong. For some experiments I have to consider light as a wave and others as a particle, it depends on the phenomenon I have to describe. For example, refraction with Newton's model could be explained by a lot of calculations while according to Huygens model it was much simpler. In chemistry, I should consider the electron as a wave that is in its orbital and in others as a ball that moves. "*

The answers given by the students of the third case (mainly from group 1 and 7) are short answers as "I think a quanton like a particle" and they usually rely only on the photoelectric effect. They do not know or cannot discuss the double slit experiment and the ideas of Einstein and Lévy-Leblond correctly. In many of these cases it is worth noting a lack of student participation worsen by distance learning methodologies. In these cases, the didactic sequence has failed to engage their attention and their vision stays limited to Einstein's model to explain the tutorial they had to carry out.

Some other observations raised spontaneously from students. The usefulness of the global view of the topics and the review and in-depth study of some topics previously studied in physics was explicitly raised from 8 students. 6 of them appreciated the historical point of view. This is clearly stated by two students from group 2 that at the end of the lectures wrote their opinions to prof. Lippiello which we now cite:

Student A from group 2: "*This morning lesson was very interesting, especially because we are reviewing past physics topics that will also be useful for the university entrance tests! Furthermore, I really liked also the historical part about the path that led to certain hypotheses and subsequent theses*".

Student B from group 2: "*As for today's lesson, it was very interesting, also because we were able to take up and review many past physics topics*".

In conclusion, 4 students explicitly said to have difficulties in scientific subjects and, from question 6, we know 8 of them would like to continue their studies in healthcare professions and medicine, 4 of them engineering, 3 of them biology, physics and mathematics, 5 of them human and social sciences and 1 in economics.

## 5.5 Comment from the teacher

To complete the description of the teaching learning sequence and its results, we report the final comment made by the teacher Stefania Lippiello.

*"Given the peculiarity of the time, this type of proposal has allowed an increase in student participation. I saw them very happy with the initial revival of various concepts, the value of the path was great compared to a reorganization of knowledge with a broader perspective.*

*The method and models were explained very well. Furthermore, the experiments have been carefully described. The final part on the quanton perhaps would have required a little more time, it was slightly more time constrained. We were in distance learning and therefore with reduced hours of video lessons and with students a little more strained for the period and for the sum of commitments at the end of the school year.*

*Using the simulator through the tutorial was absolutely a winning choice! The students were able to get their hands on it and be more actively involved. The correction of it lasted a little too long because of external reasons (two bank holidays weekends in addition to the reorganized timetable for the distance learning), but the works with students divided in groups and lecture notes delivered to students were very useful. The files provided by the graduate student are very useful since the textbook explains the photoelectric effect in a couple of pages and introduces quantum physics with the black body radiation, without all the initial discussion on the method and concept of model in physics. "*

# 6. Conclusions

From the review of the literature in teaching and learning of quantum physics and from the analysis of the initial interviews with secondary school tenured teachers, we proposed a teaching learning sequence with the aim of satisfying the needs that raised from teachers in order to make the TLS itself testable in a fifth class of an italian "liceo scientifico".

The teaching of quantum physics presents multiple intrinsic difficulties that are connected to the necessary condition of "changing the way of thinking, reasoning and imagining reality". The main learning difficulties are therefore linked to the contrast that arises between the ideas and methods of the classical and quantum world. In fact, quantum phenomena cannot be traced back to something already known in classical physics and it is often difficult to create a faithful representation of them without making distorting simplifications, which can lead to erroneous conceptions and to contradictions as the wave-particle dualism.

An exposition of the formalism underlying quantum physics can be problematic especially in view of the results obtained from the interviews about the prerequisites that students in a fifth grade should have. Many of the mathematical tools on which the didactic proposals analyzed are based are little or not at all explored during the scientific high school (such as the concept of abstract vector, complex numbers and probability distributions), as found in the results of the interview to the teachers. For this reason, we chose a historical-conceptual approach rather than a formal or axiomatic one. This approach satisfied the students' need for "visualization" through the tutorial of the proposed experiment, simulations, videos and readings and increased the interest and curiosity of students as confirmed in the final interviews with the students.

According to the teachers interviewed, the main limit concern the “esame di Stato”, which places a bound on the topics to be addressed and on the exercises that could be proposed in the written test, the risk of working with students focused on the exam itself or on the university entrance tests and distance learning made necessary due to the spread of COVID-19 pandemic.

From the gathering of the students' initial conceptions we observed that almost all the students (with the exception of two of them) have already had the opportunity to meet quantum physics ideas through personal readings, during the chemistry course or in meetings at school and from popular physics. It is therefore important to note that the student has on average his own vision about quantum physics and any course must take into account their initial ideas which are often confused by the typical contradictions presented in popular physics. The goal of our learning sequence is therefore also to idetify students' initial preconceptions by stimulating an initial discussion on their knowledge about the subject. This discussion is then taken back in the final when we propose a synthesis with the idea of “quantons” by Lévy-Leblond.

The initial activity on the concept of models is necessary for the development of scientific language suitable for subsequent developments of the module and presents historical examples that are not limited to modern physics in order to give the message that these methodologies are typical of science and not limited to modern physics. This is an opportunity to think on how scientific research progresses and this was acknowledged by the students.

The tutorial, as central activity of the TLS was appreciated by the students so as the opportunity to study a complex experiment, since it combines various topics of physics and allows a review useful for the “esame di Stato” as raised by both students and teachers. The simulator allows the students to "see" and "put hands on" and to discuss it in groups and then together in class during the correction. Furthermore, the results show that all the students get aware of the incompleteness of the classical model they use.

From the final interview to the students we can deduce that 11 out of 21 students are able to discuss the properties of quantons and recognize that some of these can be described with the formalism we usually associate with classical waves or particles but they don’t identify them with neither waves or particles overcoming the wave-particle dualism. 4 students follow a different reasoning based on the experiment which are analyzing: although they recognize that quantons have some properties in common with those of particles and waves, in the description of the experiments they identify quantons with one or the other. 6 students identify the quanton with particles and the understanding of the topics is limited to the photoelectric effect.

We can conclude that most of the students at the end of the didactical proposal have reached the enduring understandings which we have identified in our design, and they are able to discuss about the use of model in physics and their limits of applicability, the role of the experiments in determining the nature of a physical entity from its properties and most of them have overcomed the idea of wave-particle dualism, being able to discuss the models that describe the behavior and nature of quantons.

In conclusion, for the majority of the students, the TLS stimulated attention and interest despite distance learning, it promoted an active participation during the completion of the tutorial and classroom discussions and it fostered a deeper understanding of key ideas. The students also appreciated the global vision, the interdisciplinarity, and the opportunity to review various physics topics in view of the “esame di Stato”.

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# *Appendix*

## *Annex A: Planning of the lectures based on the backward design*

| Goals from national and international standards |
| --- |
| From the national indications for the scientific high school, in the paragraph on quantum physics we find:<br>"[…] The affirmation of the model of the quantum of light can be introduced through the study of thermal radiation and Planck's hypothesis (also addressed only in a qualitative way), and will be developed with the study of the photoelectric effect and its interpretation by Einstein, and with the discussion of the theories and experimental results that highlight the presence of discrete energy levels in the atom. The experimental evidence of the wave nature of matter, postulated by De Broglie, and the uncertainty principle should conclude the path in a significant way […]".<br><br>These indications are clarified and listed in more detail in the reference framework for the "esame di stato" of scientific high schools which, among the essential contents, include:<br>- The black body emission and the Planck hypothesis;<br>- Lenard's experiment and Einstein's explanation of the photoelectric effect;<br>- The Compton effect;<br>- Bohr model of the atom and interpretation of the atomic spectra;<br>- The Franck - Hertz experiment;<br>- De Broglie wavelength;<br>- Wave-particle dualism. Limits of validity of the classic description;<br>- Diffraction / Interference of electrons;<br>- The uncertainty principle.<br><br>These topics are in agreement with learning objectives reported in literature [Knight 2004]:<br>- to recognize phenomena that cannot be explained by classical physics, thus motivating the need for a new theory;<br>- to extablish experimental evidence by which we know about the existence of atoms and about their properties;<br>- to understand the photoelectric effect experiment and its implications;<br>- to understand the photon model and its application to the photoelectric effect;<br>- to understand the evidence for matter waves and the de Broglie wavelenght. |

| |
|---|
| Furthermore, these topics agree with the quantum physics courses curricula from fifteen European countries as investigated by Staderman et al. [2019]. |

| Area of the meanings |
|---|
| **Enduring understandings** |
| • The concept of model in physics. Limits of applicability: the student must not develop the incorrect feeling that everything he has previously studied in physics is wrong;<br>• Role of the experiments;<br>• Overcoming the wave-particle dualism. Knowing how to argue about the models that describe the behavior and nature of quantons. |

| **Area of acquisitions** | |
|---|---|
| **Knowledge** | **Skills** |
| • Describe Lenard's experiment and discuss Einstein's explanation of the photoelectric effect.<br>• Describe the black body emission and interpret it using Planck hypothesis.<br>• Define the de Broglie wavelength and explain the reasons why it was introduced.<br>• Discuss the wave model and the particle model. Know the limits of validity of the classic description.<br>• Describe diffraction and interference of electrons.<br>• Discuss the idea of quantons relating it with the wave-particle duality. | • Apply Einstein's model to the photoelectric effect.<br>• Illustrate the black body model by interpreting the emission curve on the basis of Planck's distribution law.<br>• Discuss the terms wave and particle.<br>• Calculate the wavelength of a particle and compare it with the wavelength of a macroscopic object. Estimate Planck's constant.<br>• To analyze experiments of interference and diffraction with particles, illustrating how they can be interpreted starting from the De Broglie hypothesis.<br>• Knowing how to show, referring to specific experiments, the limits of the |

| | |
|---|---|
| | classical paradigm of explanation and interpretation of phenomena and being able to argue the need for a quantum vision. |

| **Evidence of learning** |
|---|
| The evaluation process goes through the following stages:<br>• An initial moment in which initial conceptions are collected by the students. Student are divided into groups of three and, through a discussion at home, they have to describe their ideas about light, electrons and atoms, illustrating their main properties and which experiments they have studied about them.<br>• An evaluation of the work done on the tutorial to verify the understanding of the photoelectric experiment and the relationships between the fundamental quantities involved in the phenomenon.<br>• A written essay after introducing Einstein's quantum model in order to verify if the student has understood the need for a new model to explain the phenomena observed through the photoelectric effect.<br>• A final informal interview with students divided into the same groups as in the tutorial. In this interview some general questions on the learning path were added in order to evaluate the TLS itself. |
| **Activities plan** |
| - Initial discussion in classroom on models in physics with reference to the historical debate between I. Newton and C. Huygens about light.<br>- Gathering initial students' ideas through a table to be filled at home in groups<br>- Introduction to the photoelectric effect and introduction to the tutorial.<br>- Tutorial to be done at home in groups.<br>- Discussion about the critical points of the photoelectric effect through the correction of the tutorial. Introduction to the Einstein's photon model to explain the phenomena observed. |

- Introduction to further experiments of the first years of the 19$^{th}$ century (Black body, Double slit with electrons).
- Debate in classroom linked to the first discussion made on models in physics. The concept of quanton to overcome contradictions and wave-particle dualities.
- Readings from Einstein and Lévy-Leblond.

# *Annex B: Tutorial*

Università degli Studi di Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

GRAPE Gruppo di ricerca in Didattica della Fisica e dell'Astronomia

## EFFETTO FOTOELETTRICO

### 1. <u>Predizione</u>

Albert Einstein

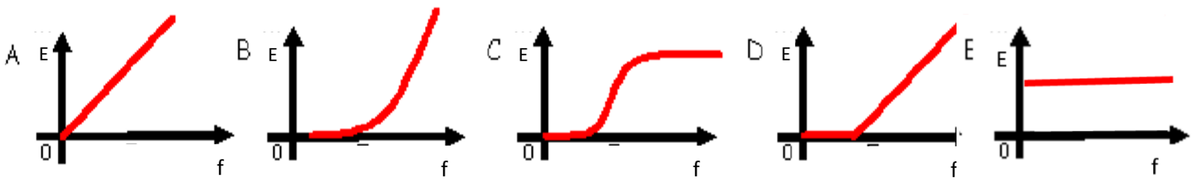
Fai riferimento al fenomeno dell'emissione termica da parte di una superficie metallica.

a) Cosa succede alla superficie metallica quando la luce incide su di essa? Come lo rappresenteresti con un disegno?

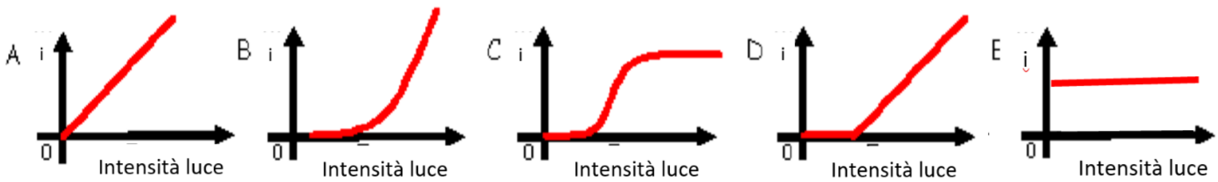
b) Il fenomeno dell'emissione di elettroni avviene per qualsiasi valore della frequenza della luce?

c) Scegli il grafico che rappresenta correttamente la relazione tra le seguenti grandezze:

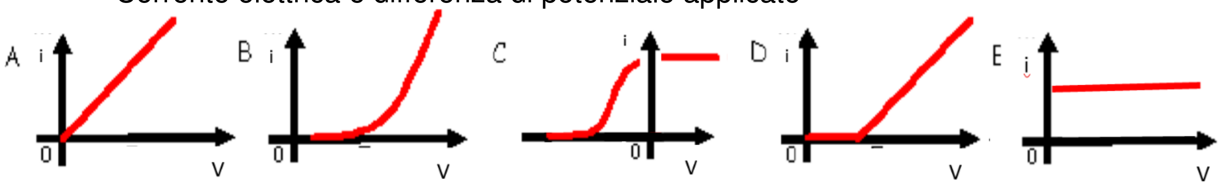
- Energia cinetica degli elettroni emessi e frequenza della luce incidente




- Corrente elettrica ed intensità della luce incidente

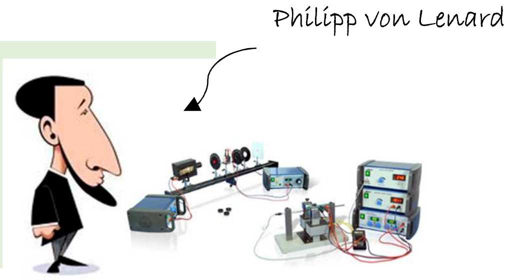



- Corrente elettrica e differenza di potenziale applicato



2. **Avvia** il simulatore

3. **Esplorazione** preliminare




a) Nella figura successiva, etichetta con le seguenti lettere i vari elementi dell'esperimento/simulatore:

**A** – Catodo metallico

**B** – Anodo

**C** – Luce incidente

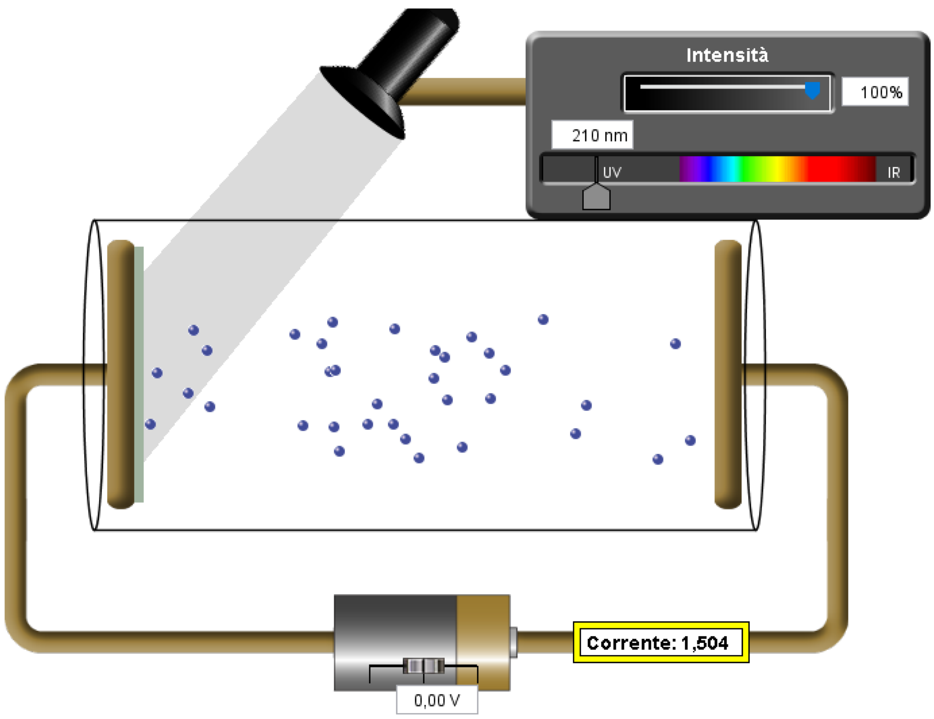
**D** – Elettroni

**E** – Amperometro. A cosa serve?

**F** – Cursore per regolare la differenza di potenziale tra i due elettrodi

**G** – Cursore per regolare l'intensità della luce

**H** – Cursore per regolare la lunghezza d'onda della luce. Come calcoli la frequenza della luce a partire dalla sua lunghezza d'onda? Nel caso specifico della figura quanto vale la frequenza in Hz?



b) Utilizzando i due cursori **G** e **H**, imposta la lunghezza d'onda a 690 nm (corrispondente al rosso) e varia l'intensità della luce, poi varia la lunghezza d'onda finché osservi l'emissione di elettroni dal catodo metallico. Ora prova regolando anche il potenziale applicato tramite il cursore **F.**
La variazione di quale grandezza ha causato l'inizio dell'emissione degli elettroni? Spiega.

## 4. Ruolo della frequenza di soglia

a. **Esplorazione tramite la simulazione:**
- Scegli un materiale. Sposta il cursore che regola la lunghezza d'onda al valore massimo e, mantenendo fissa l'intensità luminosa al 100%, inizia a muoverlo lentamente.

- A quale valore della lunghezza d'onda inizia l'emissione?

- Cosa succede diminuendo ancora la lunghezza d'onda?

- Ripeti l'osservazione per tutti i materiali. Per ciascuno ricava dalla simulazione la lunghezza d'onda a cui inizia l'emissione (che viene quindi definita **lunghezza d'onda "di soglia"**) e calcola la frequenza corrispondente (**frequenza di soglia**).

| **Materiale** | **Lunghezza d'onda di soglia (nm)** | **Frequenza di soglia (Hz)** |
|---|---|---|
| Sodio | | |
| Zinco | | |
| Rame | | |
| Platino | | |
| Calcio | | |

b. Da questo momento in poi concentrati su un solo materiale per il catodo, il Rame. Riporta in seguito il **grafico** *Energia degli elettroni vs. Frequenza della luce* che ottieni impostando l'intensità della luce al 100% e muovendo il cursore che regola la lunghezza d'onda.

c. Identifica sul **grafico** i seguenti:
**A** - la frequenza di soglia
**B** - l'intervallo di frequenze che determinano un'energia cinetica degli elettroni maggiore di zero
**C** - l'intervallo di frequenze che non determinano emissione di elettroni

d. Sul grafico viene riportato il valore dell'energia degli elettroni e visivamente puoi percepire anche le variazioni della velocità degli elettroni. Se l'energia aumenta…
… aumenta la velocità degli elettroni
… diminuisce la velocità degli elettroni
Qual è la relazione tra queste due grandezze?

## 5. Ruolo dell'intensità della luce nell'effetto fotoelettrico

a. **Dai la definizione dei seguenti concetti chiave**
Intensità della luce


Intensità di corrente elettrica

b. **Esplorazione tramite la simulazione:**
- Regola la lunghezza d'onda della luce incidente in modo che sia superiore alla lunghezza d'onda di soglia precedentemente determinata (quindi frequenza minore della frequenza di soglia). Ora sperimenta muovendo il cursore che regola l'intensità della luce.

Ci sono valori dell'intensità della luce che determinano una corrente elettrica nel circuito?

- Regola la lunghezza d’onda della luce incidente in modo che sia inferiore alla lunghezza d’onda di soglia (quindi frequenza maggiore della frequenza di soglia). Ora sperimenta di nuovo con il cursore che regola l’intensità della luce.

L’intensità della luce influenza il numero di elettroni che vengono emessi?

L’intensità della luce influenza la velocità con cui gli elettroni vengono emessi?

c. Riporta in seguito il **grafico** *Corrente vs. intensità luminosa* che ottieni impostando la lunghezza d’onda della luce a 150 nm e muovendo il cursore che regola l’intensità luminosa.

Quale di questi fenomeni provoca un aumento dell’intensità della corrente elettrica?

Un aumento del numero di elettroni che arrivano all’anodo
Un aumento della velocità degli elettroni all’anodo
Un aumento dell’energia cinetica degli elettroni all’anodo

Come cambia l'intensità della corrente elettrica nel circuito? Spiega perché collegandoti alle risposte precedenti.

## 6. Potenziale di arresto

a. **Esplorazione tramite la simulazione:** Imposta la lunghezza d’onda della luce incidente a 150 nm, l’intensità della luce al 100% e il valore della differenza di potenziale della batteria a zero (è utile per questo punto selezionare l’opzione “mostra solo gli elettroni con energia più alta”).
- Cosa succede al moto degli elettroni se muovi il cursore impostando valori positivi della differenza di potenziale della batteria?

- Cosa succede al moto degli elettroni se muovi il cursore impostando valori negativi della differenza di potenziale della batteria?

b. Riporta in seguito il **<u>grafico</u>** *Corrente vs. tensione della batteria* che ottieni impostando la lunghezza d'onda della luce a 150 nm, l'intensità luminosa al 100% e muovendo il cursore che regola il valore della differenza di potenziale della batteria.

Usa il grafico per trovare la differenza di potenziale che devi applicare per azzerare l'intensità di corrente. Questa differenza di potenziale è la **differenza di potenziale di arresto**.

Una volta impostato per la batteria il valore trovato della differenza di potenziale di arresto, varia il cursore dell'intensità della luce e della lunghezza d'onda della luce. Il valore della differenza di potenziale di arresto cambia variando l'intensità della luce? E variando la lunghezza d'onda?


## 7. <u>Commento</u>

Confronta i grafici ottenuti nei punti 4b, 5c e 6b con quelli scelti nel punto 1c. La simulazione è in tutti i casi in accordo con le predizioni fatte sulla base del modello classico dell'emissione termica? Quali differiscono? Discuti.

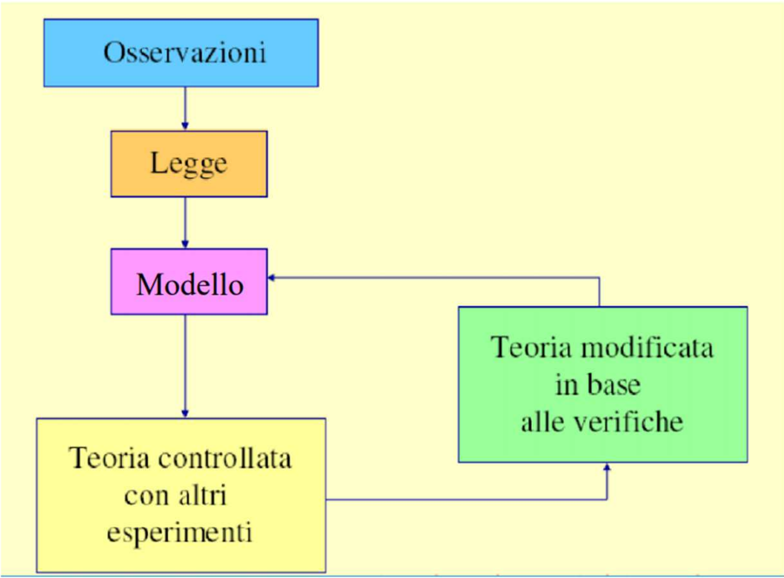
# *Annex C: Lecture notes*

## Lesson 1

### MODELLO FISICO E METODO SPERIMENTALE

Che cosa è un modello in fisica? In classe (virtuale) sono emersi termini quali "rappresentazione", "predizione"…

Iniziamo dal metodo sperimentale:




Un modello fisico è una descrizione semplificata di un insieme di fenomeni, che si basa su osservazioni e su leggi sperimentali.

Un modello consente di fare delle previsioni. Così, ad esempio, la meccanica di Newton, il modello che descrive come si muovono gli oggetti sotto l'effetto delle forze che agiscono su di essi, permette di prevedere con alta precisione quando avvengono le eclissi di Sole.

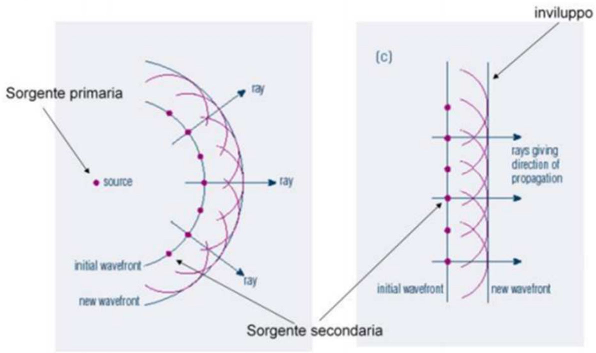
Il campo di applicabilità è dato dall'insieme di tutti i fenomeni per i quali la teoria fornisce previsioni in accordo con l'esperienza. Nuovi esperimenti possono estendere il campo di applicabilità di un modello se lo confermano altrimenti si deve essere disposti a modificare o ampliare il modello se gli esperimenti sono in disaccordo.

Un esempio? La luce!

## LA LUCE

Esempio di coesistenza di due modelli interpretativi dei fenomeni luminosi nello stesso periodo storico (XVIII secolo):

Sia Newton che Huygens conoscevano bene l'ottica geometrica che adotta per la luce il modello di raggio che si propaga in linea retta e attraverso le leggi di riflessione e di rifrazione (legge di Snell!) descrive un'ampia gamma di fenomeni ottici (abbiamo parlato di occhiali e cannocchiali…).

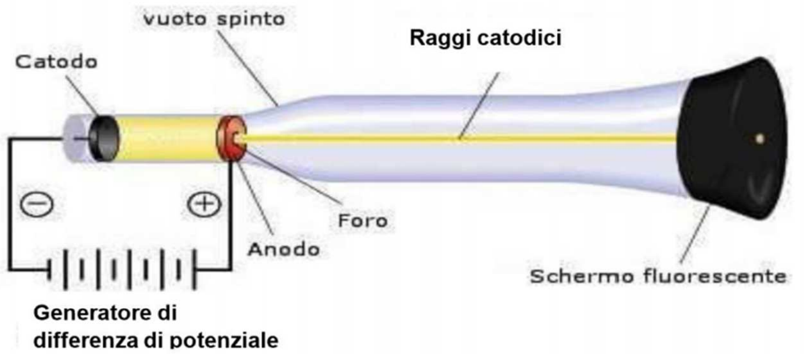
| **MODELLO CORPUSCOLARE** (I. Newton) | **MODELLO ONDULATORIO** (C. Huygens) |
|---|---|
| La teoria della luce di Newton si fondava sulle ipotesi seguenti:<br><br>• La luce è composta da piccolissime particelle di materia emesse da sostanze luminose (avete nominato il Sole, il fuoco, le lampade…) in tutte le direzioni.<br><br>• Tali particelle vengono liberate dai corpi luminosi e si propagano in linea retta (in un mezzo omogeneo). Come nell'ottica geometrica!<br><br>Un esempio di propagazione in linea retta, la meridiana del duomo di Milano<br><br><br>• Queste particelle hanno diversa massa:<br>– i corpuscoli con una massa maggiore provocano la sensazione del rosso;<br>– i corpuscoli con una massa minore danno la sensazione del violetto;<br><br>• Quando queste particelle entrano in un mezzo come l'acqua o il vetro, le molecole della sostanza esercitano delle forze sulle particelle di luce deviandone la direzione. | La teoria ondulatoria di Huygens invece si può fondare sulle ipotesi seguenti:<br><br>• La luce è costituita da un insieme di onde meccaniche che si propagano in linea retta a velocità finita. Il "raggio" è perpendicolare al fronte d'onda, è la direzione di propagazione dell'onda.<br><br>• Le vibrazioni dei corpi luminosi producono tali onde.<br><br>• La propagazione della luce è dovuta all'oscillazione dell'etere (lo stesso di cui avete parlato affrontando la teoria della relatività di Einstein!).<br><br>• Le onde luminose obbediscono al principio di Huygens, riassumibile in due punti:<br>- Ciascun punto del fronte d'onda è il centro di onde secondarie<br>- Il fronte d'onda è determinato dalla tangente comune alle estremità di queste onde secondarie (questa tangente viene chiamata inviluppo!)<br><br><br>onda **sferica** onda **piana** |

## Lesson 2

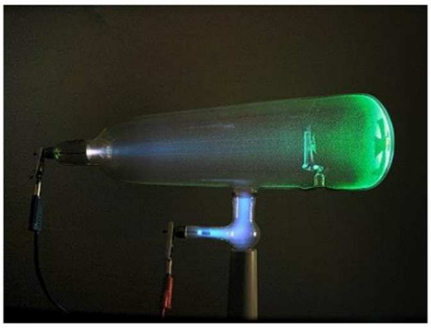
Gli elettroni, così come le entità della fisica atomica, non sono percettibili ai sensi (come è emerso anche da alcune delle vostre tabelle). Storicamente infatti, fisici e chimici hanno ideato esperimenti che permettessero di svelare e chiarire le proprietà di questi oggetti.

Concentrandoci sugli elettroni, alcuni esperimenti interessanti che abbiamo visto sono quelli sui raggi catodici e l'esperimento di Millikan.

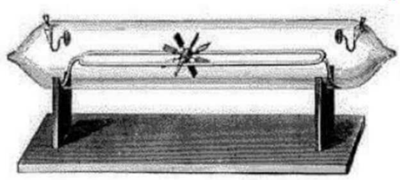
Le prime prove sperimentali dell'esistenza di questa particella si ebbero nel 1860, quando il fisico e chimico inglese Sir William Crookes effettuò esperimenti con il **tubo di Crookes**.




Crookes, in un tubo da vuoto, inserì due lamine metalliche che collegò a un generatore di differenza di potenziale molto elevata (circa 30000 V, i tralicci dell'alta tensione sono tra i 60000 V e i 220000 V!). Durante tale esperimento, Crookes si accorse che si generava una luce avente una colorazione differente a seconda del gas utilizzato ma indipendente dal materiale delle lamine metalliche. Tale emissione luminosa aveva origine dalla lamina metallica detta catodo (polo negativo) e fluiva verso la lamina metallica detta anodo (polo positivo). Per tale motivo furono denominati "**raggi catodici**".



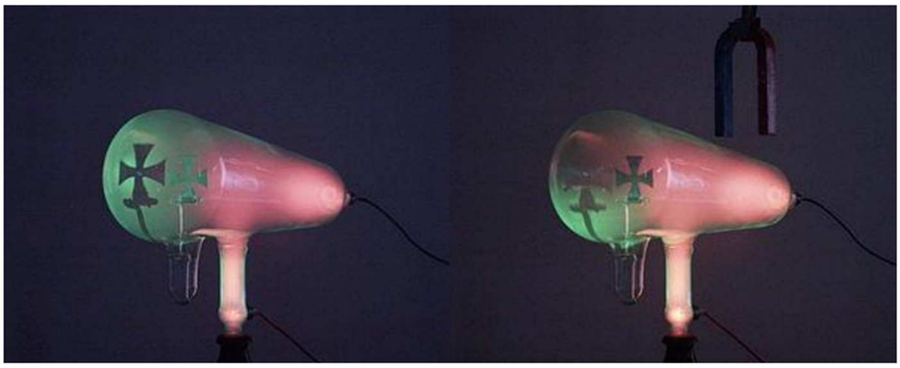
Per dimostrare che questi raggi si **propagavano dal polo negativo al polo positivo** si inserì un oggetto lungo il loro cammino e si osservò la sua ombra come nella figura a destra.

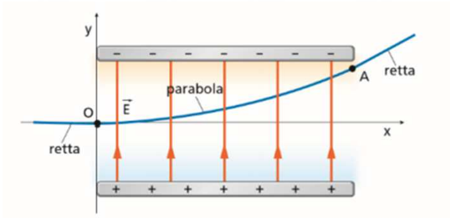


Crookes dimostrò inoltre che questi raggi possono esercitare forze su degli oggetti, **trasferendo loro energia**, come verificato introducendo un mulinello (figura a sinistra) che inizia a ruotare alla presenza dei raggi.

Tali evidenze scientifiche non permisero però di avere un chiaro **modello** che descrivesse questi fenomeni. Come per la luce, ci si chiedeva se questi raggi catodici fossero una sorta di **particelle** o **un'onda**. Crookes stesso pensava che questi raggi fossero costituiti dalle molecole dell'aria interna al tubo che collidendo con il catodo acquisivano una carica negativa e si propagavano quindi ad alta velocità verso l'anodo (ma a quelle pressioni, il cammino libero medio delle molecole sarebbe solo di 6mm!).

Nel 1896, il fisico britannico J. J. Thomson svolse una serie di esperimenti che dimostrarono che i raggi catodici erano costituiti da **singole particelle**, piuttosto che onde, atomi o molecole come si riteneva in precedenza. Thompson capì di poter utilizzare, a questo scopo, la deflessione dei raggi catodici posti all'interno di un **campo magnetico**. (nella figura a sinistra non c'è il campo magnetico, in quella a destra si)






*Perché il campo magnetico e non il campo elettrico?*

*Precedentemente altri esperimenti furono eseguiti posizionando delle piastre metalliche parallele ai raggi catodici e applicando una differenza di potenziale elettrico fra loro. In questo modo, se i raggi sono costituiti da particelle cariche, il campo elettrico avrebbe dovuto deflettere i raggi verso la piastra carica positivamente (se le particelle sono cariche negativamente) oppure verso la piastra carica negativamente (se le particelle sono cariche positivamente). A causa però della presenza dell'aria nel tubo (che è comunque presente anche a basse pressioni!) questa deflessione, per motivi oggi chiari, non avveniva. Esperimenti più recenti, con lo sviluppo delle tecniche per creare il vuoto, hanno confermato che questi raggi deflettono nel campo elettrico.*

Grazie al suo esperimento, Thomson poté stimare in maniera accurata il **rapporto tra la massa e la carica** delle particelle dei raggi catodici. Queste avevano un rapporto massa/carica migliaia di volte inferiore a quella dello ione idrogeno ($H^+$), lo ione più leggero che si conoscesse a quel tempo!

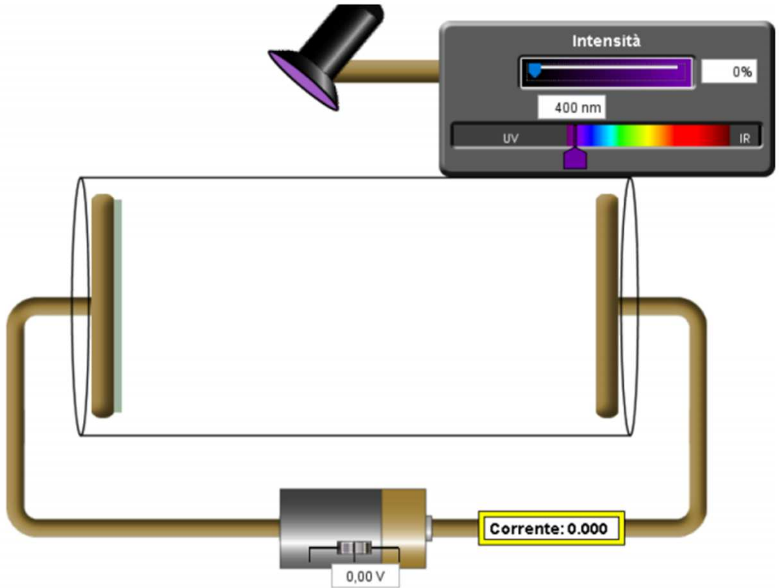
La **carica** degli elettroni fu misurata da Robert **Millikan nell'esperimento della goccia d'olio** del 1909. In tale esperimento venne usato un campo elettrico per frenare la caduta, dovuta alla gravità, di una goccia d'olio elettricamente carica. Grazie a tale apparato strumentale, fu possibile misurare la carica elettrica con un margine di errore inferiore allo 0,3% e fu quindi possibile stimare la massa dell'elettrone conoscendo, da Thomson, il valore del rapporto tra massa e carica elettrica.

## EFFETTO FOTOELETTRICO

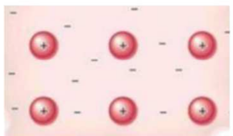
Abbiamo visto come tra la fine dell'Ottocento e gli inizi del Novecento, prevalse un modello ondulatorio per descrivere fenomeni riguardanti la luce (vista quindi come parte dello spettro elettromagnetico descritto da Maxwell) e un modello corpuscolare per descrivere i costituenti dei raggi catodici: gli elettroni. Alcuni esperimenti, a metà tra l'Ottocento e il Novecento, hanno iniziato a porre alcuni dubbi sulla validità di tali conclusioni.

Uno tra i più rappresentativi è l'effetto fotoelettrico. Gli esperimenti sull'effetto fotoelettrico furono condotti dal fisico tedesco Lenard prendendo un tubo a vuoto, all'interno del quale si trovano due lastre metalliche, di cui una funge da anodo, e l'altra da catodo, il tutto inserito in serie in un circuito dotato di amperometro e generatore di differenza di potenziale (vedi figura). Già verso la fine del secolo XIX si era scoperto che un fascio di luce monocromatica incidente su una lastra metallica provocava l'emissione di elettroni. La luce incide sul catodo, il quale emette una corrente di elettroni che poi colpiscono l'anodo.

Le **frequenze** $f$ della luce possono essere variate, nel simulatore, passando dall'infrarosso alla luce visibile all'ultravioletto. Notate che il simulatore permette di regolare, con il cursore, la lunghezza d'onda $\lambda$ della luce (espressa in nanometri!) che è legata alla frequenza da: $f = c/\lambda$ (dove $c$ è la velocità della luce).




## METALLO E LAVORO DI ESTRAZIONE



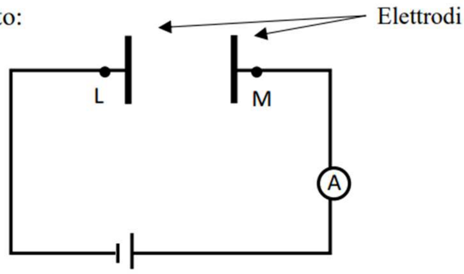
Possiamo schematizzare un metallo come un solido costituito da cariche positive (i nuclei) e cariche negative (elettroni) libere di muoversi dentro il metallo, ma sottoposte ad un potenziale che ne impedisce l'uscita in condizioni normali. Se il metallo viene sottoposto a radiazione elettromagnetica gli elettroni possono acquistare un'energia cinetica sufficientemente alta da permettere di superare il potenziale di richiamo dei nuclei positivi e quindi di "saltare" fuori. C'è bisogno infatti di un'energia minima che occorre fornire per estrarre un elettrone da un metallo. La luce, per fornire questa energia, effettua un lavoro sugli elettroni che si chiama proprio lavoro di estrazione $L_0$. Questo lavoro dipende dal tipo di metallo e si aggira in genere intorno a qualche elettronvolt.

Questo ci ha portato a scrivere l'equazione di bilancio energetico, che esprime matematicamente il fatto che l'energia della luce $E_{luce}$ che incidente sul metallo si trasforma in lavoro $L_0$ compiuto per estrarre gli elettroni e in energia cinetica $E_c$ che possiedono gli elettroni una volta estratti:

$$E_{luce} = L_0 + E_c$$

## CIRCUITO

Schema del circuito:




*Batteria: generatore di differenza di potenziale* $\Delta V_b$

La *corrente* che scorre nel circuito è misurata con un amperometro *A* molto sensibile ed è funzione del numero di elettroni emessi nell'unità di tempo dal catodo e che raggiungono l'anodo.

Per la seconda legge di Kirchoff, la differenza di potenziale della batteria $\Delta V_b$ e la differenza di potenziale ai capi degli elettrodi $\Delta V_{LM} = V_M - V_L$, stanno nella seguente semplice relazione:

$$\Delta V_b = \Delta V_{LM}$$

Il valore della differenza di potenziale della batteria $\Delta V_b$ può essere variato ed è anche possibile cambiarne il segno (notate come varia la distribuzione delle cariche in eccesso sugli elettrodi, che il simulatore rappresenta con i simboli + e -, variando la differenza di potenziale della batteria).

La differenza di potenziale della batteria viene anche chiamata *tensione*, come nel simulatore.

**NOTA BENE**: Nel simulatore si può selezionare una voce dove c'è scritto "mostra solo i *fotoni* ad energia maggiore". C'è un errore nella traduzione italiana, infatti selezionando questa opzione si "mostrano solo gli *elettroni* con energia maggiore" e non i fotoni. Durante il tutorial comunque non dovete selezionare quella voce, a meno che non vi venga richiesto esplicitamente.

## INTERPRETAZIONE CLASSICA DELL'EFFETTO FOTOELETTRICO

Classicamente (teoria di Maxwell) la luce è costituita da un campo elettrico $\mathbf{E}(\mathbf{r},t)$, con l'intensità $I \propto E^2$. In presenza di un campo elettrico gli elettroni sono soggetti ad una forza $\mathbf{F} = e\,\mathbf{E}$ e quindi acquistano energia. Come visto nel bilancio energetico, parte di questa energia è necessaria per estrarre gli elettroni dal metallo e la restante si trasforma in energia cinetica degli elettroni stessi. Quindi ci si aspettava che gli elettroni non fossero emessi istantaneamente: gli elettroni dovevano prima assorbire l'energia sufficiente per poter essere estratti. Una volta estratti, gli elettroni proseguono il loro moto verso l'altro elettrodo e vengono catturati permettendo la misurazione di una intensità di corrente nel circuito.

Quindi ci si aspettava:

i) l'esistenza di una intensità "di soglia" della luce, cioè di una intensità minima al di sotto della quale l'effetto non avviene perché l'energia della luce non è sufficiente per estrarre gli elettroni;
ii) che il numero di elettroni emessi nell'unità di tempo dovrebbe aumentare al crescere dell'intensità della luce incidente.

**<u>Lesson 3</u>**

**OSSERVAZIONE SULLA VELOCITÀ ELETTRONI**

Nel nostro caso l'energia degli elettroni è dell'ordine di $E_e \sim 10\ eV \sim 1{,}6 * 10^{-18} J$.

Supponendo di poter usare l'approssimazione classica: $v \sim \sqrt{\frac{2E_e}{m_e}} \sim 1{,}87 * 10^6 \frac{m}{s}$ con $m_e \sim 9{,}11 * 10^{-31}\ kg$.

Essendo $c \sim 3 * 10^8 \frac{m}{s}$, otteniamo $\frac{v}{c} \sim 0{,}6\%$ che giustifica l'uso delle relazioni classiche piuttosto che relativistiche.

## Lesson 4 and 5

### SPIEGAZIONE DELL'EFFETTO FOTOELETTRICO SECONDO EINSTEIN (1905)

**Svolgendo il tutorial sull'effetto fotoelettrico avete potuto osservare "sperimentalmente" che si verificano i seguenti fatti:**

1) Vengono emessi elettroni soltanto se la frequenza della luce è superiore ad un valore di soglia $f > f_0$, dove $f_0$ è la **frequenza di soglia** che dipende dal materiale metallico considerato; (visto nel punto 4a del tutorial)
2) L'emissione è **istantanea**;
3) L'**energia cinetica** massima degli **elettroni** emessi $E_c$ è proporzionale alla frequenza della luce incidente; (visto nel punto 4b del tutorial)
4) Il **numero di elettroni** emessi (e non la loro velocità) è proporzionale all'intensità della luce incidente $I$; (visto nel punto 5b e 5c del tutorial)
5) Esiste una **differenza di potenziale di arresto** $\Delta V_0$, indipendente dall'intensità $I$ della luce incidente, ma dipendente dalla sua frequenza $f$. (visto nel punto 6b del tutorial)

**Secondo la spiegazione classica (luce come onda elettromagnetica) che potete trovare nel file sull'effetto fotoelettrico si è in accordo solo con l'osservazione 3) perché l'energia trasportata da un'onda è proporzionale all'ampiezza dell'onda e non alla sua frequenza.**

Per ricapitolare, abbiamo l'equazione del bilancio energetico per determinare l'energia cinetica che gli elettroni possiedono appena sono emessi dal metallo (con la simbologia già usata):

$$E_{luce} = E_c + L_0 \qquad (a)$$

Perciò l'energia cinetica che possiedono gli elettroni, appena emessi, è $E_c = E_{luce} - L_0$.

Il moto degli elettroni tra i due elettroni, avete osservato dal tutorial, può essere modificato variando la differenza di potenziale della batteria: gli elettroni sono attratti dall'accumulo di carica positiva creata dalla differenza di potenziale e cambiano anche verso del moto (se d.d.p. negative) e velocità.

Calcoliamo la relazione che sussiste tra la differenza di potenziale di arresto $\Delta V_0$ e l'energia cinetica $E_c$ di un elettrone appena estratto. Il flusso di elettroni va verso l'elettrodo carico positivamente. Consideriamo di impostare nella batteria la differenza di potenziale d'arresto, ossia la differenza di potenziale tra i due elettrodi L ed M (vedi figura circuito del file precedente) sarà $\Delta V_{LM} = \Delta V_{batteria} = -\Delta V_0$ (il segno meno è per poter considerare $\Delta V_0$ positivo dato che sappiamo che il potenziale di arresto è sempre negativo). Questo è il caso in cui non viene misurata corrente dall'amperometro. Ciò significa che *anche gli elettroni più veloci vengono arrestati nel momento in cui giungono alla seconda armatura* e lì avranno energia cinetica nulla (quelli meno veloci sono stati già del tutto arrestati e hanno cambiato verso tornando indietro).

Applichiamo il teorema della conservazione dell'energia agli elettroni più rapidi. Si ha $\Delta E_c+\Delta U=0$ (dove U è l'energia potenziale elettrostatica) cioè $\Delta E_c-e\Delta V_{LM}=0$. Dato che $\Delta E_c=0 - E_c$ perché l'energia cinetica finale vale 0 (essendo gli elettroni arrestati) e l'energia iniziale è $E_c$ (quella che possiedono appena estratti), si ottiene:

$$E_c = e\Delta V_0 \qquad (b)$$

ossia l'energia cinetica degli elettroni è proporzionale al potenziale di arresto $\Delta V_0$.

Questo risultato permette quindi di **misurare l'energia cinetica degli elettroni attraverso la misura della differenza di potenziale di arresto**.

Inserendo la (b) nella (a) otteniamo la seguente relazione:

$$e\Delta V_0 = E_{luce} - L_0 \qquad (c)$$

Se lavorassimo con il modello classico l'energia della luce sarebbe proporzionale all'intensità della luce e quindi anche la differenza di potenziale di arresto dovrebbe essere proporzionale all'intensità della luce. Ma abbiamo osservato nella simulazione che la differenza di potenziale di arresto è proporzionale alla frequenza della luce e non alla sua intensità (punto 5). Perciò vediamo ora come Einstein risolse tutto.

## QUANTI DI LUCE

Per spiegare l'effetto fotoelettrico, Einstein nel 1905 introduce il modello dei quanti di luce che si fonda sulle seguenti ipotesi:

a) La luce di frequenza $f$ consiste di "quanti" (particelle, chiamati anche fotoni) discreti, ognuno dei quali con energia $E_{luce} = hf$ dove $h$ è una costante (chiamata costante di Planck);
b) Un fotone interagisce con un altro elettrone (in rapporto 1 a 1) trasferendogli tutta la sua energia.

Possiamo ora interpretare e spiegare i vari punti (all'inizio del documento) osservati tramite il tutorial utilizzando il modello di Einstein.

Consideriamo un fotone che interagisce con un elettrone. L'elettrone potrà lasciare il metallo se l'energia ricevuta $E_{luce}$ è maggiore del lavoro di estrazione: $E_{luce} = hf > L_0$.
Questa semplice osservazione permette di ricavare subito il punto **1)**, in quanto segue che, per avere l'emissione termica, la frequenza deve essere $f > L_0/h \equiv f_0$. Fornisce inoltre un modo per calcolare la frequenza di soglia $f_0$ a partire dal lavoro di estrazione e giustifica il fatto sperimentale che la frequenza di soglia varia al variare del materiale (perché cambia $L_0$).

Il punto **2)** segue dal fatto che ora non bisogna più attendere che l'elettrone acquisisca in maniera continua l'energia dall'onda elettromagnetica fino al punto di averne a sufficienza per uscire dal metallo ma il fenomeno è istantaneo così come è istantaneo l'urto tra due particelle.

Dall'equazione del bilancio energetico (a) e dall'ipotesi di Einstein $E_{luce}=hf$ segue immediatamente il punto **3)**. Infatti, $E_c = E_{luce} - L_0 = hf - L_0$ cioè l'energia cinetica degli elettroni dipende, come visto nel tutorial, dalla frequenza.

Aumentando l'intensità $I$ della radiazione incidente, il numero di fotoni incidenti aumenta. Siccome ogni fotone interagisce 1:1 con un elettrone, aumenta anche il numero di elettroni emessi. Questo spiega il punto **4)**.

Per spiegare il punto **5)** basta considerare l'equazione (c) e, di nuovo, l'ipotesi di Einstein $E_{luce} = hf$.
Infatti, si ottiene $e\Delta V_0 = E_{luce} - L_0 = hf - L_0$ e quindi si ricava la dipendenza della differenza di potenziale di arresto dalla frequenza e non dalla intensità della luce incidente:

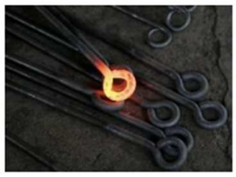
$$\Delta V_0 = \frac{hf - L_0}{e} = \frac{hf - hf_0}{e} = \frac{h}{e}(f - f_0)$$

Osservazione: finora abbiamo considerato un solo fotone ed un solo elettrone nell'analizzare i fenomeni perché, nelle ipotesi di Einstein, il fotone urta con un solo elettrone (in rapporto quindi 1:1). Il singolo fotone, come detto, possiede una energia data da $E_{luce}=hf$. Qual è allora l'energia complessiva dell'intero fascio di luce? Supponiamo che il fascio sia composto da $n$ fotoni (che aumentano se aumentiamo l'intensità della luce e viceversa), allora l'energia del fascio sarà la somma delle energie degli $n$ fotoni che singolarmente vale $hf$, ovvero:

$$E_{fascio}=nhf$$

## Lesson 6 and 7

### CORPO NERO



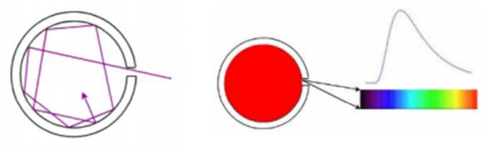
Dall'esperienza osserviamo che un corpo solido freddo non produce alcuna emissione, ma al crescere della temperatura comincia a diventare luminoso e a cambiare colore.

*Esempio*: un metallo che diventa incandescente cambia il suo colore e diventa prima rosso, poi arancione, e infine di un giallo-bianco abbagliante.

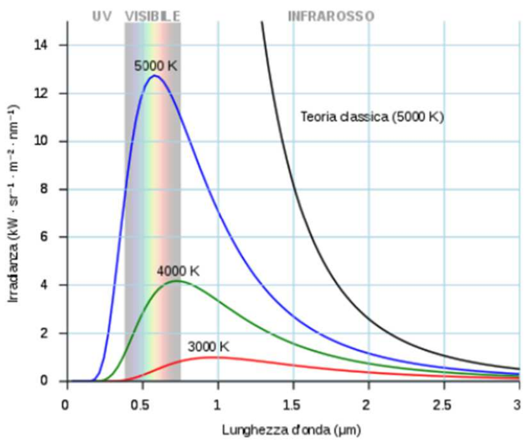
Un **corpo nero** è un oggetto **teorico** che assorbe il 100% della radiazione che incide su di esso perciò non riflette alcuna radiazione e appare nero. In pratica nessun materiale assorbe tutta la radiazione incidente (la grafite ne assorbe il 97%).

Un corpo nero riscaldato ad una temperatura sufficientemente elevata emette radiazioni in maniera isotropa che dipende solo dalla temperatura del corpo e non dalla sua forma o dal materiale di cui è costituito. Questa energia viene chiamata **radiazione di corpo nero**.

*Esempio* di corpo nero emittente: la fornace. L'energia entra da un piccolo foro e viene assorbita dalle pareti della fornace che si riscaldano ed emettono radiazione.



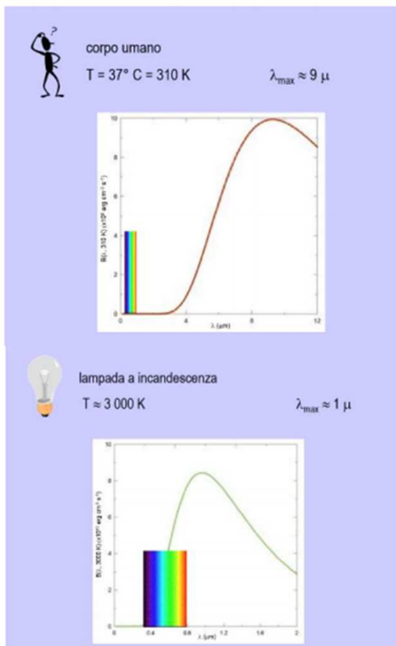
Facendo passare la radiazione emessa da un corpo a temperatura T attraverso uno spettrografo e misurando l'intensità dell'energia alle varie lunghezze d'onda si osserva uno spettro riprodotto dalla funzione di Planck (ripasso su cosa è uno spettro). Come si nota, la funzione di Planck ha un massimo di emissione molto ben definito, con l'intensità che cresce molto rapidamente alle lunghezze d'onda più corte e diminuisce più lentamente alle lunghezze d'onda maggiori (vedi SIMULATORE).




*Esempi*:

La funzione di Planck per un corpo nero che emette alla temperatura del *corpo umano*. Il massimo di emissione si ha a circa 9 micron, mentre al di sotto di 3 micron non c'è praticamente alcuna emissione. Infatti al buio una persona risulta invisibile, mentre diventa visibile con un sensore di luce infrarossa.

La funzione di Planck per un corpo nero che emette alla temperatura di una *lampadina a incandescenza*. Di nuovo, il massimo di emissione è collocato nell'infrarosso, eppure la lampadina emette luce visibile. Questo è possibile perché come si vede dal grafico la funzione si estende fino a 0.3 micron, includendo l'intervallo di lunghezza d'onda visibile. Quindi solo una frazione della radiazione globale emessa dalla lampadina è luce visibile. Per questo motive le lampade ad incandescenza sono energeticamente meno efficenti di lampadine, ad esempio, a LED.



## Legge di Wien

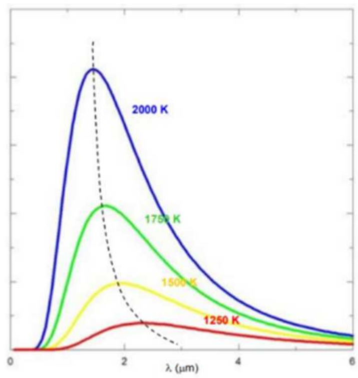
Lo spettro di emissione del corpo nero mostra un massimo di energia ad una certa lunghezza d'onda ($\lambda_{max}$) All'aumentare della temperatura T del corpo, la lunghezza d'onda del massimo di emissione decresce.

Matematicamente per trovare il Massimo bisogna calcolare la **derivata** della funzione e porla uguale a zero ottenendo la legge di Wien:

$$\lambda_{\max} T = b$$

con b costante,

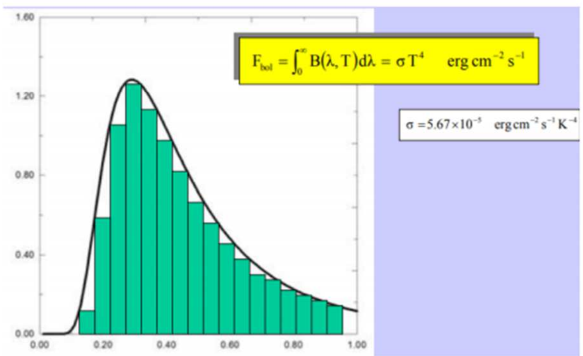
$$b = 2{,}8978 \cdot 10^{-3}\ \mathrm{m \cdot K}$$




Questo grafico rappresenta la funzione di Planck per un corpo nero a quattro temperature diverse, crescenti dalla curva rossa a 1250 K fino alla curva blu a 2000 K. Il grafico dimostra lo spostamento del massimo di emissione verso lunghezze d'onda più corte all'aumentare della temperatura.

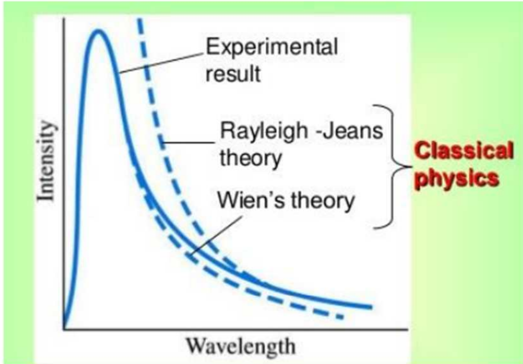
## Legge di Stefan-Boltzmann

Abbiamo appena visto che all'aumentare di T non solo diminuisce il valore di $\lambda_{max}$, ma accade anche che la funzione di Planck assume valori con intensità rapidamente crescente. Se sommiamo i valori della funzione ad ogni lunghezza d'onda, otteniamo il flusso globale di energia, cioè la quantità di energia emessa dall'unità di superficie nell'unità di tempo. Questo è possibile calcolando **l'integrale** della funzione che nel grafico è rappresentato tramite l'approssimazione dei rettangoli, e si ottiene una semplicissima soluzione, secondo cui il flusso è proporzionale alla quarta potenza della temperatura. Questo risultato è noto come legge di Stefan-Boltzmann.




All'aumentare della temperatura, l'energia totale emessa cresce, perché aumenta l'area totale sotto la curva.

Già nel XIX secolo i fisici tentavano di ricavare una teoria che fosse in grado di predire lo spettro della radiazione emessa da un corpo nero. Applicando le leggi di Maxwell dell'elettromagnetismo classico Wilhelm Wien e Lord Rayleigh e James Jeans ottennero le leggi rappresentate in figura. Il tentativo di Wien falliva nel riprodurre i dati sperimentali alle grandi lunghezze d'onda mentre quello di Rayleigh-Jeans falliva alle lunghezze d'onda corte e non mostrava nessun massimo di emissione.




Nel 1900, Max Planck riesce a ricavare una formula che riproduce i valori osservati nello spettro del corpo nero. Nella sua derivazione Planck introduce una sorta di **discretizzazione dell'energia E=hν** a cui però non dava alcun valore fisico considerandolo solo un "*trucco matematico*".

$$B(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/k\lambda T} - 1} \quad \text{erg cm}^{-3}\,\text{s}^{-1}$$

$$B(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \quad \text{erg cm}^{-3}\,\text{s}^{-1}$$

$$h = 6.63 \cdot 10^{-34}\ \text{J s} = 6.63 \cdot 10^{-27}\ \text{erg s}$$

Costante di Planck

$$\lim_{\lambda \to \infty} B(\lambda, T) = 2\pi ck \frac{T}{\lambda^4} \rightarrow \text{Rayleigh-Jeans}$$

$$\lim_{\lambda \to 0} B(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} e^{-\frac{hc}{k\lambda T}} \rightarrow \text{Wien}$$

In alto le formule della legge di Planck in funzione della lunghezza d'onda (λ) o della frequenza (ν). La costante h è chiamata costante di Planck, c è la velocità della luce.

Se calcoliamo l'andamento della legge di Planck alle grandi lunghezze d'onde, otteniamo l'approssimazione di Rayleigh-Jeans, mentre alle lunghezze d'onda corte abbiamo l'approssimazione di Wien: è sufficiente considerare il **limite** per lunghezze d'onda grandi (Rayleigh-Jeans) o tendenti a zero (Wien).

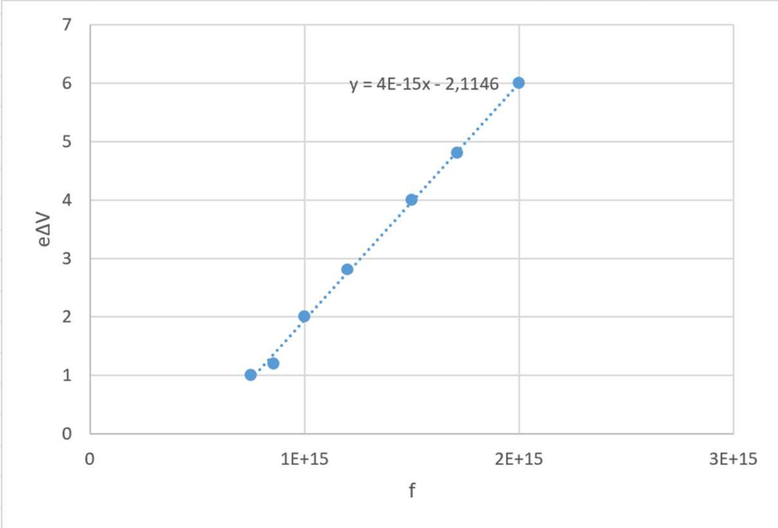
Calcolando il massimo della funzione di Planck otteniamo la legge di Wien e calcolandone invece l'integrale otteniamo la legge di Stefan-Boltzmann.

## Lesson 8

Stima della costante di Planck attraverso i dati ottenuti dal tutorial:

| λ [nm] | f [Hz] | eΔV [eV] |
|---|---|---|
| 400 | 7,5E+14 | 1 |
| 350 | 8,57E+14 | 1,2 |
| 300 | 9,99E+14 | 2 |
| 250 | 1,2E+15 | 2,8 |
| 200 | 1,5E+15 | 4 |
| 175 | 1,71E+15 | 4,8 |
| 150 | 2E+15 | 6 |

| | | |
|---|---|---|
| h | = | 6,4E-34 J*s |




Discussione sui quantoni tramite le letture presentate nel capitolo “quantons”.

# *Annex D: Answers to the interviews with teachers*

| **PARTE 1**: | DOCENTE 1 | DOCENTE 2 | DOCENTE 3 | DOCENTE 4 | DOCENTE 5 | DOCENTE 6 |
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| **Q1** | Siamo ancora in una fase di passaggio su questo argomento. Felice che sia stata espansa la fisica in generale che ora si riesce a fare bene ma sono critico per la fisica quantistica. Ci sono vari obiettivi quando si fa la fisica quantistica: importante da conoscere per chi poi sceglie facoltà scientifiche ma mi sono sempre chiesto a cosa serva a livello liceale. È cultura scientifica ma per quelli che non faranno indirizzi scientifici non la inserirei tra le conoscenze di base.<br>Inoltre si crea un problema di metodo: rigore assoluto fino alle onde elettromagnetiche ("mai fidarsi del prof", generalmente si dimostra tutto tranne quando non si conosce la matematica) con la fisica quantistica invece no ed è un problema anche portare esempi sperimentali. Poi questione di tempo nel coprire gli argomenti. Va bene la relatività perché si unisce bene dalle onde elettromagnetiche e da qui si apre un mondo inclusa la cosmologia però di fatto è obbligatoria la quantistica visti gli esami di stato. Non condivisione delle priorità. | Favorevole, è una fisica che ormai ha 100 anni. Ma nei libri di testo c'è stata semplicemente l'aggiunta di un ultimo capitolo senza una revisione completa anche del modo di insegnare i concetti precedenti. Altrimenti sembra che tutto ciò che è stato fatto prima era sbagliato. Ha messo in crisi il corpo docente perché sono argomenti che non venivano trattati all'università (per chi ha fatto matematica). Si riescono a fare poche cose semplificate.<br><br>Il rischio non è tanto per gli studenti più bravi quanto per lo studente medio che rischia di farsi un'idea sbagliata | Il problema è riuscire ad arrivare a farla. Nonostante siano state introdotte le due ore di fisica anche in prima e seconda in realtà al biennio non si riesce a fare molto. E in quinta c'è anche la parte di relatività da fare. Si inizia relatività da marzo.<br><br>C'è la fretta di finire e poi c'è l'esame di stato. | Favorevole, la fisica si fermava all'800. Fatto esperienza di questo argomento in 3 anni con 3 quinte (tipicamente mai per tutto il triennio) e per i ragazzi stimola curiosità. Sarebbe interessante trovare anche un aggancio con filosofia. | Ne ha già avuto esperienza con un percorso sperimentale (PNI degli anni 90) che ha avuto esiti positivi. Le attuali indicazioni nazionali prevedono però delle scelte diverse dal percorso sperimentale provato in passato. | Sfruttare la fisica quantistica per parlare di alcune antinomie. Discreto vs continuo (che si può fare sia in matematica che fisica). Far emergere come procede la scienza: rapporto tra teoria ed esperimento. Importanza dell'esperimento. Rapporto con la matematica quindi far emergere la natura probabilistica. Superamento del dualismo. |
| **Q2** | Crisi fisica classica, quantizzazione utile anche solo per capire dove è la crisi: si è costretti ad inquadrare la fisica | I programmi ministeriali prevedono di fatto la fisica dei quanti. Si fa percorso di natura storica. Primi esperimenti, | Vedi Q5 | Gli argomenti che hanno messo in crisi la fisica classica e anche la loro modellizzazione mettendo in evidenza come certi modelli | Visione storica dell'insegnamento della fisica. Dalle origini storiche (ricette ad hoc per gli esperiemnti) anche | Nuovo concetto di discretizzazione e superamento del dualismo onda corpuscolo: per l'esperimento sulla doppia |

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| | fatta fino a quell momento. In molti quindi riclicata come un “saper usare queste formule che chiedono all’esame” però la si sfrutta per capire cosa dice la fisica classica e capire dove è il problema. Quindi più attenzione su problema che su soluzione. Utile per mettere in collegamento i vari argomenti svolti. Non dare l’impressione, come si è pensato, che “la fisica è finita”. | modelli atomici, corpo nero e poi effetto fotoelettrico e Compton. Atomo di Bohr e, a seconda del tempo, indeterminazione. | | riuscivano a spiegare alcuni fenomeni come l’effetto fotoelettrico, Compton, corpo nero. Anche l’atomo di Bohr e le sue criticità. Sarebbe interessante arrivare alla indeterminazione. Sarebbe interessante provare ad individuare percorsi di approfondimento come fisica delle particelle (anche se il rischio è che diventi una zoologia delle particelle) oppure stato solido, consigliati anche dalle Indicazioni nazionalii. Anche modelli di meccanica statistica raccontando evoluzione da modello cinetico in poi. Il problema è calarli nella realtà concreta. | fino all’idea delle onde materiali, la funzione d’onda (onde di probabilità) fino all’interpretazione quantistica. Si possono usare strumenti matematici come distribuzioni di probabilità. | fenditura già messo in evidenza al 4o anno che è importante perché indice di natura ondulatoria.<br><br>Atomo di Bohr lo conoscono anche da chimica ma l’impressione è che la usino senza conoscerne il perché. Sarebbe interessante scegliere in base agli interessi che emergono dalla classe. Mi aspetto negli anni di cambiare scelte. |
| **Q3** | | Storico | Più storico (si cerca di far capire cosa non funzionava…) | Storico ma sarebbe una sfida trovare un modo di tradurre la matematica in un una maniera che possano comprendere gli studenti senza aver fatto operatori ecc. Alcuni studenti notano che in questa parte ci sono poche formule. | Storico, concettuale.<br>Dettaglio matematico e a volte banale, a volte trope pesante. | |
| **PARTE 2**: | | | | | | |
| **Q4** | Questa parte da fine aprile, ottimisticamente parlando. Per me la sconfitta importante è il metodo. Usavo il laboratorio ma non ho in mente nessuna esperienza in fisica quantistica che posso fare in un laboratorio. Similmente per le dimostrazioni: al massimo riesco a dare qualche simulazione online. Molta connessione con la chimica del terzo anno (esercizi dal testo di fisica e dal testo di chimica per | Uso di app che scaricano anche i ragazzi (anche su effetto fotoelettrico) per presentare alcuni concetti. Secondo lui più utile di una lezione frontale (gli sembra meno astratto e variare loro i parametri li aiuta a capire e a focalizzarsi sulle cose importanti del fenomeno).<br><br>Usano il Walker. Anche secondo lui case editrici non erano pronte | In generale si stanno spostando gradualmente da lezioni prevalentemente frontali a più laboratorio ma di fisica moderna non c’è molto. Oppure si cerca in internet qualche filmato. (ad esempio Millikan).<br><br>Usano il Kutnell della Zanichelli, prima usavano l’Amaldi (ma ci sono “molte parole” ed i ragazzi non hanno piu la pazienza di leggere molto). C’è comunque | Un anno invertito relatività e quantistica ma di solito da Febbraio relatività e quantistica dopo marzo.<br><br>Spesso è necessario avere un impianto più storico. Un po’ per condensare in poco tempo i concetti trascurando la formalizzazione, anche se è molto debole. | In generale si inizia nella seconda parte dell’anno. Personalmente cerco di far intuire concetto di quanto da dopo le onde elettromagnetiche.<br><br>Il laboratorio è un problema (anche limiti della mia preparazione)<br>Lezione frontale ma dialogata con sostegno importante della matematica (“la lavagna ci vuole…”). Non do spazio | |

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| | capire che è lo stesso argomento).<br>Riguardo al testo usano l'Amaldi ora ma cambiati molto in maniera ossessiva perché ho più problemi rispetto ai libri di matematica (didattica della matematica pensa sia più consolidata). Le case editrici non erano pronte all'inserimento della fisica quantistica. | all'introduzione della fisica quantistica nei testi. | sempre bisogno di integrare con qualcosa (ad esempio risonatori di Planck). Anche scritti da Einstein, qualcosa di storico. | Lezioni fontali, non laboratori a parte gli spettri visti con Unipd. Molti studenti sono proiettati a università ed esame di stato. Fatica a tenere attenzione.<br><br>Usato video ma non simulazioni. Uso di slide.<br><br>Amaldi poi Romeni e ora Kutnell. I libri di stampo americano hanno poca parte storica. A volte non è chiara differenza tra spiegazione classica e quantistica. | fondamentale al laboratorio nella didattica in generale. Approccio teorico ma non formale.<br><br>Quindi approccio storico ma con distribuzioni di probabilità. Per esempio capire orbitali atomo idrogeno.<br><br>Adottato l'Amaldi della Zanichelli | |
| **Q5** | Crisi fisica classica, quantizzazione corpo nero, quantizzazione luce, quantizzazione orbite di Bohr (che hanno già fatto in chimica però in un momento in cui non potevano comprenderla), De Broglie. Effetto fotoelettrico è facile, divertente e un esperimento con il quale si capiscono molte cose. Diffrazione con elettroni solo nominata. | Fisica dei quanti ma equazione di Schrodinger solo se qualcuno pone la domanda. | Corpo nero e ipotesi di Planck. Effetto fotoelettrico (con l'ipotesi dei risonatori di planck prima e poi con la spiegazione di Einstein). Si racconta l'ipotesi della natura ondulatoria della materia con de Broglie e l'indeterminazione (cenni). Infine richiamo su modelli atomici visti già in scienze. | Fino Bohr con diversi livelli di approfondimento. In un anno anche lettura su indeterminazione e parlato di Schrodinger.<br><br>Con il programma vincolati all'esame di stato.<br><br>Arrivati alla quantistica hanno tanta fisica alle spalle che non ricordano tutto e anche il dover ricostruire tutto con una matematica nuova: le derivate ecc. | Si arriva a Schrodinger e risoluzione di un elettrone in buca infinita solo con pochissime classi.<br>La matematica sottostante costituisce uno scoglio che superano gli alunni bravi e con ciò crescono molto. | |
| **Q6** | Tradizionale nella valutazione. Non cambia tra i vari moduli. 70% capacità di operare con gli esercizi. Per quantistica non verifica scritta ma alla lavagna con esercizi. Ok quando esercizio è della tipologia che c'è all'esame di stato ma situazione critica quando gli si chiede cosa sta succedendo. | Vincolati da questo fatto perché la fisica quantistica è nell'esame di maturità. Quindi quiz oppure video del PSSC e poi questionario di comprensione del video. Ma in generale teoria perché poi chiesto all'orale. | Ugualmente, con orale ma anche scritto. C'è la possibilità di fare qualche piccolo esercizio. | In questa fase cerco sempre più di interrogare sia perché si avvicina al colloquio dell'esame di stato sia perché consente di monitorare se lo studente segue e se riesce ad individuare i vari modelli e collegare con la fisica classica fatta. Per gli esercizi MIUR a volte semplice applicazione di formule che si possono fare anche alla lavagna e a volte esercizi troppo complessi e articolati. | Di solito compiti scritti che dovrebbero avere anche una valenza per l'orale. Prove orali alla lavagna.<br><br>In fisica quantistica un po' varia. Si possono fare dei problemini sulle parti iniziali. Ma sulle cose successive no. | |

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| **Q7** | Acquisiscono l'idea della quantizzazione e tre formulette di uso per i quesiti. | Nonostante sia uno scientifico c'è pur sempre un gruppo di studenti che "tirerà a campare" e sono irrecuperabili e quindi anche per il modulo sulla fisica quantistica. Nonostante questo, non migliora la loro valutazione perché sono comunque cose difficili e dipende anche da come si studiano. Poi anche perché in quel periodo studenti stanchi e proiettati a esame di maturità. | Ci sono studenti interessati, anche da letture o approfondimenti personali e studente medio che non trova più interesse di altri argomenti.<br><br>Spesso capita che devono accontentarsi di ciò che gli viene raccontato. Come fanno già con scienze e chimica per i modelli atomici. | Interesse sulla parte della narrazione più che nella parte tecnica e collegamento con scienze e chimica. Hanno preconoscenze da riprendere o valorizzare. | Gli studenti questa parte se la aspettano prima perché le idee le hanno già sentite da qualche parte. In una classe tipica non ci arrivano tutti di fatto, soprattutto quelli che hanno problemi in matematica. | |
| **PARTE 3**: | | | | | | |
| **Q8** | a)Concetto di probabilità ma non proprio i conti con l'integrale. Calcolo combinatorio in terza perché si fa Boltzmann.<br>b)Metodo scientifico in generale. La prima riflessione più profonda sul modello quando si fa la termodinamica (Boltzmann: scrivono ipotesi e quali sono i limiti del modello; ma anche da Keplero a sistema solare).<br>c)Vettore come grandezza con modulo direzione e verso. Matrici solo per i sistemi.<br>d)Excel, simulatori solo alcuni se fatto laboratorio. | a) In 4a (calcolo combinatorio) e in 5a (distribuzioni) ma crea qualche problema perché ci sarebbe bisogno delle distribuzioni già da prima.<br>b)Accenni ma nel libro di testo queste cose sono oscure. Un esempio in cui si usa è nel modello di Rutherford e Bohr.<br>c)Dalla classe prima concetto di vettore ma usati dalla 3a in poi in maniera massiva. Ma non si dice tutto subito, vengono introdotti laddove servono. Quindi prodotto scalare e vettoriale quando serve ma con regola mano destra. A volte anche rispiegate più volte se non lo usano per un po'.<br>d)Utile uso simulatori. Per il laboratorio conosce esperimenti ma non riesce a replicarle in classe sia perché non ha abbastanza materiale sia perché dipende molto dal gruppo classe. Non tutte le esperienze sono di presa dati, alcune solo qualitative. | a) calcolo delle probabilità<br>b) sempre in applicazione a casi che si affrontano (tipo dualità luce ma viene solo raccontata a parole)<br>c) con componenti solo quando si fa geometria analitica nello spazio. Più che altro dalla necessita di equazione del piano perpendicolare.<br>d) laboratorio si, software per fare grafici e tabelle. Geogebra anche per geometria solida.<br>e) Ottica geometrica anche in biennio e gli specchi e lenti sottili. Poi nel triennio fori di Young e onde. Polarizzazione in quinta con le onde elettromagnetiche ma non sempre e si può vedere qualcosa in laboratorio. | a) si accennano soltanto le distribuzioni ai fini degli esercizi dell'esame di stato.<br>b) al biennio è difficile, si parla più di leggi. Poi già in terza col modello cinetico.<br>c)matrici no, vettori e prodotto scalare e vettoriale per componenti ma notazione riga e colonna no.<br>e)polarizzazione alla fine delle onde elettromagnetiche. Bisogna scegliere cosa fare. L'ideale sarebbe dopo maxwell fare polarizzazione e quantistica invece c'è prima il modulo sulla relatività. | a)già emerso.<br>c) algebra lineare è un problema. È stato un grande inserimento nel PNI ma nelle indicazioni nazionali ora non c'è più. Quindi no matrici, no trasformazioni. Bisogna fare delle scelte soprattutto insieme all'università che ci dica cosa serve (e ministero dovrebbe accettare delle scelte libere rispetto le indicazioni nazionali).<br>d) prima laboratorio ma poi condizionamenti (protocolli sicurezza, cose che si possono usare e no e costo attrezzature). Siti con animazioni in Cabri e Flash. Interessanti le uscite in laboratori e l'interdisciplinarità. | a)statistica univariata in prima, in seconda probabilità frequentista, in terza si dovrebbe fare statistica bivariata (correlazione lineare minimi quadrati per retta regressione) in quarta calcolo combinatorio fino al processo di Bernoulli ed in quinta dovrebbero arrivare alle distribuzioni di probabilità. Il collegarlo alla fisica dipende da insegnante, è un modulo che non a tutti piace.<br>c)Vettore come segmento orientato fino a poco tempo fa. A volte versore e coordinate cartesiane. Anche sfruttando il campo elettrico.<br>d)Non abituata a uso laboratorio. Analisi dati con Excel (anche se non si può dare per scontato che sappiano usarlo). |

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| | | e)Polarizzazione con elettromagnetismo in quinta. | | | | |
| **PARTE 4**: | | | | | | |
| **Q9** | Insegna da 18 anni<br>Laurea in fisica a Pisa e dottorato in astronomia a Padova<br>Vari corsi di formazione come quello di fisica moderna online dell'università di Roma Tor Vergata (rinforzo sugli argomenti ma di didattica non c'era nulla), anche corsi di società italiana di astrofisica. | Insegna da 14 anni<br>Laurea in matematica<br>Ha seguito un corso all'università di Padova, uno di Roma3 (qualcosa del materiale lo usa ancora) e letture personali per capire come insegnarla (didattica della fisica). | Laurea in matematica<br>Corsi post-laurea sempre a Padova in didattica fisica, esperienza spettri con Unipd. Un corso a Ferrara dove han visto esperimenti di fisica moderna (provando gli strumenti). Esigenza di un corso dal punto di vista didattico.<br>30 anni di insegnamento. | Insegna sia mate che fisica negli ultimi 3 anni.<br>Laurea in fisica,<br>insegna dal 2006 come precario. Nel perfezionamento c'era didattica della fisica ma in generale non fisica quantistica nello specifico. Il problema è che molti master danno contenuti e non modalità didattiche. | Laurea in matematica.<br>Nessun corso sulla didattica della fisica quantistica. Ho visto che tante offerte non sono all'altezza: tanto vale prendere un libro e studiarselo. | Laurea in matematica.<br>Complessivamente 4 anni di insegnamento.<br>TFA come formazione per poi fare il concorso, un anno assegno di ricerca in didattica. |
| **Q10** | | In generale corpo docente non preparato. Non sarebbe meglio far fare questo modulo solo a chi è laureato in fisica? è in periodo dell'anno infelice, a ridosso dell'esame. Paradossalmente questanno (emergenza sanitaria covid-19) è stato meno di intralcio perche modalità di esame diverse e non c'è stato il quiz. | | | | |