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"Can old quantum theoretical description of physics be rendered coherent?": A pilot experimentation for high schools

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Summary. — While many models of the Old Quantum Theory (OQT) have long been incorporated into international school *curricula* and textbooks, research in Physics Education regarding effective educational approaches to the OQT is predominantly centred only on individual topics (mainly black-body spectrum, photoelectric effect, and Bohr's atomic model), leaving a notable lack in providing a coordinated and comprehensive pedagogical, historical, and conceptual presentation that encompasses the entirety of the OQT. The following research questions thus arise: can the OQT be presented coherently and meaningfully without substantial alterations to prerequisites, topics presented, mathematical formalism, and time usually devoted at school, deepening the physics contents and making it effective from an educational point of view? What are the several disciplinary and learning knots of the OQT? Addressing these research questions, this paper explores the design, implementation, and testing of three extracurricular educational workshops focused on the OQT and conducted in 2022–23 and 2023–24 by the Physics Education research group of the University of Milan, with 210 high-school students and 93 teachers. Meetings included commented readings of original papers, collaborative group works with active understanding, and several qualitative and quantitative assessments and examples. Results obtained are here reported and discussed.

1. – Introduction

The aim of this work is to delineate the outcomes derived from the design, implementation and assessment of a pilot experimentation on the Old Quantum Theory (OQT). The experimentation was organised by the Physics Education Research (PER) group of the University of Milan and spanned three educational workshops conducted in 2022–23 and 2023–24, involving high school students and teachers. In fact, despite the widespread integration of the OQT into international high school *curricula* [1] and textbooks [2-5], PER has traditionally focused only on few isolated topics, mainly the black-body spectrum [6-8], the photoelectric effect [9-12], and Bohr's atomic model [13-15]. This approach lacks a comprehensive and unified framework, resulting in a significant gap in presenting the OQT coherently from pedagogical, historical, and conceptual perspectives.

In line with prevailing findings in PER, which emphasise the importance of introducing a precise theory for quantum physics —*i.e.*, Quantum Mechanics (QM)— at school [16, 17], we firmly believe that confining the educational focus to the OQT is not the most fitting and efficacious way for introducing quantum physics. However, despite ongoing

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efforts made by various PER groups [18] —including ours [19, 20]— to introduce QM in high schools using diverse approaches and methodologies, one cannot ignore that, in conventional school practices and textbooks [1, 21], quantum physics is frequently discussed predominantly in terms of the OQT.

The problem is that not only the OQT is not itself a theory, but also it is presented with a standard pseudo-historical approach [22] that delves into the alleged "crisis of classical physics" (an expression often used by textbooks which is, however, historically and physically inaccurate, since no crisis was perceived by the physicists of the early 20th century) and the attempts to overcome it through well-known *ad hoc* models. Such a presentation leads to profound misunderstandings, rendering quantum physics confusing, obscure, and somewhat incomprehensible [1, 18, 23, 24]. Therefore, given the prevailing *status quo*, with teachers and textbooks often dwelling on the OQT, we deem it crucial to explore and research also this direction, conducting an educational reconstruction for the OQT that is historically accurate, pedagogically effective, and culturally meaningful.

2. – Our research questions

Our research endeavours to identify an effective approach for presenting the OQT in an educational context. Consequently, it becomes imperative to assess the efficacy of our approach. Therefore, based on the insights derived from the existing research literature and the concise overview provided earlier, the following research questions guided our investigation:

*RQ*1. Can the OQT be coherently, meaningfully and effectively presented at high school?

*RQ*2. Is it feasible to achieve this, without making radical changes to topics, mathematical formalism, prerequisites, and without substantially altering the total time typically devoted to the OQT?

*RQ*3. What are the principal disciplinary and learning knots of the OQT?

3. – "Old (but Gold) Quantum Theory": the educational laboratory of the University of Milan

In 2022–23, the PER group of the University of Milan designed, implemented, and tested a first educational workshop entitled "Old (but Gold) Quantum Theory". Conducted from January to February 2023, this initiative was embedded within the Italian National Plan of Recovery and Resilience (PNRR), targeting a cohort comprising 36 high school students of the last three years (grades 11th-13th) and 9 teachers.

The course structure encompassed five weekly afternoon sessions, each lasting three hours, resulting in a total duration of 15 hours. Drawing from the literature and prevalent topics presented at school, we chose to focus on three central themes: black body, quantisation of radiation, and atomic models. To this end, we carefully examined not only the research literature and textbooks most used at school, but also hundreds of primary sources concerning these subjects. Utilising an active-learning approach, the workshop thus engaged participants in a conceptual exploration of models derived from the OQT concerning: black-body radiation, early atomic models (Kelvin, Thomson, Nagaoka, and Rutherford), the photoelectric effect, the Compton effect, and Bohr's hydrogen atom.

As can be seen, we constructed a pedagogical framework that, from a chronological perspective, does not always adhere strictly to the order of events. This choice was not due to a lack of historical rigour but had a precise educational reason, since it emphasised the physical and conceptual connections between different models, the insights and suggestions of their creators, highlighting interconnections to present a cohesive narrative rather than portraying models as isolated entities. This approach allowed us to highlight the disciplinary and learning knots of the OQT. Moreover, the deliberate inclusion of topics that are not strictly "quantum related" was motivated by three educational considerations. Firstly, these themes (in particular, Thomson's and Rutherford's models) typically constitute part of the knowledge acquired by high school students in chemistry classes during the initial years of high school. Additionally, these topics are commonly presented in the majority of physics textbooks of the final year in high school. Furthermore, delving into the discussion and analysis of early atomic models, despite their lack of quantum aspects, contributes to a more profound comprehension of Bohr's hydrogen atom. This approach enables students to appreciate the challenges inherent in constructing a stable atomic model capable of explaining well-established phenomena, such as atomic spectra or the periodic table of elements, while also predicting new phenomena.

Students and teachers attended the meetings together. The simultaneous presence of teachers and students is typical of the training courses organised in Milan, allowing teachers to assess the effectiveness of the proposed path and evaluate students' understanding. The course was the first occasion in which students were presented the OQT, as they had not previously attended quantum physics courses at school.

Meetings included several experimental activities (for example, experiments with spectral lamps and the determination of electron charge-to-mass ratio), commented readings of 24 excerpts from original papers, and numerous 10 minute group assignments involving active reading and comprehension, by means of a conceptual enquiry approach on theoretical tasks. The selected readings were chosen based on the readability and on the disciplinary and learning knots highlighted from the literature. Groups were asked to reflect on many qualitative examples, as well as on quantitative aspects. Additionally, problems not typically covered in textbooks were addressed and discussed.

For instance, in the photoelectric effect, excerpts from Einstein's original paper of 1905 were read, followed by group discussions among participants. Starting from the heuristic model, participants were asked how it could be used to predict new facts and explain more complex situations (from now on, we will denote with "*Q.*" the question posed and with "*A.*" an example of the answers obtained).

> *Q.* Consider Einstein's heuristic model of 1905. Suppose a photon hits the metal plate and is absorbed by an electron but does not have enough energy to eject it and induce the photoelectric effect. What do you think will happen to the energy of the photon? What effects will it produce in the metal?
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> *A.* If a photon strikes the metal plate but lacks sufficient energy to extract an electron, the energy of the photon will still be absorbed by the electron. This process will lead to an increase in the electron's energy within the material, but the electron will remain anchored to the metal. The excess energy of the photon will be dissipated as thermal energy, resulting in a localised increase in the metal's temperature in the region of interaction between the photon and the electron.

4. – Experimentation's effectiveness: data analysis

The effectiveness of the experimentation was assessed through different data sources, including all written group assignments, five individual ongoing tests, a satisfaction questionnaire, and a final test with 10 open-ended questions that had not been previously either encountered or discussed during the course. It is noteworthy that a variety of evaluation methods were employed, extending beyond those conventionally beneficial for teachers, to comprehensively gauge effectiveness also from research group's perspectives. Each answer was individually evaluated by the researchers actively engaged in the experimentation; subsequently, a comparative analysis of the evaluations was conducted, and the scores presented in this paper reflect the consensus reached after the comparison process.

4·1. *Students' average grade.* – One of the aims of this research was to demonstrate to teachers that the OQT can be effectively presented at school, yielding students outcomes comparable to those achieved in classical topics. Using an assessment grid conventionally employed in school settings (developed with the aid of the participating teachers), students achieved an average score of 6.6 out of 10 in the tests (in Italian grading system, the passing threshold is set at 6.0). The obtained average, with a standard deviation of 0.7, aligns with the average grades typically observed in physics tests. This result significantly contributed to fostering a perception among teachers that the proposed approach is both viable and suitable for implementation in a school context (*RQ2*). Moreover, in this regard, it is pertinent to note that, during the course, students were not provided with handouts or slides, but had to rely solely on notes taken during the meetings.

4·2. *Critical thinking.* – Concerning the learning significance, participants appear to have recognized that the addressed issues possess intrinsic cultural meaning. This recognition stems, for example, from the realisation that the development of physics is far from a linear, brief, and simple path [22, 25]. Additionally, participants seem to have developed a heightened capacity for critical thinking in answering the presented questions (*RQ1*). For instance, when tasked with delineating the characteristics of a good physical model, students highlighted the necessity for it to offer an explanation of the described phenomenon (89%), be underpinned by mathematical foundations (42%), anticipate and foresee new phenomena (64%), and integrate into the physical universe (81%), aligning with the existing framework of already established theories. This way of proceeding thus helped students in a better understanding of the Nature of Science (NOS) [26].

> *Q.* In your opinion, what characteristics (from a physical, mathematical, conceptual point of view) must a good physical model have? What must it be able to say and do? Justify your answer.
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> *A.* A good physical model must possess various characteristics to be considered valid and useful in the context of understanding nature. From a physical standpoint, the model should be able to accurately represent and explain observed phenomena, providing also a coherent and predictive description of reality. This entails a close correspondence between the model's predictions and the experimental data collected. From a mathematical perspective, the model must be expressed rigorously, using a consistent mathematical language. Furthermore, the model should be capable of integrating existing theories and extending them to explain a wide ensemble of phenomena. Conceptually, a good model should contribute to the construction of a unified view of the physical world, providing a logical connection between different areas of physics. Additionally, it should be adaptable to new discoveries and theories, offering a flexible framework capable of evolving with progress.

4·3. *Textbooks' ambiguities and errors.* – A critical approach emerged also in interpreting explanations, diagrams, and figures presented by textbooks, with participants autonomously expressing criticism for perceived inaccuracies or misleading contents. For example, the common representations of the photoelectric effect, in which the incident photon is always represented as a wave (or a wave packet) while the emitted photoelectron is depicted as a particle. In addition to this inexplicable asymmetry, another question arose: that is, how can the photoelectron be emitted from the metal plate on the same side of the incident photon? It is evident that an image of this kind, when scrutinised closely, induces confusion in both students and teachers. During the experimentation, it emerged that 77% of teachers had never considered these issues before.

On the other hand, even the way in which the photoelectric effect is narrated in textbooks can easily lead to misunderstandings and incorrect ideas. In fact, the version commonly provided by textbooks

> "...of the history of the photoelectric effect is grossly oversimplified and contains several myths or plain errors. Among the myths which usually enter the quasi-historical presentation, are the following: 1) Einstein's theory of 1905 relied upon and was a natural extension of Planck's theory of 1900, which Einstein adopted and applied to the nature of light; 2) Einstein's work was a theory of the photo-electric effect; 3) The core of Einstein's theory was an explanation of experiments which proved that the kinetic energy of the photoelectrons depends linearly on the frequency of light, but is independent of its intensity; 4) This experimental fact was (and is) inexplicable without the photon hypothesis; 5) Since there thus was no classical alternative to Einstein's explanation, it was of course accepted; 6) The final verification of Einstein's theory was provided by Millikan in experiments of 1916. [...] all these assertions are misrepresentations of the actual history [...]." ([22], p. 352).

These are all crucial aspects for a coherent and meaningful comprehension, and were highlighted and discussed during the course.

4·4. *Knowledge integration construct.* – We have also exploited the Knowledge Integration Construct (KIC) to assess students' ability to connect ideas within a specific context, assigning scores from 0 to 5 for the following parameters: no answer, off task, no link, partial link, full link, complex link [27]. In fact, students develop ideas from experience, education, peer interaction, and other scientific activities. Therefore, a multi-modal approach, such as that proposed in the course, assists students in articulating their ideas, incorporating new concepts and ideas, developing criteria for distinguishing among these ideas and forming a more coherent and consistent understanding of scientific phenomena. The result is that 68% of students demonstrated the capacity of establishing scientifically valid connections between (at least) two relevant ideas in a given context (*RQ1*). Additionally, 72% of them successfully tackled and solved new problems in situations they had never encountered before.

> *Q.* Based on your idea of a "good physical model", do you think that Einstein's explanation of the photoelectric effect was a "good model"? Justify your answer.
> *A.* Einstein's heuristic model of 1905 can be considered a good model to describe the photoelectric effect, since it manages to explain many aspects of the phenomenon with the introduction of the simple concept of quantum and with the extension to it of some laws of classical mechanics (first of all, why electrons leave the atom; then, why this happens or not, depending on incident light's frequency). The model thus provides a description which is consistent with a corpuscular interpretation of light. However, it does not integrate at all with the well-established model that interprets light as a wave, and fails to explain the phenomena that are so accurately described by the latter.

The student adequately justified the answer, starting from the concept of quantum of light employed by the model and understanding its links with classical laws. The student also highlighted the challenges associated with reconciling the corpuscular interpretation of light with its wave counterpart, an aspect not discussed in the course. Hence, the evaluation assigned using the KIC was categorized as a "complex link" with a score of 5.

4·5. *Comparison with peers.* – Finally, we conducted a comparative analysis between the answers provided by the participants of "Old (but Gold) Quantum Theory" course and those from a cohort consisting of 86 undergraduate students majoring in mathematics and physics, along with 46 teachers. Participants of "Old (but Gold) Quantum Theory" course appear to have developed a more profound comprehension of the topics addressed (72% *vs.* 33%) and a greater awareness of the addressed topics compared to peers who encountered similar subjects through traditional educational approaches (*RQ1*).

> *Q.* In your opinion, how will the photon-electron interaction work in the case of the photoelectric effect produced by X-rays? Which electrons will be involved? What will happen differently than the situation described by Einstein?
> *A.* In my opinion, the photoelectric effect produced by X-rays must have some important differences compared to the situation described by Einstein. Since X-ray photons have a very high energy compared to UV light, the atoms of the target material will be expelled faster and easier than photons in UV region. [...] Furthermore, not only the most superficial electrons will be involved, but also those more internal. Consequently, I believe that, given such a high electron release, a higher amperage will be recorded than when using UV light.

5. – Disciplinary and learning knots

Given the limited number of available pages, there is not enough space to analyse all the disciplinary and learning knots (*RQ3*) which were highlighted *a priori* by the literature [6-15] and which emerged from the experimentation. Therefore, we will focus only on some few examples related to the photoelectric effect.

Firstly, it must be stressed that the study of the photoelectric effect is not an "exclusive" to Einstein but rather the result of a long and articulated process (started with Hertz) and various studies conducted by different scientists —for example, the extraordinary contribution of Righi (never mentioned in textbooks), to whom, *inter alia*, the name "photoelectric effect" is due. This point constitutes a historical disciplinary issue. Furthermore, it is important to highlight that Einstein's model was a response to a general problem concerning the emission and absorption of radiation. Within this context, it certainly provided a solution to the experimental data obtained by Lenard, but such a solution was not Einstein's primary objective (contrary to what it might seem from textbooks). This aspect is a disciplinary knot.

A further fundamental knot, of a conceptual nature, concerns the existence of momentum for the photon (which is entirely reasonable but was historically hypothesised by Einstein only in a second moment, in 1909). It is important that this fact is put in evidence, also for reasons of historical accuracy. Another crucial issue pertains to the principles of conservation in the photon-electron collision. The aspect of conservation principles is fundamental because it connects and establishes coherence between the photoelectric effect and the Compton effect. These two effects, despite being separated by nearly 20 years, are linked by a strong conceptual chain that needs to be emphasised (considering that, in textbooks, they are generally presented side by side, in two adjacent pages, but often explained in two completely different and inconsistent ways —the former as absorption, while the latter as collision). How is it possible that, during the early years of high school, students study collisions with the conservation of momentum, and the same ideas are not then applied, in the last year, to the photoelectric effect? Why is the conservation of momentum used in the Compton effect not connected with that in the photoelectric effect? Why do students know (from electromagnetism knowledge) that radiation has momentum E/c but do not apply this knowledge to the photon when studying the photoelectric effect? These are problems of coherence and organisation of prior knowledge (which exist individually, but are not then integrated into a unified and coherent framework) and clearly represent important learning knots.

In addition to these points, a further learning knot became evident through the analysis of test responses and the questions and observations raised during the meetings, demanding special attention. While the photoelectric effect may initially appear straightforward and simple (especially in Einstein's model of 1905), both students and teachers encounter difficulties in utilising it to elucidate diverse scenarios and make predictions. They often resort to relying on other pre-existing knowledge, attempting to draw analogies with familiar concepts (such as applying knowledge of geometrical optics with a reflective surface or a transparent plate) in an inaccurate manner (43% of them, in our experimentation). Consequently, there is a deficiency in the capacity to thoroughly explore the model, a crucial aspect for attaining a profound conceptual understanding.

6. – Further experimentations and new open questions

Analysis of the responses obtained from the satisfaction questionnaire revealed that participants expressed a high level of appreciation for the course and the employed approach, with a notable emphasis on group activities (91%) and the reading of original papers (79%). Consequently, in 2023–24, two additional experimentations were organized.

6˙1. *Old (but Gold) Quantum Theory II*. – A second edition of the course (within the PNRR) was offered in January 2024 to 30 student of 12th and 13th grades and was organised in two whole-day meetings, for a total of 15 hours. To improve the second edition, we started by addressing and facing the disciplinary and learning knots that had emerged during the first experimentation. Some of the knots previously discussed were more explicitly elaborated, and participants were repeatedly prompted to use the specific model to explain different situations, articulating their expectations in diverse scenarios through targeted and precise questions (*e.g.*, "What happens to the photon?", "Where does the electron go?"). There was an explicit request for a "pictorial" rendering and imagination of the situation. This explicit request enabled students to better anticipate and envision various situations that could arise from the models, such as the possibility of multiple absorption with a lowering of the threshold, metal heating, and a prototype of the Auger effect (that is, when in presence of a significant increase in radiation frequency, the emission of inner electrons and the rearrangement of others occur).

6˙2. *Principles and Equations of Physics III: Quantum Mechanics*. – An online experimentation of 22 hours overall (8 of which devoted to the OQT), featuring the OQT as an introduction to QM —a crucial aspect, being QM our main goal—, was held from October 2023 to January 2024, within the National Plan for Science Degrees (PNLS), and involving 144 students and 84 teachers. The online mode allowed it to be delivered to a much larger number of participants from different parts of Italy. Despite it made the group-work activities more difficult, resulting in a less-active learning, the average grade obtained was only slightly below the sufficiency level (5.7/10, SD 0.8). Moreover, this experimentation allowed us to formulate a further research question, namely "Which aspects of the OQT are crucial for the formal construction of QM?", which will be a central focus of our future research, deserving special analyses. In any case, at the moment, it seems already quite evident that, for example, Planck's explanation of the black-body problem clearly aids in the quantisation of the harmonic oscillator, and the explanation of the photoelectric effect give hints for the quantisation of the electromagnetic field. Nevertheless, these aspects need to be investigated more and deepened further.

7. – Conclusions

The outcomes of these three educational workshops are promising, suggesting that it is feasible to present the OQT in high school in a meaningful and coherent manner.

Simultaneously, they rose awareness among teachers that its accurate presentation does not, in any way, offer something comparable from a pedagogical standpoint to a genuine physical theory, as QM is. The common didactic ineffectiveness of the OQT is clearly dependent on the logical incoherence of the approach used in presenting contents. However, we believe that this incoherence is more a teaching tradition than a substantial physical aspect. In fact, despite the lack of a reference theory at the time, the conceptual foundations of the OQT logically took shape, and the OQT represents a coherent and coordinated development of ideas, comprised of small —and sometimes not even so small— steps, not random but directed towards a specific goal. On these bases, it is evident why, despite a significant logical and epistemological leap, the OQT led to QM.

Presenting the OQT does not imply following a historical approach but rather involves a reasoned cultural introduction, departing from historical aspects but addressing physics problems through an inquiry-based approach, emphasising its connection to QM [22].

In fact, the OQT shows that reasoned exploration of models, accompanied by experiments, aids in understanding theory construction and explaining a broad phenomenology. Approaching the OQT adequately may thus serve as a "privileged" path for introducing QM, aiding in understanding its challenges and peculiarities, and fostering the right perspective on quantum physics, stressing the importance of investigating its conceptual intricacies. Our research horizon is thus wide open (also) towards this direction.

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