Can Old-Quantum-Theorethical description of Physical Reality be considered worth teaching?

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The current state of Phys. Educ. research

Old Quantum Theory (OQT): long been integrated into high school curricula

but

research in Physics Education (PE) generally focused on single topics*.

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- lack of a comprehensive and unified approach.
- lack of a coherent pedagogical, historical, and conceptual presentation.

* Blackbody spectrum
Z. Navrátil, *et al.* (2013). *Phys. Educ.* **48**, 289.
I. Kardaras, M. Kallery. (2020). *Phys. Educ.* **55**, 045010.

* Photoelectric effect
M.A. Asikainen, P.E. Hirvonen. (2009). *Am. J. Phys.* **77**, 658.
A. Sokolowski. (2013). *Phys. Educ.* **48**, 35.

* Bohr's atomic model
S.B. McKagan, *et al.* (2008). *Phys. Rev. ST Phys. Educ. Res.* **4**, 010103.
G. Papageorgiou, *et al.* (2016). *Chem. Educ. Res. Pract.* **17**, 209.

OQT or not OQT?

Introducing a precise theory for Quantum Physics (QP) in high school*: solely relying on the OQT is the most suitable and effective way to introduce QP

but

- OQT could aid in grasping why Quantum Mechanics (QM) is just the way it is;
- current *status quo*: teachers and textbooks waiting at the "OQT stop".

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Educational reconstruction: historically accurate, didactically effective and culturally meaningful ($\sim$ classical physics).

* C. Singh, *et al.* (2006) *Phys. Today* **59**, 43-49.
M. Giliberti. (2018) *Ita. Jour. Educ. Res.* **19**, 29-40.
M. Michelini, A. Stefanel. (2021) *Teaching-Learning Contemporary Physics*, 3-17.

Our research questions

RQ1: Is it possible to present the OQT in a significant way?

RQ2: Is it possible without radically changing:

- the physics contents,
- the mathematical formalism,
- the prerequisites,

and with the common intervention times?

RQ3: What are the disciplinary and learning knots?

RQ4: And which aspects of OQT are important for the axiomatic construction of QM?

Old (but Gold) Quantum Theory: the course

A research, started from an <u>educational laboratory on OQT</u> (<u>PNNR</u>) in January-February 2023:

- 5 afternoon meetings (15 hours),
- 36 high-school students + 9 teachers,
- <u>active-learning approach</u>; conceptual exploration of the models of OQT.

1) Blackbody radiation

2) Early atomic models

3) Photoelectric effect

4) Compton effect

5) Bohr's hydrogen atom

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During the 5 meetings

- 10-minute workgroups and commented reading of original papers,
- qualitative examples (*e.g.*, Einstein's idea of light-quanta),
- quantitative aspects (*e.g.*, calculation of Planck's unit of measure),
- open questions (*e.g.*, *«Why in the Compton effect does an electron not "eat" a quantum of light as in the photoelectric effect?»*).

Photoelectric effect: Einstein's 1905 paper and meaning of the term "heuristic".

Question: *«How could the model be used to predict new facts and explain more complex situations?»*

e.g., 1) transparent plate; 2) intensity increases at a fixed frequency; 3) frequency increases by several orders of magnitude (Compton effect).

Question: *«What is the connection between Einstein's model and the conservation principles of E and p studied at school in the case of collisions?»* Understand that the plate must recoil (binding energy).

Experimentation’s effectiveness

Data collected:

- all written groupworks,
- 5 individual ongoing tests,
- a satisfaction questionnaire,
- a final test with open questions (links between concepts).

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Effectiveness for the research group (more ways of evaluations, not only those useful for teachers).

Data analysis – Students' average grade

Average grade: 6.6/10 (SD: 0.7) with traditional evaluation grid (RQ2).

Examples of questions given:

- *«Let us take a cubic box, with a small hole in one of the walls. Which part of the box corresponds to a black body? Justify your answer.»*
- *«Describe the structure of Nagaoka's atomic model.»*
- *«Explain how Einstein interpreted the photoelectric effect, in terms of "quanta of light" that impinged on a metal plate and interacted with the plate's electrons.»*
- *«Let us consider the explanation of the photoelectric effect given by Einstein in 1905. If, instead of the metal plate, we used a transparent substance, what do you expect would happen to the light incident on the transparent plate? Justify your answer.»*

Data analysis – Critical thinking

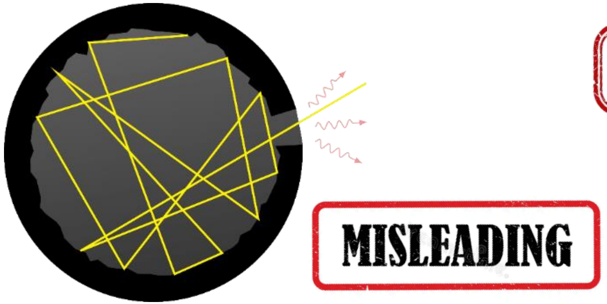
- Cultural meaning of OQT (and physics, in general).
- Critical thinking: answers given (RQ1).

Question: *«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».*

Student: *«Above all, a physical model must provide a plausible explanation of the phenomenon it describes [...], but this explanation must be supported by mathematical foundations which are essential, because they allow the insertion of the model within our universe. However, despite the fact that a model has solid mathematical and physical foundations, it must also be able to fit in the framework of the various models that already coexist in physics, because, if it is true that a model stands on its own, however, it does not necessarily mean that it is able to coexist with the other models, and with the laws deriving from them, as happened to the Rayleigh-Jeans law (which in itself managed to provide a partial solution to the problem of blackbodies, but it collided with thermodynamics aspects)».*

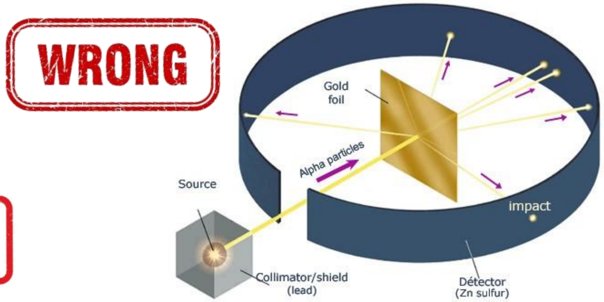
Data analysis – Textbooks' ambiguities

- Critical approach: some explanations and figures presented by textbooks criticised for being misleading or erroneous.



Blackbody cavity.

Is the yellow beam going in or out? What does incident radiation do? And where does that emitted come from?



Rutherford's gold-foil experiment.

The experiment that never was*.

* M. Leone, *et al.* (2018). *Phys. Educ.* **53**, 035003.

Data analysis – KIC

Knowledge Integration Construct*: links between different contexts.

68%: scientifically valid links between (at least) 2 relevant ideas (RQ1).

Question: *«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.».*

Student: *«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). However, this model does not integrate at all with the well-established one that sees light as a wave, and fails to explain the phenomena that are so accurately described by the latter.».*

* O.L. Liu, *et al.* (2008). *Educ. Assess.* **13**, 33-55.

Data analysis – Comparison with peers

86 undergraduate students in maths and physics + 46 teachers*:

- a deeper understanding of the contents (72% vs. 33%) (RQ2)
- greater awareness (RQ1).

Question (not addressed during the course): *«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?».*

Student: *«In my opinion, compared to the classic situation described by Einstein, the photoelectric effect produced by X-rays must have some important differences. 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. [...] 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 by using ultraviolet light.».*

* L. Lovisetti, M. Giliberti. (2022). The reasonable ineffectiveness of Physics in teaching: the example of Thomson's atomic model (GIREP 2022, Ljubljana).

Further experimentations

Satisfaction questionnaire: course and approach used really appreciated (4.8/5), in particular, groupworks and reading of original papers.

Two new experimentations in A.Y. 2023/2024:

- "Old (but Gold) Quantum Theory" (second edition): to a wider audience and with further readings and questions (PNNR project).
- "Principles and Equations of Physics III": OQT as an introduction to QM, with 144 students and 84 teachers (PLS laboratory).

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OQT for understanding QM difficulties

OQT generates a sense of bewilderment (difficulties in interpreting physical phenomena). OQT functional to a deeper understanding of QM.

Not a historical approach, but a reasoned cultural introduction, which passes through a series of concrete physics problems, and which opens up to an inquiry approach → *«What do we do to solve a certain interpretative problem?»*

Not an alleged «crisis of classical physics» (historically wrong!) nor few selected examples of technological applications for introducing QM.

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Awareness of the necessity of a new theory starting from physical and experimental aspects.

OQT for QM: crucial knots

What are the disciplinary and learning knots (RQ3)?

- Photoelectric effect (Einstein's heuristic model): not so easy to understand. Difficulties in using the model to explain different situations and make predictions.
- Tendence to use other previous knowledge, trying to find analogies with things already known (*e.g.*, geometric optics with reflecting or transparent plates)

Question: *«How do you use Einstein's model in the case of a transparent plate?»*

Student: *«When light passes through air it does not change direction, but if it passed through water or glass (i.e., two transparent substances) the light would change its direction. the ray of light will not be a reflection but will be a refracted ray that changes depending on the medium that the light passes through and also changes depending on how the light arrives on the transparent substance.»*

OQT for QM axiomatic construction

Aspects of OQT that are important for the axiomatic construction of QM (RQ4):

- blackbody: helps in the quantization of the harmonic oscillator;
- photoelectric effect: quantization of the EM field.

Reasoned exploration of models + experiments that help in understanding the construction of the theory (*e.g.*, double slits, interferometers...).

Fundamental point: an approach to QP that does not result in the interpretation of natural facts is rejected by students and teachers (*«What do I need it for?»*).

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We need to explain the world and understand why a theory is made a certain way.

OQT: a sort of "privileged" path: it allows to develop "the right gaze" to look at QP.

A reconstruction for "inquiring minds"

Comprehensive historical and pedagogical reconstruction of the birth and development of QP (part of a PhD research project).

Primary aim: to establish an epistemological and educational framework crucial for fostering a meaningful cultural comprehension of QM.

- Didactical detours within a predominantly historical work.
- More than 800 primary sources.
- Several pedagogical explanatory comments and notes.

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Not a mere historical narration but a commented reconstruction for "inquiring minds".

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