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Investigating the beliefs of experts on teaching quantum physics at secondary schools: key concepts, topics, and fundamentals

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Abstract
This study presents the findings of a series of interviews conducted with 17 Italian academic experts in the field of physics. The interviews aimed at exploring various aspects of teaching quantum physics (QP) at the secondary school level. The focus was on evaluating the overall suitability of teaching QP, the benefit of introducing it with an historical approach, the necessary mathematical grounds, as well as foundational and controversial aspects, along with the topics that should be included in the curriculum. Based on the insights gathered from the interviews, a questionnaire was formulated and administered to 31 additional experts, with the primary objective of exploring the experts' perspectives on whether QP should be included in secondary school curricula and the underlying reasons for their stance. Indeed, some of the scholars argue that teaching QP is crucial as it contributes to the promotion of scientific literacy, considering QP as one of

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the most significant cultural advancements in science over the past centuries. On the other hand, some experts believe that the emphasis should be placed on informing and educating society about quantum technologies and upcoming technological advancements. The second objective of this questionnaire was to further deepen the investigation into the key subjects that specialists deem essential for teaching at the secondary level. The results revealed a consensus among the experts regarding the concepts that hold significant importance, namely atomic energy levels and quantisation, particle behaviour of light, Heisenberg's uncertainty principle, and probability, and regarding the examples, i.e. the photoelectric effect, spectral lines, and the double slit experiment. The last objective of the questionnaire was to address foundational and controversial aspects of QP that are relevant to high school curricula. This entailed examining the consensus among experts regarding their perspectives on the view of these topics. Lack of such consensus emerged.

Keywords: physics education, quantum physics, secondary school

1. Introduction

Quantum physics (QP) is an important part of knowledge which is the basis of many areas of physical research, underlies many scientific studies and plays a central role in technology, both older—such as micro- and nanoelectronics—and newer, such as quantum computing. QP has been an important part of university education for a long time, and in recent years it has become part of the high school curriculum in many countries [1], due to its importance for current research in general [2] and for the modern understanding of science in particular [3]. However, significant challenges are inherent in the teaching of QP in secondary school since it requires fundamental changes in the understanding of the physical world and a deep revision of classical thinking [4]. Thus, there is a need for research-based instructional strategies that focus on conceptual understanding and cover the key topics of QP needed to achieve such an understanding [5].

In recent years, teaching QP has been the focus of research by many scholars in physics education [6]. The approaches to teach QP may hold different focuses, ranging from historical aspects [7] to technological applications [8]. The approaches also differ in the way the theory is presented in a formal sense: different educational reconstructions range from two state approaches based on spin [9, 10] or light polarization [11], to the sum over paths approach [12, 13] or experiment-based approaches that are in line with quantum electrodynamics [14]. Moreover, there is no consensus on what should be taught in introductory QP courses, and a wide range of topics have been explored as bases for a more conceptual approach. Examples of introductory topics used at the secondary level include wave–particle duality [15, 16], entangled photons [17], the infinite potential well [18], quantum states [11], spin [9, 19]. More recently, several scholars proposed subjects related to the European Competence Framework for Quantum Technologies [20, 21]. Obviously, the choice of the key topics, the clarification and the analysis of the science content are crucial in science education research [22]. In order to clarify which key topics of QP should be taught, some studies [23–26] were carried out to investigate which subjects the experts (typically academic researchers in QP and related fields) consider important. Often, in these studies, no consensus emerged on what should be taught in introductory QP courses [27], with some physicists even doubting the appropriateness of teaching QP before the university level due to the conceptual and mathematical complexity of the topics.

This paper presents our investigation on these matters, based on a series of interviews conducted with 17 academic experts and on the answers to a questionnaire which was designed starting from the main outcomes of the interviews and was administered to 31 more scholars. The complete questionnaire is reported in appendix B. Our consultation was limited to experts who possess a thorough understanding of QP topics and have a vast experience in scientific research and technological advancements associated with QP. Our aim is answering different research questions about teaching QP in high school:

RQ1. **WHETHER** it is appropriate to teach QP at pre-university level and it possible to understand quantum physics without a thorough knowledge of its formal mathematical structure.
RQ2. **WHY** QP should be taught in high school, by comparing the motivations related to culture, technology, and scientific literacy.
RQ3. **WHAT** subjects the experts prioritize to be taught. These subjects encompass specific concepts, exemplifications, and experiments.
RQ4. **HOW** to teach QP, i.e. if it is appropriate teaching QP by following a quasi-historical reconstruction and if there are foundational and controversial aspects in QP concerning topics included in school curriculum, which should then be cleared up.

For every research question, we also aim to address the following inquiries:

I1. Is there a consensus among experts in the field?
I2. Do scientists embrace distinct interpretations of quantum physics depending on their specific areas of study?

As evidenced by the limited number of participants, the present study is to be considered a pilot test. We are carrying out an analogous investigation conducted with high school teachers, which will be the subject of a forthcoming publication.

2. Purpose and method of the study

As said, we began the research process by conducting interviews. At first, we prepared a draft version of the interview questions and shared it with three experts. Their responses aided us in refining the questions and generating valuable insights, which consequently led to the formulation of supplementary inquiries incorporated in the final interview. Subsequently, we proceeded to administer the same set of questions to 14 additional participants. Each researcher works in one of the fields listed in table 1.

Starting from the outcomes of the interviews, we designed a Likert scale questionnaire to evaluate in a quantitative way the consensus about a specific topic. The five levels of the Likert scale range from ‘strongly disagree’ to ‘strongly agree’. At this stage, 31 professors and postdocs in physics participated in the study. Again, each involved researcher is active in one of the fields reported in table 1. Being all involved scholars at least postdocs, it is reasonable to assume that they have at least some years of experience in their field and thus that they are accustomed to a specific subject culture.

The research method is intended to search for consensus among experts concerning the questions reported above. Thus, the measurement of consensus, which is needed to measure accurately people’s attitudes using a Likert scale, is a key component of our data analysis. In this study we present two independent measures of consensus among respondents: the Consensus (Cns) [28] and the level of agreement (LoA or naïf consensus). The corresponding algorithms are reported in appendix A. More measures exist in the literature, however it can be shown that there is a strong correlation between different consensus measures, so that in the following we just report the above two.

3. Whether

As stated above, the first aim of this work is to understand whether the experts believe that QP should be taught in secondary school and why, or why not. Most of the respondents to the interview agree with teaching QP in high school. The main objections to this teaching can be summarised in these two extracts from the interviews: *‘If one is unable to utilize formalism, teaching QP*

Table 1. Overview of the experts' research fields. Concerning theoretical physicists, when asked they themselves identified themselves according to the Italian classification scheme, which distinguishes between researchers in theoretical high energy physics, i.e. fundamental interactions (including gravitation and cosmology) and theoretical low-energy physics, i.e. condensed matter and quantum optics (cf for example www.cun.it/uploads/storico/settori_scientifico_disciplinari_english.pdf, Retrieved 29 September 2023).

Expertise		Number of experts (interviews)	Number of experts (questionnaire)
Astro- and astroparticle physics	Experimental physicists	0	2
Applied physics		2	2
Experimental condensed matter physics and optics		2	6
Experimental nuclear and subnuclear physics		2	2
Theoretical physics (fundamental interactions)	Theoretical physicists	2	5
Theoretical physics (optics and condensed matter)		5	6
History of physics	History and education	1	2
Physics education		3	6

becomes futile and a mere waste of time. Serious engagement with QP is impossible without a dedicated approach to formalism.' and '*I believe that no one can really understand quantum mechanics, one can use it. We know how certain things happen and not why. In high school one should limit oneself to the fact that quantum mechanics is there, there are quantum phenomena, but the only way to go into QP is to use it.*'

The same question was asked again in the questionnaire to estimate the degree of consensus among experts:

(Q1) Is it appropriate to teach QP at pre-university level?

Results are reported in figure 1.

The majority of respondents (with an average Likert score of 3.7) agree or strongly agree that teaching QP at the secondary school level is appropriate. However, surprisingly, the questionnaire results do not show a clear consensus (Cns = 0.5) on this issue. At best, we can say there is a small level of agreement (62%). The differences between groups exhibit significant disparities, as indicated by a substantial effect size (theoretical physicists demonstrate a higher favour compared to Experimental physicists, with an η^2 of 0.19 and a Cohen's d of 0.9 between experimental and theoretical physicists).

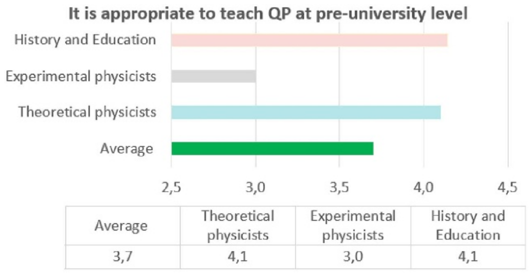


Figure 1. Results of the answers to Q1.

The main criticism against teaching QP at school is that students do not have the necessary mathematical grounds. An eminent researcher in the field of Physics Education Research, who was among the interviewed experts, answered us that '*QP can only be understood at a level that is useful for later use if the necessary formalism and mathematics are used… and it would be better to do only a "chatter" at a popular level, without formulae or formalism, because one does not have the tools to do so and risks giving wrong concepts that then remain with the students for a long time.*' Furthermore [5], many researchers have questioned the extent to which mathematical skills are necessary to understand quantum concepts, and some authors [27] have argued that

QP cannot achieve more than a brief knowledge without knowing the mathematical structure.

A further item in the questionnaire related to this issue was formulated starting from the answers to the interviews:

(*Q2) According to some experts it is impossible to understand quantum physics without knowing its formal structure well, so incomplete mathematical knowledge hinders or prevents the learning of quantum physics for high school students. Do you agree?*

The majority of experts who participated in the questionnaire do not view the absence of mathematical knowledge as an insurmountable barrier to teach QP (with an average Likert score of 2.6). However, also here, there is no agreement among the respondents (Cns = 0.5); in this case, there are not significant differences between the groups.

4. Why

Many experts who agree with teaching QP at school believe that QP plays a role in promoting scientific literacy because it is one of the most important cultural achievements of science of all time, while others on the other hand believe that it is mainly necessary to inform and educate society about technological development and the emerging quantum technologies. The opposition between a cultural versus an applicative view is summed up in this answer *'I avoid arguments such as ≪I study science because it serves me well≫. The study of science lies outside. One should realize that QP is the best tool to investigate science and everything else comes later, quite naturally; knowledge should not be motivated by purely practical matters.'*

We investigated this dichotomy of motivations behind the importance of teaching QP also through the questionnaire by asking the following two questions:

(Q3) Teaching quantum physics in high school is important because it is one of science's greatest cultural achievements. Do you agree?
(Q4) Teaching quantum physics in high schools is important for its technological applications. Do you agree?

The respondents indicated that the primary reason for teaching QP is its cultural significance (with an average Likert score of 3.9) and a high level of agreement (77% in favour). Accordingly, the implications of technological applications are given relatively less importance by the experts (with an average Likert score of 3.3) and only 52% of them hold a favourable view on this aspect. The consensus about these items is small (Cns = 0.5–0.6). No significant statistical differences were observed between the groups. However, it is noteworthy that Experimental physicists exhibit the lowest level of significance attributed to technological applications.

An important contemporary issue is the fact that, in parallel to the increasing exposure in the conventional media of QP technological achievements, a growing body of misinformation and pseudo-scientific quantum-related claims spread through the media. This has been dubbed 'quantum disinformation' [29]. We added a question concerning this issue in the questionnaire:

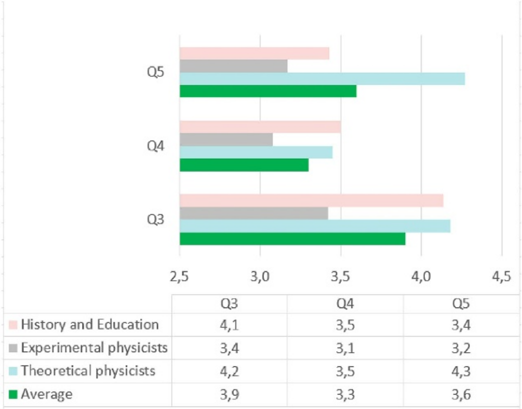
(Q5) The teaching of quantum physics in high schools is important to counter the large amount of misinformation present in various media about the contents and consequences of this theory. Do you agree?

The issue of countering misinformation is deemed significant by the majority of experts, with 60% of them expressing this view and an average Likert score of 3.6. There is a modest level of consensus (CNS = 0.6) among the respondents regarding this matter. Theoretical physicists demonstrate a higher level of importance attributed to countering quantum misinformation compared to experimental physicists (average rating of 4.3 compared to 3.2, respectively). This discrepancy is statistically significant, with an effect size of $\eta^2 = 0.19$. Results are summarised in figure 2.

5. What

5.1. Previous research

As mentioned in the introduction, in recent years much research has been conducted to identify



	Q3	Q4	Q5
🟥 History and Education	4,1	3,5	3,4
▨ Experimental physicists	3,4	3,1	3,2
🟦 Theoretical physicists	4,2	3,5	4,3
🟩 Average	3,9	3,3	3,6

Figure 2. Answers to questions Q3 Q4 Q5 about the motivations to teach QP in high school.

key subjects in the field of QP and determine which ones should be taught in introductory courses. In 2019, Stadermann *et al* [1] conducted a study where official curriculum documents from 15 countries were collected and analysed to identify the key components present in most curricula. This inventory revealed a common core curriculum for QP consisting of 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 QP.

Concerning Italy, the official curriculum document, known as 'Indicazioni Nazionali' (National Indications), from the Ministry of Education, also provides guidelines for teaching modern physics. It suggests that teachers should introduce the concept of the 'light quantum' by studying thermal radiation (the black body) and Planck's hypothesis. The development of this concept should further involve the study of the photoelectric effect and its interpretation by Einstein, as well as discussing theories and experimental results that demonstrate energy levels in atoms. The sequence should then conclude with the presentation of experimental evidence supporting the wave-like nature of matter as postulated by de Broglie and the introduction of the uncertainty principle.

In a recent work [6], 'The future quantum physics curriculum at secondary schools' was investigated. This paper contains a study to determine essential concepts for teaching QP in secondary schools, emphasising a community-based perspective also with the aim of incorporating different specifications based on QTEdu's Competence Framework [20, 21] that should be included in the secondary school curriculum. In 2017, Krijtenburg-Lewerissa *et al* [23] conducted a Delphi study with the aim of investigating the quantum mechanics topics that experts consider important to teach at the secondary level, along with the arguments provided by these experts. The results indicated a consensus on the significance of certain topics, specifically duality, wave functions, and atoms. Experts based their rankings on the interconnections between concepts and the fundamental nature of the quantum mechanics topics. Previous studies have attempted to address the same question. The authors of [26] surveyed faculty members at the undergraduate level to identify the three most important topics in quantum mechanics. Although this interview resulted in a list of nine topics, there was significant variation in the choices made by the faculty members. The researchers acknowledged that this list does not represent a consensus opinion. Recently, the lack of consensus concerning the key topics on QP suitable for secondary school teaching was also investigated in an exploratory study [23] which showed that scientist favour different concepts QP depending on their field of research. These differences are not individual, but typical favoured concepts were detected in specific fields.

During our interviews, the participants provided their opinions concerning QP concepts, examples, and applications that they deemed appropriate for inclusion in a secondary school curriculum. A total of 35 topics were proposed. In the questionnaire, the experts were asked to categorise and rank these topics on a scale of relevance, ranging from irrelevant to very relevant. To arrange these concepts into classes we adopted the classification of [23].

5.2. Results

The results, presented in tables 2–4, indicate that the first six concepts and the first three examples are considered relevant by at least 70%

Table 2. Summary of experts' answers to the questionnaire on the importance of the selected 18 quantum topics for the secondary school curriculum.

	Average	Cns	LoA %
Atomic energy levels and quantisation	4,5	0,7	90
Particle behaviour of light	4,1	0,7	81
Heisenberg's uncertainty principle	4,1	0,8	83
Probability	4,1	0,7	81
Superposition	3,8	0,6	77
Wave–particle duality	3,7	0,5	70
Quantum measurement	3,6	0,6	53
Quantum state	3,5	0,5	50
Entanglement	3,4	0,6	50
De Broglie wavelength	3,4	0,6	45
Wave function	3,3	0,6	53
Pauli principle	3,3	0,6	53
Tunnelling	3,3	0,6	45
Spin	2,9	0,5	
Incompatible observables	2,9	0,6	
Fermions/bosons	2,9	0,5	
Time evolution	2,1	0,7	

Table 3. Summary of experts' answers to the questionnaire on the importance of the selected 11 examples for the secondary school curriculum.

	Average	Cns	LoA %
Photoelectric effect	4,1	0,7	74
Double slit experiment	3,9	0,6	71
Spectral lines	3,7	0,5	70
Black body radiation	3,6	0,6	58
Radioactive decay	3,4	0,5	
Compton scattering	3,2	0,6	
Schrödinger's cat	3,0	0,6	
Specific heat of solids	2,9	0,6	
Harmonic oscillator	2,9	0,5	
1D infinite potential well	2,8	0,6	

Table 4. Summary of experts' answers to the questionnaire on the importance of the selected 6 applications for the secondary school curriculum.

	Average	Cns	LoA %
Lasers	2,9	0,6	32
Semiconductors	2,8	0,7	23
Solar cells	2,7	0,6	27
LEDs	2,7	0,5	29
Quantum information	2,7	0,5	32
Quantum computers	2,6	0,5	26

of the experts. Furthermore, the level of consensus measurement confirms a general agreement on most of these topics. None of the applications was considered relevant with consensus.

6. How to teach QP

The last aim of this work is investigating the experts' opinion about some educational, foundational, and controversial aspects of QP which concern potentially includable topics, usually present in secondary school textbooks.

6.1. The quasi-historical approach

In recent decades, some scholars have criticised the common textbook approach that unwinds the development of quantum theory with essential experiments, following a quasi-historical reconstruction that does not aim to faithfully convey history. Quasi-history can be defined as '*a type of material which looks historical, but in which there is no attempt to convey history truthfully: the aim is solely to put over scientific facts and the "history" is there to provide a framework inside which the scientific facts it easily, appear to "make sense" and may be easily remembered for examination purposes. It also provides, maybe, a little light relief from the hard facts of the science itself.*' [30] Sometimes the choice of quasi-history over history may be legitimate for educational purposes, but the students are rarely made aware of it. An inaccurate description of the history of physics can lead to misconceptions regarding the development of scientific knowledge. Moreover '*Quasi-history has a practical function by offering historical legitimation for a simplistic methodology and conception of what constitutes good science. In other words, it is ideological.*' [31].

Despite these criticisms most of the respondents to the interviews agree with the common textbook approach in high school. The main objections to this approach can be summarised in this answer from the interviews *'The quasi-historical approach leaves the impression that new ideas are discovered and immediately accepted. Despite appearing as a historical approach, it does not give the sociological perspective of how science develops.*'

In the questionnaire, this point was investigated through the question:

(Q6) In textbooks the most used approach is the historical one: in fact, experiments that represent the break with classical physics are presented, such as the photoelectric effect, the spectrum of the hydrogen atom, the black body, the Compton effect, etc. Do you agree with this approach?

A total of 60% of experts support the traditional approach suggested by textbooks. Nevertheless, the average Likert score of 3.4 and a Cns value of 0.56 indicate that there is no significant consensus regarding this viewpoint. The difference between the groups is not significant even if experimental physicists are more strongly in favour of this approach than theoretical physicists. This is probably due to the fact that the quasi-historical approach is an inductive approach based on the emergence of anomalies in classical physics from phenomena and experiments.

6.2. The photoelectric effect: Einstein and the photon

Several studies conducted in the past few decades [32, 33] have indicated that there exist numerous misunderstandings, both historical and conceptual, regarding the photoelectric effect experiment. Moreover, numerous textbooks contain pseudo-historical 'myths' regarding this phenomenon. These myths include claims such as (a) Einstein's theory of the photoelectric effect being a straightforward expansion of Planck's theory, (b) Einstein's 1905 paper primarily focusing on the photoelectric effect, (c) the experiment being incomprehensible without the concept of photons, and (d) immediate acceptance of Einstein's explanation. For example, Italian textbooks [34] commonly state: '*The photoelectric effect can only be explained by acknowledging that each individual photon interacts with a single electron in the metal when struck by radiation.*' Despite the fact that '*it is held by many* [35, 36] *that it is not necessary to have photons in order to explain the photoelectric effect successfully'* [33].

Klassen [32] specifically focused on the depiction of photons in relation to the photoelectric effect, highlighting that '*The concept of the photon has evolved since its initial proposal* *and that its interpretation, even today, is rather murky and even difficult.'* And that *'It should be made clear that the behaviour of photons between the emitter and detector is not known but we only know their quantum mechanical behaviour when they are detected.'* While Jones [33] underlined that *'The major picture developed (by Einstein's paper of 1905) was not in any way that of recasting light in terms of small spatially defined 'particles', but of saying that the energy and momentum transfer between field and radiation could only be explained by consideration of the quantization of both those physical quantities, not of the entities involved in the interaction.'*.

However, the image of photon that students hold for a long time is that of a localised particle, with a defined energy and momentum, in fact the 'photon' hardly gets a mention until postgraduate courses.

We inquired the experts we interviewed for their thoughts on the viewpoint presented by the researchers cited above, asserting that the successful explanation of the photoelectric effect does not require the utilisation of photons since this effect just demonstrates the quantisation of energy rather than the quantisation of the electromagnetic field. The majority of interviewees expressed disagreement with the criticisms reported in [32, 33], and their support for the traditional approach can be summarised through three types of responses. Firstly, some respondents stated that '*I would still utilize photons to explain the photoelectric effect in order to maintain tangibility*.' Secondly, others argued that '*If I do not consider the role of energy, it becomes impossible to explain. It is difficult to separate radiation from the electromagnetic field itself.*' Lastly, a few respondents dismissed the issue, stating that '*it is a trivial matter; there's no need to dwell on it. The photoelectric effect is a brilliant insight that suggests when a quantum of energy arrives, the electron simply jumps away.*'

We examined this aspect also by utilising the questionnaire that included the same question:

(Q7) In recent times, some researchers have argued that it is not necessary to use photons to successfully explain the photoelectric effect, as the latter is evidence for the quantization of energy and not of the electromagnetic field. What do you think?

The item offered three alternatives derived from the interview responses. Additionally, we incorporated an 'other' text field to allow individuals to provide alternative answers if the provided choices were not applicable to them. The outcomes of the questionnaire revealed a lack of consensus among experts regarding the validity of the criticism. However, the majority of experts do not believe that the teaching approach should be modified. None of the experts think that it would be preferable not to utilise photons for explaining the photoelectric effect. One third of these experts argue that the semiclassical model is incoherent and suggest that the concept of photons should be utilised to explain the photoelectric effect. Another third of the experts agree with the objection in principle, but they do not advocate for a modification of the teaching approach based on this disagreement. The remaining third of the experts do not align themselves with either of these viewpoints.

Regarding the mental representation of the photon, there a wide range of opinions emerged from the interviews. Some experts believe that '*The photon is a boson; it represents the quantum of an electromagnetic wave and possesses zero mass. The frequency of the photon is precisely defined.*' On the other hand, there are those who argue that '*the photon is not a wave packet*' or '*The photon is a particle without mass, but it possesses definite energy and momentum.*' Conversely, there are experts who state that '*The photon is a quantum particle that can exhibit similar characteristics to other particles. It is not necessary for it to have well-defined momentum and energy*' or '[…] *In general, the photon is considered as a packet* […]'. Based on these responses, we included a dedicated item in the questionnaire to explore the conceptualisation of the photon. Our question is:

(Q8) Einstein introduced the concept of quantizing electromagnetic radiation into localized packets with clearly defined energy and momentum, which then were named photons. How would you describe the true nature of the photon?

We provided two options based on the prevalent interview responses and included an 'other' text field to allow for alternative answers. There is no consensus regarding the two alternative perspectives concerning the energy and momentum of the photon. Out of the participants, 35% affirm that it is not essential for the photon to possess clearly defined momentum and energy, while 32% hold the opposite perspective. A third of the experts do not align themselves with either of these alternatives.

6.3. Foundational challenge: the complementary principle and the uncertainty relations

During the interviews, we posed a further inquiry regarding certain contentious elements of QP. Our emphasis was on the complementary principle, which is commonly discussed in high school textbooks. The description of the complementary principle, frequently utilised in textbooks to elucidate the dualistic nature of quantum particles, remains highly disputed. This principle bears a striking resemblance to the particle-wave duality principle, as mentioned in [37]:

'*…. Einstein introduced in 1909 the 'particle-wave duality principle' for light (see e.g.* [38]*) postulating that photons behave either as waves or as particles depending on the specific conditions. In our opinion, such a dual nature is unphysical and complicated.* […]*Niels Bohr…. introduced the 'Complementarity principle' according to which: 'Wave and particle are two aspects of describing physical phenomena, which are complementary to each other. Depending on the measuring instrument used, either waves or particles are observed, but never both at the same time, i.e. wave- and particle-nature are not simultaneously observable'* [39].

Nevertheless, two distinct and contradictory formulations of this principle can be presented:

1) The Bohr–Pauli formulation suggests that the particle and wave aspects of a physical phenomenon never coexist simultaneously. Any experiment designed to observe one aspect prevents the observation of the other. It is important to note that in fact the idea of complementarity resulting from the experimental apparatus is to be attributed to Pauli rather than Bohr [40].
2) The formulation proposed by Greenberger and Yasin [41] states that '*The duality states that a quantum system can exhibit simultaneously particle-like and wavelike behavior, but a stronger manifestation of the wave-like nature implies a lesser manifestation of the particle-like nature, and vice versa.*' In this definition, the wave-like and particle-like natures can intertwine.

In general, Italian high school textbooks [34, 42] commonly present this principle using the Pauli-Bohr formulation. During the interviews, the participants generally admitted that they did not perceive any contradiction between the above two formulations of the principle. However, some of them expressed a preference for teaching the nature of quantum objects in a different manner, without employing the concept of duality, as the latter rests on classical physics ideas. They believe that '*discussing dualism is akin to using Newton's dictionary to describe modern concepts*', emphasising the absence of dualism.

We further explored this fundamental aspect in the questionnaire by including a question that inquired about the experts' preference for one of the two formulations:

(*Q9*) […] Which of the two formulations is more adequate in your opinion?

We presented six options based on the prevalent interview responses and again included an 'other' field to accommodate alternative answers. However, no consensus emerged regarding the two alternative perspectives concerning the complementarity principle, even though the formulation proposed by Greenberger and Yasin is considered more appropriate by some (43% overall) while just the 30% prefer the traditional Bohr Pauli formulation. Results are reported in figure 3:

Although this topic is usually present in secondary school curricula among experts, the conclusion is that there is in fact no agreement on what the correct formulation of the principle of complementarity is.

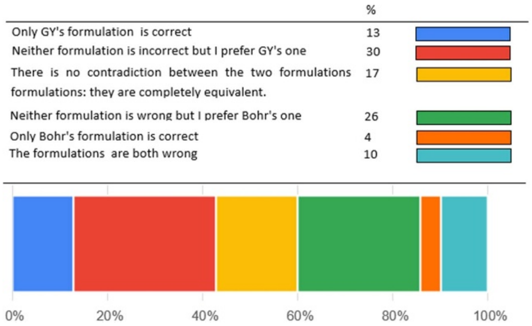


Figure 3. Answers to question Q9 about the complementarity principle.

Concerning the uncertainty relations, a strong tradition in physics education has suggested to move forward, in textbooks and other learning materials, from the historical-like presentation based on the thought experiment of Heisenberg's microscope [43]. Other strategies have been suggested, most notably the one based on an analysis of single slit diffraction of an individual quantum object [44], which allow to present the relations in a form more akin to the spirit of Robertson's ones, i.e. as limits on the possible preparations of a state, in terms of variances of two non-commuting observables. The issue is however not easy to disentangle from a theoretical point of view, since some authors have worked on experimental uncertainty relationships which are different from Robertson's, and more similar to Heisenberg's original intuition, the so-called error-disturbance relationships [45, 46]. Thus, the two relationships, although of a radically different nature (they are sometimes called *intrinsic* and *operational* uncertainties [47]) might coexist in practice as two separate sources of quantum uncertainty.

The Item we proposed to experts very briefly summarised the above debate and proposed three alternatives, plus an 'other' field. The three alternatives essentially consisted in the opinion that (a) the Heisenberg microscope example is appropriate, although it exemplifies error-disturbance relationships; (b) the Heisenberg microscope example can be used to teach error-disturbance relationships, but the Robertson relationships must also be taught separately; (c) the Heisenberg microscope example is inappropriate, and only the Robertson relationships should be taught in secondary school. This last option, advocated by educational research, was chosen by a plurality of experts (43%).

7. Conclusions

We presented the findings of a study conducted in collaboration with QP experts, which involved 17 interviews and 31 responses to a questionnaire. The inquiries focused on various aspects of teaching QP at the secondary school level, specifically evaluating its overall suitability, the historical approach used, the required mathematical background, and the topics to be covered. We also addressed some foundational and contentious aspects of QP that pertain to potentially included subjects.

The experts exhibited a limited consensus regarding the general appropriateness of teaching QP at the pre-university level. There was a lack of agreement among the scholars, and their responses heavily depended on their respective research fields. Similarly, there was only a modest level of agreement concerning the effectiveness of employing a traditional, quasi-historical approach to teach QP. Once again, the respondents' answers were influenced by their specific areas of research.

According to experts, the reasons behind advocating for the inclusion of QP in education primarily stem from cultural aspects or, more broadly, from the pursuit of scientific literacy and the combat against disinformation. The practical implications associated with advancements in technology are regarded as less significant by these experts.

The key topics recommended by the experts for inclusion in the curriculum largely aligned with the traditional approach. These topics encompassed atomic energy levels and quantisation, spectral lines, the photoelectric effect, the particle behaviour of light, and Heisenberg's uncertainty principle. However, concepts such as quantum state, quantum measurement, entanglement, and applications like quantum information and quantum computers, which are associated with the second quantum revolution, were generally considered irrelevant to secondary school curricula.

Regarding the foundational and controversial aspects of QP investigated in this study, namely the nature of photons and the principle of complementarity, our results confirmed the absence of consensus among scientists.

Clearly, a reform of secondary school curriculum need not emerge from, or be solely founded on, expert consensus on what or how to teach. However, the emerging lack of consensus is an important piece of information for physics education researchers interested in the teaching of QP, since it points out how much work is still to be done in this field. In particular, researchers in PER should be aware that, notwithstanding decades of work on innovation in teaching QP in secondary school, many physics experts hold quite traditional opinions about the content and structure of a secondary school curriculum in this area; and that their support to an innovative reform should not be taken for granted. Besides extending the survey to larger numbers of experts, another very important task, as mentioned in the introduction, is the investigation of the opinions of high school science teachers themselves. We expect that a comparison of their ideas with those of academic experts will provide much relevant information and be more effective in pointing to a viable selection of teaching strategies and contents.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Ethical statement

This study was performed in accordance with the Declaration of Helsinki.

Appendix A. The measures of consensus

We can build three different definitions of consensus for a Likert scale:

1. **Level of Agreement or Naif Consensus.** We consider the percentage of favourable responses P_f (adding up agree and very much agree) and unfavourable P_s (adding up little agree and not at all) and define a scale as follows:

Full agreement	$P_f = 100\%$	Full dis-agreement	$P_s = 100\%$
Huge consensus	$90\% < P_f < 100\%$	Huge dissensus	$90\% < P_s < 100\%$
Large consensus	$75\% < P_f < 90\%$	Large dissensus	$75\% < P_s < 90\%$
Small consensus	$60\% < P_f < 75\%$	Small dissensus	$60\% < P_s < 75\%$
Controversial-No agreement $P_f < 60\%$ & $P_s < 60\%$			

2. **Entropy Based** [28]. A new measure of dispersion is introduced as a representation of consensus (agreement) and dissention (disagreement). Building on the generally accepted Shannon entropy, this measure utilises a probability distribution and the distance between categories to produce a value spanning the unit interval. The measure is applied to the Likert scale (or any ordinal scale) to determine degrees of consensus or agreement. Using this measure, data on ordinal scales can be given a value of dispersion that is both logically and theoretically sound. The consensus is defined as:

$$\mathrm{Cns}\,(X) = 1 + \sum_{i=1}^{n} p_i \log_2 \left(1 - \frac{|X_i - \mu_X|}{d_X}\right)$$

where μ_X and $d_X = X_{\max} - X_{\min}$ are is the mean value and the width of X, respectively. In our case, where a five-value Likert scale is used, $d = 4$. By definition, $0 \leqslant \mathrm{Cns}\,(X) \leqslant 1$. There is significant consensus if $\mathrm{Cns}\,(X) \geqslant 0.7$, small consensus if $\mathrm{Cns}\,(X) \approx 0.6$ and small consensus if $\mathrm{Cns}\,(X) \leqslant 0.5$.

Appendix B

Below, the reader can find the complete survey we have administered to the chosen experts, translated in English. If the possible answers are not listed, questions are to be answered in Likert scale (1—totally disagree, 5—totally agree). Notice that the numbering of the questions slightly disagrees with that reported in the article, since there some questions were reported without number.

Whether and why

(Q1) Is it appropriate to teach quantum physics in at pre-university level?

(Q2) According to some experts it is impossible to understand quantum physics without knowing its formal structure well, so incomplete mathematical knowledge hinders or prevents the learning of quantum physics for high school students. Do you agree?

(Q3) Teaching quantum physics in high school is important because it is one of science’s greatest cultural achievements. Do you agree?

(Q4) Teaching quantum physics in high schools is important for its technological applications. Do you agree?

(Q5) The teaching of quantum physics in high schools is important to counter the large amount of misinformation present in various media about the contents and consequences of this theory. Do you agree?

What

(W1) We asked a group of university researchers about the most important concepts that high school students should learn in order to develop an adequate mental picture of Quantum Physics. Please assign a number from 1 to 5 to each of the following concepts, which are those singled out by the interviewed expert (1—not or barely important, 5—very important):

- Atomic energy levels and quantization
- De Broglie wavelength

- Entanglement
- Fermions/bosons
- Heisenberg's uncertainty principle
- Incompatible observables
- Particle behavior of light
- Pauli principle
- Probability
- Quantum measurement
- Quantum state
- Spin
- Superposition
- Time evolution
- Tunnelling
- Wave function
- Wave–particle duality

(W2) We asked a group of university researchers about the most important phenomena to be presented to high school students to make them develop an adequate mental picture of Quantum Physics. Please assign a number from 1 to 5 to each of the following phenomena, which are those singled out by the interviewed experts (1—not or barely important, 5—very important):

- 1D infinite potential well
- Black body radiation
- Compton scattering
- Double slit experiment
- Harmonic oscillator
- Photoelectric effect
- Radioactive decay
- Schrödinger's cat
- Specific heat of solids
- Spectral lines

(W3) We asked a group of university researchers about the most important applications of Quantum Physics to be presented to high school students. Please assign a number from 1 to 5 to each of the following phenomena, which are those singled out by the interviewed experts (1—not or barely important, 5—very important):

- Lasers
- LEDs
- Quantum computers
- Quantum information
- Semiconductors
- Solar cells

How

(Q6) In textbooks the most used approach is a quasi-historical one: in fact, experiments that represent the break with classical physics are presented, such as the photoelectric effect, the spectrum of the hydrogen atom, the black body, the Compton effect, etc. Do you agree with this approach?

(Q7) In recent times, some researchers have argued that it is not necessary to use photons to successfully explain the photoelectric effect, as the latter is evidence for the quantization of energy and not of the electromagnetic field. What do you think?

- I do not agree. The consistency of the semiclassical model is at best doubtful, and the photoelectric effect must be explained using the concept of photon;
- I agree in principle with this objection, but I do not think that this should lead to a modification of the current teaching approach;
- I agree: it would be better not to use photons to explain the photoelectric effect;
- Other.

(Q8) Einstein introduced the concept of quantizing electromagnetic radiation into localized packets with clearly defined energy and momentum, which then were named photons. How would you describe the true nature of the photon?

- The photon is a quantum particle like any other; it must not necessarily have well-defined energy and momentum;
- The photon is a massless particle, with well-defined energy and momentum;
- Other.

(Q9) A popular formulation of the complementarity principle is as follows (Bohr–Pauli): 'The particle and wave aspects of a physical phenomenon never simultaneously manifest themselves, rather any experiment that allows the observation of one aspect prevents the observation of the other. The two aspects are nevertheless complementary, being both necessary to a complete physical description of the phenomenon. It is therefore the experimental apparatus that determines whether the physical system behaves like a wave or like a particle.' Some researchers advocate a reformulation of the principle as follows (Greenberger–Yasin): 'An experimental apparatus can simultaneously provide information of the wave and particle aspects of a quantum system, but the more information it gives on one aspect, the less information it will give on the other. Quantum objects can sometimes display both particle and wave aspects at the same time (wave–particle duality).' Which of the two formulations is more adequate in your opinion?

- There is no contradiction between the two formulations, they are completely equivalent;
- Only GY's formulation is correct;
- Neither formulation is incorrect, but I prefer GY's one;
- Only Bohr's formulation is correct;
- Neither formulation is incorrect, but I prefer Bohr's one;
- The formulations are both wrong

(Q13) Some textbook explain Heisenberg's uncertainty relations using Heisenberg's microscope thought experiment, which displays error-disturbance uncertainty relations (cf. e.g. the recent work by M Ozawa). Such relations are fundamentally different from the statistical uncertainty relations (cf. the classic work by H P Robertson). In your opinion, at the high school level:

- it is appropriate to discuss only the error-disturbance relations using Heisenberg's microscope thought experiment;
- it is not appropriate to discuss only the error-disturbance relations using Heisenberg's microscope thought experiment;
- it is appropriate to discuss the error-disturbance relations, but also the statistical uncertainty relations;
- Other.

Comments and suggestions:

Please state your research area:

- Astro- and astroparticle physics
- Applied physics
- Experimental condensed matter physics and optics
- Experimental nuclear and subnuclear physics
- Theoretical physics (fundamental interactions)
- Theoretical physics (optics and condensed matter)
- History of physics
- Physics education
- Other.

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