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Key topics, motivations, and approaches for quantum physics instruction in Italian secondary schools: a teachers' perspective

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Abstract

Quantum Physics (QPs) is increasingly being integrated into secondary school curricula across Europe; however, its practical implementation remains challenging. This study investigates the views of 165 Italian high school teachers on the inclusion of QP in secondary education, using a structured questionnaire addressing four research questions: whether QP should be taught, why it is important, what core topics and experiments should be prioritised, and how it should be taught. Teachers' responses were

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compared with expert views, which we investigated in a previous study. While teachers broadly support QP instruction, they report insufficient curricular time and inadequate preparation as major obstacles. Cultural motivations emerged as the primary rationale for including QP in the curriculum, but the growing relevance of quantum technologies and the need to address quantum misinformation were also acknowledged. In terms of content, teachers tended to prioritise topics and examples from ‘old quantum physics’, reflecting textbooks treatments and national guidelines. Regarding teaching methods, most reported relying on quasi-historical narratives, although with low consensus about their appropriateness. Finally, teachers expressed interest in professional development opportunities and indicated some specific areas of interest. The findings of this study may serve as a guide for targeted teacher training.

Keywords: quantum physics education, teacher training, secondary school

1. Introduction

Quantum Physics (QPs) is a foundational body of knowledge that underpins major areas of contemporary research. Since its early conceptualisation, it has fascinated both physicists and the broader public [1], due to several factors including its dramatic departure from classical physics [2] and its wide array of technological applications [3]. At the same time, the counterintuitive behaviour of quantum particles often evokes a sense of mystery and strangeness, which can give rise to pseudoscientific beliefs, exploiting the public’s limited understanding of the subject [4–9]. In light of these aspects, QP has been increasingly integrated into secondary school curricula in many countries [10, 11], and calls have been made to include QP in pre-university education in a more meaningful and coherent way [12, 13].

However, the teaching and learning of QP presents several challenges. These include the need to move away from classical ways of thinking, the difficulty of visualising quantum objects and phenomena, the complexity of the mathematical formalism, and the existence of multiple interpretations of the theory [14–18]. In response, a growing body of physics education research (PER) has focused on QP instruction, leading to the development of teaching sequences aimed at fostering students’ conceptual understanding of quantum concepts and applications. These proposals adopt a variety of pedagogical approaches, including historical perspectives [19, 20], quantum experiments [21–24], analog experiments [25] and virtual labs [26, 27], as well as quantum games [28–30] and coding environments [31]. The formal presentation of quantum theory also varies: prominent educational reconstructions are based on two-state systems such as spin [32–35] or light polarisation [36, 37], and on the sum-over-paths approach [38, 39], among others. In terms of content, several core topics have been identified as essential for developing conceptual understanding, including wave–particle duality [12, 20, 27], the infinite potential well [40], and quantum states [12, 37].

More recently, with quantum technologies (QTs) emerging as a major area of research and international collaboration [41], the *European Competence Framework for QTs* has been published [42, 43], and collaborative initiatives such as QTEdu have been launched [44]. In PER, growing attention is being devoted to educational reconstructions and topics related to the second quantum revolution [45–49].

While the selection, clarification, and analysis of scientific content are undeniably central to science education research [50], school physics curricula are shaped by a variety of factors and educational goals [51–53]. For instance, while some advocate for QP education as preparation for careers in the QT sector, others emphasise the development of scientific literacy and civic engagement. Stakeholder perspectives on QP education have been explored to identify core topics for instruction [13, 54–56]. For example, Merzel *et al* [55] examined the views of high school teachers, university physics educators, and PERs on key QP concepts and illustrative examples for secondary education. Their analysis highlighted both commonly valued concepts and preferences specific to each professional group. Our own recent study [56] further supported a lack of consensus among experts regarding the core content for pre-university QP instruction.

The present work contributes to this ongoing debate by presenting findings from a survey conducted with 165 high school teachers in Italy. The survey was based on our previous study [56], in which QP experts were interviewed using a self-designed questionnaire exploring multiple dimensions of QP teaching. For the current study, the questionnaire was adapted to address the following research questions:

RQ1. WHETHER

- **RQ1.a:** Is QP actually taught in Italian secondary schools, and if so, how do teachers approach its teaching?
- **RQ1.b:** Is the teaching of QP appropriate at the pre-university level?
- **RQ1.c:** Is a comprehensive understanding of QP achievable without in-depth knowledge of its formal mathematical structure?

RQ2. WHY:

- What are the primary motivations for teaching QP in high school, comparing perspectives related to culture, technology, and scientific literacy?

RQ3. WHAT

- Which specific concepts, examples, and experiments do teachers prioritise for inclusion in the QP curriculum?

RQ4. HOW:

- Is a quasi-historical reconstruction an appropriate method for teaching QP? Are there foundational and controversial aspects within standard school QP topics that require clarification?

For each of these RQs, we aimed to assess (1) whether there is consensus among teachers, (2) whether, and in what ways, teachers' views differ from those of experts.

2. Methods

As detailed in [56], the initial questionnaire was developed based on open-ended interviews with QP experts, which informed the construction of a structured version subsequently administered to 31 additional experts. For the present study, a revised version of the questionnaire was piloted with 10 high school teachers collaborating with our research groups. Based on their feedback, the questionnaire was further refined, and the final version (comprising 23 items) was distributed via Google forms to the full teachers' mailing list of the two research groups.

Table 1. The respondents' academic background.

Degree	Subfield (if present)	N
Physics	Theoretical physics	31
	Experimental physics	27
	Astrophysics	9
	History/physics education	3
Mathematics		80
Engineering		14

To analyse the degree of consensus among respondents, it was essential to adopt measures appropriate for Likert-scale data. Following the approach in [56], we employed two independent metrics: the Consensus index (Cns) [57] and the level of agreement (LoA). The algorithms used to compute these metrics are detailed in appendix of [56].

The final sample consisted of 165 qualified in-service physics teachers. As shown in table 1, the majority had an academic background in either mathematics (48%) or physics (42%), reflecting national trends in Italy.

3. Results and discussion

3.1. Whether

3.1.1. QP in Italian teaching practices.

We began by assessing whether teachers include QP in their teaching, in accordance with Italian national guidelines [Q1–Q4]. Overall, 76% reported covering QP in their teaching to some extent: 41% stated they do so 'often' or 'always', while 47% indicated 'sometimes' or 'never'. No significant differences emerged based on academic background. Regarding satisfaction with their current approach, 63% of teachers expressed a desire to dedicate more time to QP, while only 8% preferred to avoid the topic. The most frequently cited

Table 2. Answers to the question 'How would you rate your own preparation on quantum physics?' [Q6]. LoD indicates the 'level of disagreement'.

Degree	N	Mean	LoA	LoD	Cns
Physics	70	3.9	73	7	0.74
Others	95	2.6	11	36	0.71

obstacle was limited instructional time (54%). Other factors included insufficient preparation, the need to prioritise the fundamentals of classical physics, and students' limited mathematical skills.

The perceived lack of preparation, further self-assessed in Q5, appears to reflect teachers' academic background. A majority held degrees in mathematics, where QP is not included in the curriculum. Consistently, teachers without a physics degree felt significantly less prepared than those with a background in physics (table 2). Specifically, as emerged from the demographics part, 37% of respondents reported never having taken a QP course, and an additional 20% had only studied 'old quantum physics', meaning that 57% received no instruction beyond early QP.

3.1.2. Appropriateness of teaching QP in high school and challenges related to its formalism.

Overall, 60% of respondents strongly endorsed teaching QP in secondary education, although consensus was low (Cns = 0.5). Teachers with a background in experimental physics expressed the highest levels of support and agreement, in contrast with the trend observed among experts in our previous study [56].

That study had also highlighted experts' concerns about the level of mathematical formalism needed to fully grasp key QP concepts. To explore teachers' views on this issue, the new questionnaire included the following item:

[Q9] *According to some experts, it is impossible to understand QP without knowing its formal structure well, hence incomplete mathematical knowledge hinders or prevents students from properly learning QP. Do you agree?*

Responses revealed a lack of consensus, with both agreement and disagreement exceeding 30%, and reaching 45% among teachers with a theoretical physics background.

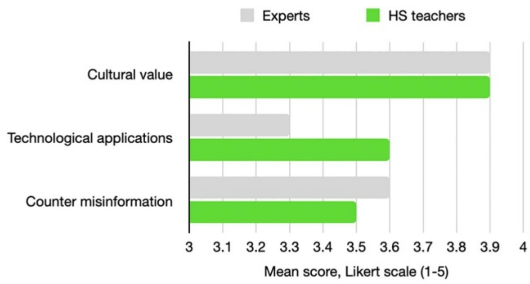

Figure 1. Teacher and expert views on key motivations for teaching quantum physics in high school [Q6–Q8].

3.2. Why

As discussed in the introduction, different priorities may underlie support for the inclusion of QP in secondary education. In our previous study [56], experts prioritised its cultural significance (LoA 77%) over technological applications (52%). Addressing the spread of 'quantum misinformation' [58] was also considered important (60%), with theoretical physicists attributing greater importance to this issue than experimentalists.

To explore teachers' perspectives, we asked them to indicate their LoA with these statements:

[Q6] *Teaching QP in high school is important because it is one of the greatest cultural achievements of science.*

[Q7] *Teaching QP in high school is important because of its technological applications.*

[Q8] *Teaching QP in high school is important to counter the large amount of misinformation present in the media about its contents and implications.*

Figure 1 compares responses from teachers and experts. Teachers showed strong consensus on the cultural value of QP, aligning with expert views (mean = 3.9, LoA 77%). They rated technological applications slightly higher than experts (mean = 3.6 vs. 3.3), although still below cultural relevance and with lower consensus (Cns = 0.5). A small group difference was observed (effect size $\eta^2 = 0.07$), with teachers from an experimental

Table 3. Summary of teachers' views about the importance of seventeen quantum concepts for secondary education. Results are compared with expert responses from [56].

	Teachers				Eperts		
Topic	Mean	LoA	LoD	Cns	Mean	LoA	Cns
Particle behaviour of light	4.3	78	5	0.7	4.1	81	0.7
Wave–particle duality	4.2	78	7	0.6	3.7	70	0.5
Atomic energy levels and quantisation	4.2	79	7	0.6	4.5	90	0.7
Heisenberg's uncertainty principle	4.0	72	8	0.6	4.1	83	0.8
Probability	3.9	65	11	0.6	4.1	81	0.7
De Broglie wavelength	3.9	67	15	0.6	3.4	45	0.6
Wave function	3.5	53	18	0.6	3.3	53	0.6
Superposition	3.5	53	23	0.5	3.8	77	0.6
Pauli principle	3.3	47	23	0.6	3.3	53	0.6
Quantum states	3.3	46	29	0.5	3.5	50	0.5
Spin	3.3	43	28	0.6	2.9		0.5
Tunnelling	3.2	40	31	0.5	3.3	45	0.6
Quantum measurement	3.1	40	36	0.5	3.6	53	0.6
Incompatible observables	3.1	36	32	0.6	2.9		0.6
Fermions/bosons	2.9	30	39	0.6	2.9		0.5
Entanglement	2.9	33	40	0.5	3.4	50	0.6
Time evolution	2.8	26	43	0.5	2.1		0.7

physics background showing the highest appreciation for technological applications. Finally, teachers also agreed on the role of QP education in addressing misinformation (mean 3.6, LoA 60%, Cns 0.6), closely mirroring expert opinions.

3.3. What

Recent research has sought to identify the essential QP concepts to be included in secondary education. Stadermann *et al* [10] analysed national curricula from 15 countries, identifying a common core of seven key topics: discrete atomic energy levels, light-matter interactions, wave–particle duality, de Broglie wavelength, technological applications, Heisenberg's uncertainty principle, and the probabilistic nature of QP. In Italy, the national guidelines (*Indicazioni Nazionali*) recommend introducing 'modern physics' in the final year of secondary school, following a quasi-historical approach [59–61]. Specifically, they suggest presenting the 'quantum of light' through black-body radiation and Planck's hypothesis, followed by Einstein's explanation of the photoelectric effect and the interpretation of discrete atomic energy levels. De Broglie's matter-wave duality and the uncertainty principle are mentioned as a possible 'culmination' of the curriculum.

Experts' views, as highlighted in the study by Krijtenburg–Lewerissa *et al* [13], revealed consensus on the importance of wave–particle duality, wave functions, and atomic models, due to their conceptual interconnectedness and foundational role. In our previous study, interviews with experts yielded 35 distinct QP topics considered appropriate for secondary education, which we categorised using Krijtenburg–Lewerissa's framework [56].

Building on these studies, we asked teachers to rate the importance of a set of (1) concepts [Q12], (2) phenomena and experiments [Q13], and (3) technological applications [Q14], using a five-point Likert scale (*1 Not important at all; 5 Very important*). As shown in tables 3–5, approximately 70% of teachers identified a limited set of concepts and experiments as significant, while no strong consensus emerged regarding quantum-based technologies.

Teachers' views on essential QP concepts were generally consistent with expert opinions, with the top five topics overlapping across the two groups (table 3). However, only three topics (particle behaviour of light, wave–particle duality,

Table 4. Summary of teachers' views about the importance of ten quantum phenomena and experiments for secondary education. Results are compared with expert responses [56].

	Teachers				Eperts		
Topic	Mean	LoA	LoD	Cns	Mean	LoA	Cns
Double-slit experiment	4.4	84	5	0.7	3.9	71	0.6
Photoelectric effect	4.3	81	6	0.7	4.1	74	0.7
Black-body radiation	3.9	67	10	0.6	3.6	58	0.6
Spectral lines	3.9	70	13	0.6	3.7	70	0.5
Compton scattering	3.9	65	17	0.6	3.2		0.6
Schrödinger's cat	3.6	61	17	0.6	3.0		0.6
Radioactive decay	3.6	56	16	0.6	3.4		0.5
Harmonic oscillator	3.2	43	28	0.6	2.9		0.5
1D potential well	3.0	40	38	0.5	2.8		0.6
Specific heat of solids	2.8	32	41	0.5	2.9		0.6

Table 5. Summary of teachers' views on the significance of six technological applications of QP for secondary education. Results are compared with expert responses from [56].

	Teachers				Eperts		
Topic	Mean	LoA	LoD	Cns	Mean	LoA	Cns
LASER	3.9	65	10	0.6	2.9	32	0.6
LED	3.8	64	13	0.5	2.7	29	0.5
Semiconductors	3.7	60	12	0.6	2.8	23	0.7
Solar cell	3.5	54	23	0.5	2.7	27	0.6
Quantum computer	3.1	39	32	0.5	2.6	26	0.5
Quantum information	2.9	36	37	0.5	2.7	32	0.5

atomic energy levels and quantisation) reached over 75% agreement among teachers, compared to five concepts among experts. Some notable differences emerged: the de Broglie wavelength was rated as more important by teachers (60% agreement) than by experts (45%), whereas superposition was endorsed by 70% of experts but only 50% of teachers. The lower consensus on topics like superposition likely reflects teachers' limited familiarity with such concepts, which are rarely covered in textbooks and are not mentioned in the national guidelines. In contrast, eight of the nine most frequently selected topics are explicitly mentioned in the *Indicazioni Nazionali* and commonly found in textbooks. Similar divergences were observed for topics like probability and the uncertainty principle, both highly rated by experts but less so by teachers.

On the other hand, teachers expressed stronger agreement than experts on key experiments to be included in the curriculum (table 4). Two experiments (the double-slit experiment and the photoelectric effect) received over 80% agreement, and four others exceeded 60% (black-body radiation, spectral lines, Compton scattering, Schroedinger's cat). In contrast, experts showed consensus above 70% on only three experiments (double-slit, photoelectric effect, and spectral lines).

Finally, while experts rated the inclusion of quantum-based applications in the curriculum more modestly, teachers evaluated them more favourably, although with moderate levels of agreement and consensus. The LASER, the only application consistently featured in textbooks, received the highest rating and LoA (table 5).

Despite its importance for the research-based 'two-state' approach to QP teaching in secondary school [45–49] the Stern–Gerlach (S–G) experiment does not appear in table 4. This is because our list of topics, experiments, and applications was derived from an expert consultation in which the S–G experiment did not emerge [56]. Consistently, Krijtenburg–Lewerissa *et al* [11] excluded the S–G experiment from the list of recommended curriculum examples during the third round of their Delphi study. One can see such exclusions as a hint that the two state approach is not widely considered or known in the community of University educators in Italy or Europe; indeed from table 3 one can see that the concept of spin is even considered less important for secondary education by experts than by teachers. However, given the centrality of the experiment in the aforementioned educational approach, it may be worthwhile to explicitly include the experiment in future versions of the questionnaire.

3.4. How

3.4.1. The quasi-historical approach. Most school textbooks present the development of QP through a sequence of key experiments, following a 'quasi-historical' narrative that does not accurately represent the history of science. A major drawback of this approach is that it can convey a distorted view of how scientific knowledge develops, overlooking key controversies and debates that were central to the historical construction of QP theory [59–61].

To explore teachers' views on this issue, we included a set of targeted questions in the survey. First, they were asked whether they agreed with the current instructional approach [Q15], followed by a question about the broader role of historical content in physics education [Q16].

The section then introduced to the notion of *quasi-history*, contrasted with a rigorous historical reconstruction of the development of quantum theory. Teachers were then asked to assess the value of a quasi-historical approach for teaching QP in high school [Q17] and to evaluate whether the current presentation of 'old quantum physics' experiments should be considered a simplified quasi-historical narrative or an accurate representation of the historical development of QP.

Over 70% of teachers viewed the traditional approach based on a sequence of 'old quantum physics' experiments positively (mean rating 3.9), a higher score than the expert rating (mean = 3.0, LoA 60%) [56]. This preference likely reflects the orientation of national guidelines and aligns with the respondents' limited exposure to QP in their background.

Regarding the role of historical context in physics teaching, 51% of respondents considered it essential to understand physics, 41% saw it as important but not necessary, and 8% deemed it unnecessary. While these responses indicate broad appreciation for historical content, they also reveal varying views on its centrality. This divergence was further captured in responses to the next question, asking teachers to express a preference between a genuinely historical and a quasi-historical approach: 35% favoured the former, 29%, the latter, and 31% were unsure or had never reflected on the issue. This uncertainty was echoed in responses to the final question of the section: while most recognised the simplified nature of textbook narratives, 35% were unsure, resulting in low-to-moderate consensus.

3.4.2. The photon. Standard textbook narratives tend to portray the photon as a localised particle with well-defined energy and momentum. This view has been criticised by scholars such as Klassen [62], who emphasised the evolving nature of the concept, and Jones [63], who argued that it is energy and momentum that are quantised—not necessarily the 'physical entity' of the photon itself. In our previous study [56], experts were divided: 35% stated that the photon does not need to have well-defined energy and momentum, but 32% disagreed, and the remaining third did not align with either position.

To explore teachers' conceptions, we asked the following item:[Q19] *Einstein introduced the idea that electromagnetic radiation is quantised into localised packets with well-defined energy and momentum (later called 'photons'). Which of the following statements about photons do you most agree with?*.

Unlike the experts, the majority of teachers attributed well-defined energy and momentum to the photon, with over 70% agreement. When asked how they would personally represent the photon [Q20], their responses reflected a variety of mental models, including continuous wave (21%), wave packet (27%), and particle (29%).

However, as highlighted in the literature, such categories are context-dependent and should not be overgeneralised [64, 65].

3.4.3. Controversial aspects. One of the most iconic principles of QP is Heisenberg's uncertainty principle, yet there is lack of consensus among experts on how it should be presented. Some scholars have suggested moving away from the traditional 'Heisenberg's microscope' argument [2], favouring instead explanations based on the single-slit experiment for quantum particles [66]. These alternatives frame uncertainty relations as constrains on the possible preparations of a quantum state, aligning more closely with the Robertson formulation. As discussed in [56], 43% of experts considered the microscope example inappropriate for high school students and recommended focussing on Robertson's formulation.

In light of this, the following question was included in the questionnaire:

[Q21] *Heisenberg's uncertainty principle sets limits on the possibility of simultaneously measuring two physical quantities with arbitrary precision. At an introductory level, these are typically position and momentum. This principle is often illustrated through one of the following arguments:*

A. Heisenberg's 'microscope' thought experiment: The position of a particle is determined through interaction with a photon of short wavelength to minimise uncertainty in position. However, this introduces a large uncertainty in momentum.

B. Single-slit experiment: The position of a particle is determined by forcing it to pass through a narrow slit. This, however, introduces uncertainty in momentum, resulting in the typical interference pattern.

What do you think about these two arguments?

The majority of teachers (80%) viewed the two arguments as equivalent, while 20% expressed some level of disagreement with Heisenberg's argument or both. Notably, 'I do not know/I am not sure' was the second most frequent response (29%), suggesting a lack of confidence in engaging critically with QP concepts.

Another topic of debate involves the principle of complementarity, especially in relation to wave–particle duality [67]. Two distinct, and to some extent contrasting, formulations are commonly referenced. The Bohr–Pauli view asserts that wave and particle aspects cannot be observed simultaneously; any experiment designed to reveal one aspect necessarily precludes observation of the other [68]. Instead, the Greenberger–Yasin formulation [69] proposes that a quantum system can simultaneously exhibit both wave-like and particle like behaviour, though with 'differing degrees of manifestation'. Secondary school textbooks typically adopt the Bohr–Pauli formulation [70]. To assess teachers' view, our questionnaire included an item asking respondents which formulation of complementarity they preferred [Q22].

In our previous study [56], 43% of experts favoured the Greenberger–Yasin formulation, 30% the Bohr–Pauli formulation, and the remainder perceived no contradiction between the two formulations. Some experts also advocated for avoiding the notion of duality altogether, viewing it as a legacy of classical physics that could hinder the development of a genuine quantum framework. Figure 2 compares the responses of teachers and experts. Overall trends were similar, although a larger proportion of teachers (18%) endorsed only the Bohr–Pauli formulation.

4. Conclusions

This study investigated the views of Italian secondary school teachers regarding the appropriateness, motivations, content, and pedagogical approaches to QPs instruction. The main research instrument was a structured questionnaire administered to 165 teachers. Their responses were analysed in terms of levels of agreement and consensus, and compared with those of experts from a previous study.

While many teachers reported incorporating elements of QP into their instruction, key challenges remain, most notably limited curricular time and insufficient teacher preparation. As could be expected, teachers a physics background reported greater confidence in teaching QP

	Experts %	Teachers %
Only GY's formulation is correct	13	13
Neither formulation is incorrect but I prefer GY's one	30	35
There is no contradiction between the two formulations formulations: they are completely equivalent.	17	10
Neither formulation is wrong but I prefer Bohr's one	26	25
Only Bohr's formulation is correct	4	18
The formulations are both wrong	10	

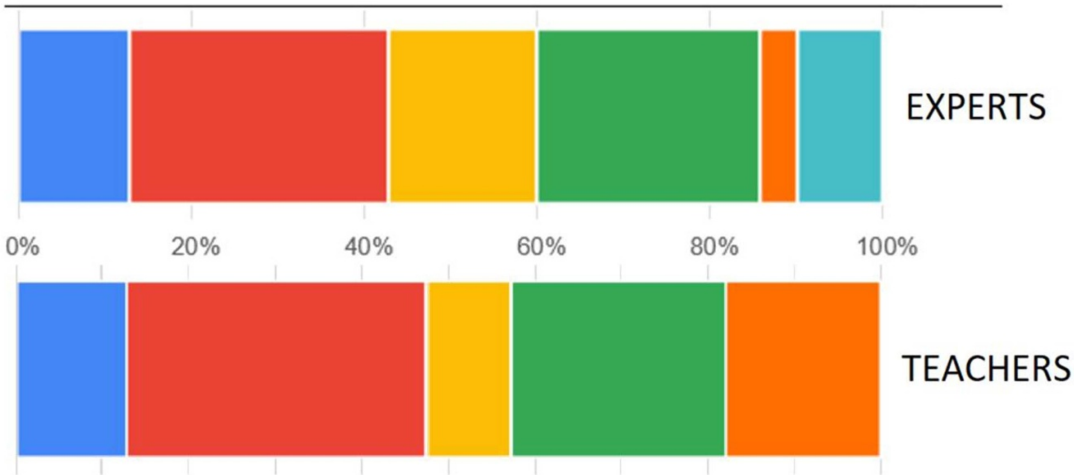

Figure 2. Experts' and teachers' responses to the questionnaire item about the two versions of the complementarity principle [Q22].

than those with a mathematics degree, underscoring the need for targeted professional development and stronger integration of QP in the academic pathways that lead to qualification as physics teachers.

The rationale for including QP in secondary education (*Whether and why?*) was primarily associated with its cultural significance, but teachers attributed value to technological applications as well. The importance of QP education for countering pseudoscientific beliefs was also clearly supported.

Regarding instructional content (*What?*), teachers expressed strong consensus on key 'old quantum physics' topics that mark the rupture with classical physics (e.g. photoelectric effect, atomic spectra), and showed weaker consensus than experts on core quantum theory concepts like superposition. Topics related to the second quantum revolution (e.g., quantum states, quantum measurement, entanglement, quantum information, and quantum computers) were perceived as more peripheral to the school curriculum, reflecting a reliance on textbooks and institutional inertia. This highlights the need to make research-based proposals more accessible and actionable for teachers.

In line with these results, the preferred instructional approaches (*How?*) revealed a tendency to adhere to quasi-historical narratives, despite criticism that such approaches may misrepresent the nature of scientific progress. Regarding controversial aspects (e.g., the formulation of the uncertainty and complementarity principles), teachers exhibited low consensus, and their conceptual models often mirrored textbook simplifications. For instance, while experts debated different formulations of complementarity, teachers predominantly endorsed the Bohr–Pauli interpretation.

Overall, our findings point to the need for focussed teacher preparation and curriculum reform to bridge the gap between expert recommendations, PER, and classroom practice. This need also emerged from teachers' responses to a final question about their expectations for a professional development course on QP [Q23]. Specifically, 61% expressed interest in instructional proposals that go beyond old QPs, and 60% indicated a need for lessons focussed on disciplinary content. A similar percentage (55%) were interested in rethinking how old QPs is taught to move beyond textbook narratives. Additionally, 62% expressed interest in exploring historical and philosophical dimensions, and 49% in learning more about QTs or interdisciplinary approaches. Finally, 45% expressed a desire to engage in discussions on how to meaningfully and sustainably integrate QP into the curriculum.

This study provides a foundation for designing professional development programs capable of engaging diverse teacher profiles. Overall, there is a clear willingness to embrace instructional innovation, although teachers need support in selecting relevant content and understanding its connection to curricular goals. This suggests the value of co-design processes—for example, within teacher communities [71]. At the same time, proposals aimed at enhancing the teaching of old QPs remain valuable, as long as they move beyond superficial narratives to address core concepts and practices, countering the oversimplification and fragmentation that often characterises textbooks.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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Ethical statement

We declare no conflict of interest related to this research. We confirm that informed consent to participate in the study, and for the results to be published was obtained from all participants. The research was carried out in accordance with the journal's ethical policy.

Appendix

Below, we report find the full questionnaire that was used in this study, translated in English.

Section A—QPs at school ***(Whether and why).*** The current National Guidelines for Italian high schools include, among the topics for the fifth year, some elements of QPs, such as 'old quantum physics' (e.g. Planck's hypothesis, photoelectric effect, etc.), as well as selected elements of quantum theory (e.g., wave nature of matter, uncertainty principle). The questions in this section aim to explore your views on this matter.

Q1. Do you think it is appropriate to teach QPs in high school? *(1 Strongly disagree—5 Strongly agree).*

Q2. If you teach or have taught physics in the fifth year of scientific high school, how frequently do you cover/have you covered QPs topics?

- Never
- Sometimes
- Often
- Always

Q3. If you have taught QPs topics, regarding the time you dedicate (d) to them:

- I am satisfied
- I would like to spend more time on them
- I prefer not to teach QPs

Q4. (Multiple answers possible) Regarding the previous question, would you like do add anything?

- I prefer to cover classical physics topics in more depth
- My students lack the necessary mathematical background to understand QPs
- There is not enough time to cover QPs
- I do not feel prepared enough to teach QPs

Q5. How would you rate your own preparation in QPs? *(1 Poor—5 Excellent)*

Q6. 'Teaching quantum physics in high school is important because it is one of the greatest cultural achievements of science.' *(1 Strongly disagree—5 Strongly agree).*

Q7. 'Teaching quantum physics in high school is important because of its technological applications.' *(1 Strongly disagree—5 Strongly agree).*

Q8. 'Teaching quantum physics in high school is important to counter the large amount of misinformation in the media about its content and implications.' *(1 Strongly disagree—5 Strongly agree).*

Q9. 'According to some experts, it is impossible to understand QPs without knowing its formal structure well, hence incomplete mathematical knowledge hinders or prevents students from properly learning QPs. Do you agree? *(1 Strongly disagree—5 Strongly agree).*

Q10. 'QPs should NOT be taught in high school, as it is not needed by students who will not pursue physics, and those who do will have the opportunity to study it later at university. *(1 Strongly disagree—5 Strongly agree)*

Section B—Which topics to teach? *(What).*

Q11. Do you feel prepared to answer questions about the teaching of specific QPs topics?

- Yes, proceed to the next section.
- No, skip to the demographics section.

Q12. We asked a group of experts which *concepts* are important for developing an adequate mental model of QPs. How important do you think it is to teach the following concepts in high school? *(1 Not important at all—5 Very important)*

- Wave–particle duality
- Tunnelling
- Entanglement
- Time evolution
- Fermions and bosons
- Wave function
- Atomic energy levels and quantisation
- De Broglie wavelength
- Quantum measurement
- Particle behaviour of light
- Incompatible observables
- Heisenberg's uncertainty principle
- Pauli's principle
- Probability
- Superposition
- Spin
- Quantum states

Q13. We asked a group of experts which *phenomena and experiments* (real or thought) are most meaningful for understanding the key ideas of QPs. How significant do you think it is to present the following phenomena or experiments in high school? *(1 Not important at all—5 Very important)*

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

Q14. We asked a group of experts which *technological applications* of QPs are most meaningful. How important do you think it is to present the following applications in high school? *(1 Not important at all—5 Very important)*

- Solar cell
- Quantum computer
- Quantum information

- LASER
- LED
- Semiconductors

Section C—Approaches to QP teaching ***(How).*** The questions in this and the next section aim to explore your views on possible approaches to teaching QPs. There are no right or wrong answers: we are interested in your own ideas and perspectives.

Q15. The Italian National Guidelines recommend introducing QPs through a sequence of experiments that represent the rupture with classical physics (e.g., photoelectric effect, hydrogen atom spectrum, black-body radiation, Compton effect, etc.). Most textbooks adopt this approach. Do you agree? *(1 Not at all—5 Completely).*

Some textbooks are very rigorous in reporting not only the physical content but also the historical evolution that led to the formulation of new theories. Other textbooks, instead, accompany the presentation of physical content with a quasi-history, a partially altered narrative (e.g., with historiographical omissions), yet more linear and easier to follow.

Q16. What do you think about integrating historical content into physics teaching?

- It is not needed to understand physics.
- It is important but not necessary to understand physics.
- It is essential to understand physics.

Q17. What do you think about the quasi-historical approach to teaching QPs in high school?

- A simplified quasi-historical approach is better than a fully historical one.
- A fully historical approach is better than a quasi-historical one.
- Teaching physics does not require historical, nor quasi-historical approaches.
- I do not know/I have never thought about this aspect.

Q18. In the textbooks that include it, 'old quantum theory' is often presented as a sequence in which black body radiation, photoelectric effect, Compton effect, and Bohr's model follow one another linearly. Which of the following statements about this presentation of 'old quantum physics' do you prefer? *(Indicate your position on a 5-point scale between the two statements)*

A. It is a simplified narrative with alterations or omissions.
B. It accurately represents the historical development of QPs.

Section D—Controversial aspects ***(How).***

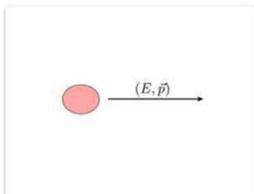
Q19. Einstein introduced the idea that electromagnetic radiation is quantised into localised packets with well-defined energy and momentum (later called 'photons'). Which of the following statements about the photon do you mostly agree with?

- A photon is a particle that has no mass but has well-defined momentum and energy.
- A photon is a quantum particle and, as such, does not have well-defined momentum and energy.
- I do not know/I am not sure.
- Other *(specify)*

Q20. In textbooks, various representations of the photon can be found. How do you personally picture or mentally represent the photon?

Option 1

Option 2



Option 3

I don't know how to represent a photon

Q21. Heisenberg's uncertainty principle sets limits on the possibility of simultaneously measuring two physical quantities with arbitrary precision. At an introductory level, these are typically position and momentum. This principle is often illustrated using one of the following arguments:

A. Heisenberg's 'microscope' thought experiment: *The position of a particle is determined through interaction with a photon of short wavelength to minimise uncertainty in position. However, this introduces a large uncertainty in momentum.*

B. Single-slit experiment: *The position of a photon is constrained by forcing it through a narrow slit, which introduces an uncertainty in momentum, leading to the typical interference pattern.*

What do you think about these two arguments?

- Both arguments correctly illustrate the uncertainty principle and are equivalent.
- Only the microscope illustrates the uncertainty principle correctly; the single-slit is a particular case.
- Only the single-slit experiment illustrates the principle correctly; the microscope is a particular case.
- Neither argument correctly illustrates the uncertainty principle.
- I do not know/I am not sure.

Q22. Another fundamental principle of QPs is the concept of **complementarity**, which is commonly formulated as:

'The particle and wave aspects of a physical phenomenon never appear simultaneously. Every experiment that allows one to observe one aspect prevents the observation of the other. However, the two aspects are complementary because both are essential for a complete physical description of the phenomenon. It is thus the experimental apparatus that determines whether the quantum system behaves as a wave or as a particle.' (*Formulation I*)

According to some experts, the principle should instead be reformulated as:

'An experimental apparatus can provide simultaneous partial information on both the wave-like and particle-like aspects of a quantum system. However, the more information is gained about one aspect, the less is obtained about the other. Quantum objects can sometimes display both wave and particle properties simultaneously (wave–particle duality).' (*Formulation II*)

Which of the two formulations do you prefer?

- There is no contradiction: the two formulations are completely equivalent.
- Neither formulation is incorrect, but I prefer the first.
- Neither formulation is incorrect, but I prefer the second.
- Only the first is correct.
- Only the second is correct.
- I do not know/I am not sure.

Section E—Formative needs

Which of the following elements would you like to find in a teacher training program on QPs?

- Lectures on quantum mechanics topics beyond 'old quantum physics' (e.g., quantum state, Schrödinger equation, …).
- In-depth exploration of QTs (e.g., quantum computing).
- In-depth exploration of historical and/or philosophical aspects of quantum mechanics (e.g., different interpretations of quantum mechanics).
- Insights into interdisciplinary STEM topics (e.g., LEDs—materials science, …).
- Teaching proposals to innovate or deepen the teaching of 'old quantum physics' (e.g., black-body radiation, spectroscopy, photoelectric effect).
- Teaching proposals for introducing quantum mechanics topics beyond 'old quantum physics'.

- Discussions on the physics curriculum in scientific high schools to explore how modern physics can be better integrated.
- Other *(specify)*

Section F—Demographics.

What is your academic background?

- Theoretical physics
- Experimental physics
- Astronomy/astrophysics
- Mathematics
- Engineering
- Other *(specify)*

During your university studies, did you attend any courses in QPs?

- No
- Yes, but only on the early QPs.
- Yes, also on quantum mechanics beyond early QPs.
- Yes, also at the PhD level.
- Other *(specify)*

Have you ever attended any teacher training courses on QPs?

- No
- Yes, during pre-service training.
- Yes, as part of in-service training (professional development courses).
- Other *(specify)*

What is your age group?

- <30
- 30–39
- 40–49
- 50+

What is your gender identity? (You may select more than one option).

- Female
- Male
- Transgender
- Non-binary/Non-conforming
- Prefer not to answer
- Other *(specify)*

How many years have you been teaching physics?

- <5
- 5–10
- 11–20
- 20+

Which textbook do you use to teach QPs? (*Open-ended response).*

To what extent do you rely exclusively on the textbook when preparing your lessons? *(1 I add a lot of supplementary material—5 I only use the textbook).*

What type of school do you teach in?

- Scientific high school (*Liceo scientifico*)
- Non-scientific high school
- Technical institute—technological sector
- Technical institute—economic sector
- Vocational school
- Other *(specify)*

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