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Teaching Quantum Physics in Secondary School: the Teachers’ Perspective

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Contents

1 Quantum Physics Curriculum 5
1.1 Quantum Physics in the Italian National Guidelines 5
1.2 Quantum Physics in other European Curricula 8
1.3 EU Projects for Enhancing the High School QP Curriculum 9
1.4 Restructuring QP Content for Secondary School Teaching 12
1.4.1 Structural Dimensions (Discipline-Culture Approach) 12
1.4.2 Theoretical-Experimental Dimensions 14
1.5 The Questionnaire from the Universities of Trento and Pavia 15

2 Approaches to QP teaching in secondary school 17
2.1 Quantum Physics in Physics Education Research 17
2.1.1 Teaching Approaches 19
2.1.2 The Mathematical Formalism of QP 22
2.2 History and Quasi-history in QP Teaching 23
2.3 The Nature of Science in QP Teaching 25
2.4 Controversial Aspects in QP Teaching 27
2.4.1 The Nature of Photon 27
2.4.2 The Complementarity Principle 30
2.4.3 The Double-slit Experiment and Uncertainty Principle 31
2.4.4 Atomic Models 34
2.4.5 Interpretations of Quantum Physics 35

3 Research Methods 41
3.1 Questionnaire 41
3.1.1 Summary of Modifications 41
3.1.2 Final Questionnaire 42
3.2 Data Analysis Tools 53
3.2.1 Consensus (Cns) 53
3.2.2 Level of Agreement or Naif Consensus 54
3.2.3 Correlation Parameters 54
3.2.4 Sample Size 56

4 Results 57
4.1 Demographics 57
4.2 Quantum Physics at School 58
4.3 Why Teach/Not Teach Quantum Physics 63

4.4 Which Topics to Teach 66
4.5 Approaches to Teaching Physics 71
4.6 Interpretations of Quantum Physics 74
4.6.1 Interpretations of Quantum Physics (Padua only) 78
4.7 Formative Needs 84
4.8 Textbooks 85

5 Discussion and Conclusions 89
5.1 Physics Teachers' Attitudes and Beliefs on Teaching Quantum Physics . . . 89
5.2 Key Aspects of Quantum Physics for High School Education 90
5.3 Insights for Quantum Physics Education Research and teachers' training . . 92

Bibliography 95

A Questionnaire 103

Introduction

The need to understand how to meaningfully teach Quantum Physics (QP) in Italian high schools, and why its teaching remains limited despite extensive research on the topic, has led to this thesis. Specifically, the questions guiding this research were:

1. What are physics teachers' attitudes and beliefs about teaching Quantum Physics in secondary school?
2. What do teachers consider as the most important aspects of Quantum Physics to be taught in secondary school, and do their views align with those of experts?

This thesis begins with a review of the Italian secondary-school curriculum, focusing on how Quantum Physics is included in the National Guidelines. This analysis is followed by an examination of other curricula and teaching proposals from the European context. A discussion of potential clusterings and classifications of QP sub-topics for teaching, as proposed in the Physics Education Research (PER) literature, is then provided.

The second chapter presents a scoping review of research findings on Quantum Physics teaching, presenting the main teaching approaches discussed in the literature and focusing on instructors' and students' views of some controversial aspects of QP. We then present a questionnaire developed at the Universities of Trento and Pavia (Onorato, Di Mauro, and Malgieri 2024), aimed at understanding experts' views on the teaching of QP in the Italian context, the results of which were the starting point for this research.

In Chapter 3, we describe the methods used to extend the questionnaire developed by Trento and Pavia to secondary-school teachers, as well as the tools used for data analysis. The research was conducted in collaboration with a MSc candidate at the University of Trento (Perli 2024), but in the Padua version we added some sections aimed at extending the research towards specific teaching aspects, as well as at gathering information useful for teacher training and professional development. The questionnaire was delivered to in-service physics teachers through an online platform.

The results are presented and discussed in Chapter 4. The final analysis of the responses provides insights into the status of Quantum Physics teaching in Veneto and Trentino high schools, which can offer an estimation of the improvements needed not only in this region but across the country.

While numerous teaching proposals exist in PER literature, the teachers' perspective - detected by this research - is essential for designing teacher training and professional development that are both research-based and respectful of the context. The findings will directly inform the planning of future teacher training and professional development initiatives, such as the "school" for physics teachers to be organized as part of the "Quantum Frontiers" Excellence Project at the Department of Physics and Astronomy at UniPD.

Chapter 1

Quantum Physics Curriculum

There is a lot of research on the structure of Quantum Physics (QP) curriculum at secondary schools and universities. This thesis focuses on understanding which topics are suitable for constructing a meaningful QP curriculum appropriate for Italian upper secondary schools. Therefore, we begin by examining the Italian National Guidelines (*Indicazioni Nazionali*), focussing on the *Liceo Scientifico* type of school, to understand how QP is addressed within these guidelines. Subsequently, we compare the Italian National Guidelines with other European curricula and with an European Project aimed at upgrading QP teaching in high schools. Finally, we will discuss the main clusterings of topics for QP teaching proposed in the literature.

1.1 Quantum Physics in the Italian National Guidelines

The starting point for analyzing the physics curriculum in Italian high schools are the *Indicazioni Nazionali per il Curricolo* (National Guidelines for the Curriculum). These guidelines outline the comprehensive student profile expected upon completion of the different types of high schools and establish the learning goals for each subject. It is important to specify that these Guidelines are not intended as strict "standards" to be met; rather, they provide a reference for schools to develop their own curricula.

Different types of upper secondary schools exist in the Italian school system. Among them, the *Liceo Scientifico* ("Scientific Lyceum") includes the largest amount of classroom time dedicated to physics and mathematics, both of which are taught throughout the five years (grades 8 to 12). For this reason, we focus our analysis on this type of school.

In the guidelines for the Liceo Scientifico, an "approach to 20th-century physics" is recommended as part of the last year (grade 12) (MIUR 2010, allegato B). Specifically, regarding QP topics, they state that:

L'affermarsi del modello del quanto di luce potrà essere introdotto attraverso lo studio della radiazione termica e dell'ipotesi di Planck (affrontati anche solo in modo qualitativo), e sarà sviluppato da un lato con lo studio dell'effetto fotoelettrico e della sua interpretazione da parte di Einstein, e dall'altro lato con la discussione delle teorie e dei risultati sperimentali che evidenziano la presenza di livelli energetici discreti nell'atomo. L'evidenza sperimentale della natura ondulatoria della materia, postulata da De Broglie, ed il principio di indeterminazione potrebbero concludere il percorso in modo significativo.

[Translation: The emergence of the quantum model of light can be introduced through the study of thermal radiation and Planck's hypothesis (even if approached only qualitatively). It will be further developed by examining the photoelectric effect and its interpretation by Einstein on one hand, and on the other hand by discussing the theories and experimental results that highlight the presence of discrete energy levels in the atom. The learning path could be completed in a significant manner by exploring the experimental evidence of the wave nature of matter, postulated by De Broglie, and the principle of uncertainty.] (MIUR 2010, allegato F)

For a more accurate description of the contents to be taught, we can refer to the MIUR 2015, i.e. the Reference Framework for the National Final Exam. This document specifies the topics that students are expected to have learned by the end of the fifth year of the Liceo Scientifico. This Framework mentions QP-related topics, contents, and skills organized as follows:

1. Prerequisites: The Rutherford experiment and atomic model, atomic spectra, interference and diffraction (waves, optics), discovery of the electron, classic collisions;

2. Essential Contents: Blackbody emission and Planck's hypothesis, Lenard's experiment and Einstein's explanation of the photoelectric effect, Compton effect, Bohr model of the atom and interpretation of the atomic spectra, the Franck - Hertz experiment, de Broglie wavelength, wave-particle dualism, limits of validity of the classic description, diffraction/interference of electrons, the uncertainty principle;

3. Content-related Skills: Illustrate the black body model and interpret the emission curve using the Planck's law of distribution, apply the laws of Stefan-Boltzmann and Wien and recognize their phenomenological nature, apply the Einstein equation of the photoelectric effect for solving exercises, illustrate and apply the Compton effect law, discuss wave-body dualism, calculate the frequencies emitted in the transitions between different levels of the Bohr atom, calculate the wavelength of a particle and compare it with the wavelength of a macroscopic object, describe the quantization condition of the Bohr atom using the de Broglie relation, calculate the quantum uncertainty on the position/momentum of a particle, analyze particle interference and diffraction experiments, also illustrating formally how they can be interpreted starting from the De Broglie relation on the basis of the superposition principle;

4. Sectorial Skills: Knowing how to show, by referring to specific experiments, the limits of the classical paradigm of explanation and interpretation of phenomena and being able to argue the need for a quantum vision, knowing how to recognize the role of quantum physics in real situations and in technological applications, be able to understand and argue popular and scientific critical texts dealing with the topic of quantum physics.

From this analysis, we can see that the QP curriculum in Italian high schools is restricted to what experts call "Old Quantum Physics" (OQP), mainly covering the first set of experiments and related conclusions that led to the emergence of the concept of "quantum" and the questioning of classical theories of light and matter. The axiomatic and mathematical formulation of QP (including, for example, vector states and the wave equation) is excluded.

However, as mentioned above, the Guidelines explicitly allow teachers some freedom to choose the specific topics to teach, as well as the approaches used to teach them. These degrees of freedom are partially reflected in the different textbooks available on the market. An analysis of six different high-school physics textbooks conducted at the University of Trento (Perli 2024) revealed that there is, in fact, some variability in terms of the topics mentioned. In Fig. 1.1, we report the results of this analysis, where the different sub-topics are grouped into broader categories (named *Quantum pre-history, Quantum concept, Quantum phenomena, Technical application*) and compared against the topics indicated as important by Quantum Physics experts.

		Amaldi	Walker	Cutnell	Romeni	Parodi	Caforio	Expert asked	Availability lower bound in Italian fifth-grade classes	Availability in Italian fifth-grade classes normalized on the sample
Quantum pre-history	Brownian motion		☑		☑				17%	23%
	Millikan experiment	☑	☑			☑	☑		62%	81%
	Early atomic models	☑	☑	☑	☑	☑	☑		76%	100%
Quantum concept	Atomic energy levels	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Particle behaviour of light	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Uncertainty principle	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Probability	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Superposition	☑			☑			☑	45%	59%
	Wave–particle duality	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Quantum measurement							☑	0%	0%
	Quantum state					☑		☑	4%	5%
	Entanglement							☑	0%	0%
	De Broglie wavelength	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Wave function	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Pauli prin./Periodic table	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Tunnelling	☑	☑				☑	☑	58%	76%
	Spin			☑		☑	☑	☑	19%	25%
	Incompatible observables						☑	☑	6%	8%
	Fermions/bosons							☑	0%	0%
	Time evolution							☑	0%	0%
Quantum phenomena	Photoelectric effect	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Double slit experiment	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Spectral lines	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Black body radiation	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Radioactive decay	●	●	●	●	●	●	☑	76%	100%
	Compton scattering	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Schrödinger's cat	☑				☑	☑	☑	50%	65%
	specific Heat of solids							☑	0%	0%
	Harmonic oscillator							☑	0%	0%
	1D infinite potential well		☑	☑	☑	☑	☑	☑	37%	48%
	Frank & Hertz exp.	☑		☑	☑		☑		60%	79%
	Molecular bonds		☑			☑	☑		22%	29%
Technical application	Laser	☑	☑	☑	☑	☑	☑	☑	76%	100%
	Semiconductor		☑		☑	☑	☑	☑	27%	35%
	Solar cell		☑		☑	☑		☑	21%	28%
	LED					☑	☑	☑	10%	13%
	Quantum information							☑	0%	0%
	Quantum computers							☑	0%	0%
	Fluorescence		☑		☑				17%	23%
	SEM	☑	☑	☑					62%	81%

☑ Argument present

● Argument present, but in a later dedicadet chapter

Figure 1.1: Overview of the high-school physics textbooks analysis conducted at UniTN (Perli 2024): "availability" is defined as as $Av = \sum_{i=1,2,...,6} p_i \delta(X_i)$ with i running on the books, p_i being fraction of the classes that adopted the i-th textbook and $\delta(X_i) = 1$ if the topic is present in the i-th textbook or $\delta(X_i) = 0$ if it is not present. The availability normalized on the sample is defined as $Av_{norm} = \frac{Av}{76.3\%}$, because the textbooks reported cover 76.3% of the Italian market share for the the fifth-grade physics classroom.

1.2 Quantum Physics in other European Curricula

A recent study (Stadermann, Berg, and Goedhart 2019) analyzed the QP curriculum in various European countries, see Fig. (1.2), and used the results to propose an "international core curriculum" for QP shown in Fig. 1.3.

Content item mentioned in the curriculum document		Countries/15	Documents/23
Q1	Blackbody radiation	(9)	(11)
Q2	Bohr atomic model	(13)	(15)
Q3	Discrete energy levels (line spectra)	15	22
Q4	Interactions between light and matter	13	21
Q5	Wave-particle duality or complementarity	15	23
Q6	Matter waves, quantitative (de Broglie)	12	20
Q7	Technical applications	13	18
Q8	Heisenberg's uncertainty principle	9	16
Q9	Probabilistic or statistical predictions	8	15
Q10	Philosophical consequences or interpretations	5	9
Q11	One-dimensional model or potential well	3	8
Q12	Tunneling	4	7
Q13	Atomic orbital model	1	5
Q14	Exclusion principle or periodic table	2	4
Q15	Entanglement	2	3
Q16	Schrödinger equation	2	3
Q17	Calculations of detection probability	1	3

Figure 1.2: Frequency of QP curriculum items for different countries analyzed in Stadermann, Berg, and Goedhart 2019.

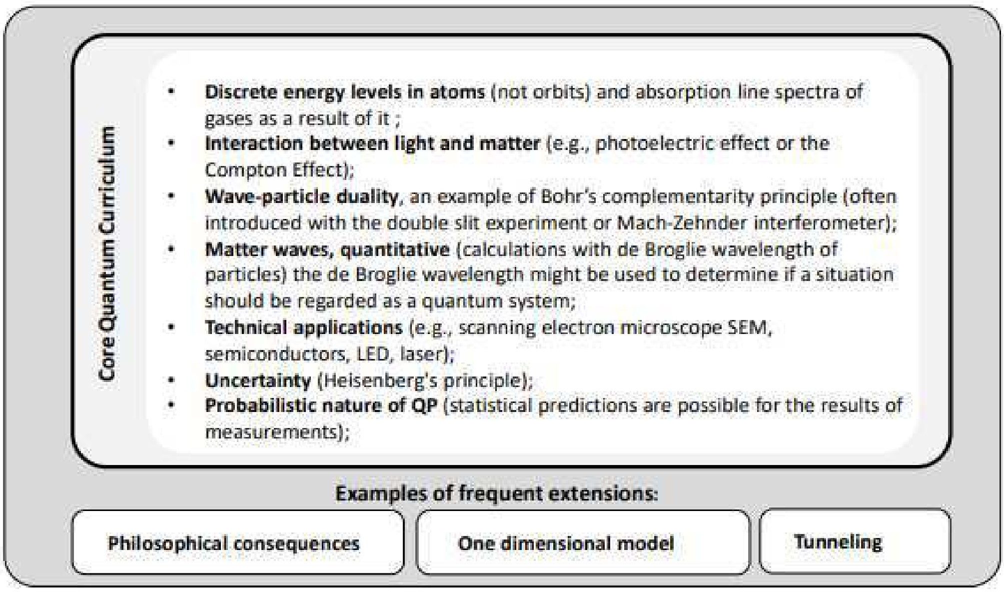

Figure 1.3: The international core curriculum in QP at the secondary school level with items from Q3 to Q9 as seen in Fig. (1.2), with possible common extensions (Q10, Q11, Q12) and better explanations from Stadermann, Berg, and Goedhart 2021.

The results presented in Fig. (1.3) suggest that the "core curriculum" is mainly composed of topics from OQP, similar to the Italian context but with some differences. In the Italian curriculum, Q7-Technical Applications and Q9-Probabilistic/Statistical Predictions are not present, while Q1-Blackbody Radiation and Q2-Bohr Atomic Model are included.

1.3 EU Projects for Enhancing the High School QP Curriculum

Some international organizations are working to propose an "upgrade" of the QP curriculum at the high school level, with projects aimed at integrating Quantum Technologies and the Second Quantum Revolution into high school curricula. These initiatives stem from the Quantum Manifesto, a document signed in 2016 by more than 3400 individuals from academia and industry across Europe. The Manifesto is intended as *a call to launch an ambitious European initiative in quantum technologies, needed to ensure Europe's leading role in a technological revolution now under way* (De Touzalin et al. 2016).

The Quantum Manifesto begins with:
This Manifesto calls upon Member States and the European Commission to launch a €1 billion flagship scale initiative in Quantum Technology, preparing for a start in 2018 within the European H2020 research and innovation framework programme. It is endorsed by a broad community of industries, research institutes and scientists in Europe. This initiative aims to place Europe at the forefront of the second quantum revolution now unfolding worldwide, bringing transformative advances to science, industry and society. It will create new commercial opportunities addressing global challenges, provide strategic capabilities for security and seed as yet unimagined capabilities for the future. As is now happening around the world, developing Europe's capabilities in quantum technologies will create a lucrative knowledge-based industry, leading to long-term economic, scientific and societal benefits. It will result in a more sustainable, more productive, more entrepreneurial and more secure European Union.

This approach is further elaborated in Riedel et al. 2017, where the conditions indicating that we are living within the Second Quantum Revolution are discussed:
We are currently experiencing a 'second quantum revolution'. In the first quantum revolution, the fundamental laws of the microscopic realm were discovered and quantum science was formulated. In the following years, ground-breaking technologies such as the transistor and the laser were developed. These inventions can only be understood and developed with the help of quantum mechanics (e.g. to understand the band structure of a semiconductor or the nature of a coherent state), but they are based on bulk effects, where many quantum degrees of freedom are manipulated at once. In the second quantum revolution, which is unfolding now, technologies are being developed that explicitly address individual quantum states and make use of the 'strange' quantum properties, such as superposition and entanglement, commonly referred to as quantum technologies (QT). Why do we believe that this revolution is happening now? On the one hand, a number of start-up companies were founded over the last decade which offer QT to very specialised markets. Quantum cryptography is among the most advanced QT with highly specialised small and medium-sized enterprises already selling their products to governments, banks and other customers with highest security requirements. On the other hand, and even more importantly, large global companies, including Google, IBM5, Intel, Microsoft and Toshiba6 have recently started to invest heavily in QT. They are attracting top talents that just a couple of years ago would have only had the choice between pursuing an academic career and leaving the field altogether.

Moving from these foundations, the proposers maintain that it is essential to:

- Run educational programmes for a new generation of technicians, engineers, scientists and application developers in quantum technologies.
- Run a campaign to inform European citizens about quantum technologies and engage widely with the public to identify issues that may affect society.

The European Commission responded to the Quantum Manifesto through the *European Quantum Technologies Flagship Programme*. The goals for this programme, as outlined in Riedel et al. 2017, were:

- Consolidate and expand European scientific leadership and excellence in quantum research, including training the relevant skills;
- Kick-start a competitive European industry in QT to position Europe as a leader in the future global industrial landscape;
- Make Europe a dynamic and attractive region for innovative research, business and investments in QT, thus accelerating their development and take-up by the market.

An important outcome of the Quantum Flagship was the "European Competence Framework for Quantum Technologies" delivered by the QTEdu CSA project European Commission, Müller, and Greinert 2021. This Framework aims to map the landscape of competences and skills in quantum technologies, thus establishing a common language facilitating communication and cooperation among different stakeholders in the education ecosystem. Among the various dimensions of competence, the framework lists the fundamental physics and mathematical concepts (Basic quantum concepts; Mathematical formalism and information theory) needed as a knowledge and skills base (Fig. 1.4). The list almost exclusively includes topics from "New Quantum Physics" (NQP) rather than topics from OQP.

It is to be noted that the competences and skills outlined in this Competence Framework are intended to be acquired by the end of university level education, rather than at the high school level. However, in order to facilitate this task, it is suggested that an upgrade in the teaching of QP in high school is necessary compared to current practices. Specifically, it would be advisable to restructure the curriculum to include some of the concepts, tools, and mathematical skills needed to engage in the study of more advanced QP topics in subsequent educational levels.

To pursue the development of these new competences and skills, some universities responded with specific projects. For example, the *I SEE (Inclusive STEM Educating to Enhance the capacity to aspire and imagine future careers)* project was a three-years Erasmus+ project (2016-2019) coordinated by the Department of Physics and Astronomy at the University of Bologna. It leveraged a strategic partnership composed by different types of institutions across four countries: Italy, Finland, Iceland, and the United Kingdom. In the Italian context (Satanassi, Fantini, et al. 2021; Satanassi, Ercolessi, and Levrini 2022) the main goals of this projects are explained: *The main objective of the project concerns the design of teaching modules aimed to i) improve students' ability to imagine the future*

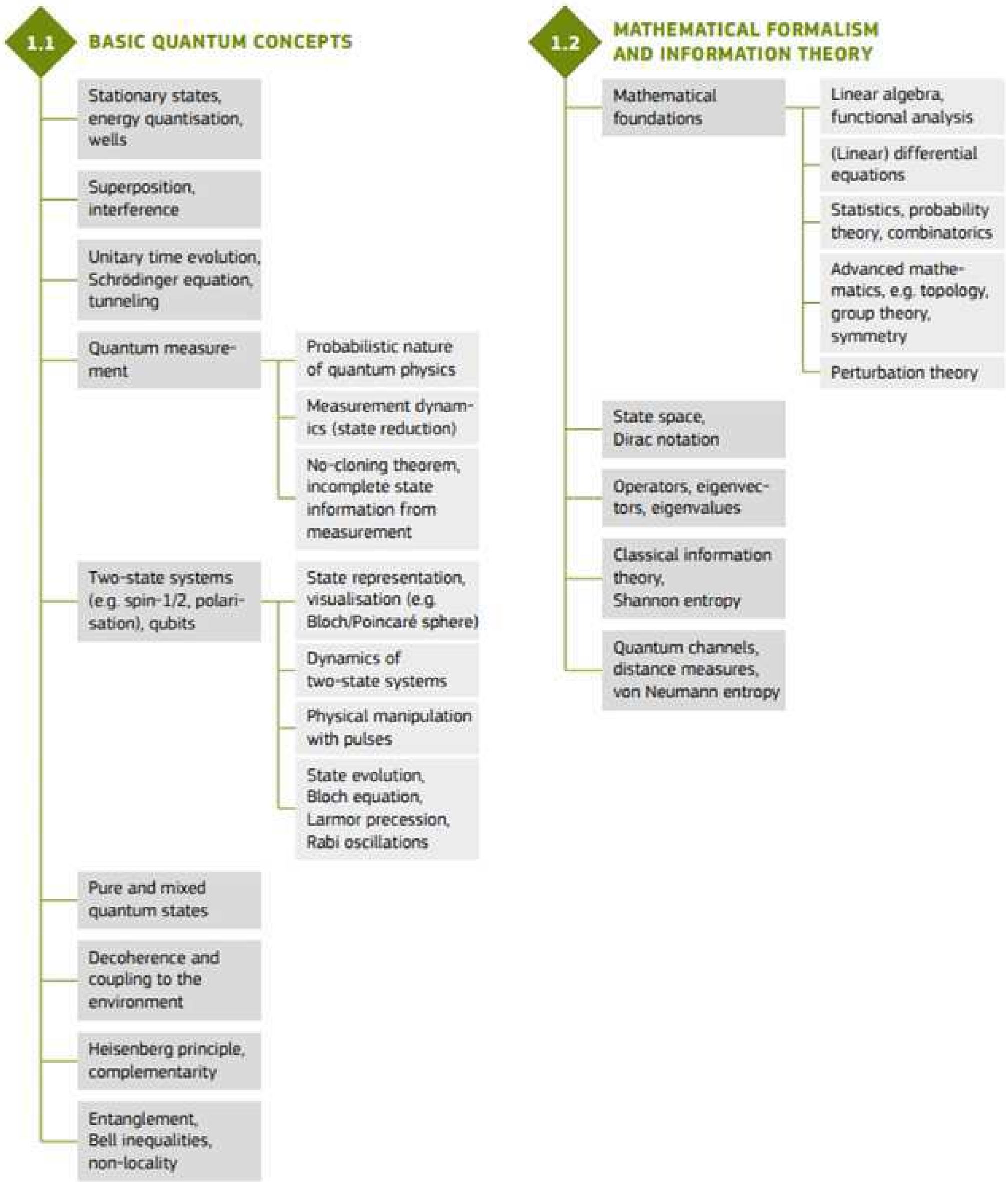

Figure 1.4: Final version of the NQP domain in the "Competence Framework for Quantum Technologies" (Greinert et al. 2024).

and to aspire to STEM careers; ii) develop transversal skills that allow students to play an active, aware and responsible role in the 'society of acceleration and of uncertainty'. (Satanassi, Fantini, et al. 2021)

The Italian module diverges from current practices as it does not include OQP topics and instead focuses on concepts such as quantum state, superposition principle, qubits, state evolution, and measurement within the context of quantum computers. It then progresses to cover advanced topics such as multi-qubit systems and entanglement, cryptography, and quantum teleportation. This approach is valuable for highlighting *how the STEM disciplines can be integrated to stress the conceptual, epistemological, and social relevance of quantum computing [...] The approach has allowed us to highlight the difference between classical and quantum computers and to bring out the interdisciplinary character that characterises the new technologies* (Satanassi, Fantini, et al. 2021).

1.4 Restructuring QP Content for Secondary School Teaching

Teaching a topic involves restructuring its content in a way that is meaningful and appropriate for the specific group of students. This process entails identifying a content structure in terms of conceptual nodes and their interconnections, deciding which parts to teach, and establishing a teaching-learning progression that facilitates robust understanding.

Researchers have studied potential organizations of QP topics suitable for secondary school education. Below, we provide a summary of the main proposals from the literature, along with the frameworks and methodologies that underpin them.

1.4.1 Structural Dimensions (Discipline-Culture Approach)

A novel approach to structuring scientific knowledge for teaching, termed the Discipline-Culture approach, was developed by Tseitlin and Galili 2005. The authors argue that an aggregate of knowledge becomes a "discipline" when it possesses a *structure* unique to that discipline. This structure not only serves a functional role but also holds cultural significance, providing a framework for interpreting the world. Consequently, it would be more appropriate to refer to a discipline as a "discipline-culture".

In Tseitlin and Galili 2005, a "structure" is defined as *the thing that makes an aggregate of knowledge a discipline, something that should be related to all of its components, an arrangement of statements in a hierarchical and meaningfully related manner.* To organize a discipline-culture in a structured way, the authors propose three essential components, arranged from inner to outer "layers", as pictured in Fig. 1.5:

1. **Nucleus:** The fundamental principles and concepts that define the identity of a discipline-culture.

2. **Body:** All conventional disciplinary knowledge, i.e. the statements (laws, phenomena, and applications) that are rooted on the principles within the nucleus.

3. **Periphery:** Knowledge items that conflict with the nucleus, including both previous interpretations superseded by current theories and new findings that pose challenges.

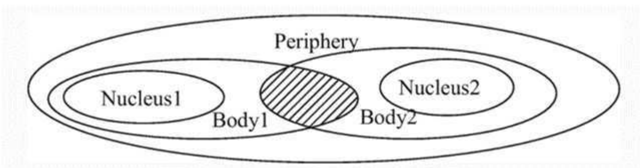

Figure 1.5: Example of two scientific theories structured using the DC approach in three layers: nucleus, body and periphery. The bodies of two disciplines-cultures can overlap, and they can share the same periphery (Tseitlin and Galili 2005).

Within this approach, different "disciplines-cultures" exist within physics, and Quantum Physics can be viewed as one of them. In subsequent works (Weissman et al. 2019; Weissman et al. 2021; Weissman et al. 2022), the authors suggested a restructuring of the high school QP curriculum based on the DC approach. To determine the nucleus, they conducted interviews a pool of experts (three QP instructors, a philosopher of science, an emeritus scholar, and four younger researchers) and analyzed nine university textbooks. The identified elements to be included in the nucleus were:

- States, eigenstates, superposition, and the wave function;
- Wave-particle duality;
- Probability and measurement;
- Heisengberg's uncertainty principle and the complementarity principle;
- Entanglement;
- Quantum indistiguishability
- Bosons and fermions.

The full QP structure according to the DC approach is reported in Fig. 1.6.

Nucleus	Body	Periphery
State–eigenstate and the principle of the superposition of states; the wave function	Dirac notations	Classical state and probability in mechanics and thermodynamics
The wavity of matter and superposition. Probabilistic interpretation and measurement	The double-slit experiment with electrons Spin and polarization The Stern–Gerlach experiment Mach–Zehnder interferometer	Classical measurement without disturbance Electron as a cloud
Heisenberg's uncertainty and complementarity principle	The BB84 protocol	Classic uncertainty—the lack of knowledge
Entanglement	An experiment to examine Bell's inequality	Hidden variables
Quantum indistinguishability Bosons and fermions	Laser, Pauli's exclusion principle, The Mendeleev periodic table	Particles distinguishable in classical statistics. Unification of matter.

Figure 1.6: The QP curriculum structured using the DC approach by Weissman et al. 2022.

The authors underscore that one of the added values of this structure, making it particularly meaningful for learning, is the importance given to the periphery. They stress the importance of comparing QP elements with classical mechanics items, as *the absence of a comparison deprives the nucleus of its status, principles, and consequently, phenomena become indistinguishable.* Moreover, they claim that the DC-structure is useful for teaching aspects of the "Nature of Science" (NOS). NOS plays a pivotal role in the learning process of QP, because QP challenges conventional worldviews and entails a mode of reasoning markedly distinct from everyday experience. Specific NOS elements emerging during the study of Quantum Physics include, for example, the relationship between theory and experiment, the role of models, and the existence of different interpretations (Stadermann and Goedhart 2021). However, the authors pointed out that experts found it challenging to define a core nucleus of Quantum Physics. They attributed it to the lack of an agreed-upon ontology for Quantum Physics despite its unquestionable predictive power. This point, its consequences for pedagogy, ant its relationship to NOS aspects, are discussed in further detail in Chapter 2.

1.4.2 Theoretical-Experimental Dimensions

Another possible clustering emerged from a Delphi study conducted by Krijtenburg-Lewerissa et al. 2019, where 48 experts were surveyed to identify the key topics deemed essential for teaching in secondary school. These topics were organized into three main dimensions:

1. **Concepts:** The fundamental theoretical underpinnings of the theory.

2. **Experiments:** The most important experiments and phenomena that showcase and explain the concepts.

3. **Applications:** The main applications of the theory in technology and society.

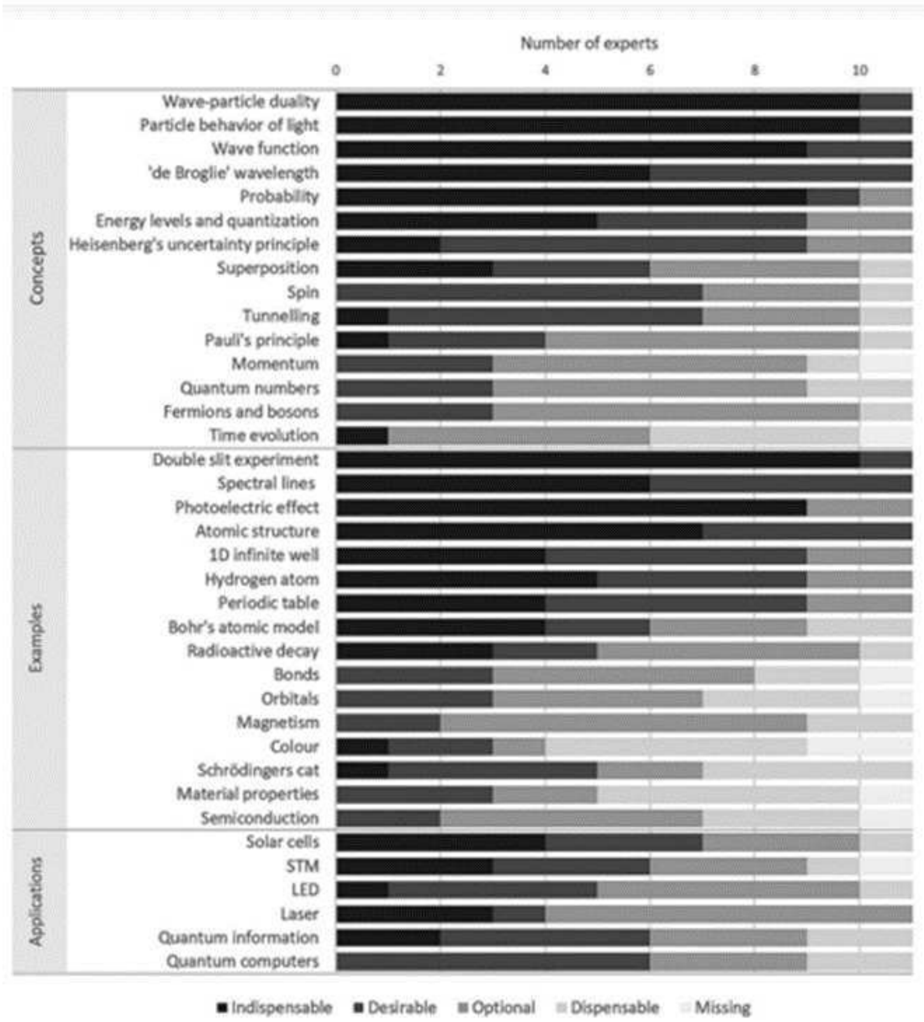

Figure 1.7: The number of experts who considered each topic indispensable, desirable, optional, or dispensable in the third round of the Delphi study in Krijtenburg-Lewerissa et al. 2019.

Fig. (1.7) shows the full list of topics identified from the study, categorized according to these dimensions, along with the number of experts who considered each topic "Indispensable", "Desirable", "Optional", or "Dispensable". We can see that the majority of the experts considered the following topics essential:

1. Duality: The wave-particle duality, the particle behavior of light, de Broglie wavelength, Heisenberg's uncertainty principle, the double-slit experiment, and the photoelectric effect.

2. Wave functions: The wave function, probability, and the 1D potential well.

3. Atoms: Energy levels, quantization, atomic structure, spectral lines, the hydrogen atom, and the periodic table.

1.5 The Questionnaire from the Universities of Trento and Pavia

Based on this literature background, and particularly moving from Krijtenburg-Lewerissa et al. 2019, researchers at the universities of Trento and Pavia (Onorato, Di Mauro, and Malgieri 2024) designed a survey that they submitted to a pool of Italian experts (university professors and post-docs). After collecting data from 17 interviews, they constructed a closed-response questionnaire and collected 31 more responses.

The questionnaire aimed at investigating the following research questions: whether teaching QP at pre-university level is appropriate and why; what topics should be prioritized in QP instruction; and how QP should be taught. Specifically, it focussed on the quasi-historical approach typically followed in Italian high schools and on some controversial aspects of QP teaching. Here we present the findings from the first two research questions, while the remaining ones are discussed in Chapter 2.

Regarding the reasons for teaching QP at the pre-university level, while experts generally agreed on its importance in high school education, their opinions varied on the motivations. While there was agreement of the cultural significance of QP, the consensus regarding its technological applications and its role in countering misinformation was smaller. This result represents a first discrepancy with Krijtenburg-Lewerissa et al. 2019, where QP applications were considered a fundamental dimension.

Concerning the topics to be prioritized, the authors identified a list of QP topics and presented them to the experts, asking them to assess the importance of each topic on a Likert scale from 1 to 5. The methods used to analyze the data will be described in detail in Chapter 3. Here, we briefly introduce the statistical measures utilized to classify the results: the mean score on the 1-5 Likert scale (Mean); the Level of Agreement (LoA), i.e. the sum of percentages of answers "4" and "5", considered "good" for values higher than 70%; and the Consensus (Cns), quantifying the "concentration" around the mean value, considered "good" for $Cns \geq 0.7$.

The results are shown in Figs. (1.8), where values considered "good" according to the above-mentions measures and thresholds are highlighted.

A comparison between the results of Krijtenburg-Lewerissa et al. 2019 and Onorato, Di Mauro, and Malgieri 2024 is displayed in Fig. 1.9, employing the same categorization as in Krijtenburg-Lewerissa et al. 2019. The comparison highlights that, in the Italian context, experts predominantly agreed on elements of Old Quantum Physics, consistent with the typical teaching approach to QP in Italian high schools.

These results prompted further investigation into these issues, extending the survey to a larger number of experts and including high school teachers in the research, given the extensive movement within the PER community to innovate QP teaching in secondary schools.

Concepts	Average	Cns	LoA %	Experiments	Average	Cns	LoA %
Atomic energy levels and quantization	**4.5**	**0.7**	**90**	**Photoelectric effect**	**4.1**	**0.7**	**74**
Particle behaviour of light	**4.1**	**0.7**	**81**	**Double slit experiment**	**3.9**	**0.6**	**71**
Heisenberg's uncertainty principle	**4.1**	**0.8**	**83**	**Spectral lines**	**3.7**	**0.5**	**70**
Probability	**4.1**	**0.7**	**77**	Black body radiation	3.6	0.6	58
Superposition	**3.8**	**0.6**	**70**	Radioactive decay	3.4	0.5	50
Wave–particle duality	**3.7**	**0.5**	**70**	Compton scattering	3.2	0.5	50
Quantum measurement	3.6	0.6	53	Schrödinger's cat	3.0	0.6	60
Quantum state	3.5	0.6	53	Specific heat of solids	2.9	0.6	44
Entanglement	3.4	0.6	50	Harmonic oscillator	2.9	0.5	56
De Broglie wavelength	3.4	0.7	45	1D infinite potential well	2.8	0.6	50
Wave function	3.3	0.6	53	**Applications**	**Average**	**Cns**	**LoA %**
Pauli principle	3.3	0.6	45	Lasers	2.9	0.6	32
Tunnelling	3.3	0.6	45	Semiconductors	2.8	0.7	23
Spin	2.9	0.6	50	Solar cells	2.7	0.6	27
Incompatible observables	2.9	0.6	45	LEDs	2.7	0.5	29
Fermions/bosons	2.9	0.6	50	Quantum information	2.7	0.5	32
Time evolution	2.1	0.7	43	Quantum computers	2.6	0.5	26

Figure 1.8: Concepts, Experiments and Applications of QP evaluated by experts using a Likert scale (1-5), using Mean, Level of Agreement (*LoA*) and Consensus (*Cns*) as statistical measures. The first six topics, highlighted in the figure, were considered relevant by at least 70%(*LoA*) of the experts.

TOPICS	Krijtenburg-Lewerissa et al. (2019)	Onorato, Di Mauro e Malgieri (2024)
CONCEPTS	Wave-particle duality Particle behavior of light Wave function* de Broglie wavelength* Probability Energy levels and quantization Heisenberg's uncertainty principle	Atomic energy levels and quantization Particle behaviour of light Heisenberg's uncertainty principle Probability Superposition Wave–particle duality
EXPERIMENTS	Double slit experiment Spectral lines Photoelectric effect Atomic Structure 1D infinite well Hydrogen atom Periodic table	Photoelectric effect Double slit experiment Spectral lines
APPLICATIONS	\	\

Figure 1.9: Comparison between Krijtenburg-Lewerissa et al. 2019 and Onorato, Di Mauro, and Malgieri 2024. The topics emerged as most relevant accordint to the measures employed in each paper are reported. Topics with (*) were included in both surveys but did not emerge as relevant in Onorato, Di Mauro, and Malgieri 2024; topics in gray were not included in the initial list of Onorato, Di Mauro, and Malgieri 2024.

Chapter 2

Approaches to QP teaching in secondary school

In this chapter, we present an overview of the various facets and approaches to teaching Quantum Physics (QP) in high school. We start by introducing the most relevant teaching approaches and proposals that have been presented in Physics Education Research literature over the past 20 years. We then discuss the role of the history of science in QP teaching and its relationship with the quasi-historical approach used in Italian high schools. We then broaden the discussion to include aspects related to the Nature of Science (NOS), which, in the context of Quantum Physics teaching, leads to the consideration of “controversial” aspects such as the nature of photons, wave-particle duality, the complementarity principle, the Heisenberg uncertainty principle, the double-slit experiment, atomic models, and interpretations of Quantum Physics.

2.1 Quantum Physics in Physics Education Research

In the first 20 years of the 21st century, Physics Education Research on QP education has seen significant growth, fueled by the scientific community’s increased interest on the topic. Some recent reviews summarized different aspects of QP education tackled in this literature. For example, the review by Krijtenburg-Lewerissa et al. 2019 provided a comprehensive overview of students’ learning difficulties, test instruments, and teaching strategies on quantum physics, focusing on secondary and lower secondary levels. Singh and Marshman 2015 offered a review of undergraduate students’ typical "misconceptions".

A different type of review was conducted by Bitzenbauer 2021 to explore *the output of the scientific community in the field of quantum physics education research from an overarching, namely bibliometric, perspective for the period from 2000 to 2021.* Their findings are presented in the top half of Fig. (2.1), with the graphs outlining co-authorship networks that correspond to different lines of research (and, often, different teaching approaches) within Quantum Physics Education Research (QPER). Also, Fig. (2.1), in the bottom half, reports the outcomes of an article keyword analysis on a time scale ranging from 2011 to 2016, allowing us to appreciate the movement towards new elements of research. Specifically, whereas in a first phase research focused on the reconstruction of QP topics for education, the latest research focuses on classroom implementations, surveys, development of instruments, and topics related to quantum technologies.

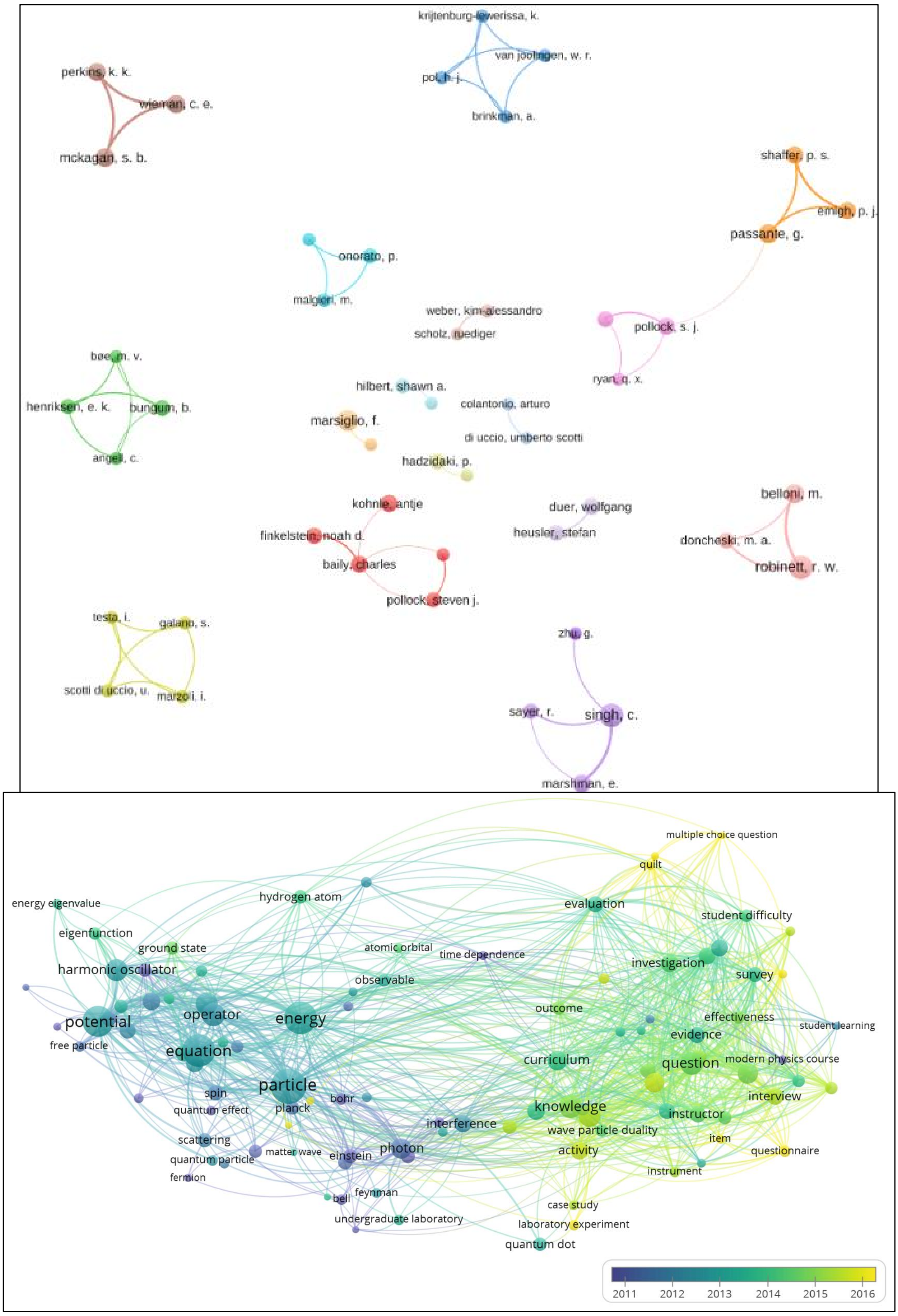

Figure 2.1: Top: *Co-authorship network focusing on authors of QPER articles from 2000 to 2021. Only authors with at least three publications on QP education have been included (126 authors).* Bottom: *Overlay visualisation of the co-word analysis results. The time scale only ranges from 2011 to 2016, as the overlay visualisation is based on the average publication year of the articles in which a specific term appeared.* (Bitzenbauer 2021)

2.1.1 Teaching Approaches

There are various approaches and methods developed in the literature to innovate QP teaching and overcome the typical difficulties faced by secondary school students. Below we present a summary of the main ones.

The Spin First/Qubit/Two-level Systems Approach

This approach utilizes the two-level system to explain quantum phenomena, using 2x2 Pauli matrices and the concept of spin. The advantages include *a concrete and robust experimental foundation, the inherently quantum mechanical nature of spin of a particle, and limited (perhaps simpler) mathematical skill requirements related to discrete bases* (Sadaghiani 2016).

The "spin first" approach can be combined with the polarization analogy because *polarization phenomena may not be the prime example to emphasize the fundamental differences between classical and quantum physics (that may be the double-slit experiment); however, it may serve as yet another case in which to derive and discuss these differences.* [...] *This can be done even without a deep understanding of the concept of interference (as is required for the double-slit).* (Aehle, Scheiger, and Cartarius 2022).

Topics for which a teaching sequence was developed in QPER literature include: the EPR experiment (Pospiech 1999); uncertainty (Pospiech 2000; Michelini, Santi, Stefanel, et al. 2014; Michelini and Stefanel 2021; Aehle, Scheiger, and Cartarius 2022); the Dirac formalism (Michelini, Ragazzon, et al. 2000; Pospiech et al. 2021); wave functions, probability and superposition (Manogue et al. 2012); quantum experiments with two-level system (Kohnle, Bozhinova, et al. 2013); and qubits (Dür and Heusler 2014; Bungum and Selstø 2022).

The Path Integral Approach

This approach, developed in the Italian context, follows the same idea as Feynman's path integral approach using the propagator (Feynman 2006). Initially developed for the university level, this approach was later adapted for high school education in Malgieri 2016 and Malgieri, Onorato, and De Ambrosis 2015.
The method can be distinguished into two different approaches depending on whether the wave function has time dependency or not (Malgieri and Onorato 2022): *In both the following expositions of the time-dependent and time-independent approaches, the concept of action is used. However, secondary school students are rarely exposed to either the full or abbreviated action in the study of classical mechanics. Typically, in both kinds of approaches a rule is given for computing the phase of path amplitudes, and then, if desired, the concept of action is introduced, and the principles of stationary action are derived, after recovering the classical from quantum behavior (correspondence principle) in the short wavelength limit.*

The Formal-Analogical Approach

This approach uses certain systems from classical physics that can be assumed as analogues of quantum systems due to some of their properties. To avoid giving students the impression of a complete continuity from classical to quantum mechanics, this approach must be complemented with an in-depth analysis of the epistemological crisis of classical mechanics in the early 20th century.

Examples of classical-quantum analogies for which a teaching sequence has been developed include:

- The Standing Waves approach: typically, oscillating strings/membranes or linearly coupled oscillators are considered, and the analogy is drawn between normal modes and quantum eigenstates. The very straightforward treatment of linearity and superposition is the strongest point in favor of this approach. This approach has been experimented also in the context of initial teacher education, obtaining promising results particularly with teachers with a degree in mathematics (Malgieri 2016), which is a typical situation in the Italian context. Specific examples within this approach are the "particle in a box" model (Hoekzema et al. 2007) or the analogy between QP and the physics of musical instruments (Andreotti and Frans 2022).

- The Electronium approach: this approach starts from the assumption that the electronic cloud can be seen as a continuous fluid. This is explained in Niedderer, Bethge, and Cassens 1990 and analyzed and tested, for example, in Budde et al. 2002a and Budde et al. 2002b, with encouraging results.

The Fields Theory Approach

This approach introduces QP directly from the concept of "field", linking it with Quantum Field Theory (QFT) but without using its mathematical formalism which is not suitable for the high school level (Hobson 2005).

In this approach, quantum particles are treated as fields: *Photons, quarks, electrons, and atoms are all quanta of various continuous space filling fields. More precisely, they are quantized excitations of the vibrations of fields. Although excitations belong to the entire field, they must interact locally; they have energy and momentum so they qualify as particles, but of a very non-Newtonian sort. Because they are excitations of the entire field, they have no individual identity and can be created and destroyed. The basic physical entity is the underlying field.*

Regarding the particle-like behavior, *there are no particles but only particle-like phenomena caused by field quantization.* [...] *But quanta are not particles; they are excitations of spatially unbounded fields. Photons and electrons, along with atoms, molecules, and apples, are ultimately disturbances in a few universal fields.* (Hobson 2013)

An example of a curriculum in secondary school that uses this approach is provided in Bitzenbauer and Meyn 2020.

The Multimedia Approach

Rather than a self-standing approach, this is a tool that can be integrated within other approaches. It is based on the Multimedia Learning Theory (Mayer 2005) which is also referred to as the Cognitive-Affective Theory of Learning with Media (CATLM), which operates on the following principles (Mayer 2005; Moreno and Mayer 2007):

1. *Multimedia principle*: people learn more deeply from words and pictures than from words alone;

2. *Dual channels*: humans possess separate channels for processing visual and auditory information, and information can be categorized according on different "modes" (e.g. the representation mode; the sensory mode);

3. *Limited capacity*: humans are limited in the amount of information they can process in each channel at one time;

4. *Active processing*: humans engage in active learning by attending to relevant incoming information, organizing information into coherent mental representations, and integrating mental representations with prior knowledge;

5. *Dynamic long-term memory*: long-term memory consists of a dynamic, evolving structure;

6. *Motivation*: motivational factors mediate learning by increasing or decreasing cognitive engagement;

7. *Meta-cognition*: meta-cognitive factors mediate learning by regulating cognitive processing and affect;

8. *Prior Knowledge Differences*: differences in learners' prior knowledge and abilities may affect how much is learned with specific media.

In the context of QP teaching, the main multimedia tools are Quantum Games and videos/simulations. A *game* (Foti et al. 2021) is *made by a goal, a set of rules, a feedback system, and voluntary participation. The goal sets the players' purpose; the rules represent a set of opportunities that can be designed to foster creative and strategic thinking; the feedback system reinforces players' motivations; and voluntary participation preserves players' safety independently of whether they decide to leave or keep up with the game, which in turn ensures an enjoyable experience and builds up on motivation.* A *Quantum Game* (Piispanen et al. 2022) is a game the rules of which are based on quantum principles such as superposition, entanglement, and the collapse of the wave function.

Some Quantum Games discussed in the literature are Qcards (Kopf et al. 2023), Quantum TiqTaqToe (Goff 2006; M. Chiofalo et al. 2022), Quantum Chess (Cantwell 2019), Quantum Minesweepers (M. Gordon and G. Gordon 2010), Cat and Hounds (M. Gordon and G. Gordon 2012), Minecraft extension qCraft (Enk 2015), Encrypt Me (López-Incera, Hartmann, and Dür 2020), Particle in a box (Hoekzema et al. 2007).

In evaluating the educational value of these games, it is important to keep in mind that *One doesn't need to understand classical mechanics to play baseball, and playing baseball will not teach one classical mechanics. However, playing baseball may help to more intuitively understand how things move. Games can provide an environment in which people can experience the strange behavior of the quantum world in a fun and mentally engaging way* (Cantwell 2019).

Regarding simulations, examples of activities or curricula that include them were developed by Kohnle, Bozhinova, et al. 2013, Bungum, Henriksen, et al. 2015; Carvalho et al. 2023 on wave-particle duality and the complementarity principle simulations; Kohnle, Baily, et al. 2015 (QuVis project, based on two-level systems); Marshman and Singh 2016 (QuILT simulation, based on quantum optics phenomena with single photons); and simulations on atomic models (McKagan, Perkins, and Wieman 2008).

2.1.2 The Mathematical Formalism of QP

The mathematical formalism of Quantum Physics is often regarded as the main obstacle to moving beyond the old physics of quanta at the secondary school level. Difficulties with the mathematical formalism have been observed even at the university level (e.g. Zuccarini, Michelini, et al. 2015; Siddiqui and Singh 2017a). The reasons for this difficulty was outlined by Johnston, Crawford, and Fletcher 1998: *The subject is shrouded in a highly mathematical formalism, and, though some textbook authors have sought to simplify the demands this makes on students, there is not yet consensus about how it might be taught less abstractly. Second, the subject is in a state of flux — questions of how the formalism should be interpreted are still discussed in the technical literature.*

Among the approaches cited above, the qubit/spin-first approach features a specific reflection on mathematics, choosing 2D vectors and matrices as an accessible mathematical tool to teach QP beyond the old physics of quanta. Through this relatively simple formalism, it is possible to approach QP formally without excessive mathematical difficulties, using the Dirac notation (Serbin and Wawro 2022; Hu, Li, and Singh 2023).

Within this approach, Pospiech et al. 2021 proposed that the reduction of complexity should be coupled with a meaningful use of visualizations and representations of two-states systems. The algebraic or formal notation is interpreted as one of the possible representations of the system (the one with the highest level of abstractness), and students are trained in switching from one representation to another, or using multiple representations at the same time. Different representations can be best suited to support the understanding of different quantum phenomena. For example, superposition and probability can be taught using the Bloch sphere (a circle for two-dimensional systems) combined with the algebraic representation, Fig. 2.2); time evolution and the measurement process can benefit from using the Bloch sphere, the algebraic representation, and geometric analogies such as animated arrows; and uncertainty can be supported using thought experiments represented with pictorial-symbolic representations.

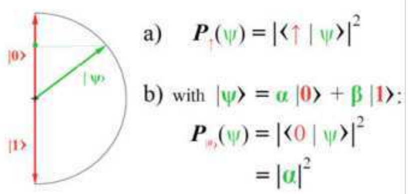

Figure 2.2: Representations of superposition of states and a measurement process using the Bloch circle and the algebraic representation enhanced by the use of colors in Pospiech et al. 2021.

2.2 History and Quasi-history in QP Teaching

The cultural and pedagogical importance of integrating elements of the history of science (HOS) into the physics curriculum is recognized by the majority of experts (e.g. Bungum, Henriksen, et al. 2015 and the literature cited within). According to Monk and Osborne 1997 the role of HOS in the scientific curriculum is mainly epistemological, answering the question "How do we know?": *The historical treatment of scientific knowledge can* [...] *provide a rich repertoire of alternative interpretations of evidence, forcing students to consider critically the status and claims of current scientific thinking.* Similarly, Klopfer 1969 states that *Familiarity with political history does enrich an understanding of contemporary world events and issues. Likewise, the history of science can help students to attain a better understanding of science.*

A linear view of HOS, as is often presented, is generally recognized as naive, and a more accurate non-linear perspective is favored. For example, Kuhn 1997 proposed the model depicted in Fig. (2.3) to explain scientific revolutions. This model portrays the evolution of science as a spiraling endeavor, progressing through scientific revolutions that replace old paradigms with new ones through debates and experiments.

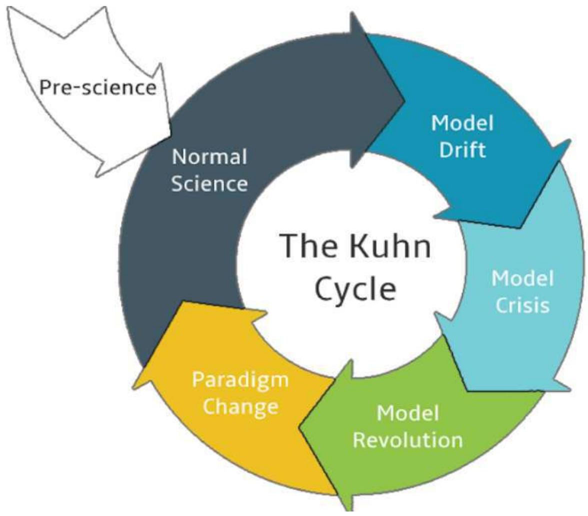

Figure 2.3: Kuhn's cycle that describes the Scientific Revolution (Khettab 2020).

History versus Quasi-History

Although the traditional teaching of QP in Italian high schools might, at first glance, appear to acknowledge the importance of HOS, it is actually more representative of a *Quasi-Historical* approach. The difference between the Historical and Quasi-Historical approaches is described in Whitaker 1979a and Whitaker 1979b:

1. Logical/Quasi-Historical: The aim is to provide scientific facts, with the history serving solely as a framework within which these facts fit easily, appear to 'make sense', and can be remembered for assessment purposes. This approach results from a rather misguided desire for order and logic, serving as a convenience in teaching and learning.

2. Historical: This approach presents a more accurate chronological order of events,

emphasizing the contributions of many scientists to the development of modern science, rather than attributing all progress to a few individuals and isolated facts.

The problem with the first approach is that sometimes the logical order differs significantly from the historical one. There is a risk of drifting into pseudo-history when teachers attempt to fit facts and scientists into the logical framework. As Whitaker says:

The quasi-history avoids the description of the crucial social elements that play a role in the discoveries [...]. *It presents the scientist not as a hard worker, using all the insight and experience he possesses to solve a problem, but either as a solver of trivia or as a superman.* [...] *Teaching a 'logical' course, [the teacher] must be watchful for these tendencies to quasi-history and should be prepared to counteract them. Teachers should make great efforts to present physics as a living discipline, rather than as a completed structure of knowledge.* (Whitaker 1979b)

In the specific case of Quantum Physics, its development has been historically very long and complex. Often, in high school textbooks, the importance given to certain facts is significantly different from the actual historical account: a notable case regards the photoelectric effect.

Many secondary school textbooks use the photoelectric effect to illustrate the concept of photon, supporting the idea of light quantization. Historically, the sequence of events that led to the acceptance of the quantization of light can be summarized according to Klassen 2011:

- Second half of XIX century: the discovery of the photoelectric effect and its characterization and initial explanation;
- 1905: Einstein's paper on the light quantum and its explanation for the photoelectric effect;
- 1916: Millikan's experimental verification of Einstein's photoelectric equation, despite not accepting Einstein's hypothesis;
- 1923: Compton's measurements and his theoretical explanation, which ultimately led to the acceptance of Einstein's hypothesis.

In many textbooks, Millikan's experiment is presented as confirming Einstein's theory of the photoelectric effect and thus the definition of the photon, although this is a quasi-historical representation. In fact, while Einstein's formula was accepted after some years as a phenomenological formula, the underlying theory was not initially accepted because other classical mechanics theories derived the same equation without abandoning Maxwell's theory (Kragh 1992). Instead, the experiment that confirmed Einstein's theory of light quanta was Compton's one: *Einstein used the term "light quantum" in his 1905 paper and the term "photon" was only invented in 1926 by the chemist Gilbert Lewis and used in his presentation of an incorrect theory of light quanta in which he proposed that photons were conserved and could be neither created or destroyed. The term was immediately adopted by the physics community when Compton began to use it in 1927 [...] Compton's experiment and his theory to explain it served to provide convincing support for Einstein's photon hypothesis, and physicists generally accepted it at that time.* (Klassen 2011)

Moving from this example, Stadermann and Goedhart 2020 explicitly critiques the use of quasi-history:

Most textbooks oversimplify the actual course of history by presenting the photoelectric effect as an unsolved problem that was brilliantly explained by Einstein and consequently led to the introduction and acceptance of the new quantum theory. Science education researchers identified this praxis as a quasi-historical approach in which historical experiments and discoveries are presented as if the chronological order of evidence of failures of classical physics made the development of a new theory necessary. Historically, the development of ideas in science is much more complicated. In particular, the early years of QP were characterized by controversies, presuppositions, contradictions, and inconsistencies. Leaving away all these struggles seems to be a justified simplification in textbooks, but on the other hand, it is a deprivation of giving students more insight into NOS [...] *Curriculum developers should be aware of the disadvantages of a quasi-historical introduction to QP. They might consider a genuinely historical approach which offers many chances for NOS teaching or a different introduction of QP, for example via two-level systems.*

Some scholars, however, have spoken in favour of a quasi-historical approach. For example, Kragh 1992 himself argued that a true historical account can be very long and beyond the scope of secondary school instruction. Therefore, a quasi-historical approach can be useful, provided that the author clearly expresses that it is not historically accurate.

Finally, other researchers have questioned the emphasis placed on both historical and quasi-historical approaches in QP teaching at all. Greca and Freire 2014 argued that there is no need for students to go through the same difficult efforts of the past and that QP should be taught in the same manner as other physics topics:

The inclusion of historical elements that incorporate cases from old quantum physics should be avoided, [...] *partly because the most important steps in the early construction of quantum theory do not show the specific quantum features in a clear cut manner and some of which are very complex for students on introductory courses to understand. A similar strategy is often employed in the teaching of classical mechanics.*

The educational value of the quasi-historical approach currently adopted in Italian high schools is therefore still an open question.

2.3 The Nature of Science in QP Teaching

The relevance of the History of Science and its epistemological role have been included in the broader discourse about the "Nature of Science". There are many definitions of NOS, although its conception is always evolving due to continuously changing socio-cultural aspects. For example, it has been defined as:

A fertile hybrid arena which blends aspects of various social studies of science including the history, sociology, and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of what science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors. (McComas, Clough, and Almazroa 2002)

The epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development. (Lederman et al. 2002)

A spectrum of ideas that describe the development and status of scientific knowledge; it characterizes science as a human endeavor and includes epistemological, philosophical,and societal aspects. (Stadermann, Berg, and Goedhart 2021)

The advantages of integrating NOS in the teaching of science have been pointed out by many authors. For example, McComas, Clough, and Almazroa 2002 showed that NOS enhances learning and increases interest in scientific subject, highlighting science as *a great adventure* rather than just memorizing the outcomes of the process. Stadermann, Berg, and Goedhart 2019 underscored the value of NOS in countering misinformation, stating that *understanding how science works is a prerequisite for distinguishing between scientific and nonscientific claims.*

Driver et al. 1996 proposed a categorization for the instructional goals that NOS can help to achieve:

1. Utilitarian argument: an understanding of NOS is necessary to make sense of science and manage the technological objects and processes;
2. Democratic argument: an understanding of NOS is necessary to make sense of socio-scientific issues and participate in the decision-making process;
3. Cultural argument: an understanding of NOS is necessary in order to appreciate science as a major element of contemporary culture;
4. Moral argument: learning about the NOS can help develop awareness of the norms of the scientific community, embodying moral commitments of general value;
5. Science learning argument: an understanding of NOS supports successful learning of science content.

In the context of QP teaching, Stadermann and Goedhart 2020 analyzed the QP curricula of 15 European countries with a lens on NOS features (Fig. (2.4). Among these features, only "Methodology of science" was explicitly found in all 15 countries; the "Role of scientific models", "Tentativeness of science", "Controversies in science", and "History of science", were found in 12 countries, including Italy; and "Creativity in science" was found only in 6 countries and not in Italy. QP topics that were mostly related to NOS aspects were atomic models, the double-slit experiment, and QP interpretations.

As a synthesis of how the different NOS aspects come into play in QP teaching, Stadermann and Goedhart 2020 state:

For learning QP, students must understand the reasons for the development of models and learn to handle different models in appropriate contexts. After years of physics lessons in which electrons are modelled as negatively charged tiny billiard balls, students might think that they are tiny billiard balls. [...] *However, quantum entities do not have simple, consistent visualisable equivalents in classical physics. For example, in the iconic double-slit experiment, individual electrons are detected on a screen as single dots as if they were miniature billiard balls. Still, the exact place of detection is unpredictable. After repeating the same experiment with many individual electrons in the same setup, an interference pattern builds up. Within familiar school physics, an interference pattern is only plausible for students if electrons are waves. This wave-particle duality is confusing to students because they are not only missing a useful framework to build on but QP* *also seems in contradiction with their idea of what physics is: predictable (deterministic) and universal (physical laws should explain phenomena on all scales).* [...] *In the case of QP, conceptual change not only affects students' understanding of concepts but also their ideas about the nature of physics. Researchers expect that students can more easily change their conceptions from classical to quantum physics if they understand science as a continuously evolving, creative human endeavour influenced by social circumstances and historical contexts. Students who are not aware of such aspects of NOS would expect one "right" explanation for experimental results and, for example, one single correct model for elementary particles; in-commensurable models and interpretations would only confuse them. However, students who understand science as a human endeavour could, for example, appreciate the development of different explanations for experimental results because it helps to develop their own understanding of difficult concepts.*

TABLE I. Aspects of nature of science and history of science in quantum physics.

Code	NOS and history aspects	Example of relevance for QP
N1	Methodology (e.g., experiments and hypothesis)	The methodology used in classical physics (relation between experiment and theory) apply as well in QP. Additionally, thought experiments were an essential means to discuss fundamental concepts in the developing of QP and eventually led to various quantum entanglement experiments.
N2	The role of scientific models	For some situations, it is appropriate to use the model of a wave for quantum objects; in other situations the model of classical particles is more helpful. A model only serves to show some aspects of phenomena. (In QP lessons, students experience different models of light or matter.)
N3	Tentativeness of science	Even though physics can explain many phenomena, the history of physics including QP shows that science is tentative. To the long-held hypothesis that light is a wave, Einstein added the photon hypothesis of light as a possible explanation of the photoelectric effect. This was one of the many steps in a historical paradigm shift which eventually led to the development of QP. The current existence of different interpretations of QP shows that scientists question existing models and interpretations and that this is an ongoing process.
N4	Creativity in science	To invent famous thought experiments scientists had to be creative and only with thinking out-of-the-box new quantum experiments can be developed. Many scientists want to find out if the wave function is more than just a conceptual tool. Therefore, they develop creative interpretations of QP.
N5	Controversies in science	The famous discussions between Bohr and Einstein were important for the development of QP. Currently, there is still discussion about different interpretations of QP. Only in an open atmosphere without dominating ideologies science can freely develop.
N6	History of science	More than in other parts of physics the history of QP is regarded as relevant for education. Historical experiments illustrate why scientists had to change their mechanical world view. (For students, this can give science a more human image and it brings theory to life.)

Figure 2.4: The NOS and HOS features taught in the QP context at the European level.

2.4 Controversial Aspects in QP Teaching

Some Quantum Physics topics have been identified as "controversial" as experts do not agree with each other on what is the best way to treat or introduce them. These aspects are often related to NOS aspects and include: the nature of the photon and wave-particle duality; the complementarity principle; the double-slit experiment and the uncertainty principle; atomic models; and the different interpretations of Quantum Physics.

2.4.1 The Nature of Photon

As mentioned above, the photoelectric effect is often used in textbooks to introduce the idea of photons as the quanta of light. The problems with the quasi-historical representation of the photoelectric effect have been discussed above. As an additional difficulty with this approach, experts have pointed out that the conceptualization of photons evolved in later years, and its current understanding through QED is very different from the historical ones: *The photon of QED is neither distinguishable nor localisable, i.e., it is no 'fuzzy ball'.* [...] *The light quantum hypothesis gained strong acceptance with Compton's explanation of* *his x-ray scattering experiments. But this then accepted light quantum (soon to be called 'photon') was a localised and distinguishable particle still, i.e., should not be confused with the current photon concept either.* [...] *Unfortunately many textbooks introduce Einstein's explanation of the photo-electric effect and Compton's kinematic derivation of the photon wavelength shift as if these explanations fit into the current understanding of quantised radiation.* (Passon and Grebe-Ellis 2017).

For teaching purposes, some authors like Jones 1991 and Stanley 1996 proposed that spontaneous emission, rather than the photoelectric effect, provides the most obvious evidence for the quantization of light. Ireson 2000 proposed using the Franck and Hertz experiment to develop $E = hf$. This further allows the development of line spectra and energy levels in the atom.

Recently, some authors (Ubben et al. 2023) revisited the photon issue by underscoring the role of models. Hubber 2006 emphasized that students' approach to the photon concept evolves from their knowledge of optics and involves an interplay between the wave and corpuscular models of light. While all students employed a wave model to explain diffraction and interference effects, and a particle model to explain the photoelectric effect, there was variation in their preferences for explaining other phenomena.

Körhasan and Miller 2020 identified four different student models, related to the wave-particle duality concept:

1. Quantum Model: coherent and connected knowledge explaining experimental results;
2. Semi-Quantum Model: acknowledges duality only for light or matter, but not for both;
3. Wave Model: acknowledges the wave nature of light and matter but not their particle nature, ignoring some experimental results;
4. In-between Model: hybrid model where light and matter have a mix of waves and particle properties instead of a dual nature.

In particular, the hybrid model explains the results by Hubber 2006 described above.

The value of hybrid models in teaching and learning is a debated topic because, while they leverage students' prior knowledge, they can also present a hurdle for them to progress towards new, more accurate models.

A recent study in the Italian context conducted by Testa et al. 2020 confirmed that students often exhibit a lack of coherence in their frameworks for making sense of QP, which makes it more likely for them to adopt a hybrid model. Moreover, they found that prior "partial" instruction on atomic models (either formal such as in chemistry classes, or informal) can act as a potential source of overconfidence, lowering students' efforts towards a deeper understanding of the new model.

To counter this tendency, authors such as Ireson 2000 and Pospiech 1999 have proposed to treat light as a quantum objects from the beginning, avoiding the use of photons. Lévy-Leblond 2003 explains what is meant by "quantum object" (Fig. 2.5):
Quantum objects are neither waves, nor particles, but are to be described by a specific and novel concept, which certainly deserve a name of its own. Bunge proposed to call them "quantons", building on the common terminology (electrons, photons, nucleons, etc.).

Classical particles are discrete under both aspects; they come in discontinuous counts and are discretely localised. Classical fields are continuous under both aspects; they have continuous amplitudes and continuous spatial extensions. But quantons exhibit the original combination of discreteness in number and continuity in extension and if the discrete character of their number is preponderant and the continuous character of their extension secondary, they can be approximately described as particles and viceversa as waves, and the latter appear most in macroscopic world when there are a lot of quantons, but in the modern quantum experiments, quantons look neither as waves nor as particles, and must be accounted for through their intrinsic and unique conceptualisation.

	Number	**Extension**
Particles	discrete	discrete
Fields	continuous	continuous
Quantons	discrete	continouous

Figure 2.5: Physical entities classification into particles, fields and quantons in Lévy-Leblond 2003.

This description can also help avoid some misinterpretations of QP results, as described by Stadermann and Goedhart 2020, and is linked with the problem of a vocabulary gap between classical physics and quantum physics when explaining the nature of photons (Vuola, Nousiainen, and Koponen 2023). Other authors have addressed the same problem by using the term “wavity” to refer to the characteristic of a quantum object to be simultaneously discrete and continuous (Weissman et al. 2019; Pospiech et al. 2021). The concept of “wavity” was included in the “nucleus” of Quantum Physics by Weissman et al. 2022 in their Discipline-Culture approach.

The "problem" of teaching wave-particle duality is tackled in a very different way within the Field theory approach (Bitzenbauer and Meyn 2020; Bitzenbauer and Meyn 2022), where the definition from QED avoids the concept of wavity (Hobson 2013). Here, the duality feature is understood through follow up experiments, where the particle nature of photons emerges in the sense that they show some particle aspects. For example, the authors propose an interpretation of the double-slit experiment using fields instead of wave-particle duality, viewing it as a situation where the fields are quantized and therefore create particle-like phenomena.

The questionnaire made by Onorato, Di Mauro, and Malgieri 2024 investigated the experts’ opinion about the nature of the photon and the consequences for teaching. Results showed a lack of consensus. One third of respondents agreed that the semi-classical model is incoherent and another third agreed with the above-mentioned objections to the use of photons, but they did not advocate for modifications of the teaching approach based on this disagreement. The remaining third did not align with either of these viewpoints. Additionally, when asked about the necessity for the photon to possess clearly defined momentum and energy, opinions were split, with 35% of the respondents stating that it is not essential and 32% holding the opposite view. The remaining third did not align with either stance.

2.4.2 The Complementarity Principle

The dual nature of light is strictly linked to the complementarity principle, one of the fundamental principle of Quantum Physics. This principle has been formulated in different ways:

Any quantum system possesses at least one pair of properties necessary to describe the system, which cannot be known simultaneously. They are mutually exclusive, in the sense that the observation of one property precludes the observation of the other. The inevitably present pair is the wave/particle pair: a quantum system sometimes manifests wave properties, sometimes particle properties. (Bohr 1928; Introzzi 2010)

Quantum systems would therefore not have an ontological status of their own, but would be determined by the interaction with the experimental apparatus. (Pauli 1950; Introzzi 2010)

Particle (Schrödinger, Born) and wave (Dirac, Jordan, Wigner and Klein) representations of the electron are simply formally different ways of describing the same entity because they are mathematically equivalent with the same empirical results. It would therefore be a wave/particle equivalence deriving from theoretical structures of different but predictively equivalent theoretical structures, which describe the same entity. (Introzzi 2010).

A new, formal formulation of the complementarity principle was introduced by Greenberger and Yasin 1988. They described an experimental apparatus with two paths (double-slit experiment; Mach-Zender interferometer) and defined two parameters:

- V is the visibility of the fringes (representing the wave behaviour);
- P is the prediction of the trajectory of the particle before it passes through the apparatus (representing the particle behaviour).

The two parameters are linked with a formal relationship that expresses the complementarity principle mathematically:

$$P^2 + V^2 \leq 1$$

where the equal accounts for a pure state.

This is a more extended way to describe the principle because in the Bohr formulation, and using the same formalism, a quantum system can have a particle behavior, so $V = 0$ and $P = 1$, or the opposite a wave behavior, $V = 1$ and $P = 0$, but none of the mixed situations.

Another formulation, as proposed by Englert 1996, builds upon the same relationship but introduced different parameters, considering Pauli's emphasis on the experimental apparatus:

$$V_o^2 + D^2 \leq 1$$

where the equal holds if the detector is prepared in a pure state. Here, V_o represents the *a posteriori* visibility and D denotes the "distinguishability", measuring the probability of correctly identifying the path taken (either A or B). These parameters are evaluated *a posteriori* after the interaction between the quantum system and the detector.

In summary, the Greenberger-Yasin formulation, a quantum object is not described as either a wave or a particle but by a mixture of both (Introzzi 2010); the wave-like and particle-like natures can intertwine.

In their questionnaire, Onorato, Di Mauro, and Malgieri 2024 asked the experts about their preferred formulation of the complementarity principle. They presented the following alternative formulations:

1. *[Bohr-Pauli] 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.*

2. *[Greenberger and Yasin] 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.*

However, they found no agreement among experts on which formulation is preferrable. One third of them stated that both are correct, but they preferred the Bohr-Pauli one; another third had a preference for Greenberger-Yasin's; 20% had no preference.

2.4.3 The Double-slit Experiment and Uncertainty Principle

The double-slit experiment is one of the most famous experiments used to introduce Quantum Physics. It illustrates how photons and electrons passing through a double-slit can produce an interference pattern on a screen; however, if observed, they produce only individual collisions, therefore exhibiting particle-like behaviour. Thus, the experiment demonstrates how the wave-like behavior and particle-like behavior depend on the act of measurement. Weissman et al. 2022 included the double-slit experiment as a component of the "body" of Quantum Physics as a discipline-culture; Ünlü Yavas and Kizilcik 2016 underscored the importance of presenting the experiment with both photons and electrons to reinforce understanding of wave-particle duality. Krijtenburg-Lewerissa et al. 2019 identified three modes of student reasoning about the double-slit experiments, categorized as classical, mixed, and quasi-quantistic (Fig. 2.6). They also found that students exhibited fewer incorrect ideas when interpreting the double-slit experiment for photons compared to electrons, as previous conceptions of electrons as particles are more firmly held and therefore more challenging to discard.

	Classical description	Mixed description	Quasiquantum description
Photons or electrons	Electrons or photons are depicted as classical particles [1,4,5,16,20,22–25]	Electrons and photons follow a definite sinusoidal path [16,29,30]	Electrons are smeared clouds of charge [5,24,25]
	Electrons or photons have definite trajectories [1,4,5,16,20,22–25]	Electrons are either a particle or a wave depending on other factors [21,29]	Electrons or photons are waves and particles simultaneously [20,30]
	Light always behaves like a wave [24,25]	Equations of properties of light also apply to electrons [21]	
Double slit experiment	Light has no momentum [1]	There is no relation between momentum and de Broglie wavelength [21,34]	There is no relation between momentum and interference pattern [21,34]
	Photons and electrons deflect at a slit and subsequently move in a straight line [21]	No interference pattern appears with single photons and electrons [24–26]	

Figure 2.6: Categories for atomic models with the different descriptions in Krijtenburg-Lewerissa et al. 2019.

In the field approach, as already mentioned, the interpretation of this experiment is different: *The quantized field for each electron or photon comes simultaneously through* *both slits, spreads over the entire interference pattern, and collapses nonlocally, upon interacting with the screen, into a small (but still spread-out) region of the detecting screen. Field-particle duality exists only in the sense that quantized fields have certain particle-like appearances: quanta are unified bundles of field that carry energy and momentum and thus "hit like particles"; quanta are discrete and thus countable. But quanta are not particles; they are excitations of spatially unbounded fields.* (Hobson 2013)

In the Italian educational context, after the double-slit experiment, textbooks often present the uncertainty principle (see the review of Italian physics textbooks in Perli 2024). A frequent issue in understanding this principle is confusing it with a relationship between statistical uncertainties, arising from our incapacity to make exact measurements. To avoid this problem, it is important to emphasize that this incapacity is not a result of experimental errors but is inherent to the system itself. This distinction can be highlighted by using the term "indeterminacy" instead of "uncertainty", aligning more closely with Heisenberg's concept (Lévy-Leblond 2003; Krijtenburg-Lewerissa et al. 2019). However, merely changing the terminology did not seem to significantly reduce student misinterpretations (Bungum, Henriksen, et al. 2015). Consequently, researchers have been examining the intrinsic learning difficulties associated with the principle and the teaching strategies to mitigate them.

As an example, Pospiech 2000 proposed a new conceptual and mathematical formulation with the help of pictures and representations:

1. Conceptual: describing the photon as existing in a superposition of possibilities for positions and momenta. This idea can be illustrated with a photograph of a moving car, either with sharp contours (defined position) but "hiding" the information on its speed, or with blurred contours, providing information on the car's speed but making it impossible to determine its exact position. The photograph represents the measurement, being the sole source of information, while the car itself remains inaccessible.

2. Mathematical: utilize the pure quantum phenomenon of spin to introduce the concept of uncertainty, leveraging its simple mathematical structure (2×2 Pauli matrices) that allows for direct computation of the uncertainty relation.

Weissman et al. 2022 proposed another formulation of the uncertainty principle as follows: *Heisenberg's uncertainty claims the existence of pairs of physical quantities, such as the position-momentum pair, in which [one observable] being in an eigenstate implies that the mate [the other observable] is in a state of superposition.* They suggest depicting this superposition through experimental and pictorial representations, like the Bloch circle introduced by Pospiech et al. 2021 (Fig. 2.2).

In textbooks, one of the most common formulation of the uncertainty principle employs the single-slit experiment as an example. Narrowing the slit width makes the width of the fringes larger, and vice versa; therefore, determining the position of a photon by forcing it through a narrow slit introduces uncertainty about its momentum, generating the typical interference pattern (Fig. 2.7).

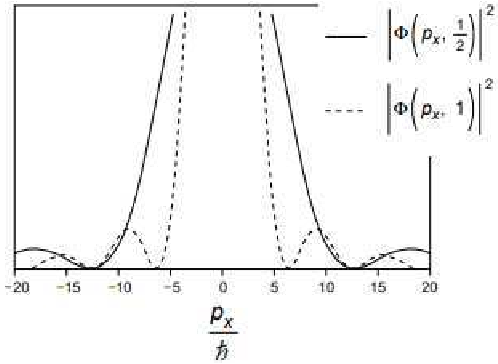

Figure 2.7: Momentum distribution at the slit screen for slit widths of $\frac{a_0}{2}$ and a_0 ($a_0 = 52.9$ pm) in Rioux 2005.

However, another common alternative presentation of the uncertainty principle is the so-called "Heisenberg's microscope", which uses a thought experiment, with only electrons, described in Heisenberg's *Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik* (Heisenberg 1927):

There is no shortage of such experiments, which in principle allow the 'position of the electron' to be determined with arbitrary precision, e.g.: one illuminates the electron and observes it under a microscope. The highest achievable precision in determining the position in this case is essentially given by the wavelength of the light used. Thus, in principle, one could build a γ-ray microscope and, with this, carry out the position determination as accurately as desired. However, there is a significant side effect in this determination: the Compton effect. Every observation of the scattered light coming from the electron requires a photoelectric effect [*the use of a detector*] *(in the eye, in the photographic plate, in the photo cell), which can also be interpreted as a light quantum encountering the electron, being reflected or scattered on it, and then scattered again through the microscope lenses to finally cause the photoelectric effect. At the moment of position determination, i.e., the moment when the light quantum is scattered by the electron, the electron changes its momentum discontinuously. This change is bigger the shorter the wavelength of the light used is, that is, the more precise the position determination is. At the moment when the position of the electron is known, its momentum can only be known up to magnitudes corresponding to that discontinuous change; thus, the more precisely the position is determined, the less precisely the momentum is known, and vice versa.* [1]

[1] Original German text: An solchen Experimenten, die im Prinzip den „Ort des Elektrons" sogar beliebig genau zu bestimmen gestatten, ist kein Mangel, z. B.: Man beleuchte das Elektron und betrachte es unter einem Mikroskop. Die höchste erreichbare Genauigkeit der Ortsbestimmung ist hier im wesentlichen durch die Wellenlänge des benutzten Lichtes gegeben. Man wird aber im Prinzip etwa ein γ-Strahl-Mikroskop bauen und mit diesem die Ortsbestimmung so genau durchführen können, wie man will. Es ist indessen bei dieser Bestimmung ein Nebenumstand wesentlich: der Comptoneffekt. Jede Beobachtung des vom Elektron kommenden Streulichtes setzt einen lichtelektrischen Effekt (im Auge, auf der photographischen Platte, in der Photozelle) voraus, kann also auch so gedeutet werden, daß ein Lichtquant das Elektron trifft, an diesem reflektiert oder abgelenkt wird und dann durch die Linsen des Mikroskops nochmal abgelenkt den Photoeffekt auslöst. Im Augenblick der Ortsbestimmung, also dem Augenblick, in dem das Lichtquant vom Elektron abgelenkt wird, verändert das Elektron seinen Impuls unstetig. Diese Änderung ist um so größer, je kleiner die Wellenlänge des benutzten Lichtes, d. h. je genauer die Ortsbestimmung ist. In dem Moment, in dem der Ort des Elektrons bekannt ist, kann daher sein Impuls nur bis auf Größen, die jener unstetigen Änderung entsprechen, bekannt sein; also je genauer der Ort bestimmt ist, desto ungenauer ist der Impuls bekannt und umgekehrt.

In the questionnaire made by Onorato, Di Mauro, and Malgieri 2024, experts were asked to choose which of the two thought experiments (single-slit experiment or Heisenberg's microscope) they preferred to explain the uncertainty principle. The majority of experts preferred the single-slit experiment over Heisenberg's microscope, as the latter could lead to more misinterpretations. Similar objections to the use of Heisenberg's microscope can be found in the literature: *[Heisenberg's microscope] could be broadly placed among the so-called disturbance interpretations of QM. For instance, the electron in the gamma microscope was supposed to exist in a perfectly well-defined state; this state could not, however, be determined exactly, because the photon–electron collision disturbed the electron in such a discontinuous (uncontrollable) way that its initial state parameters (before it was disturbed) could be measured only within the limits imposed by uncertainty relations* (Hadzidaki 2008).

2.4.4 Atomic Models

Atomic models are an important component of both physics and chemistry curricula and are introduced to students even before they engage in QP. The main atomic models taught in high school are:

1. **Thomson's Model:** developed after the discovery of the electron, this model is also known as the plum-pudding model, where the atom *consist of a number of negatively electrified corpuscles enclosed in a sphere of uniform positive electrification* (Thomson 1904);

2. **Planetary Models:** including Rutherford's model (Rutherford 1911) and Bohr's model (Bohr 1913) that introduced quantized orbits and energies[2];

3. **Quantum Mechanical Models:** these models involve orbitals instead of planetary orbits and incorporate the main QP elements such as wave-particle duality, wave functions, the uncertainty principle, spin and Pauli's exclusion principle.

QPER experts have been debating the educational value of Bohr's model, which is often emphasized in high school. Some authors, such as Ireson 1999, suggested that the treatment of Bohr's model in the description of the hydrogen atom should be avoided to prevent reinforcing the appealing but incorrect idea that electrons have well-defined planetary orbits. Others hold an opposing view. According to McKagan, Perkins, and Wieman 2008, for example, *[...] rather than making exclusive use of one expert model, real experts are able to use multiple models simultaneously, recognizing the strengths and limitations of each one and applying them appropriately.* Therefore, they advocate for introducing different atomic models, comparing them, and discussing their domains of validity. In another research (Siddiqui and Singh 2017b) a survey done with 12 university faculty members on undergraduate-level quantum mechanics teaching revealed that they were divided into two groups, one opposed to teaching simplified models, and the other one favourable. The latter group thought that simplified models can be used to introduce

[2] It has been pointed out that this is a simplistic way of referring to these models, which overlooks the contribution of other scientists working on similar ideas (e.g. Larmor 1897, Nagaoka 1904,...)

certain aspects of QP (e.g., quantization of energies) even though they miss certain other aspects. All experts, however, underscore the importance of introducing quantized energies in order to solve the issue of stability inherent in classical planetary models (Taber 2002).

Research by Krijtenburg-Lewerissa et al. 2019, following the idea of comparing different atomic models, revealed that students struggle with more advanced models after learning Bohr's model due to their misconception of a model as a true description of reality rather than an approximation. They proposed that the concept of spin could be useful for comparing the different atomic models (fig. 2.8).

Atomic models	Description	Spin
Quantistic planetary model	e- into orbits with constant radius	Seen as a rotation
Transitional model	e- into orbits sinusoidal	Seen as a rotation
Probabilistic model (visual conceptual model)	e- position is probabilistic based on probability distribution	Seen as a quantistic property of the e-
Probabilistic model (mathematical model)	e- position is probabilistic based on mathematical description	Seen as a quantistic property of the e-

Figure 2.8: Categories for atomic models with relative spin description in Krijtenburg-Lewerissa et al. 2019.

2.4.5 Interpretations of Quantum Physics

Since the birth of Quantum Physics, scientists have attempted to make sense of the theory's mathematical formalism and experimental results by proposing different "interpretations". The most famous one is the Copenhagen interpretation, detailed in Baily and Finkelstein 2010 (citing Cramer 1986) as comprising the following five principles/concepts:

- Heisenberg's uncertainty principle (including the concept of wave-particle duality);
- Born's statistical interpretation (including the meaning of the state vector given by the probability law $P = \psi \cdot \psi$;
- Bohr's concept of complementarity (encompassing the complementary nature of wave-particle duality; characterizes the uncertainty principle as an intrinsic property of nature rather than a peculiarity of the measurement process);
- Heisenberg's identification of the state vector as "knowledge of the system" (utilizing this concept to explain the collapse of the state vector);
- Heisenberg's "positivism" (declining to discuss "meaning or "reality", focusing interpretive discussions exclusively on observables).

The addition, subtraction or modification of one or more of these principles can lead to alternative interpretations.

According to Baily and Finkelstein 2010 and Stadermann and Goedhart 2020, the most prevalent interpretations of quantum mechanics, including the Copenhagen one, are:

- **Realist/Statistical (Einstein, Born, Ballentine):** asserts that the physical properties of a system are objectively real and independent of experimental observation; and that the state vector encodes probabilities for the outcomes of measurements performed on an ensemble of similarly prepared systems. The wave function is not physically real; the collapse of the wave function represents a change in the observer's knowledge of the system, not a physical change brought about by the act of measurement (Baily and Finkelstein 2010).

- **Copenhagen (Bohr, Heisenberg, Dirac):** The probabilistic nature of quantum measurements is a reflection of the inherently probabilistic behavior of quantum entities. The properties of a system are indeterminate until measured. Although the wave function is not a literal representation of a physical system, its collapse does represent a physical transition from an indeterminate state to one where certain properties of the state become well defined. Speculations about unobservable physical processes are outside the domain of science. (Baily and Finkelstein 2010)

- **Agnostic (Including/emphasising only the last element of the Copenhagen interpretation, and extending it to other possible interpretations):** The mathematical QP formalism is only an instrument to calculate the possible outcomes of an experiment. Before measuring, it does not make sense to talk about the position of a particle, as it does not have one. (Stadermann and Goedhart 2020). The purely Agnostic perspective can be distinguished from the Copenhagen one because it takes no definite stance on which interpretation might correspond to the best description of reality. The utility of quantum mechanics is explicitly favored over its interpretive aspects ('shut up and calculate!') (Baily and Finkelstein 2010).

Other interpretations, found among experts but less common for instruction, are: the Matter-Wave interpretation (Schrödinger; similar to the Copenhagen interpretation but ascribing physical reality to the wave function); the Pilot-Wave interpretation (de Broglie, Bohm, Bell; a quantum particle has a well-defined position, but its motion is guided by a wave described by the mathematical formalism of QP); and the Many Worlds interpretation (Everett, DeWitt; QP describes the state of a quantum entity in many parallel universes; we see only one branch of reality, and the outcome of a measurement cannot be considered as reality) (Baily and Finkelstein 2010; Stadermann and Goedhart 2020).

To illustrate the relationship between the main features of QP and the different interpretations, we could build a table as in Fig. (2.9).

Although the Copenhagen interpretation is the most widely accepted among the scientific community (Siddiqui and Singh 2017a), experts' attitudes toward using interpretations in a teaching context present a different landscape. Research conducted at the University of Colorado-Boulder (Baily and Finkelstein 2010) found variations among instructors in their approaches to using QP interpretations in teaching. While some implicitly employed the Copenhagen interpretation (but without stating it explicitly), others adopted an agnostic stance, adhering to the 'shut up and calculate' philosophy (Mermin 1989). Similarly, experts surveyed in Siddiqui and Singh 2017b, although comfortable using the Copenhagen interpretation in their teaching, tended to dismiss questions about

QP Features	Realist	Wavity	Hidden Variables	Wave Function (WF)
Realist/ Statistical (Einstein, Born, Ballentine)	Yes: quanta exist as localized particles at all times	Diffraction patterns explained in terms of a quantized transfer of momentum between a localized particle and a periodic object.	Agnostic	Info: only encodes probabilities for the outcomes of measurements performed on an ensemble of identically prepared systems
Copenhagen (Bohr, Dirac) Agnostic (Heisenberg)	No	Electron is neither particle nor wave, because the dual use of distinct ontologies is just a way to understand what it's going on	No	Info: mathematical constuct to make predictions about measurement outcomes that it's a physical collapse of WF
Matter-Wave (Schrodinger)	No	Each electron is a delocalized wave as it propagates through both slits and interferes with itself	No	Real: each electron is a delocalized wave that will, after auto interference, deposits its energy at a single point in space when it interacts with the detector.
Pilot wave (de Broglie, Bohm, Bell)	Yes: quanta exist as localized particles at all times but are guided by a pilot wave	Particles are guided by pilot wave so corpuscolar and wave nature both present	Yes: global hidden variables	Real: electron pass through both the slit and the pilot wave collapse with itself
Many worlds (Everett, DeWitt)	Yes (every results of measurement realize in different realities)	Every possibilities are real	No	Real: Describes a superposition of real states and the collapse is choosen by the fact that we can see only one branch of reality

Figure 2.9: Overview of the main QP features in each of the main QP interpretations analyzed in teaching context by Baily and Finkelstein 2010, Baily 2011, Baily and Finkelstein 2015 and Stadermann and Goedhart 2020.

interpretations, stating that they do not need to "worry about such things" and were focused solely on helping students learn how to apply the formalism.

However, an approach that disregards the issue of interpretations has faced criticism in the literature. After surveying the instructors, Baily and Finkelstein 2010 interviewed students who had taken quantum mechanics courses with instructors holding different perspectives on teaching QM interpretations. Their interview protocol included a pair of questions and asked students to articulate their reasoning explicitly for each question.

In the first question, students were asked to state their agreement, using a 1 to 5 Likert scale, regarding the statement: *An electron in an atom has a definite but unknown position at each moment in time.*[3]

In the second question, students were presented with a frame from the double-slit PhET simulation (Fig. 2.10), followed by a prompt to select the statement(s) they agreed with from three options, each formulated as if three students were expressing their views:

Student 1 : The probability density is so large because we don't know* the true position of the electron. Since only a single dot at a time appears on the detecting screen, the electron must have been a tiny particle, traveling somewhere inside that blob, so that the electron went through one slit or the other on its way to the point where it was detected.

Student 2 : The blob represents the electron itself, since an electron is described by a wave packet that will spread out over time. The electron acts as a wave and will go through both slits and interfere with itself. That's why a distinct interference pattern will show up on the screen after shooting many electrons.

[3] In a follow up study (Baily and Finkelstein 2015) the question was refined to: *When not being observed, an electron in an atom still exists at a definite (but unknown) position at each moment in time.*

Student 3 : Quantum mechanics is only about predicting the outcomes of measurements, so we really can't know anything about what the electron is doing between being emitted from the gun and being detected on the screen.

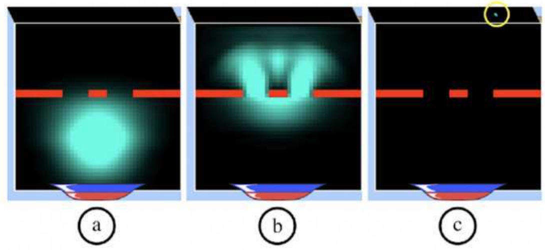

Figure 2.10: Images of the three different steps described in the second question about the double-slit experiment with single electrons simulation by PhET, used in Stadermann and Goedhart 2020 (https://phet.colorado.edu/en/simulation/quantum-wave-interference). The steps are: (a) the electron has just been emitted; (b) the electron passes through the double-slit; (c) the electron is detected on the screen.

They found that:

(i) Instructors' perspectives influence students' perspectives;

(ii) In the absence of a preferred instructor's interpretation (agnostic standpoint), students tend to shift towards realist interpretations or develop inconsistent interpretations.

They concluded that when proposing teaching innovations, it is crucial to consider instructors' personal positions on interpretations and their teaching, as this factor can significantly impact students' conceptualization of Quantum Mechanics.

Students' inclination towards a realist interpretation was also revealed in the study by Trevisan and Serrano 2018, where students provided a realist interpretation for the outcomes of the double-slit experiment and Mach-Zender interferometer. While students could describe the experimental results accurately and confidently, their reasoning lacked the same level of confidence. For example, they struggled to explain the expected interference patterns for individual electrons and photons in the absence of detectors, and were implicitly adopting a corpuscular interpretation.

Further criticism to the 'shut up and calculate' stance in QP teaching included the following arguments:

A kind of teaching that focuses too much on calculation risks reproducing a culture of physics where the only thing that matters is getting results [...]. This kind of culture does not only foreclose 'epistemological musings or the striving for ultimate theoretical foundations', but also discussions of the social aspects of science and the role of science in society. (Johansson et al. 2018)

Quantum mechanics is a subject where students arrive with high expectations, and at the same time a subject where a tension between deep conceptual understanding and 'shutting up and calculating' seem inherent. All this can at times combine to make the course a troubling experience for students. (Johansson 2018)

These arguments highlight the relevance of discussing QP interpretation to cultivate an understanding of the Nature of Science (Fig. 2.11).

NOS aspect	Example of an undesired view	Example of the desired view	Illustration of relevance for QP in secondary education
The role of scientific models	Scientific models represent reality as much as possible.	Scientific models and analogies show some aspects of phenomena in a simplified way.	Depending on the situation, either the wave model or the particle model can be used to understand quantum phenomena with Newtonian physics.
Tentativeness of scientific knowledge	Scientific methods yield absolute proof. Scientific knowledge is certain and unchangeable.	Scientific knowledge is always open to development, change, and improvement.	This was shown to understand quantum phenomena with Newtonian physics.
Creativity in science	Scientists always follow strict rules (the scientific method).	Scientists use their creativity and imagination.	Depending on the situation, either the wave model or the particle model can be used to understand quantum phenomena.
Subjectivity in science	Science is universal, and scientists are objective; therefore, only one correct interpretation of phenomena is possible.	Science is influenced by non-scientific aspects like personal preferences or historical, cultural, social, and economic factors.	In contrast to other scientists, Einstein was convinced that he could not accept the randomness of QP as fundamental.
Controversies in science	Acceptance of new scientific knowledge is straightforward. Only one interpretation can be correct.	Discussions and disagreements about scientific ideas are essential in scientific development. Different interpretations may exist.	Similar to the controversy between Einstein and Bohr, considering schools and teachers should show that ideological biases may influence the acceptance of new ideas.
The role of scientific models	Scientific models represent reality as much as possible.	Scientific models and analogies show some aspects of phenomena in a simplified way.	Depending on the situation, either the wave model or the particle model can be used to understand quantum phenomena with Newtonian physics.

Figure 2.11: Connection between aspects of NOS and QP in Stadermann and Goedhart 2020.

Stadermann and Goedhart 2020 interviewed secondary-school students about these different aspects, including the issue of QP interpretations, using a set of questions similar to those employed by Baily and Finkelstein 2010. They then introduced the topic of interpretations and asked students to choose one of the following statements, again formulated as if three "students" were expressing their views:

Student 1 : QP does not need an interpretation. As long as we can calculate with it and can build devices that work with it, we don't need an interpretation of QP. Interpretations are not science and physicists should not waste their time on it.

Student 2 : Physicists should come to an agreement about which interpretation they want to use as they did for international measurement standards. If everybody sticks to his/her own interpretation, we only get a lot of useless discussions.

Student 3 : At this moment, we cannot explain why electrons behave the way they do. But if scientists want to find out, they need a lot of creativity to find an explanation. That is how the interpretations are developed. That is part of science.

The results revealed a positive students' attitude towards NOS topics. The authors argued that, *just like professional physicists, secondary students experience the need to make sense of the results of the double-slit experiment. [...] In that sense, QP is 'science-in-the-making' where fundamental aspects are still controversial in contrast to 'ready-made science' as traditionally taught in school physics.*. They concluded by encouraging teachers to incorporate discussions on QP interpretations into their lessons. They argued that this approach not only can attract a wider variety of students to the subject but also can foster a better understanding of the Nature of Science.

Chapter 3

Research Methods

The questionnaire used in this work was developed from the one proposed by Onorato, Di Mauro, and Malgieri 2024 for QP experts, adapting and extending it for secondary school teachers. The revision was conducted collaboratively between the universities of Padua and Trento, with the Padua group adding some questions as described below.

The revision process entailed producing a first draft of the new questionnaire, which was sent to a small group ($N = 5$) of selected secondary school teachers who were asked to complete the questionnaire and provide feedback. The questionnaire was revised based on this feedback and further considerations, and optimized for large-scale delivery through the Google Forms platform.

The data ($N = 170$) were analyzed following the same methods as in Onorato, Di Mauro, and Malgieri 2024. Specifically, for the closed-ended questions, we performed a statistical quantitative analysis using the measures described in Chapter 1 (and further commented on below), while for open-ended questions (typically optional extensions to the closed-ended ones), a qualitative thematic analysis was performed to gain a more nuanced view of teachers' responses.

In the following sections, we describe the questionnaire and the statistical measures used for data analysis.

3.1 Questionnaire

3.1.1 Summary of Modifications

The questionnaire by Onorato, Di Mauro, and Malgieri 2024 was modified in several ways, described below. The full questionnaire is then detailed section by section.

First, some questions were rephrased to adapt them to secondary school teachers. Additionally, questions about the respondents' experience in teaching Quantum Physics in high school were added to the first section of the questionnaire ("Quantum Physics at School").

The second modification involved adding questions aimed at detecting the respondents' level of preparation on QP. Specifically, we added:

(i) a question asking the respondents to rate their level of preparation in QP on a Likert scale 1 to 5;

(ii) a question asking respondents whether they had followed QP courses at university or as professional development.

Based on these answers, we categorized respondents into two groups:

- **Low QP Preparation:** teachers who rated their preparation with a Likert value of 1-2, and/or teachers who did not follow university-level courses or PD courses on QP.

- **Medium-High QP Preparation:** teachers who rated their preparation with a Likert value of 3-5 and followed at least one university or PD course on QP.

We also added a filter question just before the section investigating specific QP subtopics: "Do you feel prepared enough to evaluate a number of specific Quantum Physics topics?"

This filter question allowed us to exclude respondents who felt unprepared to answer questions about specific QP topics, to avoid guessing or non-mindful answers. While we maintained the filter question in the final version of the questionnaire, the Trento group decided to remove it in their final version.

The third main modification involved introducing questions aimed at investigating Nature Of Science (NOS) aspects such as interpretations of Quantum Physics. In the draft version of the questionnaire, all the questions were formulated as Likert-scale questions. However, we realized that in some cases this format made the interpretation of answers tricky. Therefore, we modified the question format to multiple choice or open-ended. Moreover, while initial NOS-related questions were rather generic, in the final version, we made these questions more focused on specific aspects, following the literature and specifically Baily and Finkelstein 2015, Stadermann and Goedhart 2020. The wording of the questions' text was derived from Baily 2011, and the multiple-choice options were inspired by Stadermann and Goedhart 2021. We also coupled these questions with others explicitly related to the *teaching* of NOS aspects, as suggested by the respondents to the draft version. Some of these questions, such as discussing controversial aspects of QP in physics teaching or the need to revise the entire curriculum, were taken from Besson, Malgieri, et al. 2018, a PER-based book aimed at physics educators and published in the Italian context.

Finally, in the Padua version, we added a set of questions aimed at investigating teachers' specific formative needs. The aim of this section was to gain information useful for organizing a teacher professional development course.

3.1.2 Final Questionnaire

Here we report the full questionnaire, with section headings as they appear in the distributed version.

Quantum Physics at School

The current National Guidelines for the *Licei* include some elements of Quantum Physics among the topics for the fifth year, encompassing "old quantum physics" (e.g., Planck's hypothesis, photoelectric effect, etc.) and some elements of the subsequently developed quantum theory (e.g., wave-particle duality, uncertainty principle). The questions in this section aim to investigate your perspective on this.

1. Do you agree with teaching Quantum Physics in high school?
   1 Not at all - 5 Very much

2. If you teach or have taught physics in the last year of *Liceo Scientifico*, do you cover or have you covered Quantum Physics topics in your lessons?

   - Never
   - Sometimes
   - Often
   - Always
   - I have never taught Physics in the fifth year of *Liceo Scientifico*.

3. If you have ever taught Quantum Physics topics, regarding the time you dedicate or have spent on it:

   - I'm satisfied with how much time I spent on it.
   - I wish I could spend more time on it.
   - I don't want to deal with Quantum Physics.

4. Regarding the previous question, would you like to add anything? (Multiple answers were allowed and the prompt "Other" was included)

   - I prefer to cover Classical Physics topics better.
   - My students do not have enough mathematical skills to deal with Quantum Physics.
   - I don't have enough hours to deal with Quantum Physics.
   - I don't feel prepared enough to teach Quantum Physics.

5. How would you rate your knowledge of Quantum Physics?
   1 Poor - 5 Excellent

6. "Teaching Quantum Physics in high school is important because it is one of the greatest cultural achievements of Science." Do you agree?
   1 Not at all - 5 Very much

7. "Teaching Quantum Physics in high school is important for its technological applications." Do you agree?
   1 Not at all - 5 Very much

8. "Teaching Quantum Physics in high school is important to counter the large amount of misinformation present in various media about the contents and consequences of this theory." Do you agree?
   1 Not at all - 5 Very much

9. According to some experts, it is impossible to understand Quantum Physics without a good understanding of its formal structure. Therefore, an incomplete mathematical knowledge hinders or prevents the learning of Quantum Physics for high school students. Do you agree?
   1 Not at all - 5 Very much

10. "Quantum Physics should NOT be taught in high schools because it is not necessary for those who will not engage in the study of physics, and those who will do will have time to study it at university." Do you agree?
    1 Not at all - 5 Very much

Which Topics to Teach

1. Do you feel prepared enough to answer questions about teaching some specific Quantum Physics topics?
   - Yes, let's proceed (Continue to the next section)
   - No (Continue to the Demographics section)

2. We asked a group of experts which concepts are important for developing an adequate mental image of Quantum Physics. How important do you consider teaching the following concepts in high school?
   1 Not important - 5 Very important
   - Wave-Particle Duality
   - Tunneling
   - Entanglement
   - Time Evolution
   - Fermions/Bosons
   - Wave Function
   - Atomic Energy Levels and Quantization
   - De Broglie Wavelength
   - Quantum Measurements
   - Particle Nature of Light
   - Incompatible Observables
   - Heisenberg's Uncertainty Principle
   - Pauli Exclusion Principle
   - Probability
   - Superposition
   - Spin
   - Quantum States

3. We asked a group of experts which phenomena and experiments (thought or real) are most significant for understanding the ideas of Quantum Physics. How meaningful do you consider presenting the following phenomena or experiments in high school?
   1 Not important - 5 Very important

   - 1D Potential Well
   - Specific Heat of Solids
   - Radioactive Decay
   - Compton Effect
   - Photoelectric effect
   - Double-Slit Experiment
   - Schrödinger's Cat
   - Spectral Lines
   - Harmonic Oscillator
   - Blackbody Radiation

4. We asked a group of experts which are the most significant technological applications of Quantum Physics. How important do you consider presenting the following applications in high school?
   1 Not important - 5 Very important

   - Solar cell
   - Quantum Computer
   - Quantum Information
   - Laser
   - LED
   - Semiconductors

Approaches to Teaching Physics

The questions in this section aim to investigate your opinion on possible approaches to teaching Quantum Physics. There are no more or less correct answers: we are interested in your ideas and points of view.

1. The National Guidelines suggest introducing Quantum Physics through the first "quantum physics", presenting the experiments that represent the break with classical physics (e.g., photoelectric effect, hydrogen atom spectrum, blackbody radiation, Compton effect, etc.). Most textbooks follow this approach. Do you agree?
   1 Not at all - 5 Completely

2. Some texts are very rigorous in reporting not only the physical contents but also the historical evolution that led to the formulation of the new theories. Other texts, however, accompany the presentation of the physical contents with a quasi-history, a partially altered narrative, but more linear and easy to follow. What do you think about integrating historical content into the teaching of Physics?

- They are not needed to understand Physics.
- They are important, but not necessary, to understand Physics.
- They are essential for understanding Physics.

3. What do you think of the quasi-historical approach to teaching Quantum Physics in high school?

   - The simplified quasi-historical approach is better than the truly historical one.
   - The truly historical approach is better than the quasi-historical one.
   - The teaching of physics require neither historical nor quasi-historical treatments.
   - I don't know/have never thought about this aspect.

4. In the textbooks that report it, the "first quantum physics" is often presented as a path where blackbody radiation, photoelectric effect, Compton effect, and Bohr model follow one another linearly. Which of the following statements regarding the "first quantum physics" do you prefer?
   A - It is a simplified narrative with alterations/omissions. B - It correctly represents the historical development of Quantum Physics.

5. Some researchers have formulated educational proposals aimed at going beyond the quasi-historical approach currently used in high school, arguing that it is important to introduce aspects of the subsequently evolved quantum theory. Some of the proposals include, for example: the introduction of concepts such as spin, using 2x2 matrices as a relatively accessible mathematical tool; the exploration of phenomenologies, such as polarization, which can highlight some properties of quantum particles (e.g., concept of state); the study of some key experiments for the construction of the theory, such as the double-slit experiment. Would you be interested in exploring these approaches?

   - Yes, I think it is important to go beyond Old Quantum Physics.
   - I don't have a clear idea about it, but I would like to know more.
   - No, I think the quasi-historical approach currently proposed is sufficient in the high school context.
   - I'm not sure what is meant by "quantum theory beyond early Quantum Physics."

6. One of the open questions regarding the teaching of modern physics (Quantum Physics and Relativity) in high school is the following:
   Is it preferable to include some elements of modern physics at the end of the curriculum, or to revise the entire Physics curriculum to build a coherent vision of Physics that takes into account its current developments?

   - I think it's enough to include some elements at the end of the curriculum.
   - I think a curriculum revision is necessary.
   - Other...

Interpretations of Quantum Physics

The interpretative aspects of Quantum Physics are still open questions today, with active discussions among scientists. In this section, we will ask your opinion about some of these controversial aspects. There are no more or less correct answers: we are interested in your ideas and viewpoints.

1. Einstein proposed that electromagnetic radiation is "quantized" in localized packets with well-defined energy and momentum (later called "photons"). How would you describe a photon?

    - The photon is a particle that has no mass, but has definite momentum and energy.
    - The photon is a quantum particle, and as such, it does not need to have well-defined momentum and energy.
    - I don't know or I'm not sure
    - Other ...

2. In textbooks, different representations of the photon can be found (Fig. 3.1). How would you personally represent a photon?

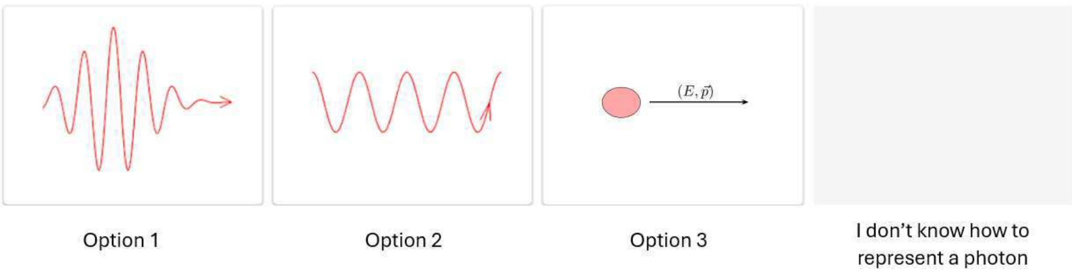

Figure 3.1: List of the possible answers to question 2 of the section "Interpretations of Quantum Physics": option 1, wave packet; option 2, sinusoidal wave; option 3, classical particle; last if they don't know how to represent a photon.

3. The Heisenberg uncertainty principle establishes the limits in the possibility of simultaneously measuring two physical quantities (e.g. position and momentum of a particle) with arbitrary precision. This principle is often presented by reporting one of the following arguments:

    - Heisenberg's "microscope" thought experiment:
    The position of a particle is determined by interaction with a short-wavelength photon to minimize uncertainty about the position. This however produces a large uncertainty in the momentum.
    - Single-slit experiment: The position of a photon is determined by forcing it to pass through a narrow slit, but this generates an uncertainty in the photon's momentum, which generates the typical interference pattern.

    What do you think about these two arguments?

    - Both arguments correctly present the uncertainty principle, they are equivalent.

- Only the Heisenberg's microscope correctly presents the uncertainty principle, the single slit is a special case.
- Only the single-slit correctly presents the uncertainty principle, the Heisenberg's microscope is a special case.
- Neither argument correctly presents the uncertainty principle.
- I don't know, I've never delved into this principle.

4. Another fundamental principle of Quantum Physics is the concept of complementarity, which is usually formulated as follows:
   - I Formulation: "The corpuscular and wave aspects of a physical phenomenon never manifest themselves simultaneously, but any experiment that allows us to observe one prevents us from observing the other. The two aspects are however complementary because both are indispensable to provide a complete physical description of the phenomenon. It is therefore the experimental apparatus that determines the quantum system as a wave or particle."
   - II Formulation: according to some researchers, the principle should be reformulated differently: "An experimental apparatus can simultaneously provide partial information on the wave and particle aspects of the quantum system under examination, but the more information it provides on one aspect, the less it will give on the other. Quantum objects can sometimes simultaneously exhibit both corpuscular and wave properties (wave-particle duality)."
   Which of the two formulations do you prefer?

   - There is no contradiction between the two formulations: they are completely equivalent.
   - Neither is wrong, but I prefer the first one.
   - Neither is wrong, but I prefer the second one.
   - Only the first one is correct.
   - Only the second one is correct.
   - I don't know or I'm not sure

5. The following frame (Fig. 3.2) is taken from a PhET simulation of the double-slit experiment with single electrons.

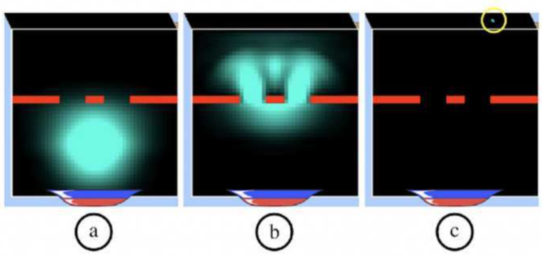

Figure 3.2: Screenshot from the PhET simulation used for question 5 of the section "Interpretations of Quantum Physics", as proposed also in Stadermann and Goedhart 2020 (https://phet.colorado.edu/en/simulation/quantum-wave-interference).

(a) The electron has just been emitted;
(b) The electron passes through the double-slit;
(c) The electron is detected on the screen.
Three students, interpreting the experiment, expressed the following arguments. Indicate which one(s) you agree with.

- Student 1: ““The probability density, represented by the colored spot, is so large because we do not know the true position of the electron. Since a single point appears on the screen at a time, the electron must have been (even during the journey) a very small particle, located somewhere inside that spot, and therefore actually passed through only one of the two slits.”
- Student 2: “The colored spot represents the electron itself, because it is described by a wave packet that propagates over time. The electron behaves entirely like a wave, passing through both slits and interfering with itself. This is why a typical interference pattern will appear on the screen after shooting many electrons.”
- Student 3: “Quantum mechanics only concerns predictions about measurement results, so we can’t really know what the electron does between when it is emitted and when it is detected on the screen.”

6. If you wish, briefly explain your choice:
Open answer

7. Indicate your level of agreement with the following statement:
When you are not observing it, an electron in an atom still has a well-defined (even if unknown) position at every instant of time.
1 Strongly disagree - 5 Strongly agree

8. If you wish, briefly explain your choice:
Open answer

9. Have you heard of different interpretations of Quantum Mechanics?
   - Yes, and I could distinguish at least two, at least in their fundamental traits.
   - I’ve heard of them, but I can’t describe them.
   - No

10. If you answered YES, can you name the ones you know and/or briefly describe their main characteristics (or how they differ)?
Open answer

11. If you answered YES, do you adopt a specific interpretation of Quantum Mechanics in your teaching?
Open answer

12. Do you explicitly address the topic of interpretations of Quantum Mechanics with your students?

- No, I've never heard of interpretations of Quantum Mechanics.
- Yes, it is a fundamental element of my proposals.
- Yes, as an extra (optional) activity.
- No, I think it's important but I don't have time.
- No, I think it's important but I don't feel prepared enough to do so.
- No, because students wouldn't appreciate its significance.
- No, I don't consider it necessary: the essential thing in Quantum Mechanics is to be able to predict results.

13. Despite the great predictive power of Quantum Mechanics, after more than 80 years, the discussion about its interpretation is still ongoing. Different interpretations lead to identical predictions, but they differ greatly in their ontological implications (about the nature of quantum objects). This aspect of Quantum Mechanics could be considered problematic.
Below are some arguments in response to this problem: which one do you personally agree with the most?

    - "Quantum Mechanics does not need interpretations. As long as we know how to use it to perform calculations and build devices that work thanks to it, we don't need an interpretation of Quantum Mechanics. It is beyond the domain of science to ask about the nature of something we cannot observe."
    - "Physicists should agree on which interpretation of Quantum Mechanics they want to use, just as they did with international measurement standards. If everyone remains tied to their own interpretation, there will only be many useless discussions."
    - "At present, we do not know why electrons behave as described by Quantum Mechanics. But if scientists want to discover it, much creativity is needed to find an explanation. This is how interpretations are developed: it is part of the construction of scientific knowledge."

14. If you wish, briefly explain your choice:
Open answer

15. What do you think about the controversial aspects of Quantum Mechanics in relation to teaching in secondary school?

    - I prefer to avoid controversial aspects or those that may create problems.
    - I think these issues should be put at the center of teaching.
    - I think these issues should/could be addressed, but as extra (optional) topics.
    - I don't feel prepared enough to answer.
    - Other...

Formative Needs

The following questions will help us organize a professional development course on Quantum Physics for in-service teachers .

1. Which of these elements would you like to find in a teacher training school on Quantum Physics?
    - Discussions on the Physics curriculum in high school to understand how to better integrate modern physics
    - Didactic proposals to introduce elements of Quantum Mechanics beyond "old quantum physics"
    - Didactic proposals to innovate or deepen the teaching of "old quantum physics" (e.g. black body, spectroscopy, photoelectric effect)
    - Insights into interdisciplinary aspects in STEM area (e.g. LED - Materials Science, ...)
    - Insights into the historical and/or philosophical aspects of quantum mechanics (e.g., different interpretations of Quantum Mechanics)
    - Insights into quantum technologies (e.g. quantum computer)
    - Lessons on the contents of Quantum Mechanics beyond the "old quantum physics" (e.g. quantum state, Schrödinger equation, ...)
    - Other...
2. Which of the following educational tools for teaching quantum physics in secondary education would you like to explore further?
    - Simulations and animations (e.g. PhET)
    - Video games based on rules simulating quantum behavior (e.g. Quantum TiqTaqToe)
    - Experiments reproducing some phenomena explored in old quantum physics (e.g. spectroscopes)
    - Mathematical tools useful for calculations in Quantum Mechanics (e.g. probability)
    - Other...

Demographics

1. In which teaching qualification category are you currently teaching?
    - A020 - Physics
    - A027 - Mathematics and Physics
    - Other...
2. What is your field of education?
    - Theoretical Physics

- Experimental Physics
- Physics Education (only in Trento's version)
- Astronomy/Astrophysics
- Mathematics
- Engineering
- Other...

3. During your university education, did you take courses in Quantum Physics?
    - No
    - Yes, but only elements of early quantum physics.
    - Yes, also on quantum mechanics beyond early quantum physics.
    - Yes, also at the PhD level
    - Other...
4. Have you attended training courses for teachers on Quantum Physics?
    - No
    - Yes, to SSIS or TFA or other pre-service training courses
    - Yes, in in-service training courses (professional development)
    - Other...
5. If you wish, you can provide further details:
   Open-ended response
6. What age group do you belong to?
    - <30
    - 30-39
    - 40-49
    - >50
7. What gender do you identify with?
    - Female
    - Male
    - Prefer not to answer
    - Other...
8. How many years have you been teaching physics?
    - <5
    - 5-10
    - 11-20
    - >20

9. Which textbook do you use for teaching Quantum Physics?
   Open-ended response

10. How much do you rely solely on the textbook in preparing your lessons?
    1 Add a lot of material - 5 Use only textbooks

11. What type of school do you teach at?

    - Scientific high school
    - Non-scientific high school
    - Technical institute - technological sector
    - Technical institute - economic sector
    - Vocational school
    - Other...

12. In which province do you teach? (if not in Veneto, choose "Other" and indicate the automotive code in uppercase letters, e.g., BS)

    - BL
    - PD
    - RO
    - TV
    - VE
    - VI
    - VR
    - Other...

13. Would you like to add any comments or suggestions?
    Open-ended response

3.2 Data Analysis Tools

For data analysis, the same quantitative tools as in Onorato, Di Mauro, and Malgieri 2024 were used. All questions were analyzed using descriptive statistics. Likert-type items were also evaluated using “Consensus” (Cns) and “Level of Agreement” (LoA). For all questions, a correlation value η^2 or V_{χ^2} was calculated to compare teachers with different backgrounds. These tools will be described in the following paragraphs.

3.2.1 Consensus (Cns)

Consensus is a measure of dispersion based on Shannon entropy (Onorato, Di Mauro, and Malgieri 2024), which utilizes a probability distribution and the distance between categories to produce a value spanning the unit interval. It is applied to a Likert scale (or any ordinal scale) to determine a “degree of consensus”, interpreted as agreement between respondents. The formula is given by:

$$Cns(X) = 1 + \sum_{i=1}^{n} P_i \cdot \log_2(1 - \frac{|X_i - \mu_X|}{d_X})$$

where P_i is the probability for the data value X_i, μ_X and $d_X = X_{\max} - X_{\min}$ are, respectively, the mean value and the width of X (in this case a five-value Likert scale is used, so $d_X = 4$). It is considered a significant consensus if $Cns(X) \geq 0.7$, medium consensus if $Cns(X) \sim 0.6$, and small consensus if $Cns(X) \leq 0.5$.

3.2.2 Level of Agreement or Naif Consensus

The Level of Agreement (LoA) is calculated based on the percentage of favorable responses P_f (the sum of Likert scale values of 4 and 5, corresponding to "agree" and "strongly agree") and unfavorable responses P_s (the sum of Likert scale values of 1 and 2, corresponding to "strongly disagree" and "disagree") and the scale is defined as in Fig. (3.3).

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 $P_f < 60\%$ or $P_s < 60\%$			

Figure 3.3: Interpretation table for the LoA values as in Onorato, Di Mauro, and Malgieri 2024 so the level of agreement P_f and of dis-agreement P_s.

3.2.3 Correlation Parameters

To study the correlation between different groups of teachers, we used two correlation parameters: the quantitative coefficient η^2 and the qualitative coefficient V_{χ^2}.

Initially, the analysis was conducted by breaking up the sample according to all possible teachers' backgrounds: Mathematics, Experimental physics, Theoretical Physics, Physics education (only in Trento's questions), Engineering and Astronomy/Astrophysics. However, this approach did not provide reliable information because categories with smaller size inflated the η^2 values of certain answers giving a false correlation value. To mitigate this issue, similar categories were combined, resulting in only two groups: teachers with a background in Physics (including Theoretical Physics, Experimental Physics, Physics Education, and Astronomy/Astrophysics), and teachers with Non-Physics backgrounds (including Mathematics and Engineering).

Eta Squared η^2

It is a measure of effect size indicating the strength of association between two variables, ranging from 0 to 1. Values closer to 1 indicate a higher proportion of variance that can be explained by a given variable in the model. Therefore, in this context, high values of η^2 indicates that a large portion of the variance among responses can be explained by the different background.

The formula to calculate this parameter for a given dataset is:

$$\eta^2 = \frac{\sum_j (M_j - M_{tot})^2 \cdot n_j}{\sum_i (A_i - M_{tot})^2}$$

where M_j is the mean value for the data group j, A_i the single data i, n_j the absolute frequency for the data group j and M_{tot} the mean value for the total sample.

The results are interpreted as follows:

- $\eta^2 < 0.01$: small correlation, i.e. the variance is not explained by the teachers' background;
- $0.01 \leq \eta^2 \leq 0.06$: medium correlation, i.e. the variance is influenced in moderate proportion by the teachers' background;
- $\eta^2 > 0.06$: large correlation, i.e. the variance is explained in a great proportion by the teachers' background.

Cramer's V_{χ^2} Parameter

It is a measure of the correlation between two qualitative variables that cannot be ordered numerically, so it has similar meaning of η^2 but with qualitative data. For data in a contingency table, see Fig. (3.4), the χ^2 coefficient is normalized using as degree of freedom (dof) of the system the ones for the independence test.

$X \backslash Y$	y_1	.	.	.	y_k	Total
x_1	n_{11}	.	.	.	n_{1k}	$n_{1,y}$
. . .	. . .	. . .	. (n_{ij}) .	. . .	. . .	. $(n_{i,y})$.
x_l	n_{l1}	.	.	.	n_{lk}	$n_{l,y}$
Total	$n_{x,1}$	.	$(n_{x,j})$	.	$n_{x,k}$	N

Figure 3.4: Contingency table example with in the middle the joint frequencies $n_{i,j}$, in the last vertical column at the right there are the marginal frequencies for the variable y called $n_{i,y}$ obtained as the sum of the single frequencies for each column (in total k) with the row x_i fixed, and in the last horizontal row at the bottom there are the marginal frequencies for the variable x called $n_{x,j}$ obtained as the sum of the single frequencies for each row (in total l). In the right-bottom corner there is the total sample size N.

So this new normalized coefficient, called Cramer's effect size, can be found as follows:

$$V_{\chi^2} = \frac{1}{dof} \cdot \sum_{i=1}^{l} \sum_{j=1}^{k} \frac{(n_{i,j} - \frac{n_{x,j} \cdot n_{i,y}}{N})^2}{\frac{n_{x,j} \cdot n_{i,y}}{N}}$$

with k = number of columns, l = number of rows, $n_{i,j}$ the joint frequencies with the first index i that represent the variable x_i while the second index j the variable y_j, $dof = N \cdot min\{k-1; l-1\}$ the degree of freedom of the system, $n_{x,j}$ the marginal frequencies for the variable x that are the values in the last horizontal row, and the opposite for the marginal frequencies for variable y $(n_{i,y})$ that are the values in the last vertical column.

In our case, the contingency tables will have every time two rows (or two columns) because of the two teachers' background groups, so $dof = N$.

The results are interpreted as follows:

- $V_{\chi^2} < 0.30$: small correlation between the variables x and y, i.e. the variance is not explained by the teachers' background;
- $0.30 \leq V_{\chi^2} \leq 0.50$: medium correlation between the variables x and y, i.e. the variance is influenced in moderate proportion by the teachers' background;
- $V_{\chi^2} > 0.50$: high correlation between the variables x and y, i.e. the variance is explained in a great proportion by the teachers' background.

3.2.4 Sample Size

In total, 170 teachers responded to the questionnaire, including respondents from both Padua and Trento. The exact number of respondents for each question varied due to filter questions and mandatory/non-mandatory questions. Specifically, in Padua, we had a sample size of 77 teachers, with 51 passing the filter question and consequently responding to the full questionnaire, including items related to specific topics and interpretations of QP.

Chapter 4

Results

In this chapter, we present the analysis of the questionnaire data, covering both the Padua sample ($N_P = 77$) and the Trento sample ($N_T = 93$). The combined population ($N_{PT} = 170$, represented in red) is analyzed together, as well as separately focusing on the Padua sub-sample (represented in light blue) to identify potential differences between the two groups that may be relevant for organizing local teacher training activities.

In the presentation of results, the Demographics section will be presented first to specify the characteristics of the respondents. For quantitative questions (including Likert scale and ordered qualitative questions), tables will include the following details: sample size, mean value, level of agreement, and consensus. Additionally, we will report the correlation coefficient η^2 to compare teachers with a Physics background and teachers with a Non-Physics background. For qualitative questions that are not ordinal, only the sample size and the chi-squared correlation coefficient will be reported. Following the presentation of data, a description and commentary on the results will be provided, including a comparison with results obtained by Onorato, Di Mauro, and Malgieri 2024 in the questionnaire for experts.

4.1 Demographics

This section focuses on the demographic results obtained from our sample using questions form the last section of our questionnaire.

The majority of respondents teaches in a *Liceo Scientifico* type of school (87%) and is qualified within the A027-Mathematics and Physics "teaching class" (98%). Geographical statistics, conducted only for the Padua sample, indicate that the majority of respondents were from Padua (43%) and Vicenza (29%), with a smaller number of teachers from Treviso (14%), Venice and Rovigo (each 7%).

Regarding educational background, responses were categorized into two main groups for correlation analysis, as explained in Chapter 3:

- **Physics:** Approximately 44% of the total population and 46% of the Padua sample hold degrees in Physics. Specializations within this group include Theoretical Physics (18%), Experimental Physics (16% overall and 18% for the Padua cohort), Physics Education (2%), and Astronomy/Astrophysics (8% overall and 10% for the Padua one).

- **Non-Physics:** The majority of respondents with non-physics backgrounds hold degrees in Mathematics (47% of the total sample), with a smaller percentage of Engineering graduates (9% overall, and 6% for Padua).

Almost one-third (37%) of the respondents did not take quantum physics courses during their university education or teacher education/professional development, while 20% took courses only on old quantum physics. Therefore, 44% of the respondents have taken courses beyond old quantum physics. As expected, those who took QP courses are predominantly physics graduates.

Regarding gender distribution, 56% of the respondents were women and 44% were men. These data only refer to the Padua sample as the questionnaire from Trento did not include this demographic feature. The majority of respondents were over forty years old and have several years of teaching experience.

4.2 Quantum Physics at School

(2) Do you agree with teaching Quantum Physics in high school?

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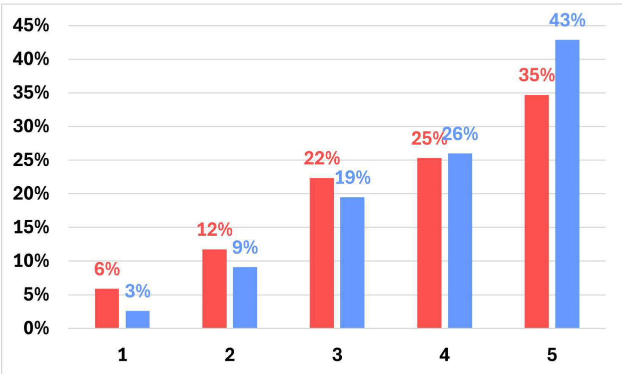


STATISTICS

Padua + Trento		Padua	
Sample	170	Sample	77
Mean	3.7	Mean	4.0
P_f (%)	60	P_f (%)	69
P_s (%)	18	P_s (%)	12
Cns	0.5	Cns	0.6
η^2	0.001	η^2	<0.001

Table 4.1: Results for question 2. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

60% of the participants agreed (values 4 and 5 on the Likert scale) with teaching QP in secondary school. However, there was only a small consensus ($Cns = 0.5$), accounting for the presence of participants who are unsure about teaching QP. Similar results were observed for the Padua sample analyzed separately, indicating that the two cohorts are similar.

In Onorato, Di Mauro, and Malgieri 2024, a similar question was asked: *Is it appropriate to teach QP at the pre-university level?*. The results were: $Mean = 3.7$, $P_f = 62\%$, $CnS = 0.5$. Therefore, the results from the experts and the teachers are almost identical.

In terms of the comparison between teachers with a Physics versus Non-physicis background, the correlation analysis revealed that the two groups were not strongly correlated, indicating that the answers are independent on teachers' training.

(3) If you teach or have taught Physics in the last year of Scientific High School, do you cover or have you covered topics of Quantum Physics in your classes throughout the school year?

Among teachers who teach or have taught Physics in the last year of secondary school, 56% have taught QP often or always, while 44% have taught QP only sometimes or not at all. This high percentage is somewhat surprising given that QP (even though in terms of the "old" QP) is explicitly mentioned in the National Guidelines and in the Framework for the final exam of the *Liceo Scientifico*. Similar results were observed for the Padua sample, and in this case as well, physicists and non-physicists were not correlated at all.

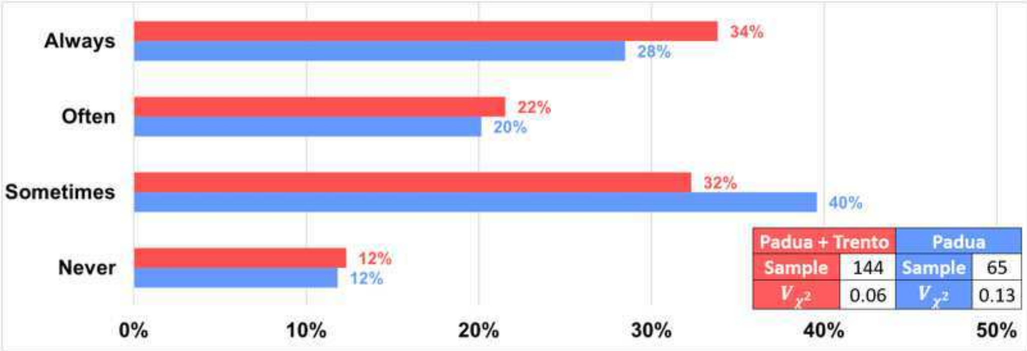


Figure 4.1: Results for question 3. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

(4) If you have ever taught topics of Quantum Physics, regarding the time you dedicate or have dedicated to their treatment:

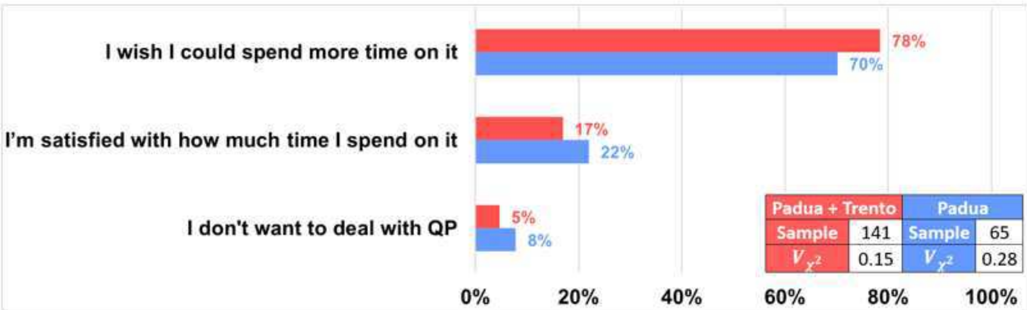


Figure 4.2: Results for question 4. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

Among teachers who teach or have taught QP in the last year of high school, 78% expressed a desire for more time to teach QP. Similar results were observed for the Padua sample. A low correlation parameter V_{χ^2} was found between physicists and non-physicists, indicating that their responses are not strongly correlated with their physical backgrounds.

(5) Regarding the previous question, would you like to add anything? (Multiple answers allowed and prompt "Other" was included)

The results indicate that the primary issue perceived by high-school teachers is a lack of time, as reported by 69% of respondents. Other significant challenges include feeling unprepared to teach QP, a preference for dedicating teaching time to better cover classical physics, and the perceived mathematical difficulty of QP. Similar results were observed for the two samples, with the Padua respondents emphasising the lack of time even more.

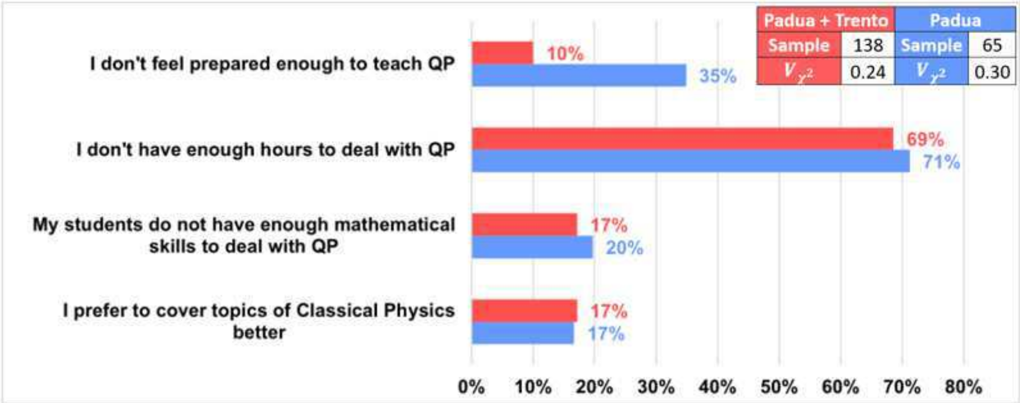


Figure 4.3: Results for question 5. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

Responses in the "Other" section provide additional context. These answers included:

- *Vanno selezionati quali argomenti e come presentarli (p. es. sì effetto fotoelettrico, atomo di Bohr; qualitativamente la radiazione di corpo nero).*
  [Translated: They must be selected as topics and how to present them (e.g., yes to the photoelectric effect, Bohr atom; qualitatively the blackbody radiation).]

- *Possibile trattarla aneddoticamente, dedicare qualche ora a collegamenti con la realtà, ma non dovrebbe essere in programma.*
  [Translated: It can be treated anecdotally, dedicating a few hours to real-world connections, but it should not be part of the formal curriculum.]

- *Devo svolgere argomenti di fisica classica per dare un significato alla fisica quantistica che quindi è relegata alla fine dell'anno scolastico.*
  [Translated: I need to cover classical physics topics to give meaning to quantum physics, which is therefore relegated to the end of the school year.]

- *Ho delle idee contrastanti circa l'opportunità di insegnare la fisica quantistica alle scuole superiori. Da un lato è una delle grandi conquiste scientifiche del XX secolo e sarebbe importante che gli studenti avessero qualche seppur minima conoscenza che gli permettesse di andare oltre la fisica da bar, tuttavia forse sarebbe più importante dare basi solide per la fisica classica poiché fornisce strumenti per comprendere la quotidianità ed è incredibile quanto gli studenti siano ignoranti da questo punto di vista. Io dunque ritengo che si possa trattare qualche aspetto ristretto di fisica moderna (ma non solo di MQ anche scegliendo tra fisica nucleare o relatività ristretta o cosmologia o fisica delle particelle) come approfondimento.*
  [Translated: I have mixed feelings about the appropriateness of teaching quantum physics in high school. On one hand, it is one of the great scientific achievements of the 20th century, and it would be important for students to have at least some minimal knowledge to help them move beyond superficial understandings. However, it might be more important to provide a solid foundation in classical physics, as it offers tools for understanding everyday phenomena. It's incredible how much students lack knowledge in this area. Therefore, I believe we could cover a few selected

aspects of modern physics (not just quantum mechanics, but also topics from nuclear physics, special relativity, cosmology, or particle physics) as an optional topic.]

- *Riesco a svolgere alcuni argomenti di quantistica ma è l'ultimo argomento del programma e entro il 15 maggio bisogna finire, per cui non riesco ad approfondirlo molto.*
  [Translated: I can cover some quantum physics topics, but it is the last subject in the curriculum and needs to be finished by May 15th. Therefore, I cannot go into much depth.]

- *Bisognerebbe riformulare la tempistica della Fisica Classica*
  [Translated: The timing for Classical Physics needs to be reorganized.]

- *Se deve essere divulgativa, preferisco fare altro.*
  [Translated: If it has to be purely informational, I prefer to focus on other topics.]

- *Gli studenti, e spesso gli insegnanti, non hanno competenze matematiche per trattare la fisica quantistica, la cui trattazione puo' essere svolta in modo molto superficiale. Spesso, molti alunni arrivano all'ultimo anno di liceo senza studiare la fisica o studiandola molto superficialmente nel corso del quinquiennio, perciò, a mio avviso, non ha senso che studino la fisica quantistica. Inoltre, mentre la fisica classica viene trattata in modo adeguato ed approfondito, la quantistica in modo superficiale, appena accennato.*
  [Translated: Students, and often teachers, lack the mathematical skills to properly handle quantum physics, which can only be covered very superficially. Many students reach their final year of high school without having studied physics or having studied it very superficially over the five years. Therefore, in my opinion, it doesn't make sense for them to study quantum physics. Moreover, while classical physics is covered adequately and in depth, quantum physics is treated superficially and only briefly touched upon.]

- *Le ore di fisica nel liceo scientifico sono poche per poter trattare tutti gli argomenti in modo approfondito*
  [Translated: The hours allocated to physics in the scientific high school curriculum are insufficient to cover all topics in depth.]

- *E' un argomento di difficile comprensione*
  [Translated: It is a difficult topic to understand.]

- *Ha senso parlarne e trattarla qualitativamente; ma le versioni dei calcoli o delle formule semplificate per adattarle agli studenti sono quasi fuorvianti; le versioni fedeli, troppo avanzate per essere capite e interpretate dagli studenti (anche un integrale risulta difficile per chi ha appena imparato a risolverli...).*
  [Translated: It makes sense to discuss and approach it qualitatively, but simplified versions of calculations or formulas tailored for students are almost misleading. Accurate versions are too advanced to be understood and interpreted by students (even an integral can be difficult for those who have just learned how to solve them...).]

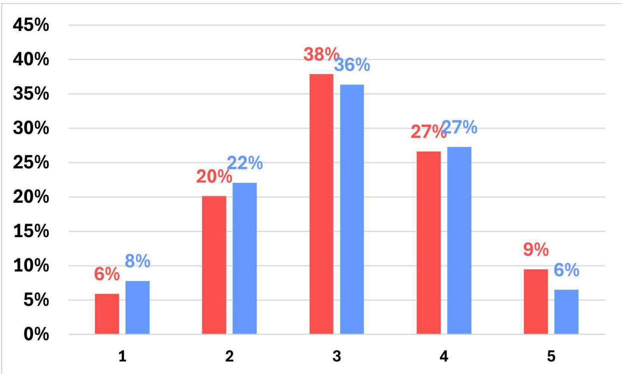
- *Dedico all'argomento tutto il tempo che riesco, ossia non molto non potendo/volendo sacrificare gli argomenti appena precedenti. Gli dedicherei più tempo se la materia avesse più ore.*
  [Translated: I dedicate as much time as I can to the topic, which isn't much since I can't or don't want to sacrifice the preceding topics. I would allocate more time if the subject had more hours.]

- *Purtroppo la fisica quantistica arriva in coda all'anno scolastico e si rischia sempre di fare molto velocemente, causa simulazioni/prove/gite ecc...*
  [Translated: Unfortunately, quantum physics comes at the end of the school year, and there's always the risk of rushing through it due to simulations, tests, field trips, etc.]

The next question was aimed at characterizing the sample in terms of their (perceived) preparation on Quantum Physics:

(6) How would you rate your knowledge of Quantum Physics? (1 Poor - 5 Excellent)

HISTOGRAM



STATISTICS

Padua + Trento		Padua	
Sample	169	Sample	77
Mean	3.1	Mean	3.0
P_f (%)	36	P_f (%)	33
P_s (%)	26	P_s (%)	30
Cns	0.6	Cns	0.6
η^2	0.219	η^2	0.256

Table 4.2: Results for question 6. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

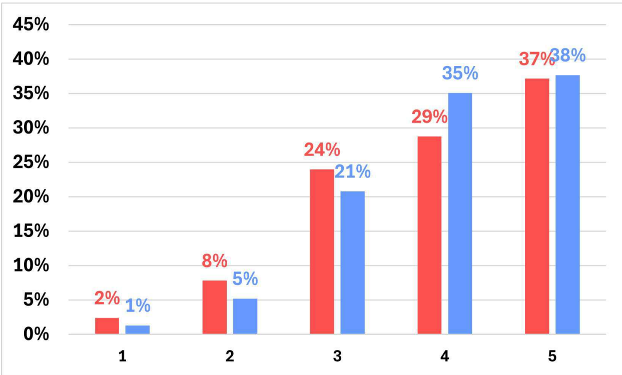
The data follow a Gaussian distribution peaked at the scale value of 3, suggesting a medium background in QP within our sample. Unlike the other questions, this case showed a high correlation in the responses from physicists and and non-physicists ($\eta^2 > 0.06$), for both the Padua sample and the total sample. This correlation indicates that teachers with a background in physics feel more prepared in QP compared to teachers with a different background, which aligns with expectations. Similar results were observed for the Padua sample.

4.3 Why Teach/Not Teach Quantum Physics

This section investigated teachers' agreement with various statements expressing reasons for teaching QP in high school. This group of questions is analyzed together as they all pertain to the same research question.

(7) "Teaching Quantum Physics in high school is important because it is one of the greatest cultural achievements of Science." Do you agree? (1 Not at all - 5 Very much)

HISTOGRAM



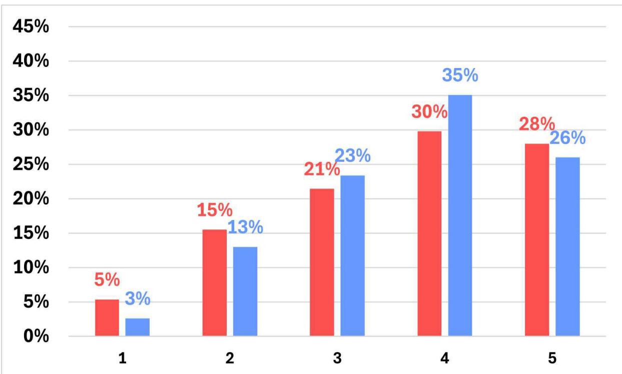
STATISTICS

Padua + Trento		Padua	
Sample	168	Sample	77
Mean	3.9	Mean	4.0
P_f (%)	66	P_f (%)	73
P_s (%)	10	P_s (%)	6
Cns	0.6	Cns	0.7
η^2	<0.001	η^2	0.001

Table 4.3: Results for question 7. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

(8) "Teaching Quantum Physics in high school is important for its technological applications." Do you agree? (1 Not at all - 5 Very much)

HISTOGRAM



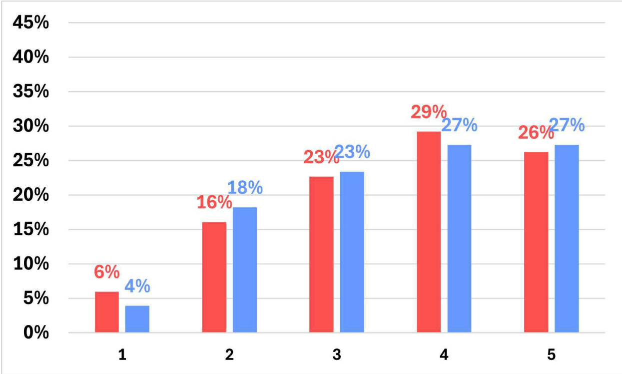
STATISTICS

Padua + Trento		Padua	
Sample	168	Sample	77
Mean	3.6	Mean	3.7
P_f (%)	58	P_f (%)	61
P_s (%)	20	P_s (%)	16
Cns	0.5	Cns	0.6
η^2	0.001	η^2	0.002

Table 4.4: Results for question 8. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

(9) "Teaching Quantum Physics in high school is important to counteract the large amount of misinformation present in various media about the contents and consequences of this theory." Do you agree? (1 Not at all - 5 Very much)

HISTOGRAM	STATISTICS

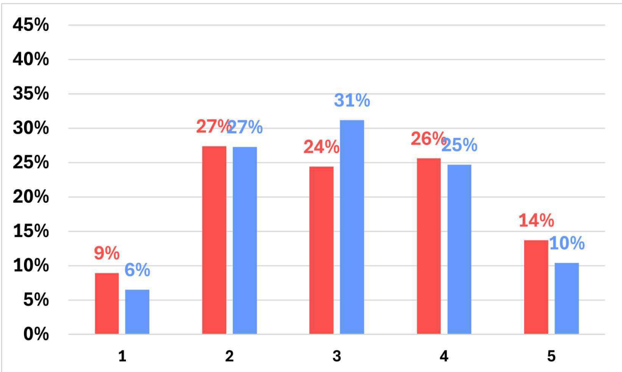


Padua + Trento		Padua	
Sample	168	Sample	77
Mean	3.5	Mean	3.6
P_f (%)	55	P_f (%)	54
P_s (%)	22	P_s (%)	22
Cns	0.5	Cns	0.5
η^2	0.001	η^2	0.008

Table 4.5: Results for question 9. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

(10) According to some experts, it is impossible to understand Quantum Physics without a good understanding of its formal structure, so incomplete mathematical knowledge hinders or prevents the learning of Quantum Physics for high school students. Do you agree? (1 Not at all - 5 Very much)

HISTOGRAM	STATISTICS

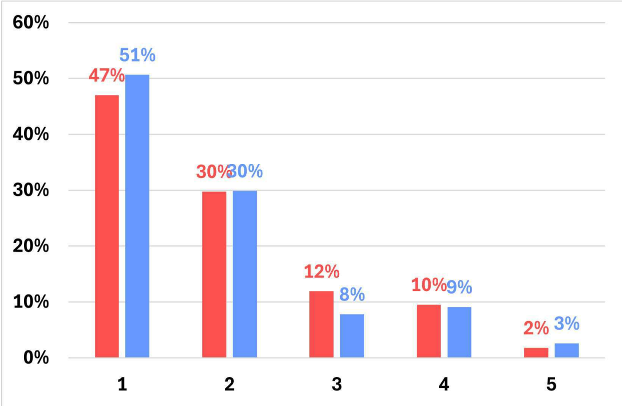


Padua + Trento		Padua	
Sample	168	Sample	77
Mean	3.1	Mean	3.1
P_f (%)	40	P_f (%)	35
P_s (%)	36	P_s (%)	33
Cns	0.5	Cns	0.6
η^2	0.001	η^2	0.001

Table 4.6: Results for question 10. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

(11) "Quantum Physics should NOT be taught in schools because it is not necessary for those who will not be engage in the study of physical sciences, and those who will devote themselves to it will have time to study it at university." Do you agree? (1 Not at all - 5 Very much)

HISTOGRAM	STATISTICS



Padua + Trento		Padua	
Sample	168	Sample	77
Mean	1.9	Mean	1.8
P_f (%)	12	P_f (%)	12
P_s (%)	77	P_s (%)	81
Cns	0.6	Cns	0.6
η^2	0.002	η^2	0.009

Table 4.7: Results for question 11. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

Analysis of questions 7 to 11

Aligning with the results obtained for experts and shown in Fig. (4.4), the highest level of agreement was found regarding the cultural value of QP with $Mean = 3.9$, although with a medium-low consensus, indicating that answers are rather spread.

Then, an average value of $Mean = 3.6$ with small consensus was found for the technological applications of QP, and a similar value was observed for the relevance of QP in countering misinformation with $Mean = 3.5$. These values are very similar to the experts' results ($Mean = 3.3$ and $Mean = 3.6$, respectively).

Regarding the difficulties inherent in the mathematical formalism of QP, an average mean value ($Mean = 3.1$) with a small consensus indicates that teachers do not, overall, hold a strong and shared idea in this regard. Similar results were found among experts, with a small consensus but a slighter lower mean value ($Mean = 2.6$).

Finally, the non-necessity of QP teaching had a very low average agreement (1.9 with a medium consensus).

Low values of the correlation parameter indicate that teachers' ideas did not depend on their background, and no differences were observed between the Padua and Trento samples, as shown in Fig. (4.4).

Questions	Teachers Mean	Experts Mean	Teachers P_f(%)	Experts P_f(%)	Teachers Cns	Experts Cns
7 (cultural achievements)	3.9 (4.0)	3.9	66 (73)	77	0.6 (0.7)	0.5
8 (technological applications)	3.6 (3.7)	3.3	58 (61)	52	0.5 (0.6)	0.5
9 (counter misinformation)	3.5 (3.6)	3.6	55 (54)	60	0.5 (0.5)	0.6
10 (mathematica difficulty)	3.1 (3.1)	2.6	40 (35)	<70	0.5 (0.6)	0.5

Figure 4.4: Comparison between teachers and experts' opinions about questions 7 to 10: in blue are the teachers from the Padua sample, in red are the ones from the total sample, and in orange are the experts from Onorato, Di Mauro, and Malgieri 2024.

4.4 Which Topics to Teach

This section presented a list of specific topics, and teachers were asked to rate the importance of each one on a Likert scale from 1 to 5. In the analysis, we labeled as "important" the topics that obtained a mean value ≥ 3.8 and a consensus $Cns \geq 0.6$.

As explained in the Methods chapter, a filter question was introduced to check whether respondents felt prepared to engage in the rating:

(12) Do you feel prepared enough to answer questions about teaching some specific topics of Quantum Physics?

Grouping the data into low and medium-high QP preparation categories, we obtained the results in Fig. 4.5. 34% of the respondents in the Padua sample did not feel confident enough to answer some QP questions.

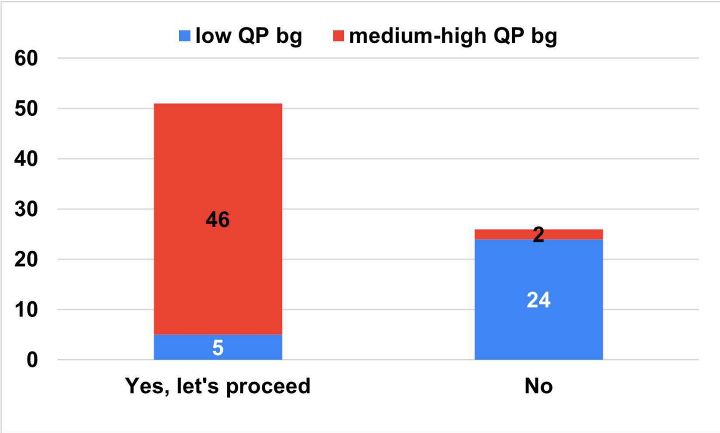


Figure 4.5: Results for the filter question using the categorization already presented between low and medium-high QP background. These data support the effectiveness of the filter question.

The question on QP topics was divided into three sub-questions (13, 14 and 15), corresponding to QP *concepts*, *phenomena and experiments*, and *technological applications*. This categorization follows the one in Krijtenburg-Lewerissa et al. 2019.

(13) We asked a group of experts which concepts are important for developing an adequate mental image of Quantum Physics. How important do you consider teaching the following concepts in high school? (1 Not very important - 5 Very important)

(14) We asked a group of experts which phenomena and experiments (mental or real) are most significant for understanding the ideas of Quantum Physics. How significant do you consider presenting the following phenomena or experiments in high school? (1 Not very important - 5 Very important)

(15) We asked a group of experts which are the most significant technological applications of Quantum Physics. How important do you consider presenting the following applications in high school? (1 Not very important - 5 Very important)

From the results in Fig. 4.6, we see that the topics that received a medium-high consensus ($P_f \geq 70\%$) were mainly related to old quantum physics. Additionally, the η^2 values indicate a medium-low correlation between physicists and non-physicists in the sample, suggesting that the answers do not exhibit a clear dependence on the respondents' background.

Regarding technological applications, there was a medium consensus for topics such as Laser and LEDs, albeit with a moderate average value. Other quantum applications received poor ratings.

The results from the Padua sample largely align with Old QP topics, although some topics showed lower importance in the total sample. Specifically, some topics shifted from high to medium importance, and from medium to low, as evident in Fig. (4.6). Nevertheless, the final results closely resemble those obtained by Onorato, Di Mauro, and Malgieri 2024 for experts, indicating an emphasis on traditional QP topics without significant focus on technological applications. Notably, topics related to Laser and LED exhibited medium relevance in Padua, which was higher compared to the total (Trento+Padua) sample.

PADUA+TRENTO							PADUA						
QP Concepts	Sample	Mean	P_f (%)	P_s (%)	Cns	η^2	QP Concepts	Sample	Mean	P_f (%)	P_s (%)	Cns	η^2
Particle Nature of Light	138	4.3	78	5	0.7	0.009	Wave-Particle Duality	51	4.5	84	2	0.7	0.014
Wave-Particle Duality	139	4.2	78	7	0.6	0.003	Particle Nature of Light	51	4.4	82	6	0.7	0.007
Atomic Energy Levels and Quantization	138	4.2	79	7	0.6	0.021	Atomic Energy Levels and Quantization	51	4.4	84	0	0.7	0.033
Heisenberg's Uncertainty Principle	137	4.0	72	8	0.6	0.013	Heisenberg's Uncertainty Principle	51	4.2	82	4	0.7	0.022
Probability	136	3.9	65	11	0.6	0.011	De Broglie Wavelength	51	4.2	75	8	0.6	0.038
De Broglie Wavelength	137	3.9	66	15	0.5	0.015	Probability	51	4.1	73	8	0.6	0.001
Wave Function	138	3.5	52	17	0.6	0.021	Wave Function	51	3.6	55	10	0.7	<0.001
Superposition	132	3.5	52	23	0.5	0.025	Superposition	51	3.6	59	18	0.6	0.001
Pauli Exclusion Principle	134	3.3	47	23	0.6	<0.001	Spin	51	3.5	53	18	0.6	0.032
Quantum States	131	3.3	47	29	0.5	0.011	Quantum States	51	3.5	51	22	0.6	0.016
Spin	134	3.2	43	28	0.6	<0.001	Pauli Exclusion Principle	51	3.4	53	18	0.7	0.035
Tunneling	136	3.1	40	31	0.5	<0.001	Tunneling	51	3.3	43	20	0.6	0.004
Quantum Measurements	130	3.1	39	36	0.5	0.022	Incompatible Observables	51	3.2	43	29	0.6	0.076
Incompatible Observables	129	3.0	36	33	0.6	<0.001	Quantum Measurements	51	3.1	41	33	0.5	<0.001
Fermions/Bosons	134	2.9	29	40	0.6	0.004	Entanglement	51	3.0	37	31	0.6	0.020
Entanglement	133	2.9	32	40	0.5	0.006	Time Evolution	51	2.9	35	39	0.6	0.031
Time Evolution	131	2.8	26	43	0.5	0.004	Fermions/Bosons	51	2.9	27	33	0.7	0.003
QP Experiments	Sample	Mean	P_f (%)	P_s (%)	Cns	η^2	QP Experiments	Sample	Mean	P_f (%)	P_s (%)	Cns	η^2
Double-Slit Experiment	137	4.4	84	5	0.7	0.041	Photoelectric Effect	51	4.6	94	0	0.8	0.020
Photoelectric Effect	137	4.3	81	6	0.7	0.032	Double-Slit Experiment	51	4.6	96	0	0.8	0.004
Blackbody Radiation	136	3.9	68	10	0.6	0.002	Blackbody Radiation	51	4.4	82	2	0.7	0.086
Spectral Lines	130	3.9	69	12	0.6	0.016	Compton Effect	51	4.2	80	12	0.6	0.070
Compton Effect	135	3.9	64	16	0.6	0.002	Spectral Lines	51	4.1	75	8	0.7	0.130
Schrödinger's Cat	135	3.6	61	17	0.6	0.001	Radioactive Decay	51	3.9	71	12	0.6	0.001
Radioactive Decay	131	3.6	56	15	0.6	0.022	Schrödinger's Cat	51	3.8	69	10	0.7	0.065
Harmonic Oscillator	130	3.2	43	28	0.6	0.025	Harmonic Oscillator	51	3.4	49	24	0.6	0.178
1D Potential Well	132	3.0	39	39	0.5	0.010	1D Potential Well	51	3.1	39	41	0.5	0.001
Specific Heat of Solids	129	2.8	32	41	0.5	0.014	Specific Heat of Solids	51	2.9	37	39	0.5	0.019
QP Applications	Sample	Mean	P_f (%)	P_s (%)	Cns	η^2	QP Applications	Sample	Mean	P_f (%)	P_s (%)	Cns	η^2
Laser	137	3.9	66	9	0.6	<0.001	Laser	51	4.0	71	6	0.7	0.171
LED	137	3.8	65	13	0.5	0.005	LED	51	4.0	71	10	0.6	0.204
Semiconductors	138	3.7	61	12	0.6	<0.001	Semiconductors	51	3.8	71	10	0.7	0.089
Solar Cell	134	3.5	54	22	0.5	0.003	Solar Cell	51	3.5	59	20	0.6	0.103
Quantum Computer	138	3.1	39	31	0.5	0.016	Quantum Computer	51	3.1	43	31	0.5	0.046
Quantum Information	135	2.9	36	36	0.5	<0.001	Quantum Information	51	3.1	41	29	0.6	0.037

Figure 4.6: Results for questions 13, 14 and 15 on the QP concepts, experiments and applications, for total sample and for the Padua sample. Topics with a mean Likert value ≥ 4.0 with $P_f > 70\%$ and a $Cns \geq 0.6$ are highlighted in green.

Comparison with experts

The comparison with the results obtained from experts in Onorato, Di Mauro, and Malgieri 2024 is described following the mean value score in Fig. (4.9).

We also compare the means and the sum of deviations from the mean value for each topic. The deviations (in percentage) are calculated as:

$$dev_i(\%) = \frac{|x_i - \langle x \rangle|}{\langle x \rangle} \cdot 100$$

where x_i is the mean value for each QP topic, and $\langle x \rangle$ is the average value of the mean values for each section. These values are displayed in Fig. (4.10), while a synthetic comparison is shown in Fig.(4.11). From this visualization, we can see that experts and teachers had similar views about the concepts, while teachers attributed higher relevance for experiments and applications but with bigger deviations, indicating disagreement.

In more detail for each section:

- **QP Concepts:** Teachers gave increased importance to Wave-Particle Duality and the de Broglie Wavelength, prioritizing them over Superposition, a topic ranked higher by the experts. The other important topics have almost the same average value, except for Atomic Energy Levels and Quantization, which were evaluated higher by the experts.

  The experts' relevant topics, in decreasing order, are the Atomic Energy Levels and Quantization, Particle Nature of Light, Heisenberg's Uncertainty Principle, Probability, Superposition, and Wave-Particle Duality.

  For the teachers instead, looking at both the results from both the total sample and the Padua's one, the relevant topics are the Particle Nature of Light, Wave-Particle Duality, Atomic Energy Levels and Quantization, Heisenberg's Uncertainty Principle, and with slightly lower importance then Probability and de Broglie Wavelength (with LoA that pass from over 70% in Padua sample to lower than that on the total one).

  Thus, the only difference in content is the substitution of the de Broglie Wavelength for teachers with Superposition for experts.

- **QP Experiments:** Teachers gave increased importance to the Double-Slit Experiment, reflecting the increased importance given to Wave-Particle Duality.

  The experts' relevant topics, in decreasing order, are the Photoelectric Effect, Double-Slit Experiment, Spectral Lines, and Blackbody Radiation.

  For the teachers instead are the Double-Slit Experiment, Photoelectric Effect and with slightly lower importance then Blackbody Radiation, Spectral Lines, and Compton Effect (with LoA that pass from over 70% in Padua sample to lower than that on the total one).

  Thus, the only difference in content is the higher importance placed on the Compton Effect by teachers.

- **QP Applications:** The differences in topic relevance order are small, and the importance given to these topics is also small, in fact only in the Padua sample there are some relevant topics, Led and Laser. However, teachers valued the topics about technological applications higher than experts (almost one Likert scale point difference).

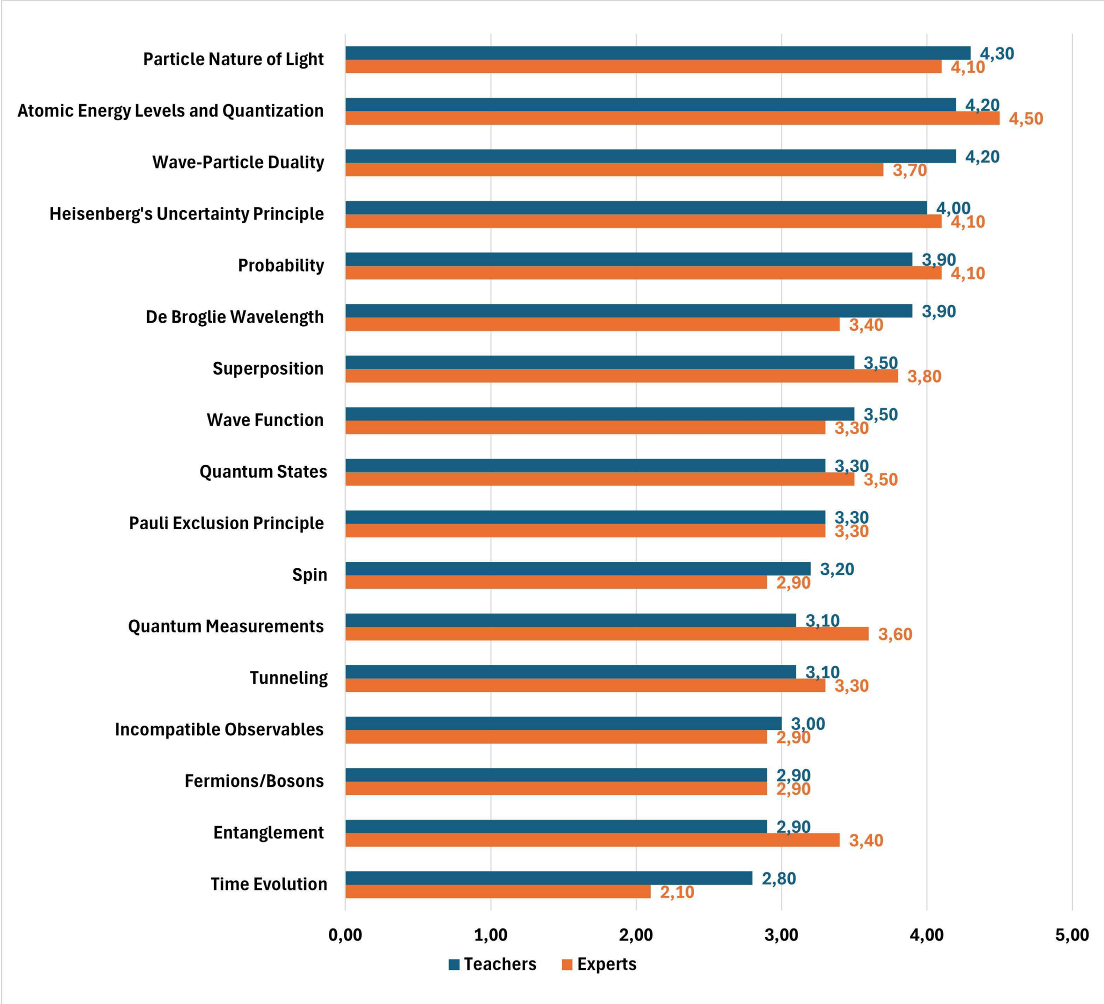


Figure 4.7: Results obtained for the mean value compared between experts (orange) and teachers (blue) in terms of QP concepts.

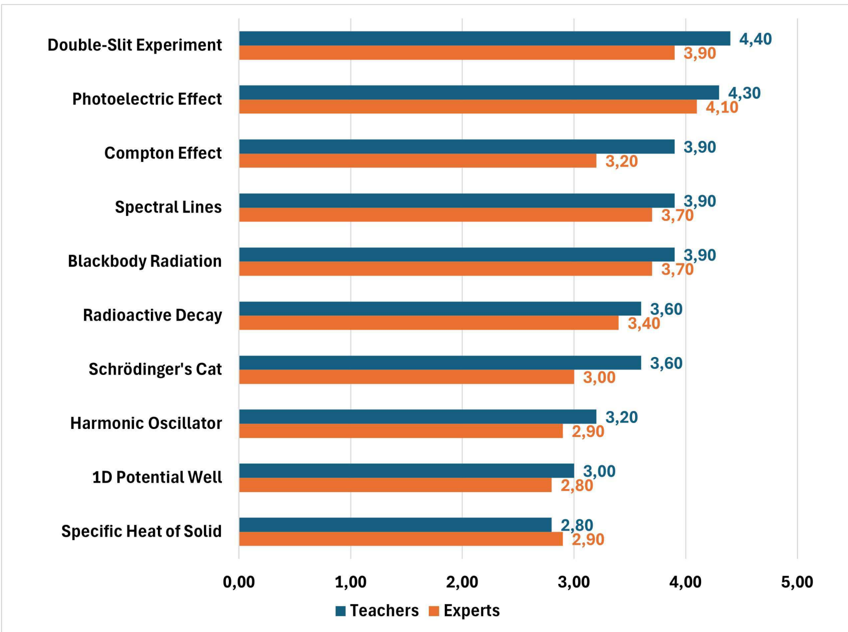


Figure 4.8: Results obtained for the mean value compared between experts (orange) and teachers (blue) in terms of QP experiments.

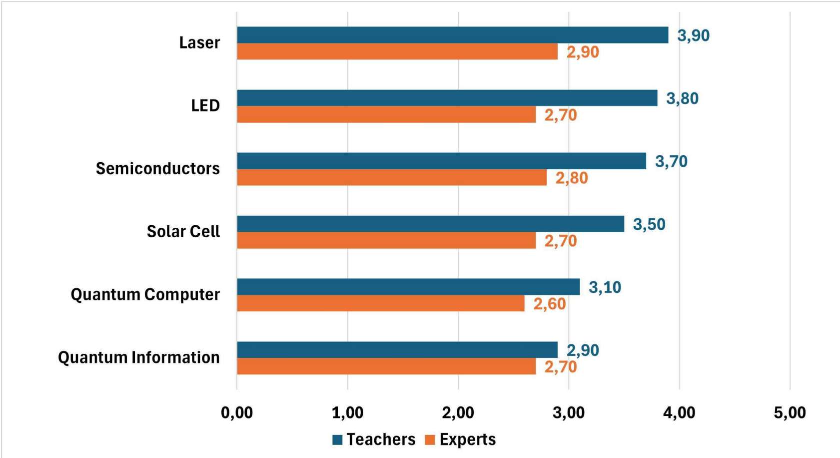


Figure 4.9: Results obtained for the mean value compared between experts (orange) and teachers (blue) in terms of QP applications.

QP Concepts	Teachers Mean	Experts Mean	Teacher Deviations [%]	Experts Deviations [%]
Particle Nature of Light	4,3	4,1	24	18
Wave-Particle Duality	4,2	3,7	21	7
Atomic Energy Levels and Quantization	4,2	4,5	21	30
Heisenberg's Uncertainty Principle	4,0	4,1	15	18
Probability	3,9	4,1	12	18
De Broglie Wavelength	3,9	3,4	12	-2
Wave Function	3,5	3,3	1	-5
Superposition	3,5	3,8	1	10
Pauli Exclusion Principle	3,3	3,3	-5	-5
Quantum States	3,3	3,5	-5	1
Spin	3,2	2,9	-8	-16
Tunneling	3,1	3,3	-11	-5
Quantum Measurements	3,1	3,6	-11	4
Incompatible Observables	3,0	2,9	-14	-16
Fermions/Bosons	2,9	3,4	-17	-2
Entanglement	2,9	2,9	-17	-16
Time Evolution	2,8	2,1	-19	-39
QP Experiments	**Teachers Mean**	**Experts Mean**	**Teacher Deviations [%]**	**Experts Deviations [%]**
Double-Slit Experiment	4,4	3,9	20	16
Photoelectric Effect	4,3	4,1	17	22
Blackbody Radiation	3,9	3,6	7	10
Spectral Lines	3,9	3,7	7	10
Compton Effect	3,9	3,2	7	-5
Schrödinger's Cat	3,6	3,0	-2	-11
Radioactive Decay	3,6	3,4	-2	1
Harmonic Oscillator	3,2	2,9	-13	-14
1D Potential Well	3	2,8	-18	-17
Specific Heat of Solids	2,8	2,9	-23	-14
QP Applications	**Teachers Mean**	**Experts Mean**	**Teacher Deviations [%]**	**Experts Deviations [%]**
Laser	3,9	2,9	12	6
LED	3,8	2,7	9	-1
Semiconductors	3,7	2,8	6	2
Solar Cell	3,5	2,7	0	-1
Quantum Computer	3,1	2,6	-11	-5
Quantum Information	2,9	2,7	-17	-1

Figure 4.10: Results of the average values for each topic in the sections QP Concepts, QP experiments and QP applications, compared between teachers (blue) and experts (orange) with their deviations in percentage.

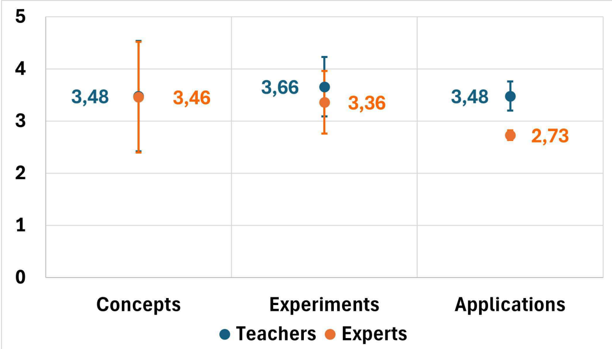


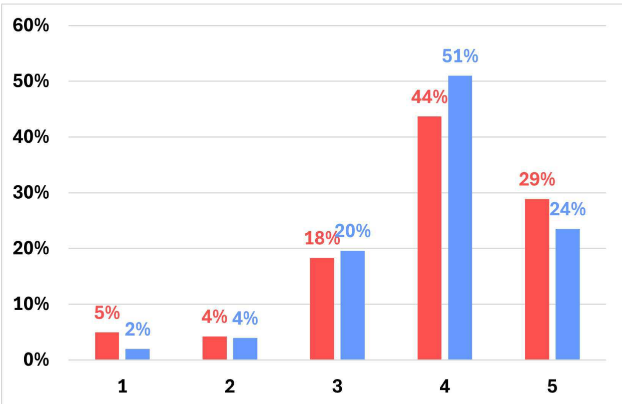
Figure 4.11: The results of the average values for the sections QP concepts, QP experiments, and QP applications, compared between teachers (blue) and experts (orange), with the deviations of each individual topic summed within each section and represented as error bars.

4.5 Approaches to Teaching Physics

The questions in this section were intended to investigate teachers' views on possible approaches to teaching Quantum Physics. They included four questions on the (quasi-) historical approach (questions from 16 to 19), a question on teachers' interest in teaching approaches to QP beyond the old physics of quanta (question 20), and a question on whether the introduction of "new QP" elements would entail a revision of the whole curriculum (question 21). Questions 20 and 21 were added only in the Padua version of the questionnaire.

(16) The National Guidelines suggest introducing Quantum Physics through the "first quantum physics", presenting the experiments that represent the break with classical physics (e.g., photoelectric effect, hydrogen atom spectrum, blackbody radiation, Compton effect, etc.). Most textbooks follow this approach. Do you agree? (1 Not at all - 5 Very much)

HISTOGRAM



STATISTICS

Padua + Trento		Padua	
Sample	142	Sample	51
Mean	3.9	Mean	3.9
P_f (%)	73	P_f (%)	75
P_s (%)	9	P_s (%)	6
Cns	0.6	Cns	0.7
η^2	0.009	η^2	<0.001

Table 4.8: Results for question 16. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

The answers for question 16 suggest a medium-high consensus about the traditional approach. However from the experts' opinions in Onorato, Di Mauro, and Malgieri 2024 there is a slighter lower average Likert value $Mean = 3.4$ and a medium-small consensus ($P_f = 60\%$ and $Cns = 0.5 - 0.6$), indicating more doubts among the experts about the quasi-historical approach compared to the teachers. The Padua sample does not differ from the whole sample, and the correlation parameter is very low, suggesting no dependence on the teachers' background.

(17) Some texts are very rigorous in reporting not only the physical contents but also the historical evolution that led to the formulation of the new theories. Other texts, however, accompany the presentation of the physical contents with a quasi-history, a partially altered narrative (e.g., with historiographical omissions), but more linear and easy to follow. What do you think about integrating historical content into the teaching of Physics?

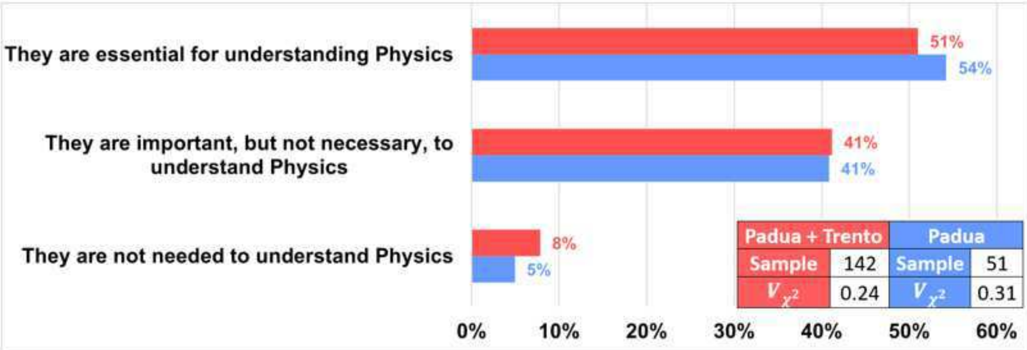


Figure 4.12: Results for question 17. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

(18) What do you think of the quasi-historical approach to teaching Quantum Physics in high school?

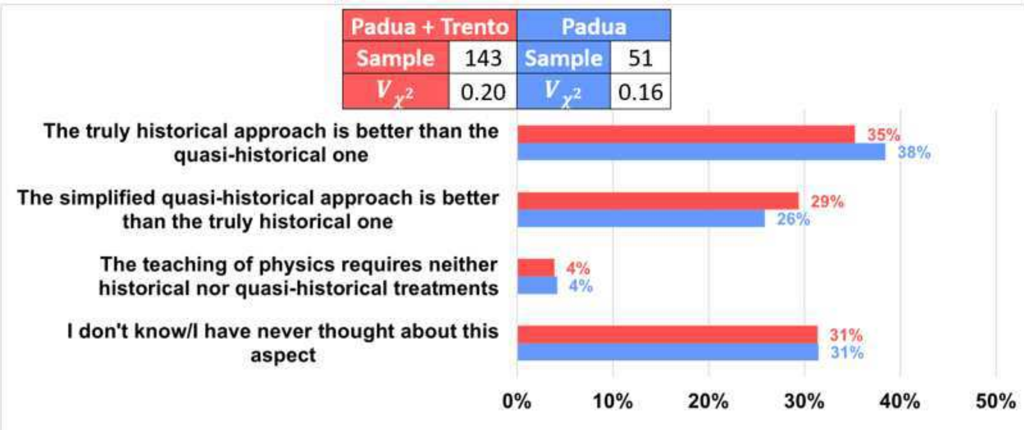
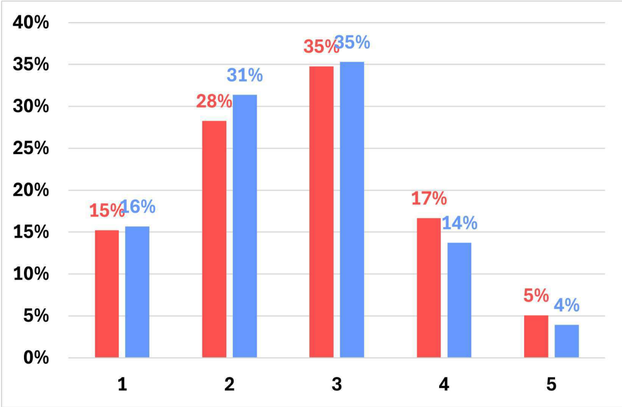


Figure 4.13: Results for question 18. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

(19) In the textbooks that report it, the "first quantum physics" is often presented as a path where blackbody radiation, photoelectric effect, Compton effect, and Bohr model follow one another linearly. Which of the following statements regarding the "first quantum physics" do you prefer? (1 - It is a simplified narrative with alterations/omissions 5 - It correctly represents the historical development of Quantum Physics)

HISTOGRAM



STATISTICS

Padua + Trento		Padua	
Sample	138	Sample	51
Mean	2.7	Mean	2.6
P_f (%)	22	P_f (%)	18
P_s (%)	43	P_s (%)	47
Cns	0.6	Cns	0.6
η^2	0.029	η^2	0.079

Table 4.9: Results for question 19. The colors represent the two different samples: blue-Padua, red-Total (Padua and Trento)

Analysis of questions 17-18-19

Most of the respondents thought that the integration of historical content in physics teaching is essential (51%), while 41% think it is important but not necessary for teaching physics. There are doubts among the teachers regarding whether an authentic historical approach is better than a quasi-historical one, with 35% of the respondents (38% for Padua) preferring the "truly historical" approach and 29% (26% for Padua) preferring the quasi-historical one, while almost one-third of the teachers (31%) do not know or have never thought about it.

A similar uncertain situation emerges from question 19, where most respondents recognized that the traditional presentation of QP experiments in textbooks is a simplified narrative, but 35% are unsure (low-medium consensus of 2.7). Based on the correlation indices, teachers with a physics background do not have an explicit preference on the teaching approach, whereas teachers with a non-physics background prefer the historical one. However, this result may be incorrect because they confuse the two approaches, as can be seen in question 19 where the physics teachers tend to recognize the simplified narrative in textbooks, while the non-physics teachers think that it correctly represents the historical development of QP.

Question 20 briefly informed the teachers about the existence of research-based proposals for QP teaching in secondary school, listing some of them, and then asked the respondents whether they would be interested in learning more about these approaches. Question 21 asked to the teachers how they would modify the Physics curriculum at the *Liceo Scientifico*.

(20) Some researchers have formulated educational proposals aimed at overcoming the quasi-historical approach currently used in high school, arguing that it is important to introduce some aspects of the subsequently evolved quantum theory. Some of the proposals include, for example: the introduction of concepts such as spin, using 2x2 matrices as a relatively accessible mathematical tool; the exploration of phenomenology, such as polarization, which can highlight some properties of quantum particles (e.g., concept of state); the study of some key experiments for the construction of the theory, such as the

double-slit. Would you be interested in exploring these approaches?

The results show that most of our sample (74%) are interested in learning more about research-based teaching proposals.

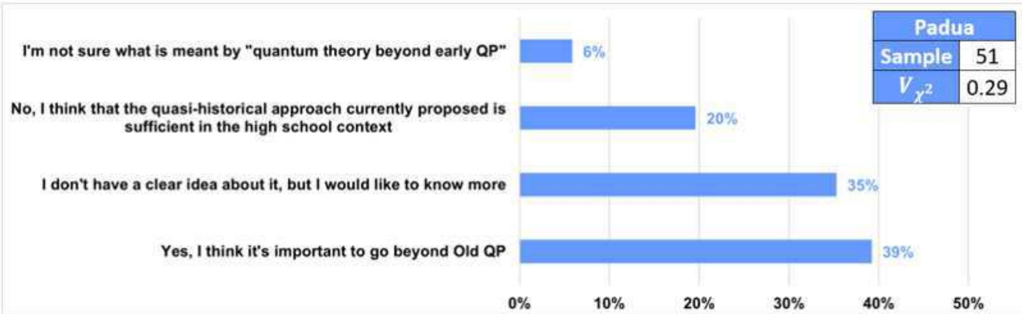


Figure 4.14: Results for question 20. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

(21) One of the open questions regarding the teaching of modern physics (Quantum Physics and Relativity) at Scientific High School is the following: Is it preferable to include some elements of modern physics at the end of the curriculum, or to revise the entire Physics curriculum to build a coherent vision of Physics that takes into account its current developments?

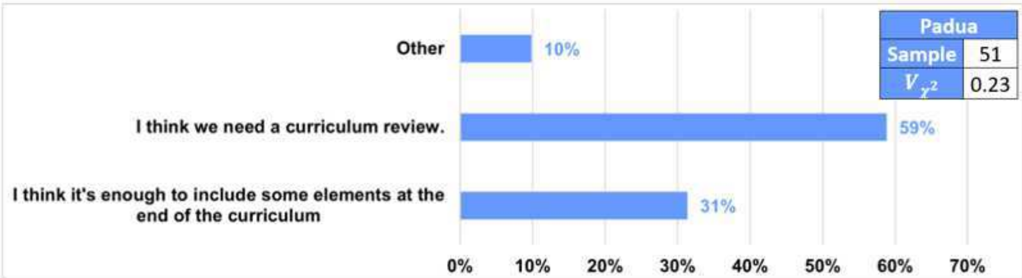


Figure 4.15: Results for question 21. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

Almost half of our set of teachers (59%) acknowledged that a revision of the entire physics curriculum would be needed to innovate the teaching of QP significantly, while 31% think that adding something at the end of the fifth year is sufficient.

4.6 Interpretations of Quantum Physics

The questions in this section covered some of the controversial aspects of QP teaching mentioned in Chapter 2. In addition to the questions already present in the Trento questionnaire, in Padua we added some questions about QP interpretations (questions 26 to 36).

Questions 22 and 23 investigated teachers' conceptions of the photon, in terms of whether it has well-defined momentum and energy, and in terms of its possible graphical/symbolic representation.

(22) Einstein proposed that electromagnetic radiation is "quantized" in localized packets with well-defined energy and momentum (later called "photons"). How would you describe a photon?

The 78% of the respondents described the photon as *a massless particle with well-defined momentum and energy*, indicating a large consensus on this point. This contrasts with the results from Onorato, Di Mauro, and Malgieri 2024 where the experts' opinion were divided: one-third agreed on the definiteness of energy and momentum, another third disagreed, and the last fraction held neither view.

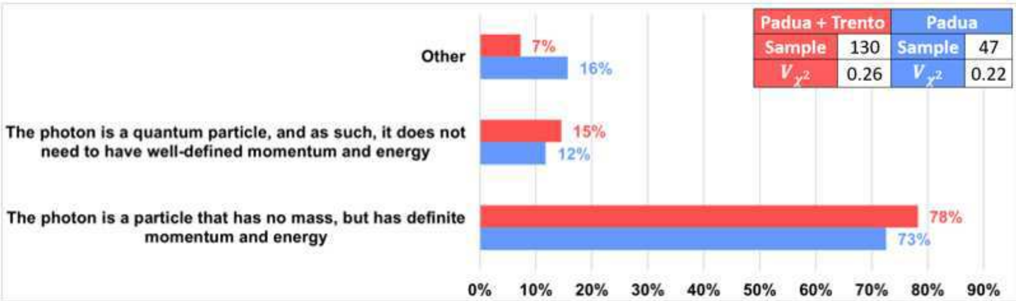


Figure 4.16: Results for question 22. The colors represent the two different samples: blue-Padua, red-Total (Trento and Padua).

(23) In textbooks, different representations of the photon can be found (Fig. 4.17). How would you personally represent a photon?

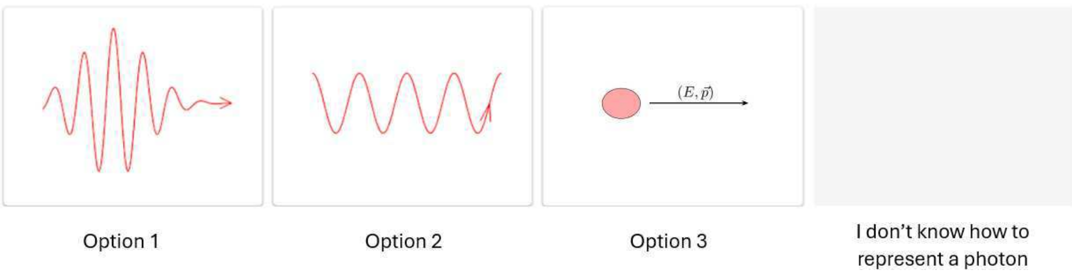


Figure 4.17: List of the possible answers to question 23: option 1, wave packet; option 2, sinusoidal wave; option 3, classical particle; last if they don't know how to represent a photon.

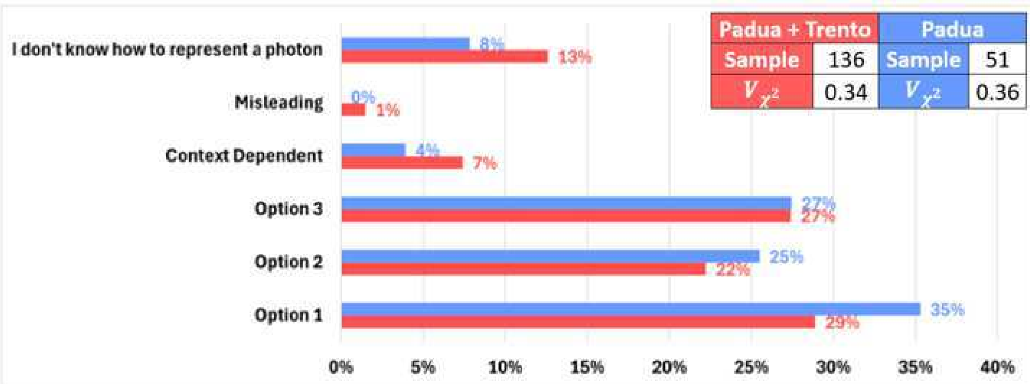


Figure 4.18: Results for question 23. The colors represent the two different samples: blue-Padua, red-Total (Trento and Padua).

The majority of the total sample was spread over the three options: wave packet (29%), sinusoidal wave (22%), and classical particle (27%).

Regarding the wave-like representation, some comments suggested that some teachers might have misinterpreted the picture, confusing it with a Feynman diagram:
Utilizzo un diagramma di Feynman, per esempio uno scattering elettrone-elettrone, in cui

disegno il fotone con una linea ondulata tipo opzione 2.
[Translated: I use a Feynman's diagram, for example an electron-electron scattering, where I represent the photon with a wavy line like option 2.]

The correlation analysis using the chi-squared parameter indicates a medium-low correlation, in fact teachers with a background in physics chose the wave representations more often than the non-physicist ones (as expected from the comments above).

From the answers, we can infer that more non-physicist teachers are unable to represent a photon compared to those with a physics background (almost a 10% difference for the whole sample).

(24) The Heisenberg uncertainty principle establishes the limits in the possibility of simultaneously measuring two physical quantities (e.g. position and momentum of a particle) with arbitrary precision. This principle is often presented by reporting one of the following arguments:

- ***Heisenberg's "microscope" thought experiment*: The position of a particle is determined by interaction with a short-wavelength photon to minimize uncertainty about the position. This however produces a large uncertainty in the momentum.**
- ***Single-slit experiment*: The position of a photon is determined by forcing it to pass through a narrow slit, but this generates an uncertainty in the photon's momentum, which generates the typical interference pattern.**

What do you think about these two arguments?

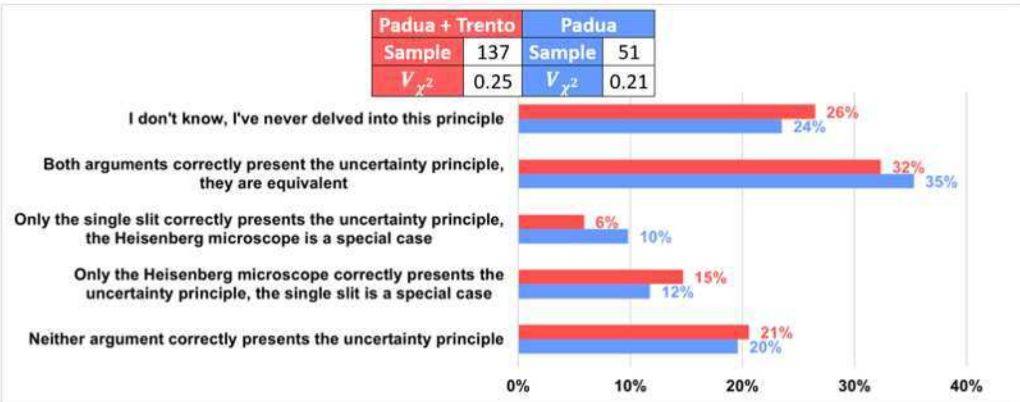


Figure 4.19: Results for question 24. The colors represent the two different samples: blue-Padua, red-Total (Trento and Padua).

There is a non-negligible fraction (36 teachers for the total sample and 12 for the Padua sample) that is unsure about the answer. 32% of the respondents stated that the formulations of the uncertainty principle using the single-slit diffraction and Heisenberg's microscope are equivalent (more non-physics teachers). According to Onorato, Di Mauro, and Malgieri 2024: *Other strategies have been suggested, most notably the one based on an analysis of single-slit diffraction [...] 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%)..* So, a very low number of respondents, 6%, may have recognized this fact (10% for the Padua sample), and a not negligible fraction (almost 20%) think that none of the two formulations represents the correct principle (more physics teachers).

(25) Another fundamental principle of Quantum Physics is the concept of complementarity, which is usually formulated as follows:

- **I Formulation: "The corpuscular and wave aspects of a physical phenomenon never manifest themselves simultaneously, but any experiment that allows us to observe one prevents us from observing the other. The two aspects are however complementary because both are indispensable to provide a complete physical description of the phenomenon. It is therefore the experimental apparatus that determines the quantum system as a wave or particle."**

- **II Formulation: according to some researchers, the principle should be reformulated differently: "An experimental apparatus can simultaneously provide partial information on the wave and particle aspects of the quantum system under examination, but the more information it provides on one aspect, the less it will give on the other. Quantum objects can sometimes simultaneously exhibit both corpuscular and wave properties (wave-particle duality)."**

Which of the two formulations do you prefer?

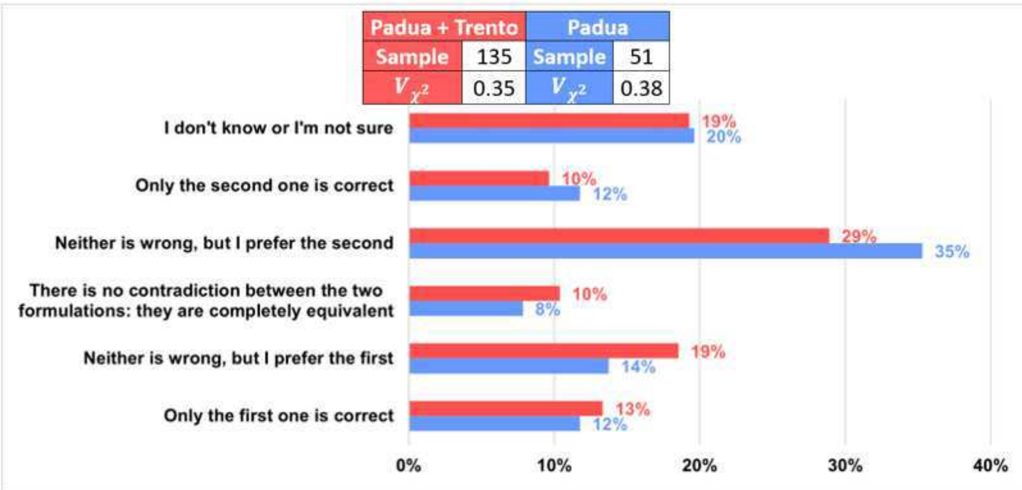


Figure 4.20: Results for question 25. The colors represent the two different samples: blue-Padua, red-Total (Trento and Padua).

There is a non-negligible fraction (26 teachers for the total sample and 10 for the Padua sample) that is unsure about the answer. Teachers tend to prefer the second formulation (Greenberger and Ya'sin) with 39% of the total sample (29% who prefer it, and 10% who recognize only this one as correct). Instead, the first formulation (Bohr–Pauli) was preferred by 32% of the respondents (19% who preferred it, and 13% who recognize only this one as correct). Therefore, there is no overall agreement on which formulation is better, with a slight preference for the Greenberger and Yasin's. Among experts, (Onorato, Di Mauro, and Malgieri 2024), 43% preferred Greenberger and Yasin's formulation and 30% preferred the other formulation, with 17% advocating for their equivalence. The comparison with only the Padua sample yields similar results. The correlation analysis shows that for this question, the two groups are not highly correlated, indicating no significant dependence on the teachers' academic background.

4.6.1 Interpretations of Quantum Physics (Padua only)

The following questions appear only in the Padua version of the questionnaire and regards the interpretations of Quantum Physics.

(26) The following frame (Fig. 4.21) is taken from a PhET simulation of the double-slit experiment with single electrons:
(a) The electron has just been emitted;
(b) The electron passes through the double-slit;
(c) The electron is detected on the screen.

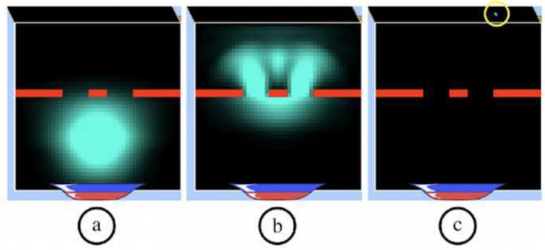


Figure 4.21: Screenshot from the PhET simulation used for question 26, as proposed also in Stadermann and Goedhart 2020 (https://phet.colorado.edu/en/simulation/quantum-wave-interference).

Three students, interpreting the experiment, expressed the following arguments. Indicate which one(s) you agree with:

- **Student 1: "The probability density, represented by the colored spot, is so large because we do not know the true position of the electron. Since a single point appears on the screen at a time, the electron must have been (even during the journey) a very small particle, located somewhere inside that spot, and therefore actually passed through only one of the two slits."**

- **Student 2: "The colored spot represents the electron itself, because it is described by a wave packet that propagates over time. The electron behaves entirely like a wave, passing through both slits and interfering with itself. This is why a typical interference pattern will appear on the screen after shooting many electrons."**

- **Student 3: "Quantum mechanics only concerns predictions about measurement results, so we can't really know what the electron does between when it is emitted and when it is detected on the screen."**

(27) If you wish, briefly explain your choice (open-ended question)

According to Baily and Finkelstein 2010, the different answers can be associated with different QP interpretations, namely:

- Student 1: Realist Interpretation;

- Student 2: Copenhagen interpretation;
- Student 3: Agnostic interpretation.

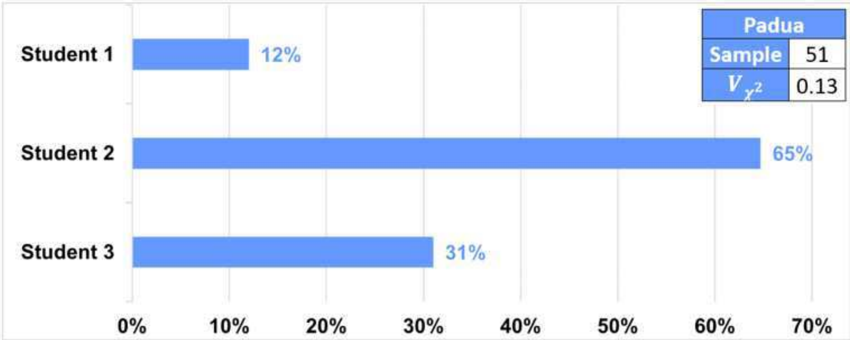


Figure 4.22: Results for question 26. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

The results indicate that the majority of teachers align with the interpretation provided by Student 2 (Copenhagen). In fact, many teachers mentioned wave-particle duality in explaning their choice. This preference does not seem to correlate with their background in Quantum Physics, as indicated by the low correlation parameter.

Specifically, the answers written by the teachers in response to the open-ended question 27 were:

- *Prima di fare la misura è corretto pensare che l'elettrone 'occupi' tutta la macchia colorata, con densità di probabilità come descritto dal modello.*
  [Translated: Before taking the measurement, it is correct to think that the electron 'occupies' the entire colored spot, with a probability density as described by the model.]
- *Mi sembra rappresenti meglio la dualità onda-particella*
  [Translated: It seems to better represent the wave-particle duality.]
- *Ho scelto quella che mi sembrava migliore, ma non direi che la descrizione sia perfetta. Avrei fatto riferimento esplicito alla complementarietà onda-particella e a come l'apparato sperimentale determini la natura dell'oggetto esaminato.*
  [Translated: I chose the one that seemed best to me, but I wouldn't say the description is perfect. I would have made explicit reference to wave-particle complementarity and how the experimental apparatus determines the nature of the examined object.]
- *Credo sia la risposta che meglio coglie la dualità onda-corpuscolo, allontanandosi dall'idea che le due visioni vadano semplicemente "sovrapposte" ma che si tratti di un oggetto diverso.*
  [Translated: I believe it is the answer that best captures the wave-particle duality, moving away from the idea that the two views should simply be 'superimposed', but that it is a different object.]
- *L'intensità del colore descrive la probabilità che l'elettrone si trovi in un punto, cioè la proiezione della funzione d'onda sull'autostato associato a quel punto dell'operatore*

posizione. È possibile descrivere l'evoluzione dell'onda di probabilità fino a che questa collassa in un punto all'arrivo sullo schermo.

[Translated: The intensity of the color describes the probability that the electron is located at a point, that is, the projection of the wave function onto the eigenstate associated with that point of the position operator. It is possible to describe the evolution of the probability wave until it collapses to a point upon arrival at the screen.]

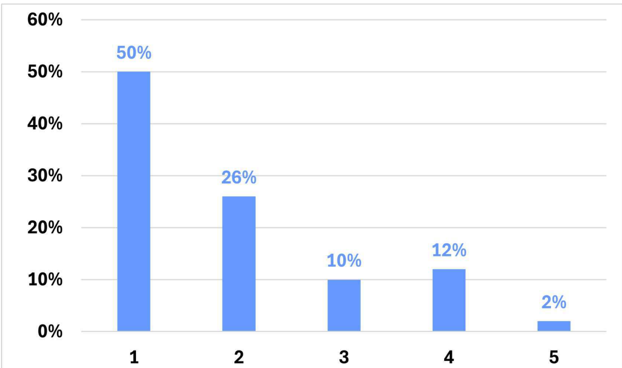
- *Preferisco l'interpretazione dell'elettrone mediante il pacchetto d'onde ma in questa affermazione manca il significato che si deve associare al modulo quadro della funzione d'onda.*

  [Translated: I prefer the interpretation of the electron through the wave packet, but this statement lacks the meaning that should be associated with the squared modulus of the wave function.]

(28) Indicate your level of agreement with the following statement: "When you are not observing it, an electron in an atom still has a well-defined (even if unknown) position at every instant of time." (1 Not at all agree - 5 Fully agree)

(29) If you wish, please briefly explain your choice (open-ended question)

HISTOGRAM



STATISTICS

Padua	
Sample	51
Mean	1.9
P_f (%)	14
P_s (%)	76
Cns	0.6
η^2	0.052

Table 4.10: Results for question 28. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

This question was utilized in Baily and Finkelstein 2010 as a "screening question" to identify respondents' interpretations for comparison with the previous one. The results indicate that at least 76% of the teachers align with the Copenhagen interpretation when answering this question. The correlation is medium-low, suggesting that a background in Physics may slightly influence teachers' views in favor of the disagreement with the statement.

Joint analysis of questions 26 and 28

Fig. (4.23) illustrates the relationship between teachers' responses to question 26 (electron in the double-slit experiment) and question 28 (electron in an atom). While none of the teachers who selected the "Copenhagen" interpretation for the double-slit experiment endorsed a completely realist view of electrons in an atom, three of them rated their realist view as 4 out of 5, and another four selected a mid-range rating of 3.

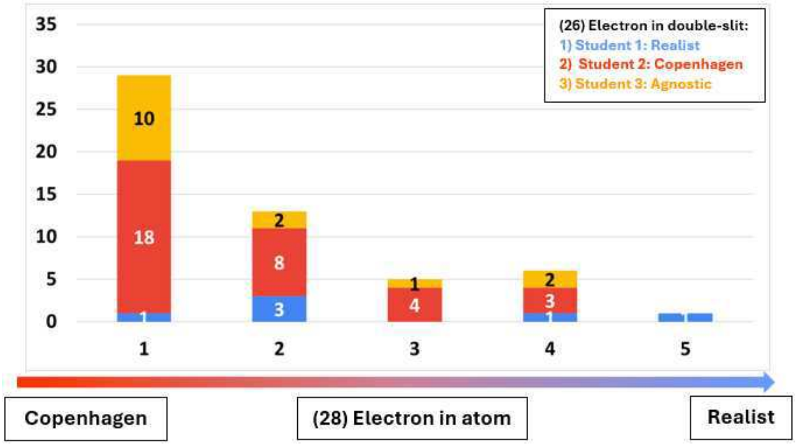


Figure 4.23: Joint analysis of questions 26 and 28. The x axis shows the results for question 28, where 1 represents a Copenhagen view and 5 represents a Realist view. The colors on each bar represent the three possible answers to question 26: blu-Realist, red-Copenhagen, yellow-Agnostic.

Conversely, teachers who identified with a "Realist" interpretation in question 26 slightly favored a Copenhagen interpretation in question 28, but their sample size is too small to be statistically significant. Then, teachers categorized as "Agnostic" according to question 26 tended to have a higher preference for a Copenhagen view in question 28.

These trends are supported by responses to the open-ended question 29 provided by some teachers:

- *L'elettrone si trova in tutte le posizioni, anche se con ampiezze di probabilità diverse* [Translated: The electron is in all positions, although with different probability amplitudes.]

- *Quando non viene osservato non posso dire dov'è (neanche cos'è in realtà...)* [Translated: When it is not observed, I cannot say where it is (or even what it is, actually...).]

The following questions, 30, 31 and 32 aimed to gain insights into teachers' explicit knowledge of different QP interpretations, to better interpret the previous answers.

(30) Have you heard of different interpretations of Quantum Mechanics?
(31) If you answered YES, can you name the ones you know and/or briefly describe describe their main characteristics (or how they differ)?
(32) If you answered YES, do you adopt a specific interpretation of Quantum Mechanics in your teaching?

The majority of the sample could not describe different interpretations of QP (only 27% of them could describe at least two different interpretations). The correlation analysis reveals a medium value, indicating a great difference between physics and non-physics backgrounds, with the former more likely to describe at least two QP interpretations. The main interpretations mentioned were Copenhagen, Bohm's Pilot Wave, and Everett's Many Worlds. Overall, teachers who were aware of interpretations and used one in their classes typically referred to the Copenhagen interpretations. Only one teacher mentioned describing the main interpretations in class along with their differences and similarities. They also noted a distinction between Bohr's and Heisenberg's interpretations, mentioning

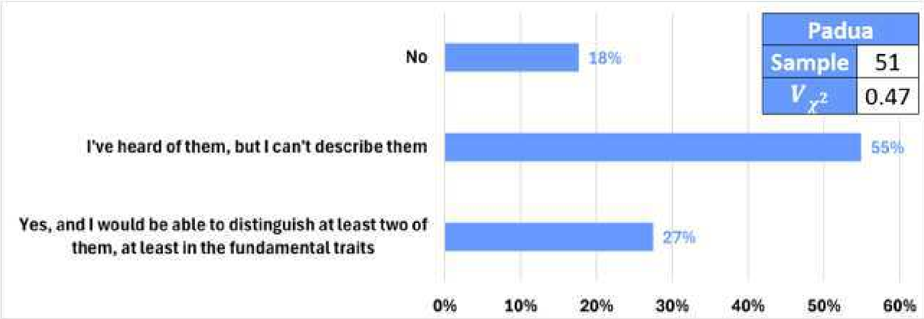


Figure 4.24: Results for question 30. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

that Bohr's interpretation aligns more with Copenhagen, while Heisenberg's tends towards an Agnostic view focused only on the mathematical formalism.

(33) Do you explicitly address the topic of interpretations of Quantum Mechanics with your students?

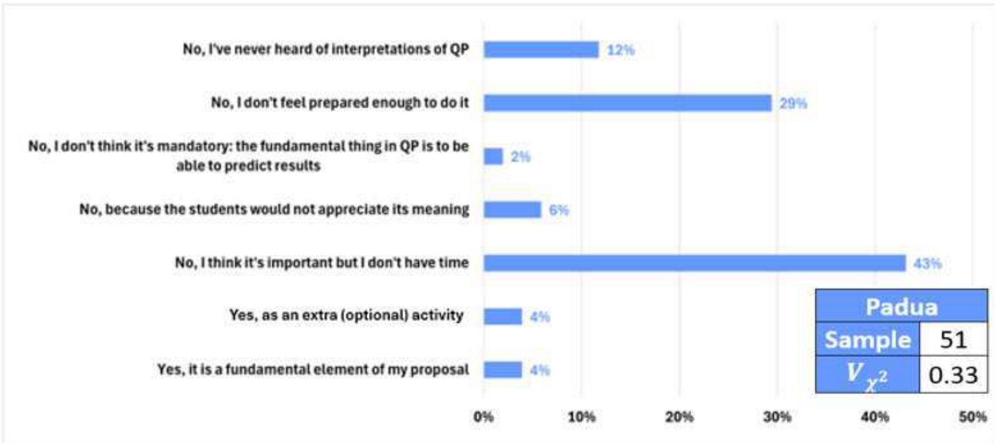


Figure 4.25: Results for question 33. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

Answers to this question highlighted the same issue as previously mentioned: lack of time and training are, in fact, also reasons why only 8% of teachers address QP interpretations at school, and half of these consider the topic as an extra (optional) activity.

Finally, questions 34-35-36 shifted the focus from interpretations themselves to the Nature Of Science (NOS), asking for teachers' ideas about the presence of controversial aspects in QP.

(34) Despite the great predictive power of Quantum Mechanics, after more than 80 years, the discussion about its interpretation is still ongoing. Different interpretations lead to identical predictions, but they differ greatly in their ontological implications (about the nature of quantum objects). This aspect of Quantum Mechanics could be considered problematic.
Below are some arguments in response to this problem: which one do you personally agree with the most?

1. **"Quantum Mechanics does not need interpretations. As long as we know how to use it to perform calculations and build devices that work thanks to it, we don't need an interpretation of Quantum Mechanics. It is beyond**

the domain of science to ask about the nature of something we cannot observe.”

2. **“Physicists should agree on which interpretation of Quantum Mechanics they want to use, just as they did with international measurement standards. If everyone remains tied to their own interpretation, there will only be many useless discussions.”**

3. **“At present, we do not know why electrons behave as described by Quantum Mechanics. But if scientists want to discover it, much creativity is needed to find an explanation. This is how interpretations are developed: it is part of the construction of scientific knowledge.”**

(35) If you wish, briefly explain your choice (open-ended question)

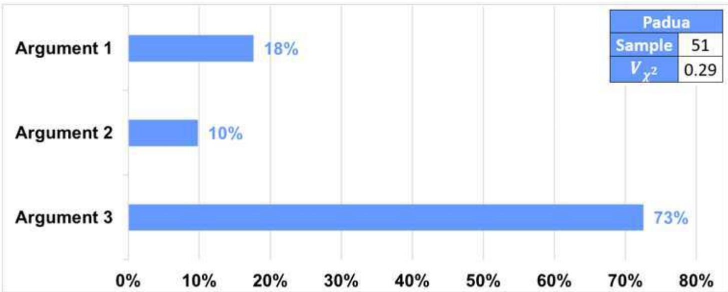


Figure 4.26: Results for question 34. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

73% of the respondents agreed that interpretations exist because we cannot explain the quantum behavior of the electron. There was also agreement on the importance of discussing the reasons for different interpretations in the classroom. However, some respondents view interpretations as standard convention to uniform with (10%) or as topics outside the domain of science (18%). The correlation analysis indicates that the responses are not strongly correlated with teachers' backgrounds.

Joint analysis of questions 33 and 34

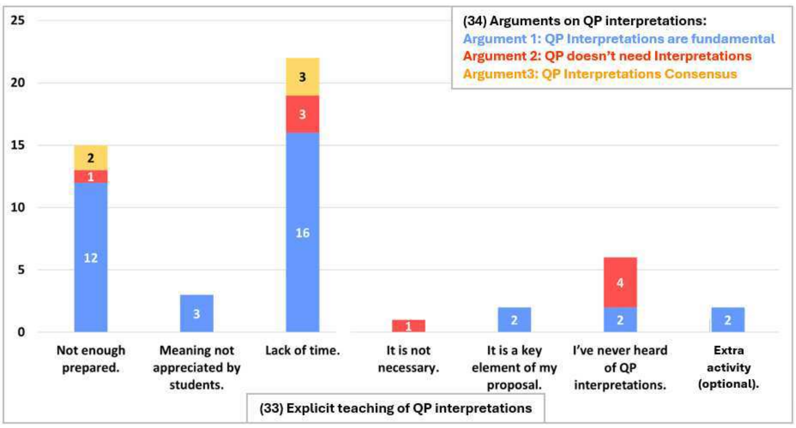


Figure 4.27: Histogram for the analysis of questions 33-34-35 and for each answers of question 33 there are the results divided into the corresponding answer on question 34: blu-student 1, red-student 2, yellow-student 3.

Figure (4.27) illustrates the joint analysis of questions 33 and 34. Some teachers believe QP does not require interpretations, often due to their unfamiliarity with them, in fact these "Agnostic" teachers attribute their stance to lack of time or preparation. This suggests that changes in teachers' attitudes towards QP interpretations could occur with additional training or revised QP curriculum that provides more time to explore these topics.

(36) What do you think about the controversial aspects of Quantum Mechanics in relation to teaching in secondary school?

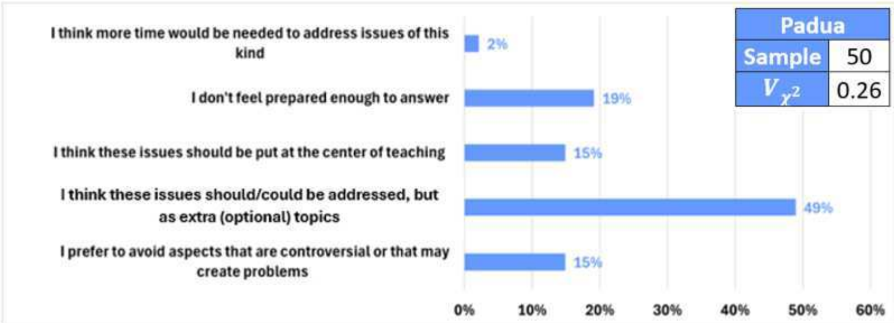


Figure 4.28: Results for question 36. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

The 49% of respondents agree that controversial aspects of QP should be addressed at the high school level, but as optional topics. Smaller fractions prefer to either avoid these topics (15%) or prioritize them in teaching (15%). Additionally, 19% expressed a lack of preparation to tackle these controversial aspects, while only one teacher highlighted the need for more time to address them adequately.

4.7 Formative Needs

The final questions were introduced specifically to investigate teachers' perceived professional development needs, as a basis for designing future training courses. These questions were included only in the Padua version of the questionnaire. The results indicate that interests among teachers appear to be independent of their QP background.

(37) Which of these elements would you like to find in a teacher training school on Quantum Physics?
(38) Which of the following educational tools for teaching quantum physics in secondary education would you like to explore further?

There is significant interest in moving beyond Old Quantum Physics with both theoretical lessons and educational proposals, but teachers also express interest in exploring ideas to innovate the teaching of old quantum physics and aspects related to the history of physics and the nature of science, e.g. the different interpretations of quantum physics. Teachers were comparatively less interested in experimenting technologies, simulations, or quantum games; however, one-third of them would like to explore experiments to support the teaching of QP.

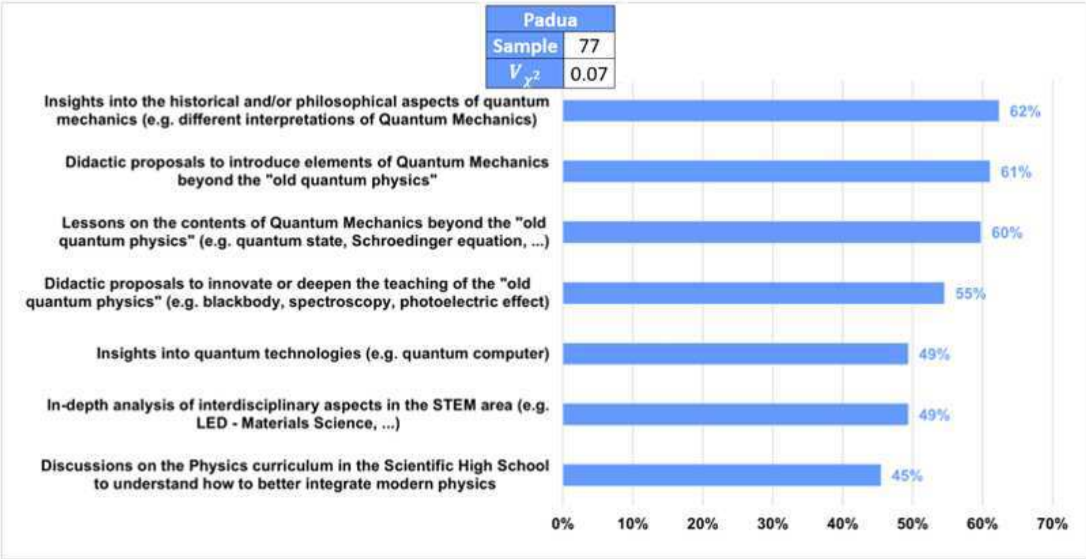


Figure 4.29: Results for question 37. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

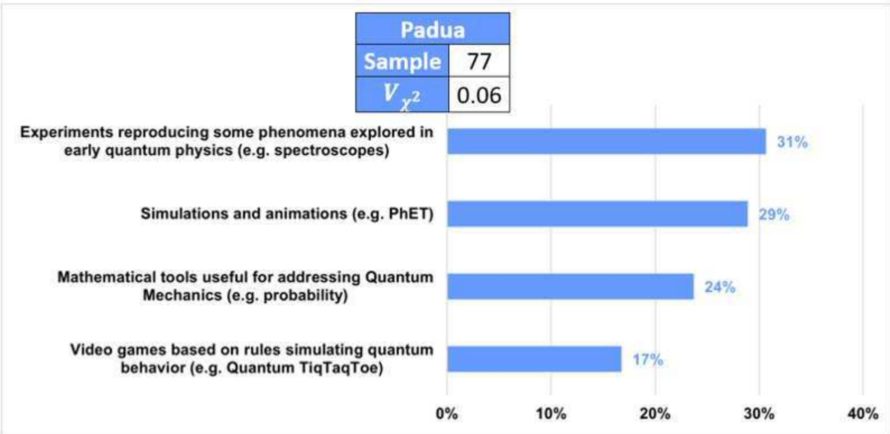


Figure 4.30: Results for question 38. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

4.8 Textbooks

This section focuses one the textbooks used for lessons and the courses taken by teachers on Quantum Physics (QP).

(47) Which textbook do you use for teaching Quantum Physics?

The most used textbooks for teaching QP in high school are:

1. Amaldi
2. Cutnell
3. Fabbri-Masini
4. Walker

These results can be compared with the analysis of textbooks conducted by Perli

2024, which produced the plot in Fig. (4.32). In our context, the usage of the Cutnell-Johnson textbook is comparable to that of the Amaldi texbook (31% Amaldi, 28% Cutnell-Johnson), whereas on a national scale the Amaldi textbook is notably more preferred (40%, with Cutnell-Johnson only accounting for 10% of the national sample). Our findings regarding the Fabbri-Masini (FTE - Quantum) and Walker textbooks aligns with national trends. The correlation analysis also shows that the Fabbri-Masini approach is mostly used by physics teachers in the Padua sample.

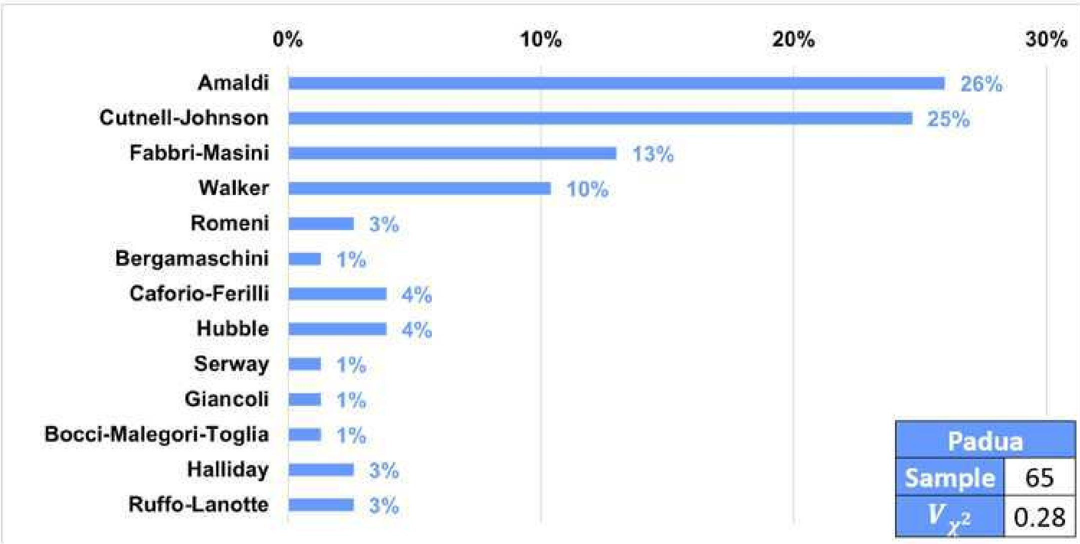


Figure 4.31: Results for question 47. The color is only blue because this question is exclusive to the Padua version of the questionnaire.

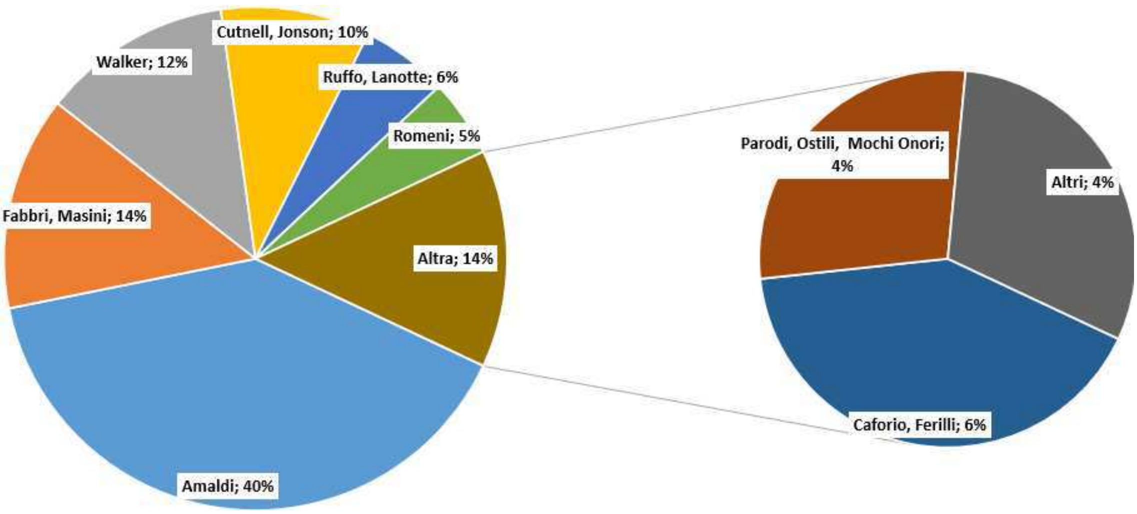
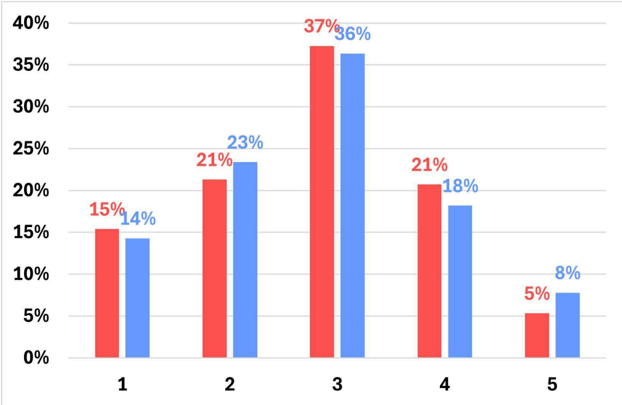


Figure 4.32: The results of the analysis of the use of physics textbooks by Italian teachers using national data, conducted by Luca Perli, MSc candidate, Uni Trento Perli 2024).

(48) How much do you rely solely on the textbook in preparing your lessons? (1 Add a lot of material - 5 Use only textbooks)

HISTOGRAM	STATISTICS
	see below

Padua + Trento		Padua	
Sample	167	Sample	77
Mean	2.8	Mean	2.8
P_f (%)	26	P_f (%)	26
P_s (%)	36	P_s (%)	37
Cns	0.6	Cns	0.6
η^2	0.033	η^2	0.030

Table 4.11: Results for question 48. The colors represent the two different samples: blue-Padua, red-Total (Trento and Padua).

The results indicate that teachers frequently supplement the textbook with additional materials.

Chapter 5

Discussion and Conclusions

In this work, we analyzed teachers' opinions on various aspects of the teaching of Quantum Physics (QP) in high school, comparing them with those of QP experts. The latter were highlighted by recent research in the Italian context (Onorato, Di Mauro, and Malgieri 2024) using a questionnaire based on current Physics Education Research literature. To investigate the teachers' perspectives, the questionnaire was modified in collaboration with the University of Tranto (Perli 2024). Additionally, sections addressing aspects of the Nature of Science (e.g. QP interpretations) and teachers' formative needs were added in the questionnaire used at UniPD. The research involved a total of N=170 teachers, including data collected at UniPD and UniTN.

The research questions were:

- What are physics teachers' attitudes and beliefs about teaching Quantum Physics in secondary school?
- What do teachers consider as the most important aspects of Quantum Physics to be taught in secondary school, and do their views align with those of experts?

Insights into these questions coming from the research are discussed separately in the following sections.

5.1 Physics Teachers' Attitudes and Beliefs on Teaching Quantum Physics

Quantum Physics is already taught in the final year of *Liceo Scientifico*, but its teaching is often limited to the "old physics of quanta". While the National Guidelines primarily mention topics from old quantum physics, they do, in principle, leave space for introducing elements of contemporary quantum physics. Physics Education Research has developed approaches to teaching Quantum Physics in high school, but these proposals have not yet been integrated into the curriculum.

In agreement with experts, the teachers acknowledged the importance of teaching QP in high school. However, they also recognized significant challenges, particularly the lack of time and limited preparation. This issued was identified regardless the teachers were physics or non-physics graduates. In fact, only 44% of the respondents had university training beyond the old quantum physics, and 37% had not taken any courses on Quantum Physics at all.

According to the teachers, the primary reason for introducing Quantum Physics (QP) in high school is its cultural value, as it represents one of the greatest achievements of science. Teachers also valued the technological applications of Quantum Physics and its utility in countering misinformation. There is no shared agreement on the QP mathematical formalism as an obstacle to learning, and this view aligns with the experts' opinions.

Almost all teachers expressed interest in learning more about PER-based approached to extend QP teaching beyond the old physics of quanta. However, they also recognized that, to effectively innovate QP teaching in high school, a revision of the entire physics curriculum would be needed. Regarding the value of the quasi-historical approach adopted in most high school textbooks compared with a truly historical approach, teachers showed more agreement with the quasi-historical approach than the experts did. The results also reveal that teachers frequently complement their teaching of QP with additional material alongside the textbook.

5.2 Key Aspects of Quantum Physics for High School Education

Regarding specific QP topics, in line with current practice and the National Guidelines, the teachers mainly identified "old quantum physics" topics. Specifically, following the categorization by Krijtenburg-Lewerissa et al. 2019 into QP *concepts*, *experiments*, and *application*s, the following topics were rated as important:

- **QP Concepts:** particle nature of light, wave-particle duality, atomic energy levels and quantization, Heisenberg's uncertainty principle, and then, with slightly less importance, probability and de Broglie wavelength.
- **QP Experiments:** double-slit experiment, photoelectric effect, and then, with slightly less importance, blackbody radiation, spectral lines and the Compton effect.
- **QP Applications:** teachers' interest focussd on LED and laser technologies.

Teachers' perspectives aligned with those of experts (Onorato, Di Mauro, and Malgieri 2024), with small differences: for example, teachers prioritized the de Broglie wavelength over superposition and gave higher importance to the Compton effect. Notably, teachers assigned greater importance to technological applications. This result can be linked to teachers' desire to make lessons more engaging by providing students with stimuli from the real world.

The questionnaire also explored teachers' opinions on some controversial aspects, like the nature of the photon and its representation, the different possible formulations of the complementarity principle, and the most suitable thought experiment to explain Heisenberg's uncertainty principle.

Teachers showed little consensus on the representation of the photon, with respondents split between representing it as a particle, a wave, or a wave packet in similar percentages. Regarding the complementarity principle, teachers, like the experts, expressed slightly more agreement with Greenberger and Yasin's version of the principle. According to this version, a system can exhibit both particle (P) and wave behavior (V) simultaneously, but with different percentages ($P^2 + V^2 \leq 1$), rather than Bohr and Pauli's version, where the two behaviors are mutually exclusive. Concerning Heisenberg's uncertainty principle, teachers partially diverged from the experts' views, favoring the single-slit experiment over Heisenberg's microscope. Only one quarter of them chose one of the two formulations, while the rest of the sample was almost evenly split among the other answers, such as not recognizing either experiment as correct for the principle, or recognizing both as correct, or not being able to respond at all.

Another section of the questionnaire regarded Quantum Physics interpretations, a topic related to the Nature of Science that has been recently explored in Physics Education Research at the secondary school level (Stadermann and Goedhart 2020), following earlier studies at the university level (Baily and Finkelstein 2010). Teachers mentioned some of the most famous interpretations of Quantum Physics such as Copenhagen, Agnostic, Realistic, Pilot wave, Matter wave, and Many-worlds interpretations. They also shared the Copenhagen/Agnostic viewpoint for the interpretation of the double-slit experiment and for the measurement of an electron inside an atom. However, the majority of teachers (92%) do not address the topic of interpretations at school, primarily due to lack of time or insufficient preparation. They acknowledged, however, that engaging with the topic of interpretations can help students appreciate the provisional and evolving nature of scientific knowledge, illustrating how scientific theories are subject to change as new evidence and perspectives emerge. This engagement fosters critical thinking and a deeper understanding of NOS, emphasizing the role of creativity and philosophical frameworks in scientific inquiry. Changes in teachers' attitudes towards QP interpretations could occur with additional training or a revised QP curriculum that provides more time for exploring these topics.

Regarding additional materials for modern physics lessons in high school, a comprehensive list of the most important quantum topics covered in all of the main famous italian physics textbooks can be beneficial for teachers. All of them explain early quantum physics, as outlined in the Italian National Guidelines. In fact, they all report the relevant concepts, experiments, and applications of Quantum Physics (QP) mentioned by teachers in the questionnaire, as described above (with the only exception of LED, which is discussed only in the Parodi-Ostili-Mochi Onori and Caforio-Ferilli, as can be seen in Perli 2024). So, following the results of Perli 2024, the commonalities between the main textbooks are:

- **QP Concepts:** Particle nature of light, wave-particle duality, atomic energy levels and quantization, Heisenberg's uncertainty principle, probability, de Broglie wavelength, wave function, Pauli principle.
- **QP Experiments:** Double-slit experiment, photoelectric effect, blackbody radiation, spectral lines, Compton effect, radioactive decay.
- **QP Applications:** Laser.

Some textbooks (Walker, Romeni, Caforio-Ferilli, and Parodi-Ostili) were found to include additional materials, especially about the technological applications of Quantum Physics.

Fig. (5.1) summarizes the results of this research regarding teachers' views on the different topics addressed in the questionnaire, and compares them, where possible, with experts' views.

CONTENTS	EXPERTS	TEACHERS
Importance of QP	Greatest cultural achievement	Greatest cultural achievement
Mathematical difficulty	No shared idea but considered a lower obstacle to learning than for teachers	No shared idea
Quasi-historical approach	Higher doubts about the textbooks' approach than teachers	Medium-high consensus on textbooks' approach
QP Concepts	Atomic energy levels and quantization Particle nature of light Wave-particle duality Probability Heisenberg's uncertainty principle Superposition	Atomic energy levels and quantization Particle nature of light Wave-particle duality Probability Heisenberg's uncertainty principle de Broglie wavelength
QP Experiments	Photoelectric effect Double-slit experiment Spectral lines Blackbody radiation	Photoelectric effect Double-slit experiment Spectral lines Blackbody radiation Compton effect
QP Applications	No consensus and low relevance	No consensus but higher relevance than experts
Photon nature	No consensus	Zero mass and definite energy and momentum No consensus on representations
Heisenberg's uncertainty principle	Single-slit diffraction preferred	Heisenberg's microscope slightly preferred (with many doubts)
Complementarity principle	/	Slight preference for the Greenberger-Yasin formulation over Bohr-Pauli's one
Double-slit experiment	/	Mainly Copenhagen and Agnostic interpretations
Measurement of an electron inside an atom	/	Mainly Copenhagen and Agnostic interpretations
Importance of QP interpretations	/	Interpretations are fundamental part of the construction of scientific knowledge

Figure 5.1: Overview of the results of this thesis regarding teachers' views on Quantum Physics topics to be taught and various controversial aspects of teaching Quantum Physics in high school, compared, if possible, with experts' views from Onorato, Di Mauro, and Malgieri 2024.

5.3 Insights for Quantum Physics Education Research and teachers' training

In the past decades, the Physics Education Research community has developed different proposals to teaching QP at the high school level (e.g. Michelini, Ragazzon, et al. 2000; Michelini, Santi, Stefanel, et al. 2014; Michelini and Stefanel 2021; Aehle, Scheiger, and Cartarius 2022; Pospiech et al. 2021; Malgieri, Onorato, and De Ambrosis 2015; Bitzenbauer and Meyn 2020; ...). In the past few years, these proposals have extended to quantum technologies and the second quantum revolution (e.g. Bungum, Henriksen, et al. 2015; Satanassi, Fantini, et al. 2021; Satanassi, Ercolessi, and Levrini 2022; Bondani et al. 2022; ...). Despite that, our results indicate that the teaching of Quantum Physics in high school is still basically limited to the old physics of quanta. The reasons can be summarized as follows:

- Lack of time, which may require a comprehensive revision of the curriculum rather than simply adding new elements to an already overcrowded schedule. The revision could involve reducing the focus on some traditional topics to make room for modern physics, but also rethinking how certain mathematics or physics topics (e.g. vectors, 2x2 matrices, probability) are taught to prepare students for learning QP.

- Lack of preparation, with many physics teachers having a limited quantum physics background.
- Lack of familiarity with Physics Education Research (PER)-based teaching proposals for QP in secondary education.

These issues align with the perceived needs for professional development, as emerged from a specific question in the UniPD questionnaire. Among the potential elements of an in-service teacher training course, teachers prioritized the following:

- Lessons on Quantum Physics beyond the old physics of quanta.
- Teaching proposals to introduce elements of QP beyond the old physics of quanta.
- Insights into the historical and/or philosophical aspects of quantum physics (e.g. QP interpretations).

These results highlight the urgent need for Quantum Physics Education Research to bridge the gap between research and practice by integrating teachers' perspectives and designing new teacher education and professional development programs. To move beyond isolated successful experiments, PER initiatives must address the challenges teachers face in terms of limited preparation and lack of time. While improving teachers' preparation can be achieved through training courses, tackling the issue of limited time poses a more complex challenge. A systematic revision of the curriculum may be necessary to effectively tackle this issue. Nevertheless, long term, authentic collaborations between teachers and researchers could serve as a starting point to understand how the new teaching proposals can be integrated in the curriculum and offer insights into what this curriculum revision could entail. Updating textbooks and developing new teaching materials will also be essential to support teachers in the endeavour.

In the Padua context, the findings of this work will inform the design of two "summer schools" for physics teachers, the first of which is scheduled for September 2024, as part of the "Quantum Frontiers" Excellence Project at the Department of Physics and Astronomy at UniPD.

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Appendix A

Questionnaire

Below, the complete questionnaire will be shown in the original language as it was administered (Italian).

Informativa sulla privacy

Informativa sul trattamento dei dati per finalità di ricerca scientifica (art. 13 reg. UE 2016/679)
Al fine di massimizzare la trasparenza sul trattamento dei dati raccolti tramite il questionario, desideriamo informarla che la normativa vigente in maniera di protezione dei dati, con particolare riguardo all'ambito della ricerca scientifica (reg. UE 2016/679; d. lgs. 196/2003; d. lgs. 101/2018), sancisce il diritto di ogni persona alla protezione dei dati di carattere personale.
Finalità e base giuridica del trattamento
Il trattamento dei dati è effettuato ai sensi dell'art. 6, par. 1, lett. e del GDPR (esecuzione di compiti di interesse pubblico). I dati raccolti vengono conservati presso le unità di ricerca in didattica della fisica delle università di Padova e Trento.
Volontarietà e anonimizzazione
La sua partecipazione è volontaria e può interrompere la compilazione in qualsiasi momento, per qualsiasi motivo. Tutte le risposte dell'indagine saranno mantenute anonime e non saranno riconducibili alla sua identità.
Modalità del trattamento
L'analisi dei dati verrà effettuata mediante applicazioni informatiche per questionari/sondaggi. I dati raccolti saranno trattati in accordo con le leggi sulla privacy e in conformità al d. lgs. 196/2003 "Codice in materia di protezione dei dati personali" e al Regolamento Europeo sulla privacy UE 679/2016 (GDPR). I dati saranno custoditi per un periodo utile all'elaborazione delle analisi statistiche e alla produzione di report scientifici. Il trattamento dei dati sarà effettuato da ricercatrici e ricercatori in relazione agli obiettivi del progetto e nel rispetto dei principi di liceità, correttezza, trasparenza, adeguatezza, pertinenza, esattezza, non eccedenza, integrità e riservatezza, nonché dei principi di privacy by design e by default (artt. 5 e 25 GDPR).
Divulgazione dei dati della ricerca
I risultati dello studio verranno utilizzati esclusivamente per scopi di ricerca. La divulgazione avverrà soltanto in forma anonima e aggregata per pubblicazioni scientifiche, e

comunque secondo modalità che non rendano identificabile l'interessata/o. Se desidera ricevere i risultati della ricerca, in forma aggregata, può scrivere alla responsabile della ricerca.
Cliccando sul pulsante "ACCONSENTO" lei dichiara che:
- Ha letto le informazioni fornite fin qui fornite;
- Acconsente volontariamente a partecipare alla ricerca;
- È maggiorenne (ha almeno 18 anni);
- È a conoscenza che le informazioni che fornirà saranno usate a fini di ricerca e che i dati saranno utilizzati in forma aggregata per pubblicazioni;
- È a conoscenza che per la rilevazione dei dati sarà utilizzata una piattaforma online che garantirà il controllo e la protezione, la riservatezza e la sicurezza dei dati forniti dalle/dai partecipanti.

- Acconsento (Continua alla sezione successiva)
- Rifiuto (Invia Modulo)

La Fisica Quantistica a Scuola

Le vigenti Indicazioni Nazionali per i Licei comprendo tra gli argomenti del quinto anno alcuni elementi di Fisica Quantistica, tra cui la "prima fisica dei quanti" (es. ipotesi di Planck, effetto fotoelettrico, etc.) e alcuni elementi della teoria quantistica evolutasi successivamente (es. natura ondulatoria della materia, principio di indeterminazione). Le domande di questa sezione hanno lo scopo di indagare il suo punto di vista rispetto a questo.

1. È d'accordo con l'insegnamento della Fisica Quantistica nella scuola secondaria di secondo grado?
   1 Per niente - 5 molto d'accordo
2. Se insegna o ha insegnato Fisica nel quinto anno del Liceo Scientifico, nelle sue classi copre o ha coperto argomenti di Fisica Quantistica nell'arco dell'anno scolastico?
   - Mai
   - Qualche volta
   - Spesso
   - Sempre
   - Non ho mai insegnato Fisica nel quinto anno del Liceo Scientifico.
3. Se le è capitato di insegnare argomenti di Fisica Quantistica, riguardo al tempo che dedica o ha dedicato alla loro trattazione:
   - Sono soddisfatta/o di quanto tempo ci dedico.
   - Vorrei dedicarci più tempo.
   - Non voglio trattare la Fisica Quantistica.
4. Riguardo la domanda precedente, desidera aggiungere qualcosa? (Anche più risposte)

- Preferisco coprire meglio argomenti di Fisica Classica.
- I miei studenti/studentesse non hanno sufficienti competenze matematiche per comprendere la Fisica Quantistica.
- Non ho abbastanza ore per trattare la Fisica Quantistica.
- Non mi sento abbastanza preparata/o per insegnare la Fisica Quantistica.

5. Come giudicherebbe la sua preparazione riguardo la Fisica Quantistica?
   1 Scarsa - 5 Eccellente
6. "L'insegnamento della Fisica Quantistica nella scuola secondaria di secondo grado è importante perché si tratta di una delle più grandi conquiste culturali della Scienza." È d'accordo?
   1 Per niente - 5 Molto
7. "L'insegnamento della Fisica Quantistica nella scuola secondaria di secondo grado è importante per le sue applicazioni tecnologiche." È d'accordo?
   1 Per nulla - 5 Molto
8. "L'insegnamento della Fisica Quantistica nella scuola secondaria di secondo grado è importante per contrastare la grande quantità di disinformazione presente in vari media sui contenuti e le conseguenze di questa teoria." È d'accordo?
   1 Per niente - 5 Molto
9. Secondo alcuni esperti è impossibile capire la Fisica Quantistica senza conoscere bene la sua struttura formale, quindi la conoscenza matematica incompleta ostacola o impedisce l'apprendimento della Fisica Quantistica per le/gli studenti della scuola secondaria di secondo grado. È d'accordo?
   1 Per nulla - 5 Molto
10. "La Fisica Quantistica NON va insegnata nelle scuole perché non è necessaria a chi non si occuperà di scienze fisiche, e coloro che vi si dedicheranno avranno il tempo di studiarla all'università." È d'accordo?
    1 Per niente - 5 Molto

Quali argomenti insegnare?

1. Si sente abbastanza preparata/o per rispondere a domande sull'insegnamento di alcuni argomenti specifici di Fisica Quantistica?

   - Sì, procediamo (Continua alla sezione successiva)
   - No (Continua alla sezione Demografica)

2. Abbiamo chiesto a un gruppo di esperte/i quali concetti sono importanti per sviluppare un'immagine mentale adeguata della Fisica Quantistica. Lei quanto ritiene importante insegnare i seguenti concetti nella scuola secondaria di secondo grado?
   1 Poco importante - 5 Molto importante

   - Dualismo onda-particella

- Effetto tunnel
- Entanglement
- Evoluzione temporale
- Fermioni/Bosoni
- Funzione d'onda
- Livelli energetici dell'atomo e quantizzazione
- Lunghezza d'onda di De Broglie
- Misure quantistiche
- Natura particellare della luce
- Osservabili incompatibili
- Principio d'indeterminazione di Heisenberg
- Principio di Pauli
- Probabilità
- Sovrapposizione
- Spin
- Stati quantistici

3. Abbiamo chiesto a un gruppo di esperte/i quali fenomeni ed esperimenti (mentali o reali) sono più significativi per comprendere le idee della Fisica Quantistica. Lei quanto ritiene significativo presentare i seguenti fenomeni o esperimenti nella scuola secondaria di secondo grado?
   1 Poco importante - 5 Molto importante

   - Buca di potenziale 1D
   - Calore specifico dei solidi
   - Decadimenti radioattivi
   - Effetto Compton
   - Effetto fotoelettrico
   - Esperimento della doppia fenditura
   - Gatto di Schrödinger
   - Linee spettrali
   - Oscillatore armonico
   - Radiazione di corpo nero

4. Abbiamo chiesto a un gruppo di esperte/i quali siano le applicazioni tecnologiche più significative della Fisica Quantistica. Lei quanto ritiene importanti presentare le seguenti applicazioni nella scuola secondaria di secondo grado?
   1 Poco importante - 5 Molto importante

   - Cella solare
   - Computer quantistici

- Informazione quantistica
- LASER
- LED
- Semiconduttori

Approcci all'insegnamento della fisica

Le domande di questa sezione hanno lo scopo di indagare le sue opinioni circa gli approcci possibili all'insegnamento della Fisica Quantistica.
ATTENZIONE! Non ci sono risposte più o meno corrette: siamo interessate/i alle sue idee e punti di vista.

1. Le Indicazioni Nazionali suggeriscono di introdurre la Fisica Quantistica attraverso la prima "fisica dei quanti", presentando gli esperimenti che rappresentano la frattura con la fisica classica (es. effetto fotoelettrico, spettro dell'atomo di idrogeno, radiazione di corpo nero, effetto Compton, etc.). La maggior parte dei libri di testo segue questo approccio. È d'accordo?
   1 Per niente - 5 Del tutto

2. Alcuni testi sono molto rigorosi nel riportare non solo i contenuti fisici, ma anche l'evoluzione storica che ha portato alla formulazione delle nuove teorie. Altri testi invece accompagnano la presentazione dei contenuti fisici con una quasi-storia, una narrazione parzialmente alterata (es. con omissioni storiografiche), ma più lineare e facile da seguire. Cosa pensa riguardo all'integrazione di contenuti storici nell'insegnamento della Fisica?

   - Non servono per comprendere la Fisica.
   - Sono importanti, ma non necessari, per comprendere la Fisica.
   - Sono essenziali per comprendere la Fisica.

3. Cosa pensa dell'approccio quasi-storico per l'insegnamento della Fisica Quantistica nella scuola secondaria di secondo grado?

   - L'approccio quasi-storico semplificato è migliore rispetto a quello realmente storico.
   - L'approccio realmente storico è migliore rispetto a quello quasi-storico.
   - L'insegnamento della fisica non richiede né trattazioni storiche né quasi-storiche.
   - Non so/non ho mai riflettuto su questo aspetto.

4. Nei libri di testo che la riportano, la prima "teoria dei quanti" viene spesso presentata come un percorso in cui si susseguono linearmente radiazione di corpo nero, effetto fotoelettrico, effetto Compton e modello di Bohr. Quale delle due seguenti affermazioni riguardanti la "prima fisica dei quanti" preferisce?
   A - È una narrazione semplificata con alterazioni/omissioni
   B - Rappresenta correttamente lo sviluppo storico della Fisica Quantistica

5. Alcune ricercatrici e ricercatori hanno formulato delle proposte didattiche volte a superare l'approccio quasi-storico usato attualmente nella scuola secondaria, sostenendo che sia importante introdurre alcuni aspetti della teoria quantistica che si è evoluta successivamente. Alcuni delle proposte comprendono, ad esempio: l'introduzione di concetti come lo spin, utilizzando matrici 2x2 come strumento matematico relativamente accessibile; l'esplorazione di fenomenologie, come la polarizzazione, che possono mettere in luce alcune proprietà delle particelle quantistiche (es. concetto di stato); lo studio di alcuni esperimenti chiave per la costruzione della teoria, come la doppia fenditura. Sarebbe interessata/o ad approfondire questi approcci?

   - Sì, penso che sia importante andare oltre la prima fisica dei quanti.
   - Non ho un'idea chiara a riguardo, ma vorrei saperne di più.
   - No, penso che l'approccio quasi-storico attualmente proposto sia sufficiente nel contesto della scuola secondaria.
   - Non sono sicura/o di cosa si intenda per "teoria quantistica oltre la prima fisica dei quanti".

6. Una delle questioni aperte rispetto all'insegnamento della fisica moderna (Fisica Quantistica e Relatività) al Liceo Scientifico è la seguente:
   È preferibile inserire alcuni elementi di fisica moderna alla fine del curricolo, oppure revisionare l'intero curricolo di Fisica per costruire una visione coerente della Fisica che tenga conto dei suoi sviluppi attuali?

   - Penso che sia sufficiente inserire alcuni elementi alla fine del curricolo.
   - Penso che sia necessaria una revisione del curricolo.
   - Altro...

Interpretazioni della Fisica Quantistica

Gli aspetti interpretativi della Fisica Quantistica sono questioni aperte ancora oggi, con discussioni attive tra scienziate/i. In questa sezione chiederemo la sua opinione riguardo alcuni di questi aspetti controversi.
ATTENZIONE! Non ci sono risposte più o meno corrette: siamo interessate/i alle sue idee e punti di vista.

1. Einstein quantizzò la radiazione elettromagnetica in pacchetti localizzati con energia e momento ben definiti (chiamati poi "fotoni"). Lei come descriverebbe il fotone?

   - Il fotone è una particella che non ha massa, ma ha quantità di moto ed energia ben definite.
   - Il fotone è una particella quantistica e, in quanto tale, non ha quantità di moto ed energia ben definite.
   - Non so o non sono sicuro/a
   - Altro...

2. Nei libri di testo si trovano diverse rappresentazioni del fotone (Fig. A.1). Lei come si rappresenta personalmente il fotone?

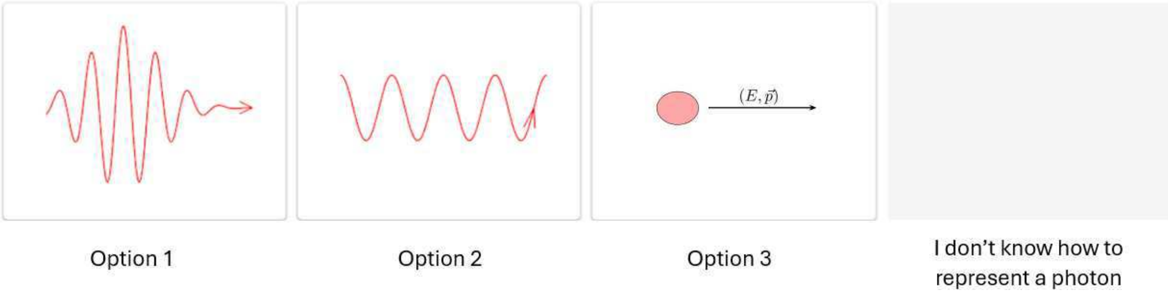

Figure A.1: Lista delle possibili risposte alla domanda 2 della sezione "Interpretazioni della Fisica Quantistica": option 1, pacchetto d'onda; option 2, onda sinusoidale; option 3, particella classica; ultima se non sanno come rappresentare un fotone.

3. Il principio di indeterminazione di Heisenberg stabilisce i limiti nella possibilità di misurare simultaneamente e con precisione arbitraria due grandezze fisiche (ad es. posizione e quantità di moto di una particella). Questo principio viene spesso presentato riportando una delle seguenti argomentazioni:

   - Esperimento mentale del "microscopio" di Heisenberg:
     La posizione di una particella è determinata tramite l'interazione con un fotone con lunghezza d'onda piccola per minimizzare l'incertezza sulla posizione. Questo tuttavia produce una grande incertezza nella quantità di moto.
   - Esperimento della singola fenditura:
     La posizione di un fotone viene determinata costringendolo ad attraversare una fenditura stretta, questo però genera un'indeterminazione sulla quantità di moto del fotone, che genera la tipica figura d'interferenza.

   Cosa pensa riguardo queste due argomentazioni?

   - Entrambe le argomentazioni presentano correttamente il principio di indeterminazione, sono equivalenti.
   - Solo il microscopio di Heisenberg presenta correttamente il principio di indeterminazione, la singola fenditura è un caso particolare.
   - Solo la singola fenditura presenta correttamente il principio di indeterminazione, il microscopio di Heisenberg è un caso particolare.
   - Nessuna delle due argomentazioni presenta correttamente il principio di indeterminazione.
   - Non so o non ne sono sicuro/a

4. Un altro principio fondamentale della Fisica Quantistica è il concetto di complementarietà, che viene solitamente formulato come segue:
   "Gli aspetti corpuscolare e ondulatorio di un fenomeno fisico non si manifestano mai simultaneamente, ma ogni esperimento che permetta di osservare l'uno impedisce di osservare l'altro. I due aspetti sono tuttavia complementari perché entrambi

indispensabili per fornire una descrizione fisica completa del fenomeno. È quindi l'apparato sperimentale a determinare il sistema quantistico come onda o particella." (I Formulazione)
Secondo alcuni ricercatori il principio dovrebbe essere riformulato diversamente: "Un apparato sperimentale può fornire contemporaneamente informazioni parziali sugli aspetti ondulatori e particellari del sistema quantistico in esame, ma più informazioni fornisce su un aspetto, meno ne darà sull'altro. Gli oggetti quantistici possono talvolta mostrare simultaneamente proprietà sia corpuscolari sia ondulatorie (dualità onda-particella)." (II Formulazione)
Quale delle due formulazioni preferisce?

- Non c'è contraddizione tra le due formulazioni: esse sono del tutto equivalenti.
- Nessuna delle due formulazioni è errata ma preferisco la prima.
- Nessuna delle due formulazioni è errata ma preferisco la seconda.
- Solo la prima è corretta.
- Solo la seconda è corretta.
- Non so o non ne sono sicuro/a

5. Il seguente fotogramma (Fig. A.2) è tratto da una simulazione PhET sull'esperimento della doppia fenditura con singoli elettroni.

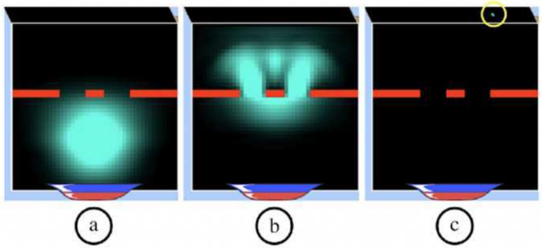

Figure A.2: Immagini dalla simulazione PhET usata per la domanda 5 della sezione "Interpretazioni della Fisica Quantistica", come proposto anche in Stadermann and Goedhart 2020 (https://phet.colorado.edu/en/simulation/quantum-wave-interference).

(a) L'elettrone è stato appena emesso;
(b) L'elettrone passa attraverso la doppia fenditura;
(c) L'elettrone viene rivelato sullo schermo.
Tre studenti, interpretando l'esperimento, hanno espresso le seguenti argomentazioni. Indichi con quale/i è d'accordo.

- Studente 1: "La densità di probabilità, rappresentata dalla macchia colorata, è così grande perché non conosciamo la vera posizione dell'elettrone. Dato che sullo schermo compare un singolo punto alla volta, l'elettrone deve essere stato (anche durante il viaggio) una particella molto piccola, che si trovava da qualche parte dentro quella macchia, e quindi in realtà è passato attraverso solo una delle due fenditure."

- Studente 2: “La macchia colorata rappresenta l’elettrone stesso, perché esso è descritto da un pacchetto d’onda che si propaga nel tempo. L’elettrone si comporta a tutti gli effetti come un’onda, passa attraverso entrambe le fenditure e interferisce con se stesso. È per questo che sullo schermo apparirà una tipica figura di interferenza dopo aver sparato molti elettroni”.
- Studente 3: “La meccanica quantistica riguarda solo le previsioni sui risultati delle misure, quindi non possiamo veramente sapere cosa fa l’elettrone tra quando è emesso e quando è rivelato sullo schermo.”

6. Se vuole, spieghi brevemente la sua scelta:
   Risposta aperta

7. Indichi il suo livello di accordo con la seguente affermazione:
   “Quando non lo si sta osservando, un elettrone in un atomo ha comunque una posizione ben definita (anche se sconosciuta) in ogni istante di tempo."
   1 Per niente d’accordo - 5 Del tutto d’accordo

8. Se vuole, spieghi brevemente la sua scelta:
   Risposta aperta

9. Ha sentito parlare di diverse interpretazioni della Meccanica Quantistica?
   - Sì, e ne saprei distinguere almeno due, per lo meno nei tratti fondamentali.
   - Ne ho sentito parlare, ma non saprei descriverle.
   - No

10. Se ha risposto SI, può nominare quelle che conosce e/o descriverne brevemente gli elementi caratterizzanti (o in cosa si distinguono)?
    Risposta aperta

11. Se ha risposto SI, nell’impostazione delle sue lezioni adotta una determinata interpretazione della Meccanica Quantistica?
    Risposta aperta

12. Affronta esplicitamente con i suoi studenti e studentesse il tema delle interpretazioni della Meccanica Quantistica?
    - No, non ho mai sentito parlare di interpretazioni della Meccanica Quantistica.
    - Sì, è un elemento fondante della mia proposta.
    - Sì, come attività di approfondimento.
    - No, lo riterrei importante ma non ho tempo.
    - No, lo riterrei importante ma non mi sento abbastanza preparato/a per farlo.
    - No, perché gli studenti e le studentesse non ne apprezzerebbero il significato.
    - No, non lo ritengo necessario: la cosa fondamentale nella Meccanica Quantistica è saper prevedere i risultati.

13. Nonostante la grande capacità predittiva della Meccanica Quantistica, dopo più di 80 anni la discussione sulla sua interpretazione è ancora in corso. Diverse interpretazioni portano a previsioni identiche, tuttavia differiscono grandemente nelle loro implicazioni ontologiche (circa la natura degli oggetti quantistici). Questo aspetto della Meccanica Quantistica potrebbe essere considerato problematico.
    Di seguito sono riportate alcune argomentazioni in risposta a questo problema: con quale si trova più d'accordo personalmente?

    - "La Meccanica Quantistica non ha bisogno di interpretazioni. Fintantoché sappiamo usarla per fare i calcoli e costruire dispositivi che funzionano grazie a essa, non abbiamo bisogno di un'interpretazione della Meccanica Quantistica. È fuori dal dominio della scienza chiedersi la natura di qualcosa che non possiamo osservare."
    - "I Fisici/Fisiche dovrebbero accordarsi su quale interpretazione della Meccanica Quantistica vogliono usare, così come hanno fatto con gli standard internazionali di misura. Se ognuno rimane legato/a alla propria interpretazione, si avranno solo molte discussioni inutili."
    - "Al momento attuale, non sappiamo spiegare perché gli elettroni si comportano nel modo descritto dalla Meccanica Quantistica. Ma se scienziati e scienziate vogliono scoprirlo, c'è bisogno di molta creatività per trovare una spiegazione. È così che vengono sviluppate le interpretazioni: questo fa parte della costruzione della conoscenza scientifica."

14. Se vuole, spieghi brevemente la sua scelta:
    Risposta aperta

15. Cosa pensa degli aspetti controversi della Meccanica Quantistica in relazione all'insegnamento nella scuola secondaria?

    - Preferisco evitare gli aspetti controversi o che possono creare problemi.
    - Penso che questi problemi dovrebbero essere messi al centro dell'insegnamento.
    - Penso che questi problemi dovrebbero/potrebbero essere trattati, ma come approfondimento.
    - Non mi sento abbastanza preparato/a per rispondere.
    - Altro...

Bisogni Formativi

Le ultime domande ci saranno utili per organizzare una scuola di formazione permanente per insegnanti sulla Fisica Quantistica.

1. Quali di questi elementi vorrebbe trovare in una scuola di formazione per insegnanti sulla Fisica Quantistica?

    - Lezioni sui contenuti di Meccanica Quantistica oltre la "vecchia fisica dei quanti" (es. stato quantistico, equazione di Schroedinger, ...)

- Approfondimenti sulle tecnologie quantistiche (es. computer quantistico)
- Approfondimenti sugli aspetti storici e/o filosofici della meccanica quantistica (es. diverse interpretazioni della Meccanica Quantistica)
- Approfondimenti su aspetti interdisciplinari in area STEM (es. LED - Scienza dei Materiali, ...)
- Proposte didattiche per innovare o approfondire l'insegnamento della "vecchia fisica dei quanti" (es. corpo nero, spettroscopia, effetto fotoelettrico)
- Proposte didattiche per introdurre elementi di Meccanica Quantistica oltre la "vecchia fisica dei quanti"
- Discussioni sul curricolo di Fisica nel Liceo Scientifico per capire come meglio integrare la fisica moderna
- Altro...

2. Quali dei seguenti strumenti didattici per insegnare la fisica quantistica nella scuola secondaria di secondo grado vorrebbe approfondire?
   - Simulazioni e animazioni (es. PhET)
   - Videogiochi basati su regole che simulano il comportamento quantistico (es. Quantum TiqTaqToe)
   - Esperimenti che riproducono alcuni fenomeni esplorati nella prima fisica dei quanti (es. spettroscopi)
   - Strumenti matematici utili ad affrontare la Meccanica Quantistica (es. probabilità)
   - Altro...

Demografica

1. Per quale classe di concorso insegna attualmente?
   - A20 - Fisica
   - A27 - Matematica e fisica
   - Altro...
2. In che ambito si è formata/o?
   - Fisica Teorica
   - Fisica Sperimentale
   - Astronomia/Astrofisica
   - Matematica
   - Ingegneria
   - Altro...
3. Nella sua formazione universitaria, ha seguito corsi di Fisica Quantistica?
   - No

- Sì, ma solo elementi della prima fisica dei quanti.
- Sì, anche sulla meccanica quantistica oltre la prima fisica dei quanti.
- Sì, anche a livello di dottorato di ricerca.
- Altro...

4. Ha seguito corsi di formazione per insegnanti sulla Fisica Quantistica?
    - No
    - Sì, alla SSIS o TFA o altri corsi di formazione pre-servizio.
    - Sì, in corsi di formazione in servizio (corsi di aggiornamento).
    - Altro...
5. Se vuole, può specificare meglio:
   Risposta aperta
6. In quale fascia d'età rientra?
    - <30
    - 30-39
    - 40-49
    - >50
7. In quale genere si identifica? (può indicare più risposte)
    - Femmina
    - Maschio
    - Transgender
    - Non-binary/Non-conforming
    - Preferisco non rispondere
    - Altro...
8. Da quanti anni insegna fisica?
    - <5
    - 5-10
    - 11-20
    - >20
9. Quale libro di testo utilizza per l'insegnamento della Fisica Quantistica?
   Risposta aperta
10. Quanto fa riferimento al solo libro di testo nella preparazione delle sue lezioni?
    1 Aggiungo molto materiale - 5 Uso solo i libri
11. In che tipo di scuola insegna?
    - Liceo scientifico

- Liceo non scientifico
- Istituto tecnico settore tecnologico
- Istituto tecnico settore economico
- Istituto professionale
- Altro...

12. In che provincia insegna? (se non insegna in Veneto, scelga "Altro" e indichi la sigla automobilistica in lettere maiuscole, es. BS)
    - BL
    - PD
    - RO
    - TV
    - VE
    - VI
    - VR
    - Altro...
13. Vuole aggiungere qualche commento/suggerimento?
    Risposta Aperta