

GIREP Community on Teaching / Learning Quantum Physics in Secondary School

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Abstract. The present paper summarizes the building of the GIREP community on teaching and learning quantum physics in secondary school and the results of the community's first discussion workshop. The questions for the workshop were prepared using feedback from the community members. The participants to the Working Discussion in Budapest Conference were divided in five groups, each focusing on distinct approaches in teaching quantum physics, as identified by the community. The five groups discussed the questions and identified core concepts that any course on quantum physics should cover. They also identified some specificities of each approach and discussed which approaches are particularly well suited or poorly suited to address specific concepts. The paper describes the creation of the community, the process of selecting the questions for the workshop and the results of the discussion on specific questions. The group identified potential research questions that should be addressed with future research. The results are summarized into a short position statement on the future goals of the community.

1. Introduction

The physics of the last century is now included in all EU curricula and in the last 10 years it appears also in the secondary textbooks, even if often not in a coherent path [1, 2]. There is a rich literature about introducing modern physics. The proposals differ in contents and goals. With respect to the contents Special Relativity and Quantum Physics are the main topics considered. But recently also proposals for other important discoveries like superconductivity at high temperature [3], space physics and high energy physics as well as the studies of Materials Science are brought forward, thanks to some EU projects [4]. Equally, different analytical techniques in Condensed Matter, like optical, Raman, RBS Spectroscopy or X-Ray Diffraction are also considered [5]. The goals are related to the general culture of citizens, popularization, guidance, instruction and applications. Correspondingly, many approaches and strategies are used: 1) story telling of the main results; 2) discussion of some interpretative problems which cannot be solved by classical physics; 3) integration in a course on classical physics or as a complementary part of the curriculum. The richness of contents runs the risk to cause cognitive overload, at the expense of the educative goals which are very important for the future generation. Some studies on introducing Modern Physics in Secondary School focus on that problem [4-6]. Physics Education Research (PER) focusses amongst others on curriculum content organization and the construction of educational sequences to develop the desired learning outcomes.

Quantum Physics (QP) plays an outstanding role in this context. In particular, Quantum Mechanics (QM) is the paradigmatic theory for the actual interpretation of the microscopic world and a theoretical and conceptual base for the development of new knowledge [6-8]. Its implications are very important in many branches of science [7] and the quantum-mechanical way of thinking is a new cultural approach to physics [6-14].

In the wide scenarios of the research based proposals on quantum mechanics [12-13] there is no consensus concerning the contents to be treated and the strategies to be adopted, but, on the contrary, in classroom practice and textbooks a surprising homogeneity appears [15]. Proposals of single activities as well as educational paths are offered in literature with the same weight [6,7]. In addition, an unclear overlapping of physics of quanta, quantum physics or quantum mechanics theory are offered adopting different approaches with different perspectives. Five main approaches can be identified **according to an educational perspective**:

1. Reconstruction of the interpretative problems in the historical developments of quantum concepts. This approach gives a general viewpoint, offering interdisciplinary bridges, but, especially at the elementary level, often the narrative treatment prevails over aspects related to the subject itself. However, the rigorous semi-classic formal treatment is too difficult for students, for example for black body radiation, as we find in the approach of Born [16]. A similar approach, is based on crucial experiments and the birth of the theory of quanta although not strictly following the historical timeline and for that it should be strictly separated from the historical approach. The discussion of crucial experiments motivates the hypothesis of quantization of different quantities, but does not offer the coherent theoretical framework of QM. These approaches seem to be more descriptive, working by means of analogies. This might be acceptable on a popularization level, but is not regarded as satisfactory on an educational level.
2. Quantum field theory offers the most modern theory of quantum physics. It includes the idea of a continuum, it is coherent and some concepts, which seem mysterious with other approaches, arise naturally, such as the photon, particles and nonlocality [17-19].
3. A conceptual approach based on two state properties (polarization, spin) as proposed by Dirac [7, 10, 14, 20-21]
4. A wave formulation of the quantum theory is a rigorous one, but it demands strong competencies both in physics and in mathematics, only partially reduced by the use of computer [9, 11-13].
5. The path integral Feynman approach is simple and elegant, but offers a partial vision of the QM way of thinking [22].

There is the need to produce the awareness of the reference assumptions of the quantum mechanics, to offer some indications on the new way of thinking and of the background formalism which is the joint basis of all the approaches. The formalism, in fact, assumes in QM a conceptual role. In Italy, the PER community developed different path proposals for QM in secondary school and 20 universities cooperate for teacher education in this area from 2006 up to now [23-25]. To share ideas and research results coming from the implementation of these proposals enriches each proposal and offers ideas for their integration. The same procedure appears now important across many countries in Europe, building a Community on Teaching/Learning Quantum Physics in Secondary School able to share and improve the single research approaches.

2. The building of GIREP Community on Teaching/Learning Quantum Physics in Secondary School

GIREP is working on improving even more the quality of teaching and learning physics with different initiatives, having the goal to support practice by means of the production of research results, studies and in general teaching proposals based on Physics Education Research (PER). Contributing to this goal are the Conferences and Seminars, organized more and more in collaboration with other bodies, the very active and qualified GIREP Thematic Groups (GTGs) instituted in the last six years and the contracts with the Springer and IOP for ISI books of selected papers. GIREP members and sympathizers carry out content related research, design based research and they integrate research with practice.

Since a long time GIREP is looking onto modern physics as an important topic. This mirrors in the early contributions of George Marx (GIREP president in the period 1992-1995) on atomic and nuclear physics, which are up to now very useful [26-30] and is continued in the very interesting and useful GIREP books available on the GIREP website (www.girep.org) for GIREP members [31-32]. To continue the tradition in this area GIREP planned the Budapest Conference in July 2019 on Teaching / Learning modern and contemporary physics-

To renew, update and improve the experience in modern physics, GIREP decided to create a Community on Teaching / Learning Quantum Physics starting from a broad basis. In a first step those GIREP members who have worked on the topic of quantum physics education and were available for a discussion and future work in this direction were identified. A letter in January 2019 invited GIREP members interested in creating a GIREP community on Teaching / Learning Quantum Physics (T/L QP) and asked them to indicate their experience and to express their main interests in this area. The goals presented in the letter were: 1) to collect the most important information of the interested persons, working in the field; 2) to submit to the Budapest Conference a Symposium (90 min) on Teaching / Learning Quantum Physics in Secondary School and ask for additional discussion time. This extra discussion should refer to the interest of participants.

The GIREP Community on T/L Quantum Physics in Secondary School

There were 46 applicants to the community from 21 countries: 39 from EU countries, 4 from USA, 2 from Malaysia and one from Vietnam. Figure 1 show the country European distribution of applicants, which affiliations is the following: 43 in universities (15 in Phys. Dept., 14 in Education Dept., 2 in Phys. & Educ. Depts.), 2 in secondary schools and one in a research institute (CNR-INFN).



Figure 1. Distribution per country of community members

The previous PER experience in T/L QP of the participants to the Community are the following: 5 members had published more than 5 papers, 5 members listed 4 papers and 6 members listed 2 papers; 8 members one paper; 4 members documented great experience in research in quantum physics. Several contributions were presented by the community to the Budapest Conference on modern physics (n.2 key-note talks, n.3 oral presentation) and in particular on Teaching/Learning Quantum Physics (T/L QP): n.2 Symposia, n.22 oral presentations (n.8 in the symposia) and n.4 poster.

Among the 5 questions suggested by each member of the community three main categories emerged: G- general aspects; C- Contents, T-Teacher education and teaching resources.

G GENERAL ASPECTS category

G.1 Role of community itself

G.1.a Vision and goal of this community (a need of discussion on the strategies of the community)

G.1.b Curriculum impact by the community - (“How can we influence the curriculum makers to renew the national teaching guidelines? How can we join and coordinate our forces to update the teaching of quantum science and technology on European scale (Quantum Flagship - as a trigger and coordination)?”) and “What changes in the classical physics educational paths can we suggest in order to be able to propose a more effective path about quantum mechanics?”)

G.2 Status of research, education and resources

G.2.a Results of empirical research (relevant research results available, main obstacles for learning QP (conceptual, mathematical, philosophical, ...))

G.2.b Teaching materials

G.2.c Status of quantum education in Europe e. g. time (How much time can be dedicated to the teaching of QM in high schools?)

G.3 Aims and perspectives of quantum physics education

G.3.a Goals of quantum physics education (“Why should we teach Quantum Mechanics?”, “Where is quantum physics education heading and where are new perspectives, e.g. Quantum Technology?”; “What should be the main educational objectives?”; “What is the cultural point in teaching modern physics to all the high school students?”)

G.3.b Target groups of quantum physics education (to whom is QP addressed? Secondary School students? ...)

G.4. Teaching Strategy/pedagogy

G.4.a QM vs Classical Physics (CP): (Do we need to introduce quantum mechanics as a "revolution"? Can QM be introduced before classical physics? What has to be emphasized? the breakdown of classical schemes? Only the new ideas? What do students learn with each of the two different world views (classical versus quantum physics)? Is it productive or confusing that students compare for example: interference in the classical and quantum context? To compare the concept of state in CP and in QM? Can the pedagogy of quantum physics benefit from the use of (classical) analogies?)

G.4.b Teaching methods: How should we teach QM? How can we build quantum literacy for upper secondary schools? Which approaches have been shown to address which conceptual ideas and up to what depth? What could be an effective way to teach QP quantitatively in high school? How can we use active learning methods such as inquiry-based/problem-based/project-based learning in teaching quantum Physics? At pre-university level education, how to improve -the influx of STEM, sketch future landscapes of career opportunities, - the perception that quantum opens another area with completely new and abundant possibilities (e.g. quantum computing). - generally: improve quantum awareness

G.4.c Assessment in quantum physics education (Which tools should we use to assess the achievements; How should or could results of quantum physics teaching be assessed at national exams?)

G.5. Gender issues (How to engage girls? What makes quantum physics more 'feminine' than many other parts of physics and how could we use this for education?)

C CONTENTS category

C.1 Shaping a curriculum

C.1.a Topics:-Which aspects of Quantum Mechanics should we teach? What do we want the students to know? Which topics should we accordingly include? Which are the most important conceptual ideas that students should learn? On what should we focus our quantum teaching on the secondary level: mathematical descriptions, philosophical questions (like interpretations of quantum physics) or modern approaches to get to the key concepts (like two-level-systems)? What should be the core curriculum for quantum mechanics at the secondary level? What

subtopics of QM do we want secondary school students to learn, and why? How to promote the conceptual change from classical physics to quantum mechanics?... in particular: The wave properties of matter, the wave function? How to introduce the superposition state? How, and to what extent, can we translate the axioms of quantum mechanics for secondary school? Quantum field Theory?" which concepts/aspects/topics have to be included in an educational approach to QM for high school students? The concepts of state? The superposition principle? the concept of properties of quantum systems? The Heisenberg principle? the particle-wave dualism? The Schrödinger equation? The undisturbed quantum behaviour? The impossibility to attribute a trajectory to a quantum object? The probabilistic nature of measurement of a quantum property? Entanglement? Non locality? Non-relativistic QM or Quantum field approach? C.1.b Quantum interpretation: (Is it better to offer to students a conceptually open path in which they choose the interpretative frame (ensemble QM; orthodox QM; hidden variables QM; particle-wave duality, uncertainty principle....) or it is better that student face just a specific perspective ...a way to look to the quantum behavior (as in the majority of studies on how students learn QM)? From a didactical perspective, which are the better formulations of quantum mechanics?)

C.1.c Role of Atomic physics: How can be faced the problems to high school students? At which level? Which one? Infinite square potential? Square barrier (Tunnel effect)? Or is it enough to explore quantum behavior in two dimensions' space (light polarization; spin; Mach-Zehnder; 2-slits exp...) or should we include some other contexts (atom; diffraction)

C.2 Mathematics & QM T/L Which mathematics should be taught to successfully introduce QM? Should we teach with or without getting through the mathematical formalism? What sort of formalism to be used (wave function, matrices, Dirac vectors, multi representations)? Which level of depth?

C.3 Experiencing

C3.1 Experiment (Is it possible to perform simple experiments in QM? what about the existing experience?)

C3.2 Daily experience phenomena (i.e.: Impenetrability of bodies; explanation, how LEDs work) (Which daily life experiences are triggering school students towards quantum explanations rather than classical ones?)

C3.3 Visual means (Work with simulations, pictures, animations)

C.4 Technological Application

Quantum computing... (How to integrate quantum computation in QP courses?; "At pre-university level education, how to improve -the influx of STEM, -the visibility of the need for Q technology in solutions for challenges that society faces today (sustainability, energy transition, medical, etc.), How can we build our teaching/learning paths to grasp the interdisciplinary essence of the advancements of quantum modern technologies (physics, mathematics, informatics, biology, engineering)? How to productively integrate modern devices in introductory physics course?

C.5 History /Philosophy (H/P)

How to go beyond the historical approach in teaching modern physics? What sort of role H/P have in an educational path on QP?

T TEACHER AND TEACHING RESOURCES category

T1. Teacher Education in MQ

What are the requirements of teaching QP in high school for teacher education? How can we deal we the education of pre-service teachers that come from other disciplines than physics, and that probably will have to teach quantum physics?

T2. Teaching Resources

Where can a teacher find resources to help him/her to better understand the concepts of QM?

What do real-world school teachers need to give inspiring quantum lessons in a real-world educational system and can we provide this? Which tools should we use to assess the achievements? How to support the teachers with experiments in modern physics? How to change the textbooks? Which kind of ICT or web resources can help teaching?

In addition to the proposals in these categories a series of initiatives were suggested for the Community work.

4. The discussion preparation

The Discussion Workshop (DW) in Budapest has been prepared very carefully in a complex procedure in order to reach its goals. These were specified to:

- 1) Build a working community that will have the continuity of a GTG (Girep Thematic Group) or a similar structure;
- 2) Draw up a scientific position paper on T / L Quantum Physics that serves to guide projects and teaching activities on these topics
- 3) Prepare a book of selected papers on PER for T / L Quantum Physics in secondary school

It seemed that the best way to achieve these goals were:

- a) Identify 5 main topics to be discussed, starting from the proposals received and the objective of drafting a position paper
- b) Identify 5 colleagues available to coordinate the group discussion and its conclusions
- c) Circulate the group themes in advance so that each participant arrives at the DW with a contribution or might send it in advance, in the case of she/he will be not present.

It was thought best to concentrate on goal 2), the goal of writing a document or a position paper on QP T/L in high schools and non-physics major courses at University level (mathematics, engineering, bio-area, informatics). Accordingly, it was decided to establish five different groups which should discuss the following approaches to T/L QP:

1. Two states systems approach (polarization, spin, double wells, ...). Responsible: Sergej Faletic (SLO), Alberto Stefanel (I), Stamatis Vokos (USA)
2. Wave function and/or Matter-wave approach. Responsible: Homeyra Sadaghiani (USA), Ed Van den Berg (NL), Erica Andreotti and Renaat Frans (B)
3. Historical approach. Responsible: Leonardo Coletti (I), Leon Jurčić (KR), Kirsten Stadermann (NL), Ubben Malte (D)
4. Quantum field theory approach (QFT). Responsible: Marco Giliberti (I)
5. Feynman path integral approach. Responsible: Maria Bondani (I), Massimiliano Malgeri (I)

The groups, each focusing on one of these five approaches, should consider during their group discussion the following topics with respect to the question if they should be taught and if yes, in which way and which role they would play:

- Properties/eigenvalues
- Probability
- States
- Superposition
- Trajectory/Which way
- Duality
- Uncertainty relations/incompatibility
- Schrödinger equation
- Entanglement,
- Non-locality
- Teleportation
- Q computing
- Should we do formalism or not?

- Which formalism to choose (vector space, wave function, matrix)?
- Interpretations (Copenhagen, Bohm, Dirac, ...)
- Should history be included or can we teach only the content?
 - Which aspects of history should be included?
- Contexts (polarization, spin, potential wells)
- Applications (laser, LED, semiconductors, ...)
- Modularity in a coherent approach:
 - Can the course be split in modules on different topics so that a teacher with time limitations can choose only one module?
 - Can the same approach be used for all modules and how?

The second important aspect was the way of teaching and the related content:
How to teach:

1. How to motivate students to QM?
2. How much time should be allotted to QM?
3. Adopt a single approach and interpretation or more, and motivations
4. Should we emphasize contrast or the similarity with classical physics (CPh)?
5. Formalism and interplay with math
 - 5.1. Should we use math formalism and how in depth?
 - 5.2. Should math be presented as having a conceptual role?
 - 5.3. What math do teachers know? What can they use to teach QM?
 - 5.4. Which formalism to choose? Dirac, wave function, multiple?
 - 5.5. Teach additional math to the students (matrices, algebra)?
6. Which experiments can be done?
7. How to include experiences, applications?
8. Assessment
 - 8.1. What type of assessment to use? Produce a universal questionnaire?
 - 8.2. What problems to use?

5. Results of the WD discussion: position paper of GIREP on quantum physics education

We report here the results of the Workshop Discussion (WD) and the position paper emerging from the reports written by the following reporters of the groups: Maria Bondani (I), Sergej Faletic (SLO), Marco Giliberti (I), Massimiliano Malgeri (I), Marisa Michelini (I), Kirsten Stadermann (NL), Alberto Stefanel (I), Ed Van den Berg (NL).

Physics Education Research (PER) developed a wide spectrum of studies oriented to building proposals or analyzing conceptual difficulties with the main concepts of the new way of thinking of the 20th century theories. Some contributions are focused on building new tools to support the understanding of certain aspects in Modern Physics. Accordingly, there exists extensive literature on teaching and learning Modern Physics. In addition to proposals that focus on the main concepts, proposals were also developed with the aim of analyzing in detail some of the students' key learning difficulties known from the literature or proposals with the perspective of contributing to cultural education. Such proposals aim to promote a sort of modern physics identity in a new generation of students, looking to its introduction in a coherent integrated way in vertical perspective [33-35].

Among the theories of Modern Physics, meaning physics of the 20th century, quantum physics plays a special role because of its concepts and principles that do not coincide with the basics of classical physics and the classical world view in general. In history this led to deep questions about its interpretation. The mathematical predictions of quantum physics are reliable and very precise, but there are different interpretations in what they mean depending on the philosophical frame work used. Since the 1980's the technological-experimental advances (see especially the experiments of the Aspect and Zeilinger groups) provided for deepening of the insight into quantum physics and clarifying of some open interpretation questions, in this way also opening the way to new teaching approaches.

Nevertheless, whereas an insight into quantum physics can contribute in a valuable and fruitful way to scientific and general education it is not clear with which contents and which focus in teaching this could be achieved best. In choosing quantum physics as a topic of physics lessons several goals can be pursued:

- 1) Developing students' physical world view including the quantum part,
- 2) Building the skills of modelling the world and going beyond classical models,
- 3) Giving insight into the nature of science especially into the ways knowledge is generated (scientific epistemology).

It is necessary that the main approaches in literature are known to select the useful perspective depending on the context and not to have as a source a reductionist single approach.

All European countries include in their science or physics curricula at the high school level quantum physics as part of teaching modern physics of the 20th century. Reviewing the curricula around Europe there seems to be a certain general agreement, which is however strongly influenced by traditional teaching approaches as often followed in textbooks [15]. The PER literature is very rich mainly for what concerns single aspects and specific proposals. Approaches and rationale are already described in a wide body of literature [36-37].

As a result of a GIREP discussion workshop the following main points, quite independently from the specific approaches and valid across all the different groups and approaches were formulated.

- **Conceptual understanding** of quantum physics is central. Students should build a coherent picture of the physical world including the classical physics. There should be a view on similarities and differences between classical and quantum physics and insight into descriptions that carry across, as e. g. in a QFT approach the role of fields and of particles.
- A first insight into the **formal description** of quantum physics should be obtained. The goal is to leave behind the qualitative and metaphorical descriptions of quantum phenomena in order to be able to make predictions and to have a strong basis for argumentation. The students should see the power of a mathematical description in physics and how it can introduce concepts never to be thought about before.
- Quantum physics is an area in which **nature of science** can be taught adequately. Also students more interested into philosophical aspects than in "hard science" can be addressed (mainly advocated with the historical approach)
- Modern recent advances in **quantum technology** open new ways into teaching quantum physics with an eye on applications and showing the development of science. This has the advantage of obviously showing that physics is a still developing science with great impact on technology and also on society.

In detail the following different approaches were discussed by GIREP groups:

A. Historical approach

The historical approach includes the long lasting interpretation debate. This aspect is especially suited for giving students insight into "nature of science". This includes seeing the role of communication and negotiating the meaning of concepts or discussing controversies. Also the historical approach can contribute to show how models are built to reflect experimental observations, even if they appear unintuitive, and in this way they advance science. In addition, students can be addressed who are not so genuinely interested in "hard science" but ask for philosophical framing.

Therefore, a suitable approach along the history of quantum physics could provide a contribution to general education, especially in the sense of learning about the nature of science and developing a broad physical world view.

B. Quantum Field Theory

The approach via quantum field theory reflects that QED is the most modern theory describing matter and light. It gives a coherent view on fields, is relativistic and can be built on classical physics and at the same time build quantum thinking. One could use Feynman diagrams, which are intuitive and easy to understand on a pre-university level, even though their real mathematical meaning is beyond pre-university level.

Some concepts arise very naturally in QFT, such as the photon, particles and nonlocality. Therefore, some paradoxical features of quantum mechanics are avoided.

C. Two state systems

The two state systems seem to be suitable for introducing the core concepts of quantum physics. They open the view on recent technology and the growing field of quantum information. This allows to generate students' interest by treating exciting applications, among which the quantum cryptography and quantum computing. Other applications are also possible such as medical diagnostics (MRI) or chemical reactions. In addition, it opens the possibility of introducing quantitative calculations.

D. Wave function approach

Waves are part of classical physics and can be used to build intuition about the behavior of quantum entities. However, important differences between waves and wave functions exist and need to be addressed. Quantum physics should generate interest and hence the teacher should be careful with mathematical formulations, which should be introduced not too early during the course and strongly supported by visualization or even gaming elements. In the center of the course would be the wave-like behavior, the double slit experiment and probability. The relation to particle-like behavior can be addressed either by wave-particle dualism or by the wave function collapse. In addition, the possibility of inquiry should be explored.

E. Feynman sum over the paths

This approach seems to open the possibility of treating quantum physics on a conceptual level. Mainly the probability of a certain outcome, which can be reached in different ways is to be calculated. Also here the double slit experiment can play an important role as an example of the application of Feynman paths. Also superposition, which way experiments and duality can be treated. However, uncertainty could be more difficult to incorporate in this approach, but it is important. In addition, quantum interpretation should be considered. Please note that this approach was successfully implemented in the Advancing Physics A-level course of the Institute of Physics in England since the year 2000.

5.1 A synthesis on topics to be taught

The five groups discussing the five approaches described above discussed the topics that they consider most important, based on the suggestion put forward by the organisers of the workshop. From their reports the following topics emerged as central:

- Probability (4 groups).
- Duality/measurement/collapse (4 groups). It appears from the reports that these terms attempt to describe the same phenomenon, the collapse of the superposition state at the time of measurement. Some participants would like to avoid the term duality, but address the particle-like properties of particles as a consequence of the collapse, while others would like to introduce duality in the sense of particle-like interactions, but wave-like propagation. The QFT group suggested that with the QFT approach the term becomes irrelevant since there are only fields and field excitations involved.
- Superposition (3 groups).
- Double slit (3 groups).
- Uncertainty principle/incompatible properties (3 groups).
- Wave-like representation (3 groups). This representation is in the form of the wave function for the wave function group, although the group strongly suggested to not introduce the wave function in a traditional sense, as is done at university level, but perhaps replace it with a probability distribution. The QFT group mentioned wave-like representations as part of field

excitations. The Feynman paths group replaces the wave function with the arrows typical of the Feynman path approach [39].

- Philosophy/interpretations (3 groups). The three groups found it important as a motivational tool and to address the epistemology or nature of science (NoS). They also suggested that non physics oriented students might be interested in the philosophical aspects more than in the physical aspects. It might also legitimise the internal cognitive conflict with classical physics that many students encounter and give them the opportunity to express and address this conflict.
- Trajectory (2 groups). It was found to be fundamental in the Feynman paths approach.
- History (2 groups). It is fundamental for the historical approach, but was mentioned as part of the NoS also in the QFT group.
- Nonlocality (2 groups). It was found to be inherent in the QFT approach, but was also mentioned as entanglement and teleportation by the two-states group.
- Quantum optics (2 groups). It was suggested as an application or source of examples by the QFT and the Feynman paths groups. It appears to be inherently suitable to these two approaches.
- One very important guideline put forward by the Feynman paths group was to treat the photon-electron interaction consistently so that students do not develop separate or even conflicting pictures for the photoelectric effect and the Compton effect. This might be an important point to consider when evaluating approaches. Approaches that cannot reconcile the two phenomena might be less suitable to build a coherent quantum conceptual base.

5.2 A synthesis on future research needed

All groups reported that they find the motivation for students or the “need to know” important. This, combined with the core concepts that the groups agreed need to be taught determines the goals. And according to the fact that different approaches are better suited for different goals, the choice of goals influences the choice of approaches. This already suggests some areas for further research. Some groups also specifically suggested many of these areas for future research. From the reports and the specific suggestions, the following research questions for future research emerged:

Topics and approaches

- What exactly should be the minimal standards of “quantum awareness” or “quantum literacy”. This probably means finding a consensus on the absolutely fundamental topics that all teaching of quantum physics should address. In this context the following sub-question was suggested by more than one group:
 - As a solid understanding of quantum concepts is the goal of teaching quantum physics and as at the same time mental models (e. g. as induced by verbal descriptions) are open for debate whereas the formalism is undoubted, the question seems important: What is the absolutely necessary part and which depth of formalism should be taught in order to efficiently develop quantum concepts?
- What approaches are best suited for which topics? This could be a review of literature and can be independent of the consensus about the importance of the topic. The Feynman paths group provided references [40-44] showing that the Feynman paths approach appears to very efficiently build a useful conceptual understanding and can be used in virtually any problem of quantum optics. They acknowledge, however, that other approaches might be better suited to treat two state systems and the photoelectric effect. In evaluating approaches, maybe the capability of the approach to describe the photoelectric effect and the Compton effect with the same model should be taken into consideration.
- How to include inquiry into the teaching of quantum physics? What inquiry based tasks can be performed using experiments, simulations or games and what are the findings that students can arrive at on their own?

Assessment

- Develop a standardised tool to assess the learning of each topic independently. The tool should probably be based on the existing tools, but modified for the intended level of the course (high-school, ...). The tool or tools would need validation.

Motivation

- What works best as the “need to know” or the motivation for student learning? This probably depends on student interests so:
 - Do best motivational elements depend on student interest and how?
 - Are there any motivational elements that are common to students of different interests?
 - Is the philosophy/interpretation of quantum physics a good motivational tool and for how many students? This has been suggested as a motivational tool by many groups especially for not physics oriented students.

6. Conclusions

The discussion focused on three main questions:

- a) What are the fundamental topics to be taught? Four groups mentioned probability and reconciliation of particle and wave properties of quantum entities either through duality or measurement/collapse. Three groups mentioned superposition, the double slit experiment, the uncertainty principle, the wave-like representation and the philosophy or interpretations of quantum physics. Two groups mentioned trajectory, history, non-locality and quantum optics.
- b) Which approaches are most suitable to address which topics? Overall, the discussion concluded that the choice of approach depends a lot on the goals of the teaching, the interests of the learners, and their previous knowledge. A teacher should carefully consider which conceptual topics they want to address, what formalism they want to use, and which goals they want to achieve. The participants recommend using one approach throughout the course.
- c) What should be research questions for future investigation? The participants agreed that further research or meta-studies are needed on the following topics: what should be the minimal standards of “quantum awareness” and the minimal formalism; which approaches are best suited for which topic; how to include inquiry into the teaching of quantum mechanics; develop a standardized tool for assessment of each topic; what are the best motivational elements and do they depend on students’ interests.

The main recommendation by GIREP Community is to discuss how to integrate the different proposals, comparing learning outcomes, by means of physics education research and *research based intervention modules in cooperation with schools and teachers, building a research based teacher and researcher professional development style of cooperation*. The main recommendation by GIREP Community is the following: (i) Discuss how to compare the learning outcomes of different proposals or interventions that did not use the same tool to assess their outcomes. (ii) Discuss how to integrate the proposals with good learning outcomes into modules on specific topics. (iii) Do (i) and (ii) in cooperation with schools and teachers to gain their insight. (iv) By way of (iii) create a research based teacher-researcher professional development cooperation.

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8. References

- [1] <http://teachers.web.cern.ch/teachers/archiv/HST2001/syllabus/syllabus.htm>
- [2] Michelini M 2010 Building bridges between common sense ideas and a physics description of phenomena *New Trends in STE* ed L Menabue and G Santoro (Bologna: CLUEB) pp 257-274
- [3] Stefanel A, Michelini M and Santi L 2014 High school students analysing the phenomenology of superconductivity *Proc. of the WCPE 2012* ed F Tasar (Istanbul: Pegem Akademi) 1253-1266
- [4] Kedzierska E, Esquembre F, Konicek L, Peeters W, Stefanel A, Farstad V S 2010 MOSEM 2 project: Integration of data acquisition, modelling, simulation and animation for learning electromagnetism and superconductivity *Il Nuovo Cimento* 33 C 3 64-74
- [5] Michelini M, Santi L, Stefanel A 2014 Teaching modern physics in secondary school *Proceedings FFP14* ed E Kajfasz, T Masson and R Triay
http://pos.sissa.it/archive/conferences/224/231/FFP14_231.pdf
- [6] Michelini M, Santi L and Stefanel A 2017 Research based proposals to build modern physics way of thinking in secondary students *TPI-15, New Learning Environments and Methods in Physics Education* ed A Király and T Tél (Budapest: Eötvös Loránd University) pp 331-349
- [7] Michelini M 2008 Approaching the theory of QM *Frontiers of Physics Education* ed R Jurdana-Sepic (Rijeka: Zlatni) 93-101
- [8] Pospiech G, Michelini M, Stefanel A and Santi L 2008 Central features of quantum theory in physics education *Frontiers of Physics Education* ed R. J.-Sepic (Rijeka: Zlatni) pp 85-87
- [9] Zollman D A, Rebello N S and Hogg K, 2002 *Am. J. Phys.* 70 (3) 252-259
- [10] Sakurai J J 1985 *Modern Quantum Physics* (Menlo Park: Benjamin/Cummings)
- [11] Müller R, Wiesner H 2002 Teaching QM on an introductory level *Am. J. Phys.* 70 (30) 200-209
- [12] *Am. J. Phys.* 2002 Special Issues 70 (3)
- [13] *Phys. Educ.* 2000 Special Issues 35 (6)
- [14] Dirac P A M 1958 *The Principles of Quantum Mechanics* (Oxford: Calderon Press)
- [15] Stadermann H K E, van den Berg E and Goedhart M J 2019 Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic *Phys. Rev. Phys. Educ. Res.* 15 010130
- [16] Born M 1969 *Atomic physics* VIII ed. (Glasgow: Blackie & Son)
- [17] Hobson A 2005 *Am. J. Phys.* 73 7 630-634
- [18] Hobson A 2007 Teaching Quantum Physics Without Paradoxes *The Physics Teacher* 45 (2)
- [19] Giliberti M 2002 A modern teaching for modern physics in pre-service teachers training *Developing Formal Thinking in Physics Forum* eds Michelini M, Cobal M (Udine: Forum) 400-405
- [20] Ghirardi G C, Grassi R and Michelini M 1997 Introduzione delle idee della fisica quantistica e il ruolo del principio di sovrapposizione lineare *La Fisica nella Scuola* XXX 3 S Q7 46-57
- [21] Michelini M, Ragazzon R, Santi L and Stefanel A 2000 Proposal for quantum physics in secondary school *Phys. Educ.* 35 (6) 406-410
- [22] Taylor E F *Demystifying Quantum Mechanics (Student Workbook): Front Matter, Reflect Exercises, One Photon Exercises, Free Electron*, <http://www.eftaylor.com/download.html> and Educational Paths developed by Rinaudo G and recently by Malgeri M
- [23] Battaglia R O et al 2011 Master IDIFO *Physics Community and Cooperation* eds D Raine, C Hurkett and L Rogers (Leicester: Lulu) 97-136
- [24] Michelini M, Santi L and Stefanel A 2013 E-learning in teacher professional development in innovation and formative guidance on modern physics: the case of IDIFO Master's Programs *Journal of e-Learning and Knowledge Society* 9 (2) 43 – 75
- [25] Italian PER groups developed four main path proposals, offered to teachers in DIFO Master: 1) Path integral according with 17 loc cit (Rinaudo G in Torino and Malgeri M in Pavia); 2) Field Theory approach (Giliberti M in Milan); 3) building theoretical way of thinking: a path inspired

- by Dirac approach to quantum mechanics (Michelini et al in Udine); 4) Wave approach in hystorical perspective (Tarsitani in Rom)
- [26] Atoms in the School (1st Danube Seminar in Vienna, 2nd Danube Seminar in Visegrád 1975)
 - [27] Structure of Matter in the School (4th Danube Seminar in Fonyód 1979)
 - [28] Nuclear Physics – Nuclear Power (GIREP’81 Conference in Balatonfüred 1981)
 - [29] Teaching Non-Linear Phenomena (UNESCO-ICPE Workshop in Csopak 1988)
 - [30] Teaching the science of condensed matter and new materials (Conference Udine 1995)
 - [31] Frontiers of Physics Education, (GIREP-EPEC Conference Opatija 2007)
 - [32] 50th Anniversary GIREP Book (Krakow 2016) and Sokołowska D Michelini M eds. 2018 *The Role of Laboratory Work in Improving Physics Teaching and Learning*, Cham: Springer, DOI: 10.1007/978-3-319-96184-2_2, ISBN 978-3-319-96183-5
 - [33] De Toni A, Michelini M eds. 2019 *L’Innovazione Didattica tra Scuola e Università: attuazione di 80 progetti all’Università di Udine* (Padova: Cleup) [ISBN 978 88 5495 106 8]
 - [34] Michelini M 2018 La Tavola Rotonda GEO sull’Innovazione Didattica *Riflessioni sull’innovazione didattica universitaria* ed. Michelini M (Udine: Forum) [978-88-3283-106-1] p.13-18
 - [35] Michelini M 2018 Da uno sguardo d’insieme all’innovazione didattica come sperimentazione *Riflessioni sull’innovazione didattica universitaria* ed. Michelini M (Udine: Forum) [978-88-3283-106-1] p. 36-50
 - [36] Stefanel A 2008 Impostazioni e percorsi per l’insegnamento della meccanica quantistica nella scuola *Giornale di Fisica* 49 (1) 15-33
 - [37] Michelini M, Stefanel A Approaches on T/L Quantum Physics from PER literature, in this book
 - [38] Taylor E F, Vokos S, O’Meara J M and Thornber N S 1998 Teaching Feynman’s sum-over-paths quantum theory *Computers in Physics* 12 (2) 190-199
 - [39] Feynman R P 1985 *QED: The Strange Theory of Light and Matter* (Princeton: University Press)
 - [40] Ogborn J and Taylor E F 2005 Quantum physics explains Newton's laws of motion *Physics Education* 40 (1) 26
 - [41] de los Angeles Fanaro M, Arlego M and Otero M R 2017 A Didactic Proposed for Teaching the Concepts of Electrons and Light in Secondary School Using Feynman’s Path Sum Method *European Journal of Physics Education* 3 (2) 1-11
 - [42] Hanc J, and Tuleja S 2005 The Feynman Quantum Mechanics with the help of Java applets and physlets in Slovakia *Proceedings of 10th Workshop on Multimedia in Physics Teaching and Learning (MPTL)*
 - [43] Malgieri M, Onorato P and De Ambrosio A 2014 Teaching quantum physics by the sum over paths approach and GeoGebra simulations *European Journal of Physics* 35 (5) 055024
 - [44] Malgieri M, Onorato P, & De Ambrosio A 2017 Test on the effectiveness of the sum over paths approach in favoring the construction of an integrated knowledge of quantum physics in high school *Physical Review Physics Education Research* 13(1) 010101.