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Work Group 3 Position Paper: Teacher Education and Teaching/Learning Quantum Physics

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Work Group 3 Position Paper: Teacher Education and Teaching/Learning Quantum Physics

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Abstract. In this article the discussion of Working Group 3 during the GIREP online seminar 2020 on teaching and learning quantum physics in teacher education is summarized. Conclusions are drawn and research desiderata formulated.

1. Introduction

Research on teaching and learning (T/L) quantum physics often focuses on the specific conceptual difficulties of students in secondary school and in university, as well as on the planning paths according to different types of approaches and investigating students' learning outcomes [1]. There are fewer studies focusing on developing teacher training programs to teach quantum physics below university level [2, 3, 4]. Yet, this is crucially important for any widespread inclusion of quantum physics topics into national curricula. In many countries, pre-service physics teachers come from a physics background, however, in some countries their background is more in general sciences or even specifically chemistry, biology or mathematics. And even in countries where teachers have a physics background, the topics of teaching and learning quantum physics might not receive an adequate amount of consideration, especially if the topic is not in the high-school curriculum (see e.g. [5]). Developing efficient teacher training programs for in-service and pre-service teachers is thus a necessity to introduce the topic into high schools and to have it taught with high quality.

The importance of teacher education for quality teaching has been repeatedly shown in physics education research in an international context [6, 7]. The meeting of European Ministers of Education in Portugal in 2000 resulted in the Green Paper on teacher education in Europe [8]. The Green Paper highlights the crucial role of designing appropriate teaching/learning situations in which pre-service teachers can find opportunities to develop the main professional skills as well as a basic scientific culture enabling them to perform successfully an educational design in spite of their limited knowledge of the subject. The suggested basic activities for teacher education are the following: educational reconstruction of subject matter, problem solving situations, research-based curricular design, planning teaching/learning interventions, learning nodes analysis, and students' reasoning analysis in teaching/learning activities.

GIREP in particular has promoted studies on teacher education since its 2000 Conference in Barcelona [9]. Out of the GIREP Seminar held in Udine in 2003 [10], three main recommendations emerged:

1. Specific professional programmes for teacher education need to be organized in all countries,
2. Didactic research needs to be integrated within teaching and teacher education,
3. Cooperation between school and university is necessary for the quality development of teachers.

Revisiting the conceptualization of pedagogical content knowledge (PCK) was another important aspect [11].

At the GIREP Workshop in Reims in 2010 the main problems in teacher education were documented. These are related to strategies and methods to develop PCK both in pre-service and in-service teacher education [11, 12]. From the EU Project STEPS TWO[2] it emerged that teachers' conceptual knowledge often remains underdeveloped. In this context some appropriate practices were discussed [3, 13, 14, 15]. In particular, *e.g.* from the HOPE Project (www.hope.org4), it was recommended that teachers should, besides the content knowledge and knowledge of common student difficulties, also know elements of the nature of science to promote scientific reasoning in students, be equipped to create environments to promote such reasoning, and continuously evaluate and develop their lesson plans. Among the outcomes of the Hope Project, benchmarks for pre-service teacher education were produced [16].

The epistemological aspects as related to the nature of science are worthy of special attention. It is often the case that quantum physics engages students on a philosophical level, more through its possible interpretations than through its formal rules and models. It is therefore important for students to understand how the knowledge about the quantum world is derived. Especially the role of models in physics is to be stressed [17]. Teachers should, therefore, be aware of these aspects of quantum physics, also because the epistemological beliefs of teachers play an important role in shaping the epistemological beliefs of students. Whereas the epistemological beliefs of teachers are only seldom studied there are some results on the beliefs of students of different levels. Experience from other fields of research in students' and teachers' conceptions shows that in general there are similarities between the two groups. This is strengthened by the observation that most teachers plan their lessons based on their own experience from school and their studies at university, carrying with them also the learned epistemological beliefs [18].

Often it can be observed that teachers do not move consequentially and clearly between the concepts of quantum physics and classical ideas. Research shows that students' conceptions may remain mixed with classical and quantum beliefs or change with the context [19]. The differences of epistemological beliefs between the classical and the quantum domain may remain even after instruction in quantum physics [20]. One aspect in this connection is the relation between mathematical and conceptual reasoning. All these results from studies with students at high school or college can also be observed with pre-service teachers and presumably also with in-service teachers.

2. Methodology and procedure of the working group discussion

The goal of the Working Group in the GIREP 2020 online seminar was to identify how the elements discussed above could be, should be and are implemented in teacher training programs in quantum physics. Therefore the overarching question that led the design of the working group discussions was: Which elements are relevant for developing the PCK of teachers in the topic of quantum physics?

The problem on how teachers in the specific context of quantum physics should be prepared is still open from many points of view:

- contents to be taught
- tools that can be used to activate students and bring quantum physics closer to them
- ways of integrating the different approaches documented in literature
- ways to offer experience
- ways to reach awareness on the fundamental aspects
- decision on educational objectives
- epistemology related to teaching and learning quantum physics.

To achieve the goal of the Working Group, a protocol was adapted for the preparation and the organization of the discussion. Participants were asked in advance to fill in a questionnaire where they submitted the topics that they feel should be addressed. They also submitted a proposal for their contribution. The Working Group leaders reviewed the proposals and divided them into two parts within Session 1: part A with 10 minute presentations and part B with 5 minute presentations. The participants were asked to read the abstracts of the contributions which were previously made available online.

Based on the suggestions of contributions and the results of the questionnaire, the Working Group leaders identified a set of questions that should be addressed in the discussion session. The participants received the questions in advance and were asked to indicate which question they could and wanted to contribute to the discussion in accordance with their experience and expertise.

The questions were the following:

1. Models, structures and strategies for teacher education in QP: In which way can teachers be supported (experiential learning, situated model, apprenticeship, ...)?
    1.1. How can teacher education be made effective in the context of QP? What are the common elements of effective approaches?
    1.2. How can the active role of involved teachers during training be guaranteed (QP)?
    1.3. How can the Nature of Science (NoS) and aspects of epistemology be included?
2. How can teacher educators benefit from the different proposals for teaching and learning QP and how can these be integrated in teacher education?
3. Which experiences are relevant for teacher education in QP (labwork, digital tools, exercises..)?
4. How should professional development of in-service teachers in QP be shaped?
5. How can teacher education in QP be carried out in distance-learning?

Session 2 was devoted entirely to the discussion of the questions. Session 3 was devoted to formulating the conclusions based on the discussion in session 2. These were then presented to the other working groups.

In this paper we present the contributions from the participants to each question. Some topics arose that were discussed under different questions revealing their overarching nature. Based on these we identified a new set of categories that emerged relevant for teacher education. We present them in the conclusion. During the discussion, several areas were identified which are in need of future research. These can be valuable guidelines for future work and are presented in the conclusion.

3. Results from the discussion among the participants

3.1. Teacher education and quantum physics by activating teachers

In this section the main question addressed could be divided into two subquestions (see above)

1. How can teacher education be made effective in the context of QP? What are the common elements of effective approaches?
2. How can the active role of involved teachers during training be guaranteed (QP)?

The answers to these questions, especially the second question, seem especially important as quantum physics is regarded an abstract part of physics. Therefore during the discussion, viable options should be discussed. The participants discussed the various approaches found in literature and pointed out the following points regarding the choice of approach:

- When planning teacher training, we should take into account the prerequisite content and abilities of the teachers and their intended students. This includes their mathematical skills, such as trigonometry, complex numbers and vector algebra, as well as their knowledge of physical concepts such as wave mechanics and interference. These prerequisites might determine the choice of approach.
- One possible approach, especially suited for students with less background, would be to focus on applications, such as quantum computing, quantum games and visualizations. These would build "quantum intuition" or experience in students before possibly later proceeding to more rigorous approaches.

- As there are quite a number of different approaches which are not compared or evaluated by empirical research no recommendation for a singular path can be given at this stage. Instead we should prepare curricular examples, possibly from different approaches.
- Ideally, teacher training programs should offer a coherent proposal based on empirical research on students' learning process. This proposal could be combined from different approaches.
- When teacher training programs are university programs (not professional development courses), it is advisable to integrate them into other physics courses on quantum physics or at least strongly relate the courses to each other.
- When developing teacher training programs, we should take into account the expected future requirements for teachers, not just the current state of national curricula.

Participants also discussed specific strategies that should be employed in teacher training programs:

- It was suggested that some preparation could be done already when teaching classical physics. The concepts of *e.g.* fields or state should be given meaning that is consistent with their meaning in quantum mechanics. If this is not possible (different teachers, schools, …) teachers should discuss the different meanings of the same terms in classical and quantum physics (meaning of state, measurement, the stochastic results, mutually exclusive and incompatible properties, entanglement). But, in any case, a mystification of quantum physics should be avoided.
- Teachers should go through the same learning path as students which was called the "experiential model". However, as part of the course, teachers should develop their own activities or get involved in improving existing activities rather than just copying activities from the course.
- Teacher training should offer teachers real-life situations, not just academic situations, whenever possible.
- It was suggested that resources for the experiential model (teacher training plans and support material) should be made available or developed.

The next topic discussed was the support for the teacher community outside organized teacher training courses. This is especially important for countries where quantum physics is not included in high school education and is often not included in pre-service teacher education.

- Participants emphasized the need for continuous support from physics education researchers and quantum physics experts, even after the course is finished, to clarify any potential questions that may arise later.
- It was suggested that valuable support can be provided from within the teacher community from fellow teachers. A forum for such exchange was suggested.
- Participants emphasized the need for resources (textbooks, guides) especially for high school level. The resources could be structured according to a specific approach (or combination thereof) or they could be modular so that teachers can use the modules according to their needs and combine them together as required to follow their own approach.

3.2. The role of epistemology of quantum physics in teacher education

During the discussion the role of epistemology took a greater part than expected before. Therefore this topic is treated separately. The question was:

How can NoS and aspects of epistemology be included?

Regarding the question, participants emphasized:

- Addressing the nature of science should be part of the culture of the teaching profession. Teacher educators as well as teachers should address it in classical physics and no differently in quantum physics. Teachers should make students aware that there were other times when new ideas were introduced and there was struggle to accept them.
- Teachers should address the role of models even in classical physics. All physics is made of models, and their goal is to describe reality with the precision that is necessary for a particular application. Quantum physics is no different.
- Teachers should emphasize the difference between description and interpretation. To address the nature of science, interpretation is important and teachers could address the history,

philosophy and cultural importance of quantum physics, but should avoid mystifying it. They should also make students aware that the 2nd quantum revolution is unfolding right now and we are part of history.

3.3. The role of different approaches to teaching quantum physics in teacher education

The question posed to participants was:

How can teacher educators benefit from the different proposals for teaching and learning QP and how can these be integrated in teacher education?

Participants agreed as already mentioned in section 3.1. that teacher training programs should not impose a particular path, although one might be used in the program. Instead, teachers and students might benefit from different approaches. To achieve this, the following suggestions were proposed:

- Whatever the approach (learning path), it has to be coherent (next step follows from previous step). Coherence of a path is described in a metacultural perspective (metacultural perspective comprises the detailed explanation of the path and the rationale of a proposed path without detailed teaching materials). There should ideally be one main coherent approach presented as a learning path, but teachers should be aware of other approaches, too. For teacher education the comparisons of different coherent paths is important, analysing power and limits.
- Participants agreed that more empirical research is needed to develop research supported paths. It might be beneficial to use different contexts to address different concepts. More research is needed also to establish which approaches might be particularly suited to develop particular concepts.
- It was suggested that to build deeper understanding it would be beneficial to use different contexts of the same approach (spin, polarization, double well are all two-state approaches) and show how concepts (for example incompatible properties) manifest in different contexts. Similarly, different approaches could be used to address the same context, for example the double slit experiment can be addressed with the wave function, Feynman path integral and as a two-state system.
- It was suggested to develop modular resources so that teachers could combine them as best suits them. A network or database with resources would be welcome.
- If the teacher training program is part of a university program (not professional development course), then an integrated course with physics topics would be beneficial.

3.4. Aspects relevant for teacher education in quantum physics

Participants discussed what are the necessary experiences that future teachers must have to be able to effectively teach quantum physics. Some ideas here are repeated from other topics:

- Teachers should go through the same learning path as students.
- They should experience the cultural and philosophical aspects of quantum physics.
- They should work in inquiry based learning spaces.
- Teachers should experience real-life and simulated experiments. Especially simple real-life experiments are appreciated even if they are only analogy experiments.
- Teachers should also develop skills in solving quantum physics problems. These problems need not be necessarily calculational, but calculational problems should also be included.

A specific topic was the mathematics that teachers should learn:

- Teachers should learn 2x2 matrix algebra and probability. In quantum physics formalism has a conceptual role, therefore understanding it is fundamental. Even if the course the teachers eventually teach contains no mathematics, formalism provides additional and fundamental insight into the workings of quantum physics.
- For special purposes, a course without mathematics can be done (Q keys, games).

3.5. Professional development of in-service teachers with focus on quantum physics
Professional development of in-service teachers may be very important in the initial stages of introducing quantum physics to high schools. In many countries, high school physics teachers are not required to have a physics background and teacher-specialized courses sometimes do not cover topics that are currently not in the curriculum. In these situations a professional development course will be the first contact of teachers with quantum physics. Such teachers must not be overwhelmed by the details of quantum physics, yet should still learn enough to enable them to talk about the topic confidently. To this end, the participants suggested the following:

- On-line forums should be established to provide a place where teachers can clarify their ideas, engage in discussions and receive support when needed either from peers or from teacher educators.
- It is necessary to take into consideration the needs of the teachers. Courses should be flexible, maybe modular, to address as closely as possible the immediate needs of the teachers. Pre-service teachers' knowledge of mathematics may be deeper than that of in-service teachers. In-service teachers' needs are different for teachers who have to teach with mathematical elements and for those who can teach without mathematics (QP for all).
- Guidelines should be developed 1) for short special interventions in quantum physics within other professional development courses and 2) for continuous professional development courses focusing in large part on quantum physics.
- Participants agreed that conceptual understanding has to be privileged. This should enable teachers to engage in meaningful conversations on broad quantum topics even if they do not possess specialist knowledge.
- A collection of formative questions for peer instruction can be used.
- Participants also discussed how professional development courses could be carried out on-line.
- Inquiry based learning spaces were proposed.
- Teachers would benefit from structured or modular resources. These sources should be reliable. Quality control is needed.
- Research supported proposals should be prioritised.
- On-line forums have already been proposed for discussions and sharing experience.

4. Conclusions of the discussion
It is clear from the discussion provided above that the same suggestions appeared under different topics. In this chapter we regroup the suggestions into new categories in order to streamline it with the overarching question “Which elements are relevant for developing the PCK of teachers in the topic of quantum physics?”

4.1. Content of Teacher Education in Quantum Physics - Elements of PCK
The following parts of the PCK correspond to a large extent to the Magnusson model of general PCK. The specific manifestations for quantum physics are mainly found in points A and C. The parts of the PCK (QP) are explained in more detail below.

4.1.1 Awareness of general educational goals in teaching quantum physics. All participants took the importance of quantum physics for general education for granted and stressed the necessity of the knowledge and awareness of teachers concerning the nature of science. From the discussion, the following points emerged as particularly important:

- Knowledge of aspects of the nature of science relevant for teaching QP.
  Knowledge of the nature of science aspects was generally considered important for physics education. However, this is especially applicable for the QP, because there was a long struggle for interpretation. However, it should be made clear that interpretations have no effect on the effectiveness of the models used.

- Cultural, historical and philosophical aspects of QP.
  Within these aspects, the different interpretations of quantum physics were mentioned. In history of science a model that worked often forced a change in paradigm, the most notorious case being the heliocentric model. The building of science knowledge from a historical perspective was also emphasized. Students should be made aware that scientific knowledge develops gradually and that the process of knowledge generation is not straightforward, for example, (teacher) students should be aware that in recent times experimental and theoretical advances contributed greatly to clarifying the open questions and significantly reduced possible interpretations. Therefore any mystification should be strictly avoided. A current example is the 2nd quantum revolution, which is developing rapidly and visibly during this time.
- Similarities and differences between classical physics and quantum physics.
  A similarity is that the world is described with (mathematical) models. The most prominent differences are some of the fundamental concepts (indeterminism, measurement process) and the fact that some terms have different meanings in quantum physics (superposition, uncertainty, entanglement). Some participants pointed out that future teachers should realize that in the teaching of quantum physics there is not necessarily a complete break with the teaching of classical physics, but that there are continuous lines. This is on the one hand on the content level, in that suitable concepts (such as the field concept) are already created in classical physics, which can be linked to in quantum physics, and on the other hand on the methodological level, in that it becomes clear to the students that physics uses suitable models to describe physical phenomena. A clear distinction must be made between description and interpretation. Overall, all agreed that quantum physics should not be mystified, but the differences to classical physics have to be made clear.

4.1.2. Solid content knowledge. The basic role of content knowledge was undoubted. However, there was a discussion on the relation of conceptual and mathematical knowledge. In general, some basic elementary knowledge (2-dimensional Hilbert space) was regarded as necessary, with possible exceptions in special circumstances. From the discussion we identified the following key elements of content knowledge that need to be acquired by the teachers:

- Conceptual knowledge.
  This was regarded as central. It entails identifying key concepts of quantum mechanics such as indeterminism, measurement process, incompatibility.
- Conceptual role of mathematics in quantum physics.
  The mathematics of quantum physics is efficient in modelling the phenomena, regardless of interpretations. Therefore, mathematics takes on a conceptual role in quantum physics. However, for special purposes and in certain circumstances (e.g. second career teachers), a course without mathematics would be preferable to inadequate knowledge (Q keys, games).
- Basic mathematical abilities
  It was agreed that 2-State systems are a suitable reduction and that knowledge about probability is necessary. It was mentioned that calculational problems could also be important in some points.
- Teachers should discuss the different meanings of the same terms in quantum physics and classical physics that rely on mathematical descriptions, among them the meaning of a quantum state, measurement, the stochastic results, mutually exclusive and incompatible properties and entanglement.

4.1.3. Knowledge of didactical knots and paths. By “didactical knots” we mean that teachers should be familiar with critical points in teaching quantum physics, the thinking process of students that is important in these knots, and possible paths or approaches to treat these knots. On the whole, teachers should take into account the previous knowledge and skills of their students and adapt the learning path accordingly. They should also be able to assess the knowledge and skills of the students. In doing so, they must take into account the appropriate use of mathematical elements. All these elements must be linked and planned long in advance.

To be on firm ground the teachers should have:

- knowledge of (at least) one coherent research-based teaching-learning path.
- the ability to transfer this knowledge to other paths (at suitable examples).
- the ability to choose between different coherent paths.

4.1.4. Knowledge of teaching strategies. As with any teaching, so also in quantum physics, the teachers should have:

- the ability to implement methods for active learning.
- knowledge of different resources for shaping lessons on quantum physics, such as visualizations, simulations and animations.
- the ability to choose between different resources.

4.2. Tasks and activities in physics teacher education for quantum physics
Here we take on the stance of teacher educators.

4.2.1. General shaping of teacher education. With regard to teacher education, it became clear that different countries have very different systems. Therefore, the extent of quantum physics in school and university education is quite different. In some cases, quantum physics can only be taught during in-service teacher training. Recommendations for teacher education must therefore take into account the fact that in-service teachers have less time to devote to the content than pre-service teachers.

This will make differences in teacher education as teacher students at university are able to study quantum physics in depth during their teacher training, while in-service teachers will need easy-to-use and flexible materials and proposals for coherent paths. Overall the topics which are part of the PCK should be addressed, even if not mentioned here explicitly.

Tasks or goals of the educators therefore are:

- Apply active learning methods in teacher education.
  Teachers should experience inquiry based learning spaces. They should go through the same learning path as students. They should develop their own lesson plans and if possible evaluate them individually. They should get involved in improving existing activities, if possible.
- Provide support for teachers and/or induce communities of teachers.
  PER or quantum physics experts should support teachers also after a course is finished (e.g. continuous professional development). There are collections of formative questions for peer instructions that should be made available. Course organizers should provide structures that could give support to teachers from fellow teachers, such as face to face discussions, on-line forums (peer and PER support) and other opportunities for discussion.
- Prepare teachers to teach flexibly
  Teachers have to be able to react to different circumstances. Therefore they need a broad spectrum of possibilities and variability in approaches. This can be provided in using different contexts to address different topics (spin, polarization, QT) or to use the same approach in different contexts (spin and polarization are different contexts for the two-state approach). For teacher education the comparison of coherent paths is important, analysing its powers and limits. Teachers should master one coherent path, but they should be aware of other approaches.

4.2.2. Specific focus in teacher education on quantum physics. The broadness of the participants in the working group included the mention of specific approaches or methods followed in some places. These can be taken as suggestions or impulse for developing further existing courses. Among these the role of applications of quantum physics might be mentioned as this is important for motivating teachers and students alike. In this context, problem solving can also be mentioned, where the discussion stressed that this should be done with meaningful problems related to applications.

4.2.3. Materials for teaching quantum physics on all levels. In quantum physics the use of visualizations and models is especially important for supporting and providing an anchor for building an understanding. Teachers depend on a variety of materials to help them design their lessons. Therefore, they must be provided with research-based, high-quality materials. We, as a physics education research community, should prepare suitable materials but only provide recommendations and curricular examples, not impose a particular path. The following points were made:

- Provide resources in a quickly and easily accessible way (perhaps in a database).
  The development of a suitable platform and of the content could be promoted by building a network of contributors. Resources could be textbooks, tasks (also with real-life situations), other similar media, real experiments, simple experiments for enacting in class, simulations, animations, video, …
- Resources should be made available to teachers in modular form
  Teachers have to adapt to very different settings, so they should be able to use the materials as they see fit, according to their teaching style and their classes. Nevertheless different complete coherent paths should also be provided.
- Resources for implementing active learning should be available.

5. Research Desiderata

An important overarching goal of the community of researchers is basic research for teaching and learning quantum physics. This includes not only descriptive or evaluative research, but above all the development of a theoretical framework that can explain the observed learning processes, learning difficulties and learning success on a theoretical basis. An example for this theoretical basis is the identification of how models can be understood with the dimensions of "Gestalt" or "Functionality" [21]. Since in teaching quantum physics visual models, simulations or games are often used, another important point concerns how learners connect the quantum concepts with visualizations of any kind, *e.g.*. to reveal if there are differences between more pictorial or symbolic iconic representations. Therefore the key research desideratum is

> Developing a theoretical framework for identifying the underlying patterns or mechanisms important for understanding the teaching and learning processes of quantum physics.

What such a theoretical framework could look like, which elements it would contain and how it can be developed in the interplay between the deduction from general principles in teaching - learning processes and empirical data on teaching and learning quantum physics, is still open. But such a theoretical framework should help to evaluate future courses on a comparable basis, which are based on different approaches, models or structures in quantum physics. The corresponding research topics to be treated as identified by the participants are:

1. Focus on learning processes and teaching paths
   a) Fundamental research on learning processes in quantum physics. An example could be in which way formal and conceptual elements in teaching quantum physics support or impede each other.
   b) Theoretically based development of coherent paths. This takes into account results from empirical research on students' learning process, as for instance critical points or didactical knots in a given path or general frequent learning difficulties.
   c) Empirical evaluation of different coherent paths, *e.g.* using suitable topics that are fertile for comparison of approaches (i.e. diffraction approach compared to 2-state, wave function approach compared to path integral). This would be the basis for recommendations for teachers based on evidence.

2. Focus on shaping teacher education
   a) Developing and evaluating materials. The resulting materials are used in teacher education.
   b) Evaluating teaching strategies with respect to their success in teaching quantum physics. By this teacher education itself is research based
   c) Evaluation of the structure and methods used in teacher education on the topic of quantum physics. Herewith the open question is if, and in which way, teacher education in quantum physics might be different or similar to teacher education concerning topics of classical physics.

3. Focus on teachers
   a) Analysis of the needs of pre-service and in-service teachers, depending on the concrete situation in a country. The needs could depend on whether the teachers have to teach with or without mathematical elements (depending on country and school type and class level).
   b) Analysis of the way resources (e.g. material in a website) are used and implemented in the classroom. This knowledge would help in providing teachers with usable and effective teaching materials.

A combination of the results from the above research topics could result in general guidelines for structuring teacher education on all levels and for developing teaching materials in an efficient way.

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