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Design and evaluation of a questionnaire on the quantum physics measurement process

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Abstract. In the context of modern approaches to quantum physics via two-state systems, the question of tools for assessing students' understanding and for identifying learning difficulties in quantum physics arises anew because these differ from traditional approaches. In addition, there are different two-state approaches with different characteristics. One of the key points for understanding quantum physics is the measurement process as it lies at the heart of the differences between quantum and classical physics. Therefore, assessing students' conceptions about the measurement process was regarded as a first step towards a comprehensive quantum concept inventory. Hence, a questionnaire to inquire the students' perspective and reasoning about the measurement process as a key concept in quantum physics was developed and presented. This contribution will describe first results of its evaluation and give hints to its further development.

1. Motivation

Recently, due to the considerable advances in quantum technologies, known as "quantum revolution 2.0", the teaching of quantum physics in the field of education has become much more important. The aim is to familiarize pupils with the basic concepts of quantum physics as part of their general school education so that they can participate in corresponding societal discourse as citizens. This goal requires both a radical renewal of the teaching of quantum physics in schools and a detailed knowledge of the learning process of students in the field of quantum physics and of understanding the basic quantum concepts. There is evidence that current approaches to quantum physics using two-state systems may help to reduce students' learning difficulties and enhance their understanding of basic concepts such as superposition, measurement process, uncertainty and entanglement [1].

To analyze the learning processes, to identify the learning success and to evaluate the suitability of such approaches, customized and variably applicable assessment tools are needed that allow to determine the level of knowledge and to diagnose the arising learning difficulties. Therefore, the existing assessment tools in quantum physics based on wave-particle duality have limited applicability in the context of two-state systems. This calls for the development of new assessment tools that could also help teachers to support their students in the conceptual change from classical to quantum physics and thus promote understanding, a so-called "Quantum Concept Inventory" (QCI) [2].

But even when choosing an approach via two-state systems, there are different possibilities of implementation. Among the different possibilities the polarization context is often used at schools [3, 4, 5] whereas the electron spin context with Stern-Gerlach apparatus is found primarily at universities, [1, 6]. But there are more contexts as for instance the double-well context [7], the integration with a wave-particle context [8] or contexts focusing on quantum technologies such as quantum cryptography [4]. All these contexts seem to have specific advantages with respect to teaching the fundamental principles of quantum physics. It might e.g. be conjectured that the electron spin context might be especially suitable for teaching uncertainty: thought experiments with several Stern-Gerlach apparatus in a row (rotated suitably) easily lead to observation of uncertainty; other contexts may show their own strengths. Up to now many quantum assessments focus on wave-particle dualism, understanding of atomic models or calculation of the Hamiltonian or Schrödinger equation. [9] However, instruments for assessing the understanding of quantum concepts in the framework of a two-state approach is mostly missing. Therefore, such an instrument still has to be developed.

It has to be taken into account that the two-state approach is not only used in university on different levels starting from college, but also in high school and it is even intended to find ways to use it in middle school. As mentioned above there are different contexts to choose from when teaching a two-state approach. Therefore, an instrument should be suitable to assess learning in all these different contexts and potentially be suited to identify differences between the learning outcomes. Within the framework of the Quantum Flagship a pilot project DQC-2stap, was therefore launched to develop such an instrument. The contribution of this instrument to the broader research in teaching and learning quantum physics is in the fact that it is the first instrument that we are aware of, that is specifically being developed to be usable in many different contexts of two-state approach and teaching/learning approaches thus enabling meaningful comparison between the learning outcomes of said approaches. It is also intended as a "test of concept" for the development of a quantum concept inventory (QCI).

2. Research Question

The incompatibility of classical physics and quantum physics culminates in the description of the measurement process in quantum physics. [10] Therefore, the understanding of the measurement process lies at the center of an understanding of quantum physics as a whole. Thus, in developing an assessment tool of how students understand quantum physics concepts, we focused on the measurement process as the most intriguing feature of quantum physics. The main objective of the project was to develop items for assessing the understanding of the measurement process that allow to distinguish between the merits of different approaches. Especially we wanted to answer the research question:

- How do the students understand the measurement process in the different contexts of a two-state approach?

In this paper we describe the development of the questionnaire, the piloting, and first results from its evaluation.

3. Design of pilot questionnaire

In order to achieve the aforementioned objectives, it is essential that the questionnaire is applicable to both upper-level secondary students and teacher students, and that it is used as a pre-test and post-test. Furthermore, the items should be formulated in a manner that allows for adaptation to the specific context under evaluation.

In the initial phase of the study, a number of key elements of the quantum physical measurement process were identified. The core point is that, in the absence of a measurement process, it is not possible to simultaneously assign fixed values to all physical quantities associated with a quantum object. This is connected to a number of other properties of the measurement process. The primary concept to be considered is that of indeterminism in quantum physics, which contrasts with the determinism characteristic of classical physics. This implies that the results of a single measurement often cannot be predicted with certainty, even when the possible measurement outcomes are clearly defined. In most cases, only the probability for each of the possible outcomes can be predicted. However, there is an exception to this non-predictability when the measurement is performed on a system that is in an eigenstate of the measured quantity. Moreover, the measurement process may be regarded as a projection onto an eigenstate, whereby the quantum state is altered by the measurement. Accordingly, the items of the questionnaire should encompass the following aspects of the measurement process: indeterminism and the differences between quantum physics and classical physics; (non)-predictability, the impact of the measurement process on the state; the probability of measurement results and the characteristics of the measurement process itself.

In the second step, a selection of items was collected and evaluated by the research group according to their relevance, based on the researchers' teaching experience and a comprehensive literature review. In this phase of the process, the group members engaged in a discussion regarding the suitability and appropriateness of the single items. To gain insight into the reasoning and understanding of the students, the test included both closed and open items. Ultimately, the questionnaire consisted of nine two-tier items with closed response options (three to four options) and four items with an open answer requirement. The closed items were single choice, and students were required to provide a written justification for their selection. The open items encompassed the aforementioned aspects of the questionnaire. Prior to administering this pilot questionnaire, it was tested with a small sample of physics students at the university level to assess clarity of formulation and duration.

4. Participants

The participants were selected according to the following criteria:
i) they should be high school students who had attended a course on quantum physics involving a two-state approach, or
ii) they should be university students who had only attended introductory courses on quantum theory.
These criteria correspond to the population for which the questionnaire is intended.

In the first pilot study, a total of 38 students participated. The participants were student teachers from Germany and Hungary who had not undergone any special intervention but had attended a traditional quantum theory lecture, which made use of a polarization approach to a certain extent. The questionnaire was administered in two formats: as a paper-and-pencil test and in an online version. Following minor modifications, a second pilot study was conducted with high school students ($N = 69$) who had received instruction on two-state systems with polarization of photons [3] (from now polarization approach is abbreviated as PA), and with upper-level secondary school students who had been taught the two-state approach in a double-well context ($N = 26$, the double-well approach is abbreviated as DW) [7]. These studies were conducted exclusively as paper-and-pencil tests in the classroom.

5. Evaluation of pilot questionnaire

We evaluate here only those items that were not changed between pilot 1 and pilot 2. The focus lies on the question if differences between the two groups, upper-level secondary school students (high school students is abbreviated as HS; if a specific group is meant than HS-PA for the polarization context or HS-DW for the double well context is used) and student teachers (abbreviated ST) mostly having attended the traditional quantum theory lecture – can be identified. The diversity of the groups was intentional to increase the likelihood of diverse responses. Here we focus on the insights gained by analysis of the justification of the open items, given by the students. These served as hints for the construction of the final questionnaire.

The justifications were analyzed by inductively generating categories. In a first step the corresponding item and answer option were co-coded, after that overarching categories were formed in several steps. The answers of randomly selected questionnaires were coded by several inter-coders independently of each other. The codes were compared and after an intensive and detailed discussion between the inter-coders the categories were adjusted. From here the descriptive categories were condensed into a category system with 5 main categories with overall 37 subcategories:

- Predictability,
- Role of probability,
- Characteristics of the measurement process,
- Effects of measurement on quantum objects and
- Differences between quantum physics and classical physics.

A coding manual was developed that served for coding both the justifications of the chosen answer option for the closed items and the answers to the open items.

6. Results of closed items

The answers of closed items were evaluated with descriptive statistics and served for deciding which items or distractors should be removed or changed. Answer options with less than 5% ticks of the participants were excluded or revised after the first pilot. Items with signs of misunderstandings were reformulated but at this stage not excluded. Even without going into detail we indicate some observations.

6.1. Possibility of preparation of states is difficult to grasp

Item 1 (see *Figure 1*) was about under which conditions the results of a measurement could be predicted even in quantum physics. Response option C), which suggested that this could only be possible with infinitely precise measurement equipment, was nearly only chosen by student teachers who had attended a traditional quantum theory lecture, not by upper-level secondary school students taught by the polarization approach.

Item 1. A quantum system is in a given state. You want to be able to predict the outcome of a single measurement of quantity P of a quantum system with certainty. Which of the following procedures would best accomplish this in your opinion?
A) No such procedure exists, because you cannot predict the outcome of a single measurement in quantum physics. (ST: 5%; HS-PA: 50%; HS-DW: 27%)
B) You must know that the system is in some particular state (an eigenstate) related to quantity P just before measurement. (ST: 69%; HS-PA: 49%; HS-DW: 73%)
C) You would have to have infinitely precise measurement equipment.
(ST: 26%; HS-PA: 1%; HS-DW: 0%)

Figure 1: item 1 of the pilot questionnaire.

6.2. Effects of measurement are unclear

It seems unclear to students, especially HS, which states can be the results of a measurement. The clear distinction between a superposition state existing before a measurement and the eigenstate after a measurement is missing which mainly occurred with HS-PA being taught with polarization approach. This might be due to the fact that an eigenstate with respect to one given measurement might be a superposition state with respect to a different measurement.

For example, HS, lacking mathematical knowledge, only use horizontal and vertical polarisation states as the basis states. However, a measurement result can also be, for example, a diagonal polarisation state that is still superposed in the V-H basis.

6.3. "Results are never predictable" is predominant

During teaching quantum physics the fact of indeterminism and of the non-predictability of results of single measurements is strongly stressed. Under this condition it seems understandable that students answer accordingly, even for two-state systems: the result of a measurement on a state prepared in an eigenstate of the corresponding physical quantity is given by the respective eigenvalue and thus can be predicted, which seems out of scope for most students. This difficulty showed in the item where students are presented with a concrete example of a sequence of measurements and have to determine the correlation of the measured results. This was the item with the most incorrect answers among almost all students. The justification given by the students indicated indeed that the non-predictability of results dominated all other possible arguments.

6.4. Consistency of (wrong) answers

HS taught with the polarization context (PA) showed an interesting pattern answering questions on the predictability of single measuring results. Students answering an item comprising the general rule, correctly, according to their justifications, seemed to understand what it means to prepare the system in a state and then make the measurement. However, they did not seem to have recognised the same situation in a concrete example: In the concrete item most students did not choose the correct answer option. This might possibly be explained by the inability to apply their knowledge. However, inspecting the response pattern showed a consistency with their concept regarding the role of superposition states before and after measurement. The reasoning hinted that students think that the new state after the measurement is still a superposition state justifying the (wrong) decision in the concrete example. So, what at a first glance seems surprising could be explained in the light of underlying (unclear) ideas on the effects of measurement.

6.5. Characteristic differences between contexts

With some items differences between the different groups were observed. This concerned e.g. the reason why in quantum physics probability is used. The answer option indicating that probabilistic predictions are needed because not all information about quantum states is accessible was chosen mainly by students attending a course with a two-state approach using the context double-well potential (HS-DW). Furthermore, students referred to the fundamentally important role of probability.

In item 5 (figure 2) answer option A) was mainly chosen by ST across the different populations (46% of answers). As reason mostly the necessary interaction or disturbance by the measurement was named. Option C) was mainly chosen by HS-DW (50% of answers). Reason was mainly that preparation of states is not controllable. In contrast the HS-PA mostly answered correctly with answer option B) (70% of answers).

Item 5. In quantum physics, in general cases, we cannot be certain which value of a quantity we will measure. Which of the following claims best describes the reasons for this phenomenon in quantum physics?
A) The reason for getting different values in quantum physics is that the measurement always disturbs the quantum system because it is microscopic. (ST: 46%; HS-PA: 19%; HS-DW: 25%)
B) Generally, results of single measurements in quantum mechanics are inherently uncertain.
(ST: 36%; HS-PA: 70%; HS-DW: 25%)
C) We can never make the state of two systems exactly the same and this leads to a range of possible results. (ST: 18%; HS-PA: 12%; HS-DW: 50%)

Figure 2. Item 5 of the pilot questionnaire

6.6. Justification of answers of closed items

In addition, the reasons the students gave for justifying the chosen answer options of the closed items were coded. The most often coded categories in all items together referred to “The measurement changes or influences the quantum state” (11% of all codings in both groups, respectively), “Prediction of probability is possible” (overall 9%) and “Single measurement results are not predictable” (overall 7%). These results indicate that the basic fact of indeterminism as well as the possibility of calculating and predicting probabilities is quite well understood at the first glance. However, often it was not completely clear if the students stating: “Measurement influences the state”, think of a disturbance or if they just accept the active role of measurement in quantum physics. This question is to be addressed in the further development of the questionnaire. Among the ST also the categories “Measurement leads to the preparation of a quantum state” as well as “Eigenstates play a special role” were coded relatively often (each category about 7% of all codings).

In addition, some differences could be detected between both groups: the ST after a traditional lecture on quantum theory and the HS-PA within two-state systems. The category “Exact measuring devices would help” was chosen mostly by ST (5% of all codings), and only to a small extent by HS (less than 1%). The same is the case for the category “Quantum states cannot be prepared experimentally due to changes on a very small-time scale”. As could be expected the ST more often argued with mathematical structures such as commutativity and eigenvalues as possible measurement results or similar mathematical justification. On the other hand, the HS much more often made the distinction if the quantum state to be measured was in an eigenstate (special state) or not. It seemed clear to them that a measurement on a quantum object in an eigenstate does not change the state. This was not the case with ST who could not imagine such a situation. Also, HS much more often than ST uttered the possibility of preparing a quantum object in a certain state, e.g. with help of polarizers.

7. Results of open items

In the following the four open items will be evaluated. These focused on the predictability, the difference between classical and quantum physics with respect to measurement, the probability and the effects of a measurement in quantum physics.

7.1. Predictability in the context of measurement

All learners seem to have understood and accepted that results of single measurements cannot be predicted, but that (only) probabilities or expectation values can be given. However, in the argumentation it is not always clear if the reason for the non-predictability lies in the superposition or in the uncertainty. Some students state that the Heisenberg uncertainty prohibits the predictability of results. Students generally state that the measurement needs interaction and influences the state. Only very few explicitly use the word “disturbs the state”. But for some students the aspect of a microscopic quantum objects and macroscopic measurement instruments is important and seems to necessitate the use of probability. One student states that the “result of measurement is “fuzzy”. Others see that the measurement leads to determining the state and thus influences the measurement itself.

7.2. Difference between classical and quantum physics

7.2.1. Differences with respect to measurement

Students mostly stated that probability is used in classical physics to deal with measurement errors (21% of all codings). Some students (about 8% of all codings) added that in classical physics the outcomes of a measurement can be predicted. Only seldom it was explicitly stressed that the use of probability in quantum physics is not due to a lack of knowledge, e.g. by reference to the “quantum nature”. That this point might pose a problem is shown by the statement: “In classical physics, when measuring a system in the same initial state, you would be able to predict the same result, but not in quantum physics, because the initial conditions are not exactly known.” or “In quantum physics we have to consider unknown variables.”.

In some cases, it is argued that there is nearly no difference between classical and quantum measurement: “In principle, it is not possible to take an exactly identical measurement in both cases because parts of the system are changed. This change cannot be completely restored in the next measurement. Therefore, the difference is extremely small, it lies solely in the reasons for the changes and the degree of these.”. Sometimes this is set in relation to precise measuring devices: “yes [it is the same], because in both classical physics experiments and quantum physics experiments, there are several factors that cannot be controlled or regulated.”. Others refer to probability: “Yes, because we reason in probabilistic terms and not in certain terms, the results are not necessarily the same”.

Therefore, it seems important in teaching to clarify the difference between the use of statistics in thermodynamics or in complex (non-linear) problems of classical physics and the fundamental role of probability in quantum physics.

7.2.2. Comparison of the role of probability

The answers addressing probability and the answers addressing measurement have some overlap. So, the student answers cover very similar topics. Concerning the difference of the role of probability in classical physics in 13% of all codings for this item they either just stated that probability plays no or only a small role in classical physics, or they described in detail possible uses of probability e.g. in thermodynamics in contrast to the use in quantum physics. Here 19% of the codings referred to the fundamental role of probability in quantum physics. This was done slightly more by ST than HS. Partly, it was stressed that the prediction of probability is possible, but not the prediction of single events.

7.3. Description and effect on state of measuring process

The focus of this analysis was on the result of the measurement. The students described that a measurement needs interaction (10% of the codings), some even described this interaction explicitly or implicitly as entanglement of system and measuring device. In consequence the measurement influences the state of the quantum object (26% of the codings). This aspect of measurement was explicitly called a disturbance in 6% of the codings. The reason given for the change of state was superposition (7% of codings), as e.g. in “Before the measurement the state can be a superposition which is changed after the measurement.”. Students also stressed that the measurement then leads to a well-defined fixed state, some even mentioned special states or eigenstates. Only seldom it was mentioned that the sequence of measurements might be important.

8. General observations

Taken all codings together some observations arise which might inform future research. It seems that the ST after traditional lecture more often than HS-PA argued that infinitely precise measurement devices would help predicting or determining quantum states. Accordingly, HS-PA less often related the need of probability to the lack of knowledge.

The ST more often used mathematical tools such as eigenvalues, eigenstates, commutativity of operators or mathematically founded concepts such as superposition and Heisenberg uncertainty in their arguments. It seemed also clearer to them that repeated measurements do not lead to a second change in the quantum state.

Some of the categories occurred much more often than others: Above all the main category “Predictability” accounted for about a third of all codings. This seems understandable as the items covered this topic and it is an important topic in teaching. Second to this category the possible measurement results (“Effects of measurement on quantum objects”) were coded in 22% of all codings. The other three main categories were used about equally often.

9. Conclusions

The results of the questionnaire provide initial hints that the questionnaire has the potential to distinguish between different teaching context in a two-state approach to quantum physics. This shows a diagnostic potential. In addition, results of school classes also show that details in lessons can lead to significant differences in the answers to the questionnaire. In this area of physics, students are particularly dependent on the formulation of concepts by teachers. This is also reflected in the fact that it is strongly ingrained in students that individual measurement results are unpredictable. They see that probability plays a central role in quantum physics; however, expectation value and possible measurement values are confused. This leads to a great deal of ambiguity about the character of a measurement process: are the measurements indeterminate, or are the measurement devices not sufficiently accurate, or does the measurement influence (uncontrollably) or disturb the state of the quantum object? The results of the questionnaire thus provide indications of how to improve the questionnaire itself for the next iteration as well as the organization of lessons and encourage us to continue this path.

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Appendix

Table 1. Examples of questions from the questionnaire. Each question was followed by: "explain your choice", which we omitted here to save space. On the right are percentages of students choosing each response by group. The tasks have been translated into the native language of the students.

1. You want to be able to predict the outcome of a single measurement of quantity P of a quantum system with certainty. Which of the following procedures would best accomplish this? A) No such procedure exists, because you cannot predict the outcome of a single measurement in quantum physics. (ST: 5%; HS-PA: 50%; HS-DW: 27%) B) You must know that the system is in some particular state (an eigenstate) related to quantity P just before measurement. (ST: 69%; HS-PA: 49%; HS-DW: 73%) C) You would have to have infinitely precise measurement equipment. (ST: 26%; HS-PA: 1%; HS-DW: 0%)
2. Which of the following sentences best describes the predictability of a result of a single measurement of quantity P in quantum physics? A) We cannot predict the value that will be measured, because the result will not be a well-defined value. (ST: 0%; HS-PA: 32%; HS-DW: 58%) B) We can only predict the probability to measure a certain value, because not all necessary information is accessible. (ST: 32%; HS-PA: 10%; HS-DW: 12%)

C) We cannot predict anything at all about a single measurement, not even the probability of outcomes. (ST: 10 %; HS-PA: 58%; HS-DW: 31%)

D) We can always predict the probability for a value to be measured. (ST: 58%; HS-PA: 0%; HS-DW: 0%)

3. What is the reason that probabilities are used in quantum mechanics?

A) The state of a system cannot be determined; therefore, the outcome of measurements can be predicted with probabilities. (ST: 18%; HS-PA: 26%; HS-DW: 15%)

B) The state of a system can be determined; however, the outcome of measurements can only be predicted with probabilities. (ST: 79%; HS-PA: 62%; HS-DW: 42%)

C) The probabilistic predictions are needed because not all informations about quantum states are accessible. (ST: 3%; HS-PA: 12%; HS-DW: 42%)

5. In quantum physics, in general cases, we cannot be certain which value of a quantity we will measure. Which of the following claims best describes the reasons for this phenomenon in quantum physics?

A) The reason for getting different values in quantum physics is that the measurement always disturbs the quantum system because it is microscopic. (ST: 46%; HS-PA: 19%; HS-DW: 25%)

B) Generally, results of single measurements in quantum mechanics are inherently indeterminate. (ST: 36%; HS-PA: 70%; HS-DW: 25%)

C) We can never make the state of two systems exactly the same and this leads to a range of possible results. (ST: 18%; HS-PA: 12%; HS-DW: 50%)

8. A quantum particle is initially prepared in a well-defined state. Immediately afterwards, the system undergoes a process of measuring a physical quantity. Concerning the state after the measurement process which statement is best adequate?

A) The process of measuring in quantum mechanics always changes the state of preparation in an unpredictable way. (ST: 37%; HS-PA: 13%; HS-DW: 12%)

B) The state in which the system will be after the measurement will be given by a distribution of states, each corresponding to one of the possible outcomes of the measurement. (ST: 42%; HS-PA: 44%; HS-DW: 69%)

C) If the preparation process and the measurement process are performed on the same physical quantity, the preparation state and the one in which the particle will be after the measurement will be the same. (ST: 21%; HS-PA: 43%; HS-DW: 19%)

10. Which statement best characterizes the measurement process in quantum mechanics?

A) Before the measurement, the system is in one of the states that correspond to the possible measurement results. The measurement causes it to change into a combination of these states. (ST: 0%; HS-PA: 7%; HS-DW: 12%)

B) The state of the system before the measurement can be seen as a superposition of the states that correspond to all the possible measurement results and the measurement process causes it to change into a different superposition state. (ST: 16%; HS-PA: 51%; HS-DW: 15%)

C) Before the measurement, the system is in one of the states that correspond to the possible measurement results, but it is impossible to determine which one. After the measurement the system is in the same state as before, but now we know which one. (ST:8%; HS-PA: 9%; HS-DW: 0%)

D) The state of the system before the measurement can be seen as a superposition of the states that corresponds to all the possible measurement results. After the measurement the system is in one of these states. (ST: 76%; HS-PA: 33%; HS-DW: 73%)

13. Imagine that Alice performs a measurement on a quantum object in a superposition state. For this she chooses a particular instrument. Now Bob measures the object with an equal instrument immediately afterwards. Alice expects that Bob will get the same result as she did. Which of the following statements applies best?

A) She is wrong because measurement results in quantum physics are unpredictable. (ST: 24%; HS-PA: 70%; HS-DW: 62%)

B) She is right, only if her and Bob's measuring apparatuses are sufficiently precise. (ST: 16%; HS-PA: 0%; HS-DW: 8%)

C) She is wrong, because Bob will certainly get a different result than Alice because of superposition. (ST: 22%; HS-PA: 22%; HS-DW: 23%)
D) She is right, because using the same instrument two times in a row must yield the same result. (ST: 38%; HS-PA: 9%; HS-DW: 8%)