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Observation in quantum physics: challenges for upper secondary physics students in discussing electrons as waves

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Abstract

Quantum physics is challenging for young students, but also a source of fascination. *Observation* is a key concept in order to understand how principles and experimental results in quantum physics differ from what we are used to in classical physics and everyday experiences. In this study we investigate how pre-university physics students understand the concept of observation in the case of the famous double-slit experiment with electrons and interpretations of its results. We found that a conception of observation as *looking*, meaning a passive registration, is prevalent among students. This causes serious problems in understanding quantum physics and leads to very unproductive speculations that links to mysticism. Some students considered observation as measurement involving some sort of apparatus, but very few expressed the key idea of measurement as interaction. We discuss how a more explicit discussion of what observation means in quantum physics can benefit students' understanding of principles in quantum physics and their philosophical consequences.

Introduction

Quantum physics is a part of physics that is challenging to grasp but that often fascinates students, since it breaks fundamentally with our experiences of the physical world and with what is taught in classical physics. Research on student conceptions has shown that students often interpret quantum phenomena in classical terms and have problems in comprehending their nondeterministic nature (see e.g. Krijtenburg-Lewerissa *et al* (2017)). It is also shown that university physics students are often taught the mathematics of quantum mechanics without going into interpretations or epistemological consequences (Baily and Finkelstein 2010, Johansson *et al* 2018).

Observation is a key component of all experiments in physics and other natural sciences. However, in quantum physics the role of observation becomes fundamentally different from classical physics, since, according to standard interpretations, a measurement will *determine* the state of a physical system rather than merely detect it. Research has shown that university

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physics students struggle with what a quantum measurement means, in terms of what happens to the state of the system after the measurement of an observable (Zhu and Singh 2012).

In the present study, we investigate upper secondary students' understanding of observation in quantum physics, and the challenges they encounter in reflecting on how observation can possibly determine the state of a quantum phenomenon. The study is undertaken in Norwegian upper secondary schools by means of recorded role-play discussions in small groups of students that forms part of teaching in quantum physics, and three group interviews focusing on interpretations of the double slit experiment with electrons. Based on the results, we discuss implications for teaching and development of teaching material for pre-university physics teaching.

Interpretations of quantum physics and the double-slit experiment

In almost a century quantum physics has been successful in describing and predicting a range of phenomena, and it forms part of the foundation for modern technology. How quantum physics should be interpreted is, however, still a matter of philosophical discussion long after the famous debates between Einstein and Bohr (see Kragh (2002)). Essential to quantum theory is that a system is described by means of a wave function, and a measurement represents a 'collapse' of the wave function into one specific state. The *Copenhagen interpretation*, represented by Bohr, entails that the system does not have a definite physical state prior to measurement, and that quantum physics can only predict probabilities for a certain outcome. A realist interpretation, on the other hand, holds that quantum objects have definite properties regardless of observation (see Bunge (2012)). Albert Einstein argued that the theories must be incomplete, favouring local realism. Argumentation for this position was outlined in the famous 'EPR-article' from 1935 (Einstein *et al* 1935), but later experimental results and theoretical argumentation known as Bell's inequalities have shown that such an interpretation is not valid (see Aspect (2016)). This clearly face students (and the rest of us) with conceptual challenges, and research in physics education has shown that many students take a realist position

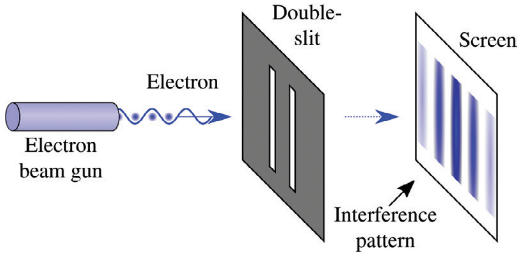

Figure 1. The double slit experiemnt for electrons source. This double-slit image has been obtained by the author(s) from the Wikimedia website where it was made available by Balajijagadesh under a CC BY-SA 4.0 licence. It is included within this article on that basis. It is attributed to NekoJaNekoJa. Wikimedia, https://commons.wikimedia.org/wiki/File:Double-slit.svg.

for granted, and hence have problems grasping the essence of quantum physics and its philosophical implications (e.g. Baily and Finkelstein (2010), Henriksen *et al* (2018)).

The Copenhagen interpretation involves that *observation* gets a fundamentally different role in quantum physics compared to classical physics. Clinton Davisson and Lester Germer showed in 1923 that electrons, like light, are subject to a wave-particle duality (Baggott 2004). Electrons will hence produce interference patterns when sent through a double slit (see figure 1). When physicists attempted to measure the movement of individual electrons, the electrons appeared as particles and the interference pattern disappeared (see e.g. Bartell (1980)). This is an illustration of the complementarity principle that quantum objects can behave as either particles or waves but cannot be observed as both at the same time.

Teaching context and research methods

The context of the research is a teaching activity about the double-slit experiment with electrons where students are given a role-play task in pairs or small groups. The task is from the web-based teaching resources developed in the ReleQuant project[2] (see Bungum *et al* (2015)) and shown in English translation in figure 2.

In the role-play task, one student acts as a science journalist and interviews the other(s) about the results of the double-slit experiment with electrons, in order to reflect on the dilemmas in

[2] The teaching resources are available from www.viten.no/eng/

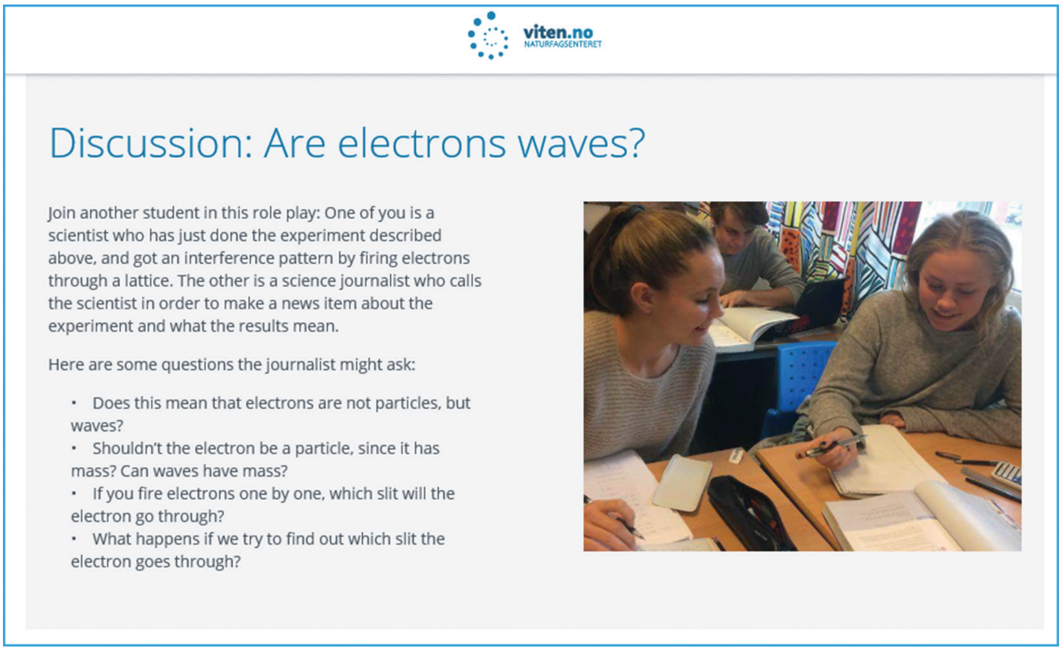

Figure 2. Task for students in the ReleQuant teaching resources. Reproduced with permission from https://www.viten.no/filarkiv/quantum-physics/#/id/5811df08ae8a53f605c7c9c5.

this experiment. Before this activity, students had been introduced to basic principles in quantum physics such as the wave-particle duality for light and the non-deterministic nature of quantum phenomena. The ReleQuant resources also includes the popular video of 'Dr Quantum'[3] demonstrating the double slit experiment with macroscopic particles and water waves, and then with electrons. He shows how electrons behave like waves by forming an interference pattern, but that this pattern disappears when a sensor, represented by a large mechanical eye, is introduced. In that case the electrons behave like particles. Dr Quantum concludes with surprise that the very act of observing determines the electrons' behavior.

In our study in the ReleQuant project students are invited to reflect on these surprising results in a role play with a journalist interviewing a physicist. The students are also given suggestions for questions as shown in figure 2.

The research was undertaken in two steps: first, the role-play discussions were analysed with regards to how students understand the wave nature of matter as it displays in the double-slit experiment. The analysis revealed that the concept of *observation* was a key obstacle for students to make sense of the experiment and particles as waves. The second step consisted of focus group interviews with a new sample of students in order to investigate these findings further. In total, the two data sets were:

1. 39 recorded role-play discussions with 87 students from seven schools.
2. Three focus group interviews, each with four or five students, in total 14 students.

The focus group interviews in data set 2 were undertaken with students at the same stage of the learning process and with similar teaching approach in quantum physics as the sample of students in data set 1. The interviews had the double slit experiment as starting point, and focused explicitly on the concept of observation.

All analysis was qualitative. The analysis of data set 1 was undertaken inductively and resulted in two main categories for how students understand observation in quantum physics. Data set 2 was analysed deductively with these two categories and enriched the results by being more systematic and focused on the problem of observation.

[3] See www.youtube.com/watch?v=Q1YqgPAtzho

Results: students' understanding of observation in quantum physics

The recorded role-play discussions revealed that most student groups were able to describe the double-slit experiment with electrons and how it demonstrates that electrons can show wave properties. To interpret the result that observing one electron at a time makes them behave like particles and not as waves is certainly a challenge to students, as it has been to physicists for decades. However, it turned out that students' reflections on the experiment also showed challenges in interpreting what the concept of *observation* involves in quantum physics. Two main categories of student interpretation of observation emerged from the analysis: (i) Observation as *looking* and (ii) observation as *measurement*. Analysis of the 39 role-play discussions show that 18 were dominated by observation as looking and nine by observation as measurement. Four discussions showed mixed understanding and from the remaining eight discussions it was impossible to extract a conception of observation.

The interpretation of observation as *looking* is illustrated by the following excerpt of a student role-play discussion, which has here developed into a discussion between students outside the script of the role play. Student 1 refers to the video with Dr Quantum that they have watched:

Student 1: It was a bit peculiar with the electrons, but they said <in the video > that there were an observer that in a way registered them, so perhaps it is not possible to find out, since once you observe it it will behave differently.
Student 2: But I do not understand it...
Student 3: But it must be possible to find out.
Student 2: How can it behave differently by being looking at? Is not that weird?

Student 2 is confused by electrons that '*behave differently by being looked at*'. This indicates that the student interprets observation as *looking*, and since the student is aware of the fact that looking is not interfering with what is looked at, the electrons' behavior appears as strange in the student's view. Physical objects are not disturbed by being looked at, while humans may change behavior when aware of being observed. This leads another student to comment:

'I do not understand, electrons are not alive, you look at them and they do something different? It does not make sense'.

The utterances indicate that the students are aware of the fact that human sight is not interfering with what is looked at, the electrons' behavior therefore appear as 'weird' in the students' view. Physical objects are not disturbed by being looked at, while humans may change behavior when we are *aware* of being observed. We see that students question what they see as an *anthropocentric* view of the electron.

The interpretation of observation as looking was dominant in student groups that considered observation in their role-play discussion. However, some students also expressed views of observation as measurement, by referring to a sensor or the act of measurement. For example:

'The only way we can find out is to place a sensor in front and investigate which slit the electron goes through. But the problem is that then we get no interference pattern and the electrons behave as particles, which they do not do when the sensor is not there'

Very few students included *interaction* as an aspect of the measurement, and the introduction of a sensor in the above quotation does not solve any problems for the student.

The focus group interviews with new student groups were conducted to investigate the problem more systematically and outside the role-play context. The interpretation of *observation as looking* was found to dominate also here, and we see many references to the problematic anthropocentric view. For example, when discussing how the results can be different under observation, one student commented that *'there is no interference pattern when somebody observes, when somebody is looking at it, sort of. It is like they have consciousness, in a way'*. The student associates the phenomenon with electrons having consciousness, since only this could make the electron 'aware of' being observed, and then somehow enable it to change behavior.

The discussions among students went on to include consideration of how the use of a video camera instead of an 'observer' would influence the result, or if the observer is turning away, turning off the measuring device or looking at the experiment from a distance (as it the electron would then not 'notice' being observed) would change the result. Students are clearly not comfortable with the anthropocentric view that the problem produce for them, and it seems that understanding observation as measurement do not completely solve the problem for students since they see measurement as a passive process in the same way as looking.

Only a few students refer explicitly to probabilities or measurement as some sort of *interaction*, for example by describing instruments using light or other forms of radiation for detection, and that these photons may disturb the electrons since they are so much smaller than objects we normally deal with. For example, one student stated:

> *'When we introduce an observer, it has to use light to find out which slit the electron go through. And that will influence the result. It is hard to find out which slit the electron goes through'.*

Although this student understands observation as measurement and that measurement involves interaction, he signals a classical and realist view of the electron as a particle that has a definite location independent of measurement. Still, his understanding is a better starting point for going further into what the Copenhagen interpretation of quantum physics means, in this case how measurement causes collapse of the wave function and the electron to behave as a localized particle with a definite position.

Final discussion and conclusion

None of the students in the present study expressed a quantum interpretation of the double-slit experiment. This is not surprising in light of how quantum physics breaks with what students are familiar with from classical physics and everyday experience. It is also in line with how earlier research has shown that students often take a realist position and interpret quantum physics in classical terms as found in earlier research (Baily and Finkelstein 2010, Bunge 2012, Henriksen *et al* 2018, Krijtenburg-Lewerissa *et al* 2017). The results of the study do, however, also demonstrate that a weak conception of observation in quantum physics is a hindrance for learning for pre-university physics students.

We found that many of the students interpret observation as *looking*, probably influenced by how we use the concept in everyday language. When we 'observe' things, it is implicit that we do not interact with them. It is then a challenge that an 'observer' is also used in scientific discourse in quantum physics and other fields of science in situations where we do not consider how the observation is done. The way the video '*Dr. Quantum*' uses a mechanical 'eye' used to represent measurement may also reinforce a conception of measurement as merely passive registration.

Still, we do not believe that the video is the main cause for students' challenges demonstrated in our results. It is rather a sign of a more general problem that what is meant with observation is not given attention in introducing students to quantum physics. This is in agreement with how Zhu and Singh (2012) have shown that students on advanced level in university physics have problems in interpreting what measurement means in quantum mechanics.

The unproductive understanding of observation seems to not only create problems for students in making sense of the double-slit experiment. It may also obstruct an understanding of how the standard (Copenhagen) interpretation entails that the very act of observation actually *creates* the state rather than merely measuring it. An understanding of observation as measurement, and that it involves interaction is a key prerequisite for developing this deeper understanding of quantum physics.

Experts point to the double slit experiment as a key topic for pre-university teaching of quantum physics (Krijtenburg-Lewerissa *et al* 2019), and our results reported in this article show that this should include a thorough treatment of what observation means. With a clearer understanding of observation as interaction, students could go on and learn about important philosophical ontological problems involved in interpretations of quantum physics, notably a realist position or a view involving hidden variables contra the Copenhagen interpretation (Bunge 2012). Instead, as our results show, the students' reflections may go in rather unproductive ways where quantum physics is seen as yet more mysterious than it is, and even related to human consciousness. The idea of measurement as interaction is, however, likely to be within reach even for pre-university physics students and should be emphasized in teaching and teaching material in order to enhance students' understanding.

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References

Aspect A 2016 Viewpoint: closing the door on Einstein and Bohr's quantum debate *Physics* **8** 123

Baggott J 2004 *Beyond Measure: Modern Physics, Philosophy, and the Meaning of Quantum Theory* (Oxford: Oxford University Press) (on Demand)

Baily C and Finkelstein N D 2010 Teaching and understanding of quantum interpretations in modern physics courses *Phys. Rev. Spec. Top.* **6** 010101

Bartell L S 1980 Complementarity in the double-slit experiment: on simple realizable systems for observing intermediate particle-wave behavior *Phys. Rev.* D **21** 1698–9

Bunge M 2012 Does quantum physics refute realism, materialism and determinism? *Sci. Educ.* **21** 1601–10

Bungum B, Henriksen E K, Angell C, Tellefsen C W and Bøe M V 2015 ReleQuant—improving teaching and learning in quantum physics through educational design research *NorDiNa* **11** 153–68

Einstein A, Podolsky B and Rosen N 1935 Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47** 777–80

Henriksen E K, Angell C, Vistnes A I and Bungum B 2018 What is light? Students' reflections on the wave-particle duality of light and the nature of physics *Sci. Educ.* **27** 81–111

Johansson A, Andersson S, Salminen-Karlsson M and Elmgren M 2018 ;Shut up and calculate': the available discursive positions in quantum physics courses *Cult. Stud. Sci. Educ.* **13** 205–26

Kragh H 2002 *Quantum Generations: a History of Physics in the Twentieth Century* (Princeton NJ: Princeton University Press)

Krijtenburg-Lewerissa K, Pol H J, Brinkman A and van Joolingen W R 2017 Insights into teaching quantum mechanics in secondary and lower undergraduate education *Phys. Rev. Phys. Educ. Res.* **13** 010109

Krijtenburg-Lewerissa K, Pol H J, Brinkman A and van Joolingen W R 2019 Key topics for quantum mechanics at secondary schools: a Delphi study into expert opinions *Int. J. Sci. Educ.* **41** 349–66

Zhu G and Singh C 2012 Improving students' understanding of quantum measurement. I. Investigation of difficulties *Phys. Rev. Spec. Top.* **8** 010117

Anders Huseby is a physics teacher with master in physics education from the Norwegian University of Science and Technology. The results presented in this article are drawn from his master thesis about students' understanding of observation in quantum physics, which forms part of the ReleQuant project.

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