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ABSTRACT

Epistemological and philosophical issues have always been relevant for the foundations of physics, but usually do not find their way into secondary physics classrooms. As an exception to this, the strangeness of quantum physics (QP) naturally evokes philosophical questions, and learners might have to change their ideas about the nature of science (NOS). In this exploratory mixed-method study, we examined possible connections between upper secondary school students' QP content knowledge and their ideas about relevant aspects of NOS in the context of QP. We administered a QP concept test to 240 Dutch secondary students (age 17–19) after they attended classes on QP without a focus on NOS. Next, we selected 24 students with a range of test scores for individual semi-structured interviews about their understanding of wave-particle duality and their views on five aspects of NOS. Contrary to NOS studies in other contexts, the interviews showed that all 24 students had well-informed NOS views in the context of QP. We contend that NOS in QP might be more easily accessible than in many other contexts. Our results suggest that QP can have an additional role in the physics curriculum by enhancing students' understanding of NOS.

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Quantum mechanics; physics; secondary school; education research; nature of science

Introduction

Modern upper secondary school physics curricula would be incomplete without some basic quantum physics (QP) concepts. QP has been one of the most important areas of physics since the beginning of the twentieth century when theoretical work by Bohr, Einstein, de Broglie, and many other famous scientists laid the foundation for the development of a new theory. Theoretical insights from QP have opened new possibilities and new ways of thinking not only in physics and chemistry but also in philosophy, biology, electrical engineering, medical diagnostics, and communication technology. Indeed, many electronic devices that students consider indispensable are based on quantum technology.

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In upper secondary physics courses, concepts like the wave-particle duality and Heisenberg's uncertainty principle are taught qualitatively without complex mathematics (Stadermann et al., 2019). Such an introduction to QP is fascinating for students (Bungum et al., 2018), but also challenging to learn and to teach (Krijtenburg-Lewerissa et al., 2017): QP phenomena are not only different from what students experience in the visible world, but many QP principles might not fit with their ideas about physics. For example, when QP is introduced with the so-called standard (Copenhagen) interpretation, students have to abandon their diligently constructed deterministic and realistic worldview of Newtonian physics to predict and explain the outcome of QP experiments, (Johnston et al., 1998; Ke et al., 2005). Learning QP concepts, therefore, causes a cognitive conflict, ideally resulting in changes in students' epistemological beliefs. To explore this relationship, we first compile some research results about students' conceptions of scientific models, the role of interpretations in QP, and nature of science (NOS) in secondary schools. Next, we will present our theoretical framework by connecting NOS aspects to learning QP.

The role of scientific models and interpretations in learning QP

Models in QP

Empirical studies have found that for learning QP, students must understand the reasons for the development of models and learn to handle different models in appropriate contexts (McKagan et al., 2008; Niaz & Rodríguez, 2002). After years of physics lessons in which electrons are modelled as negatively charged tiny billiard balls, students might think that they *are* tiny billiard balls. With that idea, a student can handle most parts of secondary school physics and chemistry. However, quantum entities do not have simple, consistent visualisable equivalents in classical physics. For example, in the iconic double-slit experiment, individual electrons are detected on a screen as single dots as if they were miniature billiard balls. Still, the exact place of detection is unpredictable. After repeating the same experiment with many individual electrons in the same setup, an interference pattern builds up. Within familiar school physics, an interference pattern is only plausible for students if electrons are waves. This 'wave-particle duality' is confusing to students because they are not only missing a useful framework to build on (Taber, 2005) but QP also seems in contradiction with their idea of what physics is: predictable (deterministic) and universal (physical laws should explain phenomena on all scales) (Dutt, 2011; Tsaparlis & Papaphotis, 2009).

Similarly, several studies have shown that students do not easily adopt a new quantum model of the atom but rather stick to the earlier learned planetary model or Bohr model (Adbo & Taber, 2009; Griffiths & Preston, 1992; Petri & Niedderer, 1998). Even after QP lessons about atoms, many students still describe an electron as a classical particle (Mannila et al., 2002) and an atom as 'being' the Bohr model (Müller & Wiesner, 2002b).

Interpretations of QP

While the impact of QP on modern technology and all natural sciences is immense, there is still no consensus on how to understand the foundations of QP (Bunge, 2003; Merali, 2015). In the early twentieth century physicists explored theoretical descriptions of subatomic processes. Coming from a classical, deterministic, and mainly positivist understanding of physics, they developed a new explanatory framework: the quantum theory. The mathematical formalism of the newly developed theory can describe and predict experimental results. What this formalism says about reality was and remains the subject of controversies which have their origin in different philosophical perspectives (Hermann, 1935; Nikolić, 2008). In subsequent decades, several physicists developed diverse interpretations of QP like the Copenhagen interpretation (Bohr, 1935), the pilot wave interpretation (Bohm, 1952) or the many-worlds interpretations (Everett, 1957). These different interpretations are all consistent with the QP formalism, but have, at the same time, peculiar philosophical consequences (Merali, 2015), which result in different understandings of the micro-world. For an introduction to different QP interpretations see, for example, Laloë (2001); distinctive features of the three interpretations we used in this research are summarised in Table S1, Appendix B.

To explain QP concepts on a qualitative level, secondary school teachers necessarily use everyday language. Therefore, it is not surprising that textbook authors and educators – explicitly or unconsciously – use metaphors and visualisable analogies to describe quantum objects and their features (Brookes & Etkina, 2007). By doing so, authors and teachers use specific interpretations; although they seldom make explicit which one they use (Greca & Freire, 2014). While there is no single accepted interpretation of QP, it is argued that it is unavoidable to address interpretations in teaching QP (C. Baily & Finkelstein, 2015; Müller & Wiesner, 2002a) and that the choice of interpretation should be made explicit (Greca & Freire, 2014).

Teaching about different interpretations of QP requires discussing connections between physical theories and reality and inevitably leads to questions that do not have final answers. Addressing such epistemological and philosophical questions on the NOS is not common in traditional secondary school physics classrooms (Bøe et al., 2018) and might feel uncomfortable for physics teachers (Davies, 1997).

NOS in secondary school

In 1998 McComas identified 15 myths about science in educational sources. He found, for example, that textbooks communicate the view that science provides absolute truth, that scientific models represent reality and that scientists use strict procedures not allowing creativity (McComas, 1998). While it is clear that these myths about science and scientists create an unrealistic and undesired view of NOS, it appears to be challenging to define the 'desired' view of NOS (Allchin, 2013; Dagher & Erduran, 2016; Lederman, 2007). Independently of the detailed definition of the term, the general goal of teaching NOS in secondary education is to make students familiar with how and why the scientific enterprise works (Jenkins, 2013). For our research, we prefer not to meticulously define the desired NOS perspective. Because, for some epistemological aspects, this would imply a preference for one philosophical perspective on QP. In this approach, we follow physics educators who emphasise that it is essential for students' QP learning to develop their own epistemological perspective (Bungum et al., 2018; Hoehn et al., 2019). Therefore we will focus on those NOS views which are relevant in the context of QP learning (see Table 1).

Many scholars advocate including history and philosophy of science into science teaching to help learners develop informed NOS views. Indeed, empirical studies have found that students' understanding of NOS improves if epistemological aspects are explicitly

Table 1. Connection between aspects of Nature of Science and Quantum Physics.

NOS aspect	Example of an undesired view	Example of the desired view	Illustration of relevance for QP in secondary education
The role of scientific models	Scientific models represent reality as much as possible.	Scientific models and analogies show some aspects of phenomena in a simplified way.	Depending on the situation, either the wave model or the particle model is appropriate.
Tentativeness of scientific knowledge	Scientific methods yield absolute proof. Scientific knowledge is certain and unchangeable.	Scientific knowledge is always open to development, change and improvement.	It is not possible to understand quantum phenomena with Newtonian physics.
Creativity in science	Scientists always follow strict rules (the scientific method).	Scientists use their creativity and imagination.	The development of QP was only possible through out-of-the-box thinking and creative (thought) experiments.
Subjectivity in science	Science is universal, and scientists are objective; therefore, only one correct interpretation of phenomena is possible.	Science is influenced by non-scientific aspects like personal preferences or historical, cultural, social and economic conditions.	In contrast to other scientists, Einstein was convinced that QP is not a complete description of nature because he could not accept the randomness of QP as fundamental.
Controversies in science	Acceptance of new scientific knowledge is straightforward. Only one interpretation can be correct.	Discussions and disagreements about scientific ideas are essential in scientific development. Different interpretations may exist.	The discussions between Einstein and Bohr show how different philosophical positions result in contrasting interpretations. There is still no consensus about the interpretations of QP. An open atmosphere without strict ideologies makes new developments in QP possible.

and reflectively addressed in historical narratives (Abd-El-Khalick & Lederman, 2000; Allchin et al., 2014; Arya & Maul, 2012; Höttecke et al., 2012; Irwin, 2000; Kim & Irving, 2010). However, explicit and reflective NOS teaching within a historical context is demanding for science teachers and rarely happens in regular lessons (Henke & Höttecke, 2015; Wang & Marsh, 2002).

The role of views of NOS in teaching and learning QP

Understanding QP on a qualitative level can be challenging in many ways, as illustrated above. Many physics education researchers compare the process of learning QP with the paradigm shift from classical physics to QP, described as conceptual change (Shiland, 1997; Tsaparlis & Papaphotis, 2009). In the case of QP, conceptual change not only affects students' understanding of concepts but also their ideas about the nature of physics. Researchers expect that students can more easily change their conceptions from classical to quantum physics if they understand science as a continuously evolving, creative human endeavour influenced by social circumstances and historical contexts (Barad, 1995; Dutt, 2011). Students who are not aware of such aspects of NOS would expect one 'right' explanation for experimental results and, for example, one single correct model for elementary particles; incommensurable models and interpretations would only confuse them. However, students who understand science as a human endeavour could, for example, appreciate the development of different explanations for experimental results because it helps to develop their own understanding of difficult concepts.

In an international comparison of curricula, five NOS aspects were identified as particularly relevant for teaching and learning QP (Stadermann et al., 2019). Table 1 illustrates the connection between these NOS aspects and QP with some examples, and it summarises desired and undesired views of NOS for the understanding of QP.

Considering how NOS and QP are tightly intertwined, researchers assume a positive effect of the development of students' NOS views on their conceptual understanding of QP and vice versa (Bungum et al., 2018; Garritz, 2013; Greca & Freire, 2014; Pospiech, 2003). Our research aim, therefore, is to investigate the connection between NOS views and QP learning for 12th-grade physics students. Our research questions are:

(1) What NOS views do secondary school students express in contexts they know from QP lessons?
(2) What, if any, is the connection between students' conceptual understanding of QP and their NOS views?

Method

Overall setup

To uncover possible connections between students' NOS views in QP and their QP content knowledge, we were particularly interested in the variations of NOS views between students with a good or poor conceptual understanding of QP concepts. Therefore we designed a mixed-methods study in which we used a QP concept test to select low, medium and high achieving students, and investigated their NOS views in semi-structured interviews. To get necessary context information about the QP lessons, especially if NOS-topics were addressed, we observed lessons and interviewed all teachers. Figure 1 shows the overall design of our study. [Figure 1 near here]

Design of the QP concept test

The primary purpose of the QP concept test is to select students in regular physics courses for the next stage of the research. In the Netherlands, QP is usually one of the last subjects to be taught before the national final exams. In that phase, teachers and students can be motivated to participate in research if it supports the exam preparations. Therefore the

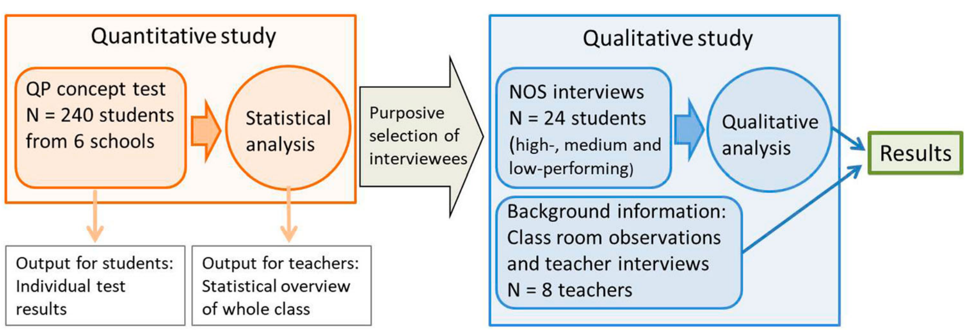

Figure 1. Schematic overview of research design.

test covers the content of the Dutch QP curriculum. To avoid spending much lesson time on administering the test and enabling fast data processing and feedback, we designed an online multiple-choice test. QP curriculum items in the Netherlands are similar to those in other countries (Stadermann et al., 2019). Our test covers seven main themes: light as wave (interference and diffraction), interaction between radiation and matter (energy absorption and emission in atoms), photoelectric effect, matter waves (de Broglie relationship, interference in the double-slit experiment), Heisenberg's uncertainty relation, the quantum model of atoms (particle in a box), and tunnelling.

Starting from existing validated QP concept tests, designed for different educational contexts (Ambrose, 1999; C. R. Baily, 2011; Falk, 2004; McKagan et al., 2010; Muller, 2008; Müller, 2003; Vokos et al., 2000; Wuttiprom et al., 2009), we selected 24 conceptual questions and added three items about interference and diffraction to cover all QP themes from the Dutch exam syllabus. After content validation by a panel of four experts, we piloted the questions in think-aloud interviews with four pre-university students. To make the test as compact and clear as possible, we deleted questions that probed the same concept and made some adjustments to the wording. This reduction resulted in a multidimensional 20 item digital multiple-choice concept test that students can answer on their own devices. We provide the (translated) test in Appendix A.

Assessing students NOS views in the context of QP

To our knowledge, no test instruments that assess students' NOS views in the context of QP have been published. For diverse other contexts, three review articles on conceptions of NOS in science education present an overview of research instruments. Abd-El-Khalick (2014) reviewed 241 empirical research studies and describes how NOS assessments between 1954 and 2013 gradually evolved from forced-choice tests to more open-ended qualitative test instruments. He concluded that open-ended questionnaires and interviews are the most appropriate measures to portray students' NOS perceptions. Abd-El-Khalick, as well as two more recent reviews (Azevedo & Scarpa, 2017; Cofré et al., 2019), found variants of the Views of Nature of Science Questionnaire (VNOS) (Lederman & O'Malley, 1990) the most widely used instruments. VNOS test instruments contain open-ended questions with slightly different examples, contexts and different levels of complexity depending on the age and background of the students. The authors emphasise that their test instrument should only be used in combination with post-test interviews of a representative subgroup of participants to clarify written answers (Lederman et al., 2002).

Despite the widespread use of the VNOS and other NOS instruments, recent studies found it questionable if students or teachers have a universal, context-free NOS understanding (Khishfe, 2017; Leach et al., 2000). Therefore, our NOS test instrument is based on the rich research tradition of VNOS tests, but all questions are focused on the context of QP. This strict context definition enhances the comparability of students' answers and improves the validity of our analysis, but it limits data collection to students who are familiar with QP. A pretest would, therefore, be meaningless, and we consequently do not intend to report on any changes in students' NOS views.

To get an insight into students' understanding of the five selected NOS-aspects (see Table 1) for central QP concepts like wave-particle duality, we carried out individual semi-structured interviews of our selected students. All selected students were cooperative to our request for an interview. We used a prestructured interview scheme with follow-up questions making it possible to reduce misinterpretations. In this, we follow other researchers who used interviews to achieve an authentic understanding of students' NOS views of specific topics (Dagher et al., 2004; Moss et al., 2001; Ryder et al., 1999; Tsai, 2002).

Context

Our target group consisted of Dutch upper secondary school physics students (grade 12: aged 17–19) from public pre-university schools. Eight teachers (five male, three female) with 2–20 years teaching experience from six schools volunteered to test their 12th-grade physics students. Interviews with the eight teachers revealed that each of them spent 16–22 h of lesson time on QP, depending on the textbook and the school's class schedule. Neither the national physics exam syllabus nor the used textbooks contain mandatory NOS aspects in the QP section. Classroom observations and teacher interviews confirmed that teaching focused on content transfer and solving textbook problems. Only one of the teachers explicitly addressed philosophical questions like interpretations of QP and Schrödinger's cat in her lessons.

Two hundred forty students (133 female, 104 male, three unknown) participated in the concept test. All students answered the online QP concept test in their regular classrooms during a physics lesson one to eight weeks after the QP lessons. The period between lessons and test did not have any significant influence on the test results. Spread over the different schools, we selected 24 students for individual interviews; six students with less than 6 points (the 'low achieving' subset), five with more than 12 points ('high achievers') and thirteen of the 'medium achieving' group with 6–12 points. The students of one teacher (not the one who had introduced philosophical issues to the students) were not available for the interviews. We interviewed at least two students of each of the other seven teachers.

The NOS-QP test instrument

The interview scheme consists of three phases with distinct goals in which we adapted test questions from various sources about scientific models (phase 2a), interpretations of QP (phase 2b and c) and NOS views (phase 2a and 3). Table 2 gives an overview of the interview design; see Appendix B for the full (translated) interview scheme.

After anonymising, four randomly selected verbatim transcribed interviews were individually coded by three independent researchers; the two authors of this paper and a university physics education lecturer. First, each researcher related interview passages to QP content, and the NOS aspects summarised in Table 1. During this first round, all three researchers got the same findings regarding the first two interview phases for each student. Only the comparison of NOS codes (phase 3) revealed differences: while one researcher labelled each statement with only one NOS aspect, the others marked some expression as belonging to multiple aspects like subjectivity, creativity or controversies in science. After discussing these statements, we agreed on possible multiple codes. By doing so, we acknowledged that students' views on different NOS aspects are naturally related to each other.

Table 2. Different phases of the interview.

Phase	Goal	Related research	Example questions
1. Introduction	Demographics & Background information		Is QP easy or difficult subject? Why? Have you heard of 'philosophy of science'?
2. Conceptual understanding	(2a) Determining students' conceptions of electrons and atoms.	(Abd-El-Khalick et al., 1998; Harrison & Treagust, 1996; Petri & Niedderer, 1998)	What are the properties of an electron? Tell me as many as possible. How would scientists describe an atom? Could you draw it? Describe exactly what you are drawing.
	(2b) Testing students' knowledge of the double-slit experiment.	(Baily & Finkelstein, 2010)	Can you describe the setup and the results of the double-slit experiment?
	(2c) Determining students' conception of wave-particle duality.	(Baily & Finkelstein, 2010)	Watch the simulated double-slit experiment with electrons. Respond to each statement (*statements represent different interpretations of wave-particle duality*)
3. NOS views	Determining students' NOS views in the context of QP	VNOS-B & D (Abd-El-Khalick et al., 1998; Lederman et al., 2002)	Respond to each statement (*statements represent different NOS views*) How is it possible that physicists have different ideas about what an electron is?

In a second individual coding round, each researcher categorised the answers per NOS aspect as 'informed views' (desired) and 'uninformed views' (undesired). A comparison showed the same results of each researcher in all cases. We applied this two-step coding procedure again to another four randomly selected interviews which resulted in agreement between the three researchers. The residual 16 interviews were mainly analysed by the first author who consulted the second author in case of doubt.

Results

QP concept test

The analysis of students' answers in the 20 item QP concept test showed a left-skewed distribution with a mean score of 7.7 (standard deviation = 3.1), indicating that it was a difficult test (see Figure 2).

A comprehensive analysis of the QP concept test is not the scope of this study, but we want to share some interesting results. The best-scoring questions were about the relation between de Broglie wavelength and the energy state of a particle (Q15, see Appendix A; 72% correct), the double-slit experiment with single electrons (Q11; 67% correct) and Heisenberg's uncertainty relation for everyday objects (Q14; 63% correct). The three least-scoring questions were on energy absorption in an atom (Q4; 9% correct), tunnelling (Q20; 19% correct), and the photoelectric effect (Q12; 21% correct).

Results of the NOS-QP interviews

In the following, we summarise the results of the three phases (see Table 2) of the individual student interviews.

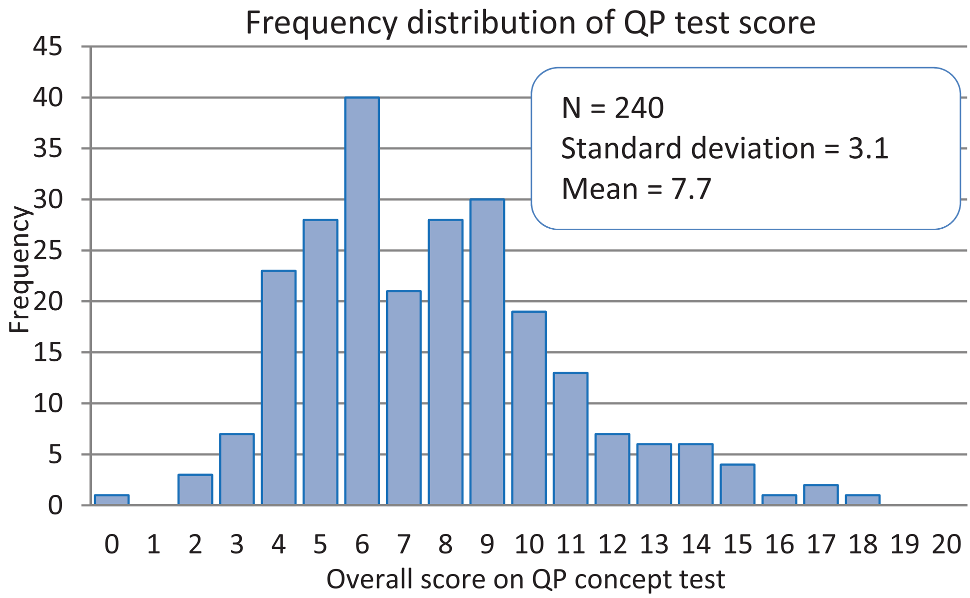

Figure 2. Frequency distribution of QP concept test results.

Phase 1: attitude and prior knowledge

As we do not use the introductory phase of the interview to answer our research questions, we only give a summary and some examples of answers that gave rise to possible educational implications in the discussion section of this article. An overview of students' responses and demographics are given in Appendix C. The student numbers (in brackets after each citations) correspond to those in Appendix C.

Six of the 24 interviewed students reported to know about the philosophy of science, either from a philosophy course ($N = 4$), from a general science course ($N = 1$) or because of personal interest ($N = 1$). We found no relationship between the students' prior knowledge of the philosophy of science and their achievement level on the QP concept test (see Appendix C). We discovered notable differences between students' reasons why they liked or disliked the subject: only one student thought that QP was just a regular item like every other item in school physics, others thought it was more interesting because QP is more mysterious than usual school physics and because there are still open questions, yet others did not like QP because of its 'haziness' compared to standard school physics. In their explanations, several students mentioned that QP was very different from other school physics, which makes it at the same time difficult but more fascinating.

For students of different achievement levels in the QP concept test, the discussions about interpretations made QP more attractive than other parts of school physics:

> I like QP, mainly because there is more than one interpretation. That is why I find it more interesting because it is not yet clear what it really is. On other things in physics, it is agreed on, and it is easier to learn, but here it is nice that you can figure out yourself what you think. (Student 12)

> I think it is very important to know that there are still many things in this world that are unclear. That is also useful to know. This is more interesting than everything that is so well known as if there is nothing more to discover. (Student 5)

Phase 2a: conceptions of electrons and atoms

When asked for properties of an electron, all interviewees initially described a bound electron in an atom as a small, negatively charged (elementary) particle, orbiting the nucleus consistent with the planetary or Bohr model. After the interviewer prompted them to tell more about electrons and their properties, only five of the 24 students added other descriptions, such as wave properties ($N = 4$), electric current in metals ($N = 2$), and beta radiation ($N = 1$).

Phase 2b: knowledge of the double-slit experiment

We asked the question 'Can you describe the setup and the results of the double-slit experiment?' before students saw a simulation of the experiment. Nevertheless, 20 of the 24 interviewed students started with explaining the experiment with electrons. Only four students (medium achievers) started their explanation with light. Asked if the described example is the only possible double-slit experiment, all students knew that the double-slit experiment could be done with light and with electrons. In their explanation of what would happen if electrons would be sent one by one through the double-slit, 23 out of 24 students knew that the same interference pattern builds up over time. Only one student (a low achiever) was wrong; he thought that electrons would be detected in two regions behind the slits.

Phase 2c: conceptions of wave-particle duality in the double-slit experiment

In this phase of the interview, students were asked to respond to given quotes from three fictitious students, representing different interpretations of QP (see Appendix B). We heard many vague or inconsistent statements in which students tried to make sense of what they saw in the simulation of the double-slit experiment. All students were struggling with expressing their view, as illustrated by the following quote:

> I just don't know very well if it is really the case that the electron is spread out over space, I think it's more of a chance. But I am not sure what to imagine. So it goes through both slits and it interferes with itself … that is necessary, … that is also the reason for the interference pattern. (Student 10)

Only two of the interviewed students (one medium, one high achieving) thought that QP is only a tool to calculate experimental results and that further interpretation is not necessary (similar to the Copenhagen interpretation, see Table S1, Appendix B). All others, independently of their achievement level in the concept test, had no explicit preference for one interpretation. In their answers, they combined more realistic (statistical) statements and representations of electrons as matter-waves.

Phase 3: students' NOS views in the context of QP

The results of this phase of the interview (summarised in Table 3) are specified for each of the five NOS aspects.

Table 3. Overview of students NOS views ($N = 24$).

NOS aspect	Uninformed view	Informed view	Remark
The role of scientific models	0	24	Various functions of models were mentioned, all suitable.
Tentativeness of scientific knowledge	0	24	All students understood science as a process that continues to develop.
Creativity in science	1	23	For one student, creativity was compatible with QP but not with physics in general.
Subjectivity in science	0	24	No student had an uninformed view about subjectivity in QP as a scientific discipline.
Controversies in science	0	24	As in previous item, students distinguished between QP and school physics.

The role of scientific models. All (24/24) students knew that there are different atomic models, and they understood the basic role of a model.

> Atoms are too small to see. The only thing you can do is to make a model. And then you try … can I make predictions with this model? And does it confirm everything we observe? (Student 1)

> Humans are very curious and of course, we want to know everything. I think a model is needed to be able to explain certain physical phenomena, or chemical or biological. (Student 13)

Most (22/24) students mentioned that better research methods and growing knowledge lead to more detailed models and that this process will go on. One student stated that this process will stop eventually:

> But at some point, you also have to say that this is correct enough […] At that point, we come to a model […] that you can almost say: this is what it looks like, but we will never know exactly. (Student 15)

Another student thought that it might be impossible to find a complete model:

> We only have three dimensions and an electron could quite well be something completely different … , which we simply cannot understand. Then, a model cannot be completely complete. (Student 24)

Tentativeness of scientific knowledge. None of the interviewed students questioned the continuous development of science. They all knew that scientific knowledge in QP now is different from what it was in the past and that it will change in the future. Students saw this tentativeness of science as fundamental and as a result of human curiosity:

> Because you can always repeat the why question. If you know one answer you can ask again. For example: why does the object fall? Then you have the answer: because gravity works. But then you can ask again: why does gravity work? And even if you can explain that, you can ask again: why? I think you can never get to the bottom of the why. (Student 1)

Students understood that tentativeness – due to new interpretations or improving methods – is a characteristic of science, as can be seen in the following example.

> Of course, you can investigate what has already been discovered, but [in science] you must be able to think differently than the people before you who have already done experiments. Because only then you might be able to find something else, which leads to new results or new investigations. (Student11)

Creativity in science. For this question, students were asked to comment on three given statements about interpretations in QP. The most popular one (23/24) was the statement that scientists need creativity to develop new interpretations. One student articulated the noteworthy opinion that creativity belongs to QP, but that QP could not be regarded as physics because of the philosophical character of QP interpretations.

> I think quantum physics is not really part of physics. […] I think that it is just an entire subject of its own … Because this is so philosophical, I think. Most physics is not really philosophical. I think that's the difference. […] If everything is clear and does not need to be discussed, then it is not philosophical. And that is certainly the case with the rest of physics. (Student 6)

Although the interview question was situated within the context of QP, 15 students spontaneously connected creativity more generally with science:

> I think that as a researcher, scientist or physicist, you need a lot of creativity … You have to think out of the box because you want to investigate something unknown. (Student 11)

> To find an explanation [as a scientist], you need a lot of creativity, a lot of experiments, and diverse ways of thinking. (Student 12)

Subjectivity in science. The interview question aimed at students' ideas about subjectivity in science, addressed the existence of different QP interpretations. We asked students how it is possible that different interpretations exist, and if it would be better to have only one interpretation. Most students (23/24) thought that physicists developed different interpretations of QP because of their diverse personal backgrounds.

> Maybe [scientists develop different interpretations] because of what they are, their profession, what they are most involved in. They developed certain ideas in their studies or so. What you think is based on that. You think: Oh, with what I learned, I could explain that. So with that in mind, you look at quantum physics. Through your environment, your upbringing you develop your ideas. (Student 16)

Five students described a difference between physics as an academic discipline and the physics they learn at school. Two low achieving students saw a diversity of interpretations as part of professional scientists' research but undesired for learning.

> I don't think they should choose an interpretation, but I do want them to show us only two or three. […] Yes, for real scientists it is different, they have to do research … but not so many different possibilities for students. (Student 4)

> I think at school you should only learn one interpretation. But as soon as you have more understanding of the subject you can learn more about other interpretations. But as long as you don't understand the basics, I think it will only get confusing. (Student 7)

Controversies in science. All students understood, in the context of QP interpretations, that controversies belong to science.

> In principle, it is useful if there is a consensus. But maybe it's just not yet the time for it. If there is not enough evidence to accept one interpretation generally over the others. In that regard, it is important that there is a discussion; that you can choose one side and try to prove it. But you must be open to other interpretations if it turns out that yours is wrong. (Student 20)

Several students (7/24) spontaneously articulated that controversies are normally not part of the physics curriculum and that this makes QP special.

> This topic [QP] is not yet done to death. I think there is still a lot of research. If there is no fixed interpretation, which everyone agrees on; so there is no right interpretation either. From what I know, we see this only in QP. You don't learn in other physics topics that there could be other theories for gravity or even three different ones. (Student 4)

Conclusion and discussion

In this study, we explored secondary students' views of NOS in the context of QP and their achievement level on a QP concept test. We then sought a possible connection between both. The students were tested after their regular school physics lessons about QP. We did not ask the teachers to pay attention to NOS, and most of them (seven out of eight) indeed did not mention NOS, as interviews and classroom observations showed.

Concerning the first research question, we found that all interviewed students exhibited desired views for the probed QP-related NOS aspects. The second research question, regarding a possible relation between students' NOS view and their ability to master QP concepts, accordingly has an unexpected answer. Because students of all QP achievement levels were able to express a variety of informed NOS views in the context of QP, it is not possible to relate performance levels in a QP concept test to specific views of NOS.

Additionally to the answers on the research questions, the students interviews gave us some insights into existing opinions about school physics and the possible role of QP in developing students' NOS views. In the following, we will discuss the results in detail.

Students' conceptions in QP

The first research step was to identify students with different performance levels in QP for the interviews. The overall low score on the QP concept test showed that our pre-university students have difficulties understanding QP. This is hardly surprising, as even university physics students find it difficult to answer similar questions on basic concepts of QP (Johnston et al., 1998; Vokos et al., 2000; Wuttiprom et al., 2009).

The next step was to interview selected students to determine their conceptions of electrons, atoms, and wave-particle duality (interview phase 2 in table 2). The interview revealed that most students gave ambiguous descriptions of electrons, as a classical particle or as a wave. This result accords with a large number of findings in research on introductory QP education (Adbo & Taber, 2009; C. Baily & Finkelstein, 2010; Harrison & Treagust, 1996; Hoehn et al., 2019; Mannila et al., 2002; Petri & Niedderer, 1998). In an atom, electrons are mainly described as classical particles but to explain the outcome of the double-slit experiment all interviewees also used wave properties. We agree with Hoehn et al. (2019) who argue that the tentative and messy reasoning about the wave-particle duality – mixing of and switching between different interpretations – is not a problem but an essential and productive step of students' sense-making in QP. In their study, the authors analysed students' explanations of the double-slit experiment with the conceptual blending framework. The researchers explicitly mentioned that students' phrasings when grappling with quantum ideas are very similar to the discourse of professional physicists. We return to this topic later when we analyse the role of NOS in QP from a student perspective.

All results from this part of the research confirm that our students are comparable to those in many other studies about learning introductory QP.

NOS views in QP

Contrary to our expectations, nearly all students were able to articulate informed views on all five selected NOS aspects, although the lessons they followed did not explicitly address NOS aspects. This finding differs from those from earlier studies into the NOS views of students, which found that students generally have uninformed NOS views and contextualised NOS teaching requires explicit and reflective teaching strategies (Abd-El-Khalick & Lederman, 2000; Clough, 2017; Khishfe & Abd-El-Khalick, 2002; Lederman, 2007).

Although surprising, our results are robust. The labour-intensive way of data collection through individual interviews gives rich information on students' NOS views. Additionally, we were able to interview a large variety of individuals with different achievement levels and from different teachers and schools.

To explain our unexpected finding, one could argue that, by contextualising our NOS questions in QP, we unavoidably created an explicit and reflective learning situation for the students. While this reasoning might partly be valid, it is still remarkable that students, who were not explicitly exposed to NOS aspects during physics lessons and had never heard of the philosophy of science, all spontaneously exhibited informed NOS views – even those students who struggled with answering QP concept questions. It seems that in the context of QP, uninformed views on the selected NOS aspects are so untenable for students that they are naturally led to more informed views.

So, is QP so different from other physics topics? In our opinion, there is one outstanding advantage of QP above historical narratives in other research (Abd-El-Khalick & Lederman, 2000; Höttecke et al., 2012; Irwin, 2000): just like professional physicists, secondary students experience the need to make sense of the results of the double-slit experiment. This becomes evident in their elusive way of answering interview questions. Students can understand that the discussion around the 'right' interpretation of QP is still not resolved. In that sense, QP is 'science-in-the-making' where fundamental aspects are still controversial (Latour, 1987) in contrast to 'ready-made science' as traditionally taught in school physics.

For other implicit NOS teaching approaches which cover episodes from the history of science, learners have to put themselves mentally in a historical context. Researchers found that this necessary change of perspective is difficult for learners (Abd-El-Khalick & Lederman, 2000). The authors found that many students perceived alternative historical controversies to be 'non-scientific' by modern standards. To make scientific controversies more accessible for students, contemporary socio-scientific issues (SSI) are another potentially fruitful context for NOS teaching (Holbrook & Rannikmae, 2007; Khishfe, 2014). However, students' emotional involvement makes it difficult for them to see these controversies as fundamentally scientific (Allchin et al., 2014; Mesci & Schwartz, 2017). Moreover, teachers commonly avoid SSI in physics lessons (Dunlop & Veneu, 2019).

The findings of this study suggest that QP provides excellent opportunities to teach NOS aspects because (1) it is a contemporary science topic that fascinates students, (2) it includes scientific controversies, (3) it is included in the regular advanced physics curriculum of many countries, and (4) students develop informed NOS views in the context of QP even without extra lesson time.

Views on school physics and QP

Although we did not ask for it, we found that some students expressed differences between school science and professional science. This is in accordance with findings from the literature and constitutes a possible additional explanation of the surprising outcome of our NOS test. Hogan (2000) distinguishes between two different understandings of science: 'proximal knowledge', which is related to students' epistemologies and beliefs about the nature of learning science ('What the teacher is telling us are trustworthy facts') and 'distal knowledge' as views of science of professional scientists, their ways of doing research and social processes to develop scientific knowledge (Hogan, 2000). Similarly, Sandoval (2005) discovered a difference between students' practical epistemologies (students' views on their own laboratory experience) and formal epistemologies (views of what science in general is). This difference is precisely what one low-achieving student expressed when he gave his opinion on various interpretations of QP: 'Yes, for real scientists it is different; they have to do research … but not so many different possibilities for students.' (Student 4) We conclude that he and several other students had an informed view on physics as a professional science but a rather narrow view of physics as a school subject. Unfortunately, this is not at all a naïve or uninformed view; it is just the result of previous physics lessons in which questions only have right or wrong answers (Bøe et al., 2018; Elby & Hammer, 2001). As a consequence, students see a difference between professional science and school science (Hodson & Wong, 2014; Sandoval, 2005). Since many NOS test instruments use non-contextualised questions and do not differentiate between school science and real science, we question their validity.

Implications for education

Our findings suggest that NOS teaching could benefit from the ease with which students develop insights into NOS in the context of QP. Although we do not expect that students will transfer their informed NOS view in QP to other contexts, QP seems to be a good starting point to talk about the processes and properties of the scientific enterprise in general. Some students already spontaneously mentioned the possibility of different interpretations for other physics concepts such as gravity.

Our research could also encourage teachers to address different QP interpretations in their lessons because many interviewees mentioned that the idea of the 'unsolved problem' of QP makes the subject more attractive than the 'facts' physicists agreed on long ago. By including philosophical aspects in QP lessons, teachers could not only broaden students' views on the subject but also involve and attract a larger variety of students (Johansson et al., 2018).

Implications for further research

Our study raises some opportunities for future research. We noticed, for example, that most teachers in our research did not explicitly address NOS aspects although NOS is clearly connected to the learning of QP. This evokes the question whether integrating explicit and reflective NOS teaching in QP lessons could help students to master this conceptually difficult subject.

To investigate if students experiences with QP leads to a change in NOS views in future learning. It would be interesting to investigate the NOS understanding of younger pupils who learn some QP concepts, for example, in the 'Einstein-First' project (Kaur et al., 2018). Could controversies in QP also be addressed in middle school physics lessons? And what effect would this have on students' development of NOS views?

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