MASTER THESIS

TEACHING THE WAVE-PARTICLE DUALITY TO SECONDARY SCHOOL STUDENTS: AN ANALYSIS OF THE DUTCH CONTEXT

Luiza Vilarta Rodriguez

FACULTY OF BEHAVIOURAL, MANAGEMENT, AND SOCIAL SCIENCES
MASTER EDUCATIONAL SCIENCE AND TECHNOLOGY

EXAMINATION COMMITTEE

Dr. Jan T. van der Veen
Ir. Kim Krijtenburg-Lewerissa

ENSCHEDE, 19 DECEMBER 2018

CONTENTS

1 FOREWORD

Writing a master thesis is no easy task, especially in a language different from your native one and in a country completely different from the one you were born and lived in for 22 years. That is why I am so grateful for all the people who made this process easier and helped me every step of the way. I am thankful to all professors, advisors, secretaries and assistants of the EST master who took their time to aid me when I needed and, most of all, to consider me as a suitable candidate for the program. I would like to especially thank my supervisors Jan van der Veen and Kim Krijtenburg for their patience and support. My thanks also go to Jan Nelissen, Yvonne Luyten, Bas Kollöffel, Susan McKenney, Ed van den Berg, Patrick Diepenbroek, and all teachers and students who were directly and indirectly involved in this study.

I also thank my dear family and friends for their support. Johan, thank you for always being there to pick me up and show me what I was capable of. Mom and dad, thank you for answering my calls, listening to me, and always having a good piece of advice to give. All my dear friends in Enschede and Campinas, I am so grateful for all the fun we had and for how much we learned with each other. To my newer friends Alisa, Chacha, Dijana, Erik, Gloria, Kelly, Ksenia, Ly, Marcella, Nadia, Nikos, Paula, and Tom, thank you for making me feel welcome and at home (and for the great parties). To my old friends Danielle, Emerson, Felipe, Gabriela, Jey, Julio, Laryssa, and Marina, thank you for making every reencounter feel as if I had never left Brazil (and for the great discussions about quantum mechanics and for your help).

Finally, I would like to dedicate this study to my aunt Leci and my grandma Neusa. I know that you two are proud of me, but it hurts everyday that you cannot tell me that. I miss you both so much.

2 SUMMARY

Quantum mechanics (QM) is a fundamental, yet complex theory of Physics. The importance of QM grew during the 20th and 21st centuries due to its success in aiding the development of new technologies. Therefore, learning QM has become a standard practice in universities and, more recently, high schools. However, research shows that students in both levels have difficulty to develop a quantum way of thinking, which leads them to make use of classical Physics to interpret QM phenomena. This stresses the need for teaching sequences and instructional methods which focus on effective conceptual change practices. In the Netherlands, QM was recently added to the secondary school curriculum, which also raises the need for more research about QM teaching in this specific context. Therefore, this study focuses on answering the following question: *What is the current state of instruction on the wave-particle duality in Dutch secondary schools and how to promote the process of conceptual change in such context?* For that, the first phase of a design-based research was conducted. The results comprise the current practices from teachers, approaches from school books, insights from literature, and remarks on students' understanding about the wave-particle duality. These results revealed deficiencies in the analysed educational practices and provided suggestions on how to resolve them. Although several aspects were not covered in depth, this study provided further input for future researches about QM instruction in Dutch secondary schools. Additionally, the results also aid teachers and developers of instructional materials, who can find in this study a compilation of best practices, students' (mis)conceptions, and suggestions for improving instruction on the wave-particle duality.

3 INTRODUCTION

Quantum mechanics (QM) has become a fundamental theory to physically understand, describe, and predict (sub)atomic phenomena. Although it has generated several controversies among scientists and is still not fully comprehended, QM made various technological advancements possible. According to Krijtenburg-Lewerissa, Pol, Brinkman, and Van Joolingen (2017), QM is the foundation of technological developments such as medical imaging, laser physics, semiconductors, and quantum computers. Given the importance and accuracy of QM, its learning has become a standard practice in university physics, chemistry, and engineering courses. Additionally, countries such as England, Germany, Italy, the USA, and France have added QM to their secondary school curricula (Krijtenburg-Lewerissa et al., 2017). According to Johnston, Crawford, and Fletcher (1998), introducing QM in high school is necessary because of the theory's complexity, which is explained by its highly counterintuitive and abstract content (Ayene, Kriek, & Damtie, 2011). Therefore, students require more time to reflect upon it, which raises the need to introduce QM at an earlier stage of instruction (Johnston et al., 1998).

The intricate character of QM poses a challenge for those who learn it and for those who teach it. More specifically, students are familiarized with Newtonian (classical) mechanics before their first contact with QM. On one hand, Newtonian instruction explains the behaviour of macroscopic objects and is more intuitively acceptable (Kaur, Blair, Moschilla, & Zadnik, 2017). On the other hand, QM concepts are difficult to visualize and do not agree with what people experience in the macroscopic world (Özcan, 2015). Therefore, researchers (e.g., Mannila, Koponen, & Niskanen, 2001; Greca & Freire, 2003; Ayene et al., 2011) found that students in various levels of education use elements of classical mechanics to comprehend QM. This results in the development of alternative ideas and models of quantum concepts which are "more or less simple extensions of classical pictures" (Mannila et al., 2001, p. 45). In other words, most students do not develop an appropriate knowledge of the quantum theory and in fact incorporate classical physics concepts into their mental models of quantum entities. Because QM learning requires a fundamental shift in perception and thinking, its instruction should focus on how *conceptual change* can be fostered (Shiland, 1997; Krijtenburg-Lewerissa et al., 2017).

The wave-particle duality is a fundamental and unique phenomenon of QM. It is characterized by the fact that quantum objects, such as electrons and photons, present wave and particle behaviours. According to Ayene et al. (2011), the wave-particle duality, together with Heisenberg's uncertainty principle, can be used as a foundation of introductory QM.

Although some researchers disagree with this introductory role of the wave-particle duality (see Olsen, 2002), several QM courses begin by teaching this phenomenon. The introductory character of the wave-particle duality enables the exploration of teaching strategies that foster early conceptual change from classical to quantum thinking and aid further comprehension of other quantum phenomena (Ayene et al., 2011). This can be achieved, for instance, using nonmathematical approaches to the phenomenon, active learning, emphasis on interpretation and mental models, cognitive conflict, and metaconceptual awareness (Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001; McKagan et al., 2008; Dangur, Avargil, Peskin, & Dori, 2014; Krijtenburg-Lewerissa et al., 2017). Such teaching strategies promote meaningful learning experiences which facilitate the incorporation of counterintuitive knowledge to students' own ideas (Vosniadou et al., 2001).

QM was added to the Dutch pre-university curriculum and national final exams since 2016 (Van den Berg, Van Rossum, Grijsen, Pol, & Van der Veen, 2018). According to Van den Berg et al. (2018), students in this level of secondary education represent an annual average of 20.000 students and 10% of all 17-18-year olds. This recent addition of QM to the Dutch curriculum implies that research regarding QM teaching at Dutch high schools is at a preliminary stage. Nonetheless, data collected by Cito (Dutch institution for national exams) since 2016 show that half of the items which covered QM topics in the last national exams have a correct response rate of 16% to 49% (Cito, 2016, 2017, & 2018). This stresses the need for research on effective teaching practices and student understanding of QM in Dutch schools. Based on this need, this study analysed the current context of the wave-particle duality instruction in Dutch high schools and how it could be improved to promote conceptual change. Therefore, the main research question of this study is: *What is the current state of instruction on the wave-particle duality in Dutch secondary schools and how to promote the process of conceptual change in such context?*

First, a preliminary literature analysis is reported to present the theoretical framework used in this study. Through this framework, the study's research questions are formulated. The theoretical framework is followed by a description of the method through which this research was conducted. Then, the results gathered through the used instruments are described. These results are further summarized and discussed, and implications to practice and research are drawn based on them. The study is then concluded with a summary of its main aspects and findings.

4 THEORETICAL FRAMEWORK

4.1 WAVE-PARTICLE DUALITY

Throughout the development of classical physics theories, scientists have observed that energy can be transferred either by waves or by particles (Eisberg & Resnick, 1985), leading scientists to develop a *wave model* to describe certain macroscopic phenomena and a *particle model* to describe other macroscopic phenomena. These models were also used to successfully explain some microscopic findings, leading physicists to believe in a *binary* characteristic of physical entities: They either behave as waves or as particles (Eisberg & Resnick, 1985). However, later findings challenged this binary model. For instance, on one hand physicists observed the success of Maxwell's wave theory to describe electromagnetic radiation. On the other hand, physicists also needed particle models to understand the Photoelectric effect, which involves the same electromagnetic radiation. Additionally, the accuracy of de Broglie's postulate (see section 4.1.2) showed that particles of matter exhibit wave behaviour (Walker, Halliday, & Resnick, 2011). Therefore, the term *wave-particle duality* was created to characterize this dual behaviour of quantum objects.

Although the wave-particle duality is one of the most fundamental phenomena of QM, it is also one of the most difficult to grasp (Olsen, 2002). Heisenberg (1930) states that the difficulty in understanding the wave-particle duality is due to:

> the two mental pictures which experiments lead us to form - the one of particles, the other of waves - are both incomplete and have only the validity of analogies which are accurate only in limiting cases. … Light and matter are both single entities, and the apparent duality rises in the limitations of our language. (p. 10)

As an attempt to avoid the use of classical analogies when describing quantum objects, Lévy-Leblond (1988) and colleagues (see Lautesse, Valls, Ferlin, Héraud, & Chabot, 2015) defended the use of the term "quanton" - together with changes in the interpretation of QM - to refer to such objects. He argued that such change would also aggregate pedagogical advantages, as it would prevent the formation of classical images by students. Greca and Freire (2003) adopted a similar pedagogical strategy when developing a teaching strategy for an undergraduate quantum physics course: they referred to quantum entities as "quantum objects" (p. 550) and avoided any reference to wave and particle models. Despite the pedagogical potential of this alternative interpretation, wave and particle analogies are still rooted and present in most QM courses and textbooks (Lautesse et al., 2015).

To comprehend students' difficulties in understanding the wave-particle duality, Krijtenburg-Lewerissa et al. (2017) analysed the findings of several studies on students' misconceptions about the subject. The authors divided such misconceptions into the clusters defined by Ireson (1999, 2000) and Ayene et al. (2011) to categorize students' descriptions of the wave-particle duality. These clusters are: *classical description*, in which quantum entities are described as either particles or waves; *mixed description*, in which students recognize the coexistence of wave and particle behaviours but still describe quantum objects in classical terms; and *quasiquantum* description, in which students know that quantum entities show wave and particle behaviours but describe the associated phenomena in a deterministic way. To provide a more detailed outline of students' misconceptions in the following sections, not only will these clusters be used, but also a division of topics within the scope of the wave-particle duality, inspired by the work of Krijtenburg-Lewerissa et al. (2017). The topics are: photons and electrons, double slit experiment, and photoelectric effect.

4.1.1 PHOTONS AND ELECTRONS

Photons and electrons are quantum objects which show both wave and particle behaviours. Researchers have found that students, when learning about photons and electrons, develop different ways to visualize the entities and have difficulty in integrating such wave and particle behaviours (Krijtenburg-Lewerissa et al., 2017). For instance, Johnston et al. (1998) conducted a phenomenographic analysis to explore the understanding of fundamental QM concepts by undergraduate students who had successfully completed a module on QM. Their results suggested that the participants learned the subject superficially through mental models composed by a collection of isolated and abstract facts. More specifically, the characteristics used by the students to describe an electron or proton were: mass and elementary charge, displacement through well-defined trajectories, and compliance with Newton's laws (Johnston et al., 1998). Tthese explanations can be categorized as classical (Krijtenburg-Lewerissa et al., 2017). Greca and Freire (2003) reported similar interpretations of quantum entities in their study, conducted with undergraduate Engineering students.

Regarding secondary school students, Masshadi and Woolnough (1999) analysed how A-Level Physics students visualized the photon and the electron. Most students described the photon as "a bright (small) spherical ball" (p. 515) and the electron as a type of particle (e.g., a spherical object or a small ball) with negative charge, which are both categorized as classical descriptions of the entities. Approximately 2% of the students explained that the electron is sometimes a wave and other times a particle, which can be categorized as a mixed description. It is important to highlight the description of the photon as a packet of energy released by the excitation of electrons, made by 14% of the students. This description shows that some students were able to provide a more elaborate definition of the photon.

Müller and Wiesner (2002) conducted studies on misconceptions about QM topics with secondary school students and pre-service Physics teachers, and highlighted the finding that both groups provided very similar answers about their understanding. When asked the essential properties of classical entities, 85% of the participants answered mass or weight, but only 15% answered position. The authors also emphasize that the velocity or momentum properties were considered more important by the students than the energy or position properties. With respect to photons, one third of the interviewed students described it as a particle of light that presents wave and particle behaviour. However, 17% of the students interpreted the wavelike representation of a photon as its trajectory, which can be considered a mixed description. This conception of a sinusoidal trajectory for the photon (and electron) has also been reported in other studies (e.g., Olsen, 2002; McKagan, Perkins, & Wieman, 2010; Özcan, 2015).

4.1.2 **DOUBLE-SLIT EXPERIMENT**

Theoretical background. The double-slit experiment consists of a set of quantum objects passing through a double slit and being detected by a screen, placed after the slits. When adequately performed, the experiment shows that quantum objects display an interference pattern, which is inherent to a wavelike behaviour of an entity (Walker et al., 2011). Therefore, the experiment's main goal is to demonstrate the wave behaviour of quantum objects (Krijtenburg-Lewerissa et al., 2017). When learning about this wave behaviour, students also become familiar with the de Broglie's postulate, hypothesized by Louis de Broglie in 1924. According to his theory, the energy and momentum of matter could be calculated in terms of properties of an *associated wave*. Such theory implies, for instance, that particles of matter could display the behaviour of a wave (Eisberg & Resnick, 1985). In 1928, de Broglie's hypothesis was empirically confirmed by Davisson and Germer (Eisberg & Resnick, 1985).

Student understanding. According to Krijtenburg-Lewerissa et al. (2017), students' understanding of quantum objects influences the understanding of the double-slit experiment. For instance, if students perceive the photon as a classical particle, they provide a classical reasoning about the experiment's outcome, as reported by Dutt in a study with secondary school students (as cited in Krijtenburg-Lewerissa et al., 2017). More specifically, these students reasoned that photons and electrons are deflected by the slits and follow straight trajectories, which is defined by Krijtenburg-Lewerissa et al. (2017) as a classical description of the experimental outcome. A similar finding was reported by Ireson (2000), who also conducted a study with secondary school students. He performed a cluster analysis, grouping items of a questionnaire answered by the participants. An interesting finding of his study is the existence of a “conflicting quantum thinking” cluster, in which students agree that “when a beam of electrons produces a diffraction pattern it is because the electrons … are undergoing constructive and destructive interference” (p. 19), which is a consistent view on quantum interference, but at the same time believe that “during the emission of light from atoms the electrons follow a definite path as they move from one energy level to another” (p. 19), which illustrates a classical view on the electrons’ behaviour.

With respect to undergraduate students, Ayene et al. (2011) conducted a phenomenographic analysis on the wave-particle duality understanding of university physics students. The authors reported that approximately 50% of the students presented correct interpretations about the double-slit experiment but resorted to classical reasoning when inquired about what would happen if electrons or photons were sent one at a time through the slits. These students thought that, in this case, the interference pattern would disappear. Similarly, Vokos, Schaffer, Ambrose, and McDermott (2000) investigated undergraduate students’ views on diffraction and interference of matter and pointed out that students’ understanding of de Broglie’s wavelength affected their answers about the interference pattern of the double-slit experiment. More specifically, many students considered the de Broglie’s wavelength as a fixed property of a particle, disregarding the dependence on the particle’s momentum.

4.1.3 PHOTOELECTRIC EFFECT

Theoretical background. The photoelectric effect characterizes the phenomenon of electron emission from a material caused by incident light. Such phenomenon cannot be explained by the wave theory of light because of its dependence on the light’s frequency. According to the wave theory of light, the photoelectric effect should be observed for any frequency of light, as long as the light is intense enough (Eisberg & Resnick, 1985). However, the photoelectric effect is observed only for frequencies above a certain cut-off frequency, which depends on the material, in accordance with Einstein’s theory of photons.

Student understanding. McKagan, Handly, Perkins, and Wieman (2009) and Oh (2011) found that undergraduate students believed that the light’s intensity does influence the energy transferred to an electron, which is a classical description. According to Steinberg and Oberem (2000), this misconception lies in the inability to differentiate between photon *flux* (related to the intensity of light) and photon *energy* (related to the frequency of light). Steinberg and Oberem (2000) also reported the following student misconceptions or difficulties related to the photoelectric effect: a belief that the photon is a charged object, the inability to relate photons to the effect, and difficulty with building a current *versus* voltage graph for the experiment.

McKagan et al. (2009) pointed out that all these student difficulties were observed in their research as well, except for the misconception that a photon is charged. McKagan et al. (2009) also observed that 42% of the students believed that voltage is necessary for the effect to occur. Sokolowski (2013) observed the same incorrect belief with secondary school students. According to Leone and Oberem (2004) and McKagan et al. (2009), the concept of voltage and the lack of prerequisite knowledge of circuits are possibly the main sources of students' difficulties when learning about the photoelectric effect.

4.2 CONCEPTUAL CHANGE

This study is based on the theoretical framework of conceptual change developed by Vosniadou (1994). Her theoretical framework was chosen for this study based on its gradual approach to conceptual change, differently from other approaches which focus on immediate replacement of concepts through cognitive conflict (Duit & Treagust, 2003; Vosniadou & Skopeliti, 2014). In addition, various studies which employed Vosniadou's theory have reported positive results concerning learning outcomes (Vosniadou & Skopeleti, 2014).

In Vosniadou's (1994) theory of conceptual change, humans build theoretical frameworks about how the physical world behaves since an early age in the form of conceptual structures (or presuppositions). Those frameworks are based on everyday experiences and are defined by Vosniadou as a framework theory of naive physics. The conceptual structures that form this framework are the ones upon which new knowledge about the physical world is built (Vosniadou, 1994).

Conceptual change, according to Vosniadou, is a gradual and complex process in which new information is incorporated into the existing conceptual structures of an individual's naive framework theory. On one hand, this incorporation can happen through the simple addition of information to the framework, when the new knowledge is consistent with the individual's presupposition. On the other hand, if the information is inconsistent with the learner's existing presuppositions (i.e., counterintuitive), a revision of such presuppositions is necessary. When students are introduced to counterintuitive knowledge, they can either incorporate the conflicting information to their framework, generating an inconsistent set of information, or alter the new fact so that it becomes consistent with their conceptual structures (Vosniadou, 1994). Therefore, conceptual change is not a simple replacement of content, as it requires several revisions and restructuration of one's conceptual structures, until a scientific model is incorporated (Vosniadou et al., 2001).

Restructuring entrenched presuppositions is a demanding task, and students require motivation to go through such process. Therefore, Vosniadou et al. (2001) provide the following recommendations for the design of learning environments which support conceptual change:

1. Focus on the instruction of fewer key concepts, allowing enough time for students to achieve a deeper understanding about them, instead of broadly covering several topics of a subject;
2. Consider the similarities between certain concepts and address them, highlighting why both concepts are not the same despite their similarities (e.g., energy and force);
3. Consider students' prior knowledge;
4. Facilitate metaconceptual awareness - i.e., help students become aware of their entrenched framework theory and of the presuppositions that construct it - through group discussions and verbal externalization of ideas;
5. Recognize information that is intuitive (easy to incorporate) and counterintuitive (demands revision of conceptual structures) and plan the instruction of each type accordingly. For instance, counterintuitive information should not be taught as a mere undeniable fact;
6. Motivate students to restructure their conceptual structures through meaningful experiences which prove that their presuppositions need revision (e.g., outcomes of real experiments and observations of phenomena);
7. Do not make use of cognitive conflict as the main form of instructional intervention to address misconceptions, but rather complement it with other forms of instruction that address why the misconception is formed;
8. Make use of model-based instruction that considers students' mental models (see section 4.2.1), therefore facilitating the restructuration of those models when necessary.

In addition to Vosniadou, several authors have proposed their own theories of conceptual change throughout the past decades. The existence of various theories and approaches to conceptual change motivated Duit and Treagust (2003) to conduct a meta-analysis about the evolution of the notion of conceptual change, its limitations, and scientific and practical relevance. An important finding of such review is that no research reported students being able to completely replace their own conceptions by an accepted scientific model. Rather, the best findings consisted of models combining students' own ideas and scientific conceptions, i.e., a "peripheral conceptual change" (Duit & Treagust, 2003, p. 673). Additionally, the authors reported recurring limitations of conceptual change approaches to teaching, namely:

1. Focus of instruction on isolated concepts, instead of on the process and context that involve the concepts;

2. No consideration for affective components of instruction, such as a supportive learning environment where students are encouraged to manifest their own ideas and ask questions (Center for Curriculum Development, 2005);
3. Limited or no emphasis on the social aspect of learning, such as group activities and peer feedback.

Nonetheless, Duit and Treagust (2003) concluded that conceptual change approaches are more efficient than traditional teaching approaches. They add that the efficiency of conceptual change "depends on the way the approaches are used in classroom practice and whether the potential they have in principle actually leads to the outcome expected" (p. 674).

4.2.1 MENTAL MODELS

As pointed out by Özcan (2015), there is no unanimous definition of *mental model*, but the term generally characterizes a mental representation shaped by an individual's interactions with the environment. Vosniadou and Brewer (1992) defined mental model as a dynamic representation, whose creation is prompted by an individual's specific need. Following that definition, mental models can be manipulated mentally to provide causal explanations of phenomena (Vosniadou et al., 2001). More importantly, the generation of mental models depends on and is limited by the person's conceptual structures (Hubber, 2006). Thus, mental models also influence how new knowledge is acquired. For example, it was found that students' explanations about the day/night cycle were limited by the students' mental models of the Earth (Vosniadou et al., 2001). More specifically, students who pictured the Earth as a flat disk or rectangle could not associate the day/night cycle with the rotation of the planet, given that the latter explanation is inconsistent with the students' mental models of the Earth. Finally, Vosniadou et al. (2001) point out that addressing students' mental models during instruction can be more effective to promote conceptual change than linguistic or mathematical explanations, as models allow students to visualize aspects which are not readily pictured.

4.3 RESEARCH QUESTION

Students in secondary and undergraduate level face several difficulties when learning about the wave-particle duality. This stresses the need for teaching sequences and instructional methods which focus on effective conceptual change practices. In the Netherlands, QM was recently added to the secondary school curriculum, which also raises the need for research about QM teaching in this specific context. Therefore, this study will investigate this context and ways to support the process of conceptual change with Dutch high school students when learning about the wave-particle duality, which results in the following research question: *What is the current state of instruction on the wave-particle duality in Dutch* *secondary schools and how to promote the process of conceptual change in such context?* This generates the following sub questions:

1. What is the current didactical approach to the wave-particle duality from Dutch school books and high school Physics teachers, and how do these approaches promote conceptual change?
2. What are the current conceptions of Dutch secondary school students about the wave-particle duality?
3. What are the shortcomings of the current didactical approaches to the wave-particle duality from Dutch school books and high school Physics teachers?
4. What alternatives are there to remedy these shortcomings?

5 METHOD

5.1 RESEARCH DESIGN

To achieve this study's purpose, a design-based research (McKenney & Reeves, 2012) was conducted using an exploratory mixed-methods design (Creswell, 2002). These methods consisted of literature and document reviews, interviews with teachers and students, a multiple-choice post-test, and a pilot test. However, the student interviews and post-test were not conducted during this study. The data collection through student interviews and post-test was done by Van den Berg et al. (2018), who authorized the use of such data for this study.

The design-based research approach was chosen because its main goal is to produce "new theories, artefacts, and practices" (Barab & Squire, 2004, p. 2) which positively impact learning and teaching in real-life settings (Herrington, McKenney, Reeves, & Oliver, 2007). Additionally, the exploratory mixed-methods design was selected because of its fit with design-based research, in which data triangulation is highly desirable (Creswell, 2002). Ideally, design-based research is performed through various iterations of analysis, design, and evaluation of solutions to a practical educational problem (Herrington et al., 2007). However, given the limitations of this study, only the analysis of the educational problem was conducted.

5.2 RESPONDENTS

This study analysed findings for three different groups. For the first group of participants, seven high school Physics teachers were chosen by convenience sampling and approached to participate in the study. According to Herrington et al. (2007), convenience sampling is common in design-based research and is adequate if the participants fit the study's focus and context. Teachers who were approached to participate were involved with projects in quantum mechanics education at the University of Twente. The eligibility criterium was whether the teacher had taught the wave-particle duality in a Dutch school. Of the seven approached teachers, six agreed to participate. Their age was between 33 and 56 years (M = 44.3, SD = 9.8). All participants of this group were men and born in the Netherlands. They had between 5 to 21 years of experience with high school Physics teaching (M = 10.5, SD = 6.0).

The second group of participants consisted of Dutch high school students. These students were participants of Van den Berg et al.'s (2018) study, conducted in 4 schools whose Physics teachers participated in the development of experiments for quantum physics in the University of Twente. The students were level 6 (grade 12) VWO students from the pre-university science track (upper 20% of the age cohort) and were between 17 and 18 years old. 24 students participated in the student interviews and 112 answered the multiple-choice post-test. From these 112 students, 45% were girls. The four participant schools were chosen based on convenience sampling of teachers involved in Van den Berg et al.'s (2018) project.

The third group of participants consisted of three high school students from an international school in the Netherlands. These students were also chosen by convenience sampling. They were sampled based on two criteria: (a) whether the student would receive instruction on the wave-particle duality and (b) the student's language of instruction (English), because of researcher's low proficiency in the Dutch language. Of the three students, two were 18-year olds and one was a 17-year old. All students were girls and were following the Cambridge International A/AS Level Physics course.

5.3 INSTRUMENTATION

To promote triangulation of data and examine the different factors involved in this study, six instruments were used. The following subsections describe these instruments in more detail and Table 1 provides an overview of how each instrument contributed to answer the research sub questions.

Table 1

Sub questions and contribution of instruments to answer them

Instrument	Sub question			
	1 (Didactical approach)	2 (Students' conceptions)	3 (Approach's shortcomings)	4 (Teaching alternatives)
Literature Review				+
Document Analysis	+	+	+	
Interview (teachers)	+	+	+	+
Interview (students)	+	+	+	
Post-test (students)	+	+	+	
Pilot test[a]		+		+

Note.[a] It is considered that the pilot test contributed partially to the sub questions because it was implemented with non-Dutch students following a different high school curriculum.

Literature and document review. The review of literature was conducted to gain insight in the current state of research on QM teaching, suggestions for future researchers and for practitioners, outcomes of previous teaching practices, and teaching strategies for QM. The analysed literature is composed by journal articles, books, and proceedings.

The review of official government documents and national exams was conducted to comprehend the desired approach to the wave-particle duality from Dutch educational authorities and curriculum developers. The analysed documents were the national curriculum for Physics in the VWO level (College voor Toetsen en Examens [CvTE], 2017), the national Physics exams for VWO level in the years of 2016, 2017, and 2018, their respective expected answers, and their item analysis (Cito, 2016, 2017, & 2018). All these documents are available for public consultation. Additionally, the chapters about QM of six Dutch school books were analysed.

Teacher interviews. To better understand student difficulties and the current instructional methods about the wave-particle duality in the Dutch context, interviews with teachers were conducted. Another goal of the interview was to conduct a SWOT analysis (McKenney & Reeves, 2012) of the teaching context. Therefore, the questions were based on McKenney and Reeves's (2012) recommendations on SWOT analyses and on the insights from the reviewed literature and documents. The interviews were unstructured and followed a pre-defined set of open questions, such as "what are common difficulties of students when learning about the photoelectric effect?". The complete interview scheme is in Appendix A.

Student interviews. To gain insight on the conceptions and understanding of Dutch students about the wave-particle duality, the transcriptions of interviews conducted by Van den Berg et al. (2018) were analysed. Students from four different schools were interviewed, and in three of these schools the interviews were done with one student at a time. In one school, the interview was done in pairs. The interviews were unstructured and contained open questions such as "what is meant by wave-particle duality?" and "how do you imagine a photon in the double-slit experiment, before it arrives at the detector?".

Multiple-choice post-test. To investigate the conceptions of students about the wave-particle duality after having received instruction about the topic, the results of a post-test conducted by Van den Berg et al. (2018) were analysed. The test was taken by 112 VWO students from three participating schools and contained 26 multiple-choice questions. Additionally, the test covered the concepts of wave-particle duality and tunnelling. Because of this study's scope, the analysis of the test's results is limited to the multiple-choice questions regarding the wave-particle duality only (20 questions). Examples of these questions are "an electron and a proton move with the same speed. What can you say about their de Broglie wavelengths λ_e and λ_p?" and "a basketball with mass of 0,4kg moves with speed of 10m/s. Why can't we observe wave effects in this case?". An analysis on the test's reliability done by Van den Berg et al. (2018) showed a Cronbach's alpha of 0.68, which indicates a questionable reliability (DeVellis, 2012). The complete test can be found in Appendix B.

Pilot test. A pilot test was conducted to assess teaching strategies on the wave-particle duality and resources which were suggested by the analysed literature. The pilot test was implemented during four 45-minute lessons, which were recorded using an Iris Connect Discovery kit. These recordings comprised students' discussions and the teacher's instruction and were not coded for analysis. Data collection during the pilot test also included a pre- and post-test, which were identical and contained 13 multiple-choice questions. These questions were a compilation of the wave-particle duality questions from surveys developed by Wuttiprom, Sharma, Johnston, Chitaree, and Soankwan (2009) and McKagan et al. (2010). The reliability of the tests was not assessed. In addition to the tests, an activity was performed during the lesson and the resulting sketches were analysed, but not coded. The complete test and activity used in the pilot are shown in Appendix C.

5.4 PROCEDURE

Literature and document review. The review of literature was conducted using the following key words and Boolean operators: ("secondary school" OR "high school" OR "secondary education") AND ("quantum mechanics" OR "quantum physics" OR "wave-particle duality"), in the databases Scopus, Web of Science, Google Scholar, ERIC, and the University of Twente's library search tool. First, only articles addressing the teaching of QM in the secondary level were included in the review. However, at a later stage, it was identified that the teaching strategies and resources which are used or proposed by literature, and which do not focus on a mathematical approach, are similar for undergraduate and high school level. Additionally, these teaching strategies and resources addressed misconceptions about QM concepts which arise in high school and undergraduate students. Therefore, that criterium was disregarded.

Teacher interviews. Teachers were approached by email with an invitation to voluntarily participate in a one-hour interview about the teaching of the wave-particle duality. The email also specified that the interview would be audio recorded and that the data would be treated and reported anonymously. The location and starting time of the interview were determined by each teacher. At the start of each interview, the researcher greeted the teachers and gave a short summary about the interview's content. Then, the interview was conducted in an informal way. Each interview took approximately 45 minutes.

Student interviews and post-test. According to Van den Berg et al. (2018), a team of teachers and researchers from the University of Twente designed a supplementary demonstration about the wave-particle duality, which included a single-photon interference experiment and a simulation developed by PhET Colorado on quantum interference (see Van den Berg et al. (2018) for a detailed description of the demonstration). This demonstration was implemented in four schools. In the first two schools the single photon interference experiment was carried out followed by the PhET simulation. As a result of the interviews with students from these two schools after the demonstration, the introduction to the activity was then modified for the next two schools. This modification included some preliminary double-slit demonstrations with spray paint, parallel light beams, water waves, and a laser beam. In one school, the interviews were conducted immediately after the demonstration. In the other three schools, the interviews took place at the end of the lesson series on QM. Additionally, the post-test was taken by students of three participating schools, at the end of the lesson series.

Pilot test. The date of the pilot test was defined by the Physics teacher responsible for the students that would participate in the pilot. When the teacher was approached to participate in the pilot, he had already taught the wave-particle duality to the students. Therefore, it was determined by the teacher that the pilot would serve as a review of the content. Prior to the pilot test, the teacher received instructions on how to conduct the activities. During the pilot, the teacher introduced the researcher, who then explained the purpose of her presence. She also clarified that the students could participate voluntarily, that their data would be anonymous, and that they could withdraw from the data collection if desired. The students were then given a student consent form, to allow the use of their data in this study. Thereafter, all students took the pre-test and the teacher proceeded with the lesson and conducted the activities as instructed. In one of the activities, students were asked to draft the pattern formed by a double-slit experiment in three cases: when the experiment is performed with bullets, water waves, and electrons. In each case, students were instructed to explain their drawings to each other. The teacher added other topics and discussions to the lesson, which were included in the Cambridge International curriculum. At the end of the pilot, the students took the post-test.

5.5 Data Analysis

Literature and document review. The literature was analysed for teaching strategies, activities, resources, and learning outcomes of such strategies. The framework of conceptual change was used to categorize the findings of the review. The analysis of school books consisted of first classifying the books' content into categories based on the Dutch national curriculum. Subsequently, those categories were refined based on the findings of the literature review. Each book's didactical approach per category was also examined. For instance, regarding the category 'single photon or electron interference', it was first determined which books included this content in their texts. Then, it was analysed how the phenomenon was discussed in each book.

For the analysis of how the wave-particle duality was treated in the national exams, the files containing the correction of the questions were used. In these documents, the test developers list the competences meant to be achieved by the students in each question. These competences were categorized and summarized. To complement the analysis of the exams, the results of a test and item analysis conducted by Cito (see Cito, 2016, 2017, & 2018) were used.

Teacher and student interviews. For teacher interviews, preliminary categories were created regarding the teachers' approach to certain topics, their use of teaching resources, and the perceived strengths and weaknesses related to teaching the wave-particle duality. As the audios of the interviews were analysed, these categories were refined. Additionally, the teacher interviews were not entirely transcribed for analysis. Only parts of the interview which concerned a certain category were transcribed. For the analysis of student interviews, the transcriptions of the student interviews conducted by Van den Berg et al. (2018) were explored. The dialogues were also classified in categories of student understanding and opinions about specific topics.

Post-test. An initial analysis of the post-test was previously conducted by Van den Berg et al. (2018). This analysis consisted of calculating the total average score, Cronbach's alpha, *p* value and discrimination index per question, and the percentage of students' answers per alternative. This study focused on the analysis of the average score, *p* value, and percentage of students' answers per alternative. At a later stage of the study, it was also known that two of the interviewed teachers in this study had taught students who took the post-tests as well. Therefore, the post-test's data from the schools where these teachers taught was compared based on the input from the teacher interviews. More specifically, the average scores of students from both schools were compared through an independent samples t-test.

Pilot test. Because the pilot test was conducted with three students only, no statistical analysis was performed with the results of the pre- and post-tests. The analysis of the tests and drawings was only exploratory. Additionally, the discourses of students and teacher were not fully transcribed and coded. Similar to the teacher and student interviews, the recordings of the lesson given during the pilot test were analysed with focus on students' questions, difficulties, conceptions about the topic, and response to the resources which were used. The relevant dialogues related to these categories were transcribed.

6 RESULTS

6.1 LITERATURE REVIEW

The purpose of this literature review was to gain insight in the current state of research on QM teaching, suggestions for future researchers and for practitioners, outcomes of previous teaching practices, and teaching strategies for the wave-particle duality. Additionally, the framework of conceptual change was used to categorize the findings of the review. More specifically, the analysed suggestions and teaching practices were categorized based on Vosniadou et al.'s (2001) and Duit and Treagust's (2003) recommendations on how to facilitate conceptual change in a learning environment. These recommendations are listed in section 4.2.

Recommendation i: focus on fewer key concepts. Vosniadou et al. (2001) advised teachers to address fewer key concepts and allow students time to acquire a deeper understanding about these concepts. Greca and Freire (2003) adopted such approach when proposing a didactical strategy for undergraduate students which focused on five basic concepts of QM: state superposition, uncertainty principle, wave-particle duality, probability distribution, and nonlocality. In their teaching sequence, these topics were recurrent in a spiral structure, i.e., they reappeared at different stages of the sequence and through different examples. Müller and Wiesner (2002) used a similar spiral approach in their course, which was divided into two parts. In the first part, they introduced the concept of photon and its wave and particle behavior, followed by a discussion of what the authors denominated "position property", and finished with Born's interpretation of probability. These concepts returned in the second phase of the course, which covered electrons. The second part also contained a discussion about the uncertainty principle and the interpretation of the wave function.

Recommendation ii: address similarities between concepts. Physics contains several concepts which might seem very similar or even the same for students who first learn about them, such as energy and force, or force and momentum. Addressing such concepts and stressing not only their similarities, but most importantly their differences, is necessary to facilitate conceptual change (Vosniadou et al., 2001).

McKagan et al. (2009) and Oh (2011) reported that students, when learning about the photoelectric effect, believed that the light's intensity influences the energy transferred to an electron. This misconception can be explained by students' difficulty to differentiate the concepts of photon flux (related to intensity) and photon energy (related to frequency) (Steinberg & Oberem, 2000). McKagan et al. (2009) addressed this issue using a computer simulation developed by PhET Colorado. This simulation illustrates a simplified experimental setup to observe the photoelectric effect, and was used in McKagan et al.'s (2009) course during lectures and homework. During the course, students were asked to use the simulation to explore and explain how changes in intensity and frequency of light influence the occurrence of the photoelectric effect.

Van den Berg et al. (2018) pointed out in their research that few students were able to grasp the most important differences between classical waves and particles. Additionally, the authors reported students' inability to define a wave or a particle and their correct properties. This difficulty to differentiate and define the concepts might affect how students perceive the wave-particle duality, as they do not understand what differentiates a wave from a particle in the first place (Van den Berg et al., 2018). Therefore, the authors recommended to address classical waves and particles and their main differences before teaching students about the wave-particle duality. Feynman, Leighton, and Sands (1963) have addressed these differences their book by proposing a (pictorial) comparison between the outcomes of the double-slit experiment with three different materials: bullets, water waves, and electrons. Feynman et al. (1963) used these thought experiments to point out the main property of the materials: they are either localized (as the bullets and electrons, which are detected as single units) or non-localized (as the water waves, which spread across the water's surface). The discussion of the thought experiments also included the phenomenon of interference to illustrate the wave behaviour of electrons.

Regarding differences between classical and quantum mechanics, Ayene et al. (2011) advised teachers to address the gap between classical and quantum concepts of waves, particles, and uncertainty. They suggested that teachers should highlight the differences between these concepts in the classical and quantum world. However, the mention of classical mechanics, or analogies using it, is a controversial topic among researchers so far. On one hand, Ireson (1999) and Greca and Freire (2003) see the use of classical analogies as a way to postpone students' contact with actual quantum phenomena. In their teaching sequence, Greca and Freire (2003) avoided references to classical models or concepts and did not emphasize wave or particle behaviours of quantum entities. Rather, these entities were referred to as 'quantum objects' in their course. This sequence was implemented with undergraduate students and showed positive results in learning outcomes and attitude towards the course. Regarding the double-slit experiment, Lautesse et al. (2015) added that the analogy between the outcomes of the experiment for photons and electrons suggests that these objects behave in the same way, when in fact the formalism needed to treat electrons is different from the formalism used for photons. Therefore, the authors discouraged the use of such comparison, as they believe that what is taught in secondary school physics should not require further study in higher education to be correctly comprehended. Rather, it should be relevant and accurate on its own. On the other hand, Didiş, Eryılmaz, and Erkoç (2014) and Michelini, Santi, and Stefanel (2016) considered comparisons with classical physics as a way to improve QM teaching by reducing the abstractness of the subject, facilitating the interpretation of phenomena, and therefore increasing student motivation. Kaur et al. (2017) planned an entire teaching sequence about introductory QM in which students performed activities using Nerf guns, and the 'bullets' were interpreted as photons. This sequence was designed as an introduction to the concept of photon and its quantum behaviour for students from grade 6 to 12. The authors did recognize the limitations of using these bullets because of their classical behaviour, and reported the necessity to emphasise such limitations to students or propose an activity in which students identify them themselves. The sequence was tested with students from grades 6 to 11 and showed positive learning gains. However, the assessment of such gains was conducted through a questionnaire which superficially covered the concepts of radiation, position, and uncertainty (Kaur, Blair, Moschilla, Stannard, & Zadnik, 2017). Regarding the photoelectric effect, Asikainen and Hirvonen (2009) planned and tested a teaching sequence in which students first elaborated a classical hypothesis about the occurrence of the effect and attempted to explain its experimental findings using that hypothesis. In a later moment, they were then instructed to seek for a quantum explanation for such findings. Based on interviews with the participants and on the favourable results of the post-test, Asikainen and Hirvonen (2009) concluded that comparing the classical hypothesis, empirical results, and quantum explanation might be effective for the learning of the photoelectric effect.

Recommendation iii: consider prior knowledge. Students' prior knowledge plays an important role on the process of conceptual change. When new knowledge is conflicting with students' presuppositions, it becomes more difficult for the new information to be properly assimilated (Vosniadou et al., 2001). Vosniadou et al. (2001) recommend that teachers consider students' prior knowledge when planning their instruction and analyse how this prior knowledge may influence the acquisition of new knowledge.

According to Leone and Oberem (2004) and McKagan et al. (2009), a source of misconceptions about the photoelectric effect is students' lack of prior knowledge about circuits and about the concept of voltage. McKagan et al. (2009) addressed this problem by using the first two lectures of their course to explain the experimental setup used to observe the photoelectric effect and review the necessary background knowledge of circuits. Additionally, the concept of voltage was further explored by their students in the PhET simulation of the photoelectric effect, which allows the user to change the voltage of the battery and observe the results. The simulation also provides a depiction of the electrons moving from one plate to the other, which has proven helpful to visualize the effects of changing the voltage (McKagan et al., 2009). It is important to emphasize that all QM simulations from PhET are developed based on research about students' understanding, misconceptions, and difficulties (see McKagan et al., 2008). Additionally, Knight (2002) suggested that students need to comprehend the role of each component of the experimental setup used to observe the photoelectric effect to be capable of comprehending the phenomenon.

Regarding prior knowledge about light, Hubber (2006) pointed out that students' prior instruction of geometric optics affected their mental models of light. For instance, he first found that year 10 and 11 students imagined rays as a constituent of light or as a continuous stream of a material. Later, in year 12, these same students received instruction on photons, diffraction and interference phenomena, and the photoelectric effect, which challenged their prior views on light rays. At the end of year 12, students did not substitute the model of light rays, but applied a new meaning to it (e.g., as streams of photons or as arrows which determine the direction of light's propagation).

Recommendation iv: facilitate metaconceptual analysis. Although every student has entrenched cognitive structures, which are used to predict and interpret reality, students are not aware of such structures and of how they influence learning (Vosniadou et al., 2001). Metaconceptual awareness (i.e., the act of being aware of one's presuppositions) is therefore necessary to aid students to detect which aspects of their cognitive structure are incorrect and need revision. To help students become metaconceptually aware, Asikainen and Hirvonen (2009) used methods based on social interaction, such as group activities and discussions with the lecturer. Additionally, some of the exercises implemented in their course also aimed to prompt students to recognize their own ideas. Hubber's (2006) strategy of discussing and building students' mental models of light (described under recommendation viii) could also be categorized as a way to facilitate metaconceptual analysis. Greca and Freire (2003) also made use of group discussions and appointed them as fundamental for students to express their own understanding and externalize underlying contradictions.

Recommendation v: identify (counter)intuitive concepts to plan teaching strategy adequately. Because QM topics are intrinsically counterintuitive, it is not necessary for books to differentiate between intuitive and counterintuitive concepts.

Recommendation vi: motivate with meaningful experiences. The process of conceptual change is long and demanding, requiring students to be motivated to go through it (Vosniadou et al., 2001). This motivation is fostered by meaningful learning experiences such as outcomes of real experiments or observations of phenomena (Vosniadou et al., 2001). Greca and Freire (2003) addressed this recommendation through a "phenomenological-conceptual approach" (p. 550) to learning, where the main principles of QM were introduced through the observation of experiments. One of these experiments, used by various researchers (e.g., Müller & Wiesner, 2002; Dimitrova & Weis, 2010; Marshman & Singh, 2016), was the Mach-Zender interferometer, which allows the experimental observation of an interference pattern built by single photons. Van den Berg et al. (2018) also made use of an experiment with single-photon interference in their lesson about the wave-particle duality. After observing the performance of the experiment and its outcome, students in Van den Berg et al.'s lesson used the PhET simulation 'quantum wave interference' to visualize the occurrence of such type of interference. The results obtained with students who participated in this lesson are described in sections 6.4 and 6.5. According to McKagan et al. (2008), simulations on QM topics are a suitable tool to complement real-life experiments, because simulations allow users to visualize phenomena which otherwise could not be observed. Such advantage was also explored by Bungum, Henriksen, Angell, Tellefsen, and Bøe (2015), who embedded computer simulations in the development of tutorials about QM concepts for secondary schools.

Recommendation vii: avoid cognitive conflict as only strategy. Previous researches regarding conceptual change focus on promoting cognitive conflict using students' misconceptions (Hewson & Hewson, 1984). The use of cognitive conflict has resulted in positive effects on conceptual change (Baser, 2006), but Vosniadou et al. (2001) suggest that it should be used together with other didactical strategies. Weis and Wynands (2003) made use of cognitive conflict as one of the didactical approaches in their teaching sequence on the wave-particle duality. The authors proposed the use of three different experiments: one in which the detection of single photons can be heard, another in which a laser beams passes through a double-slit, and one in which single photons pass through a double-slit. The authors proposed that the first experiment should be used to convince students about the particle character of light. Then, students should predict the outcome of the second experiment based on that particle character. When presented with the actual outcome, students should then experience cognitive conflict, which should be resolved using the third experiment and the concept of wave-particle duality. Knight (2002) suggested the use of cognitive conflict to teach the photoelectric effect. In his sequence, students should first be convinced of light's wave character and use it to predict the result of the photoelectric effect experiment. Once the predictions are formulated, the real findings of the experiment are shown, which should also lead students to experience conflict. The particle character of light is then presented as a solution to such conflict.

Recommendation viii: use model-based instruction. Because students think and reason using models, model-based instruction has more chances of promoting conceptual change (Vosniadou et al., 2001). According to Asikainen and Hirvonen (2009), the use of models during teaching is effective when the approach involves the phases of "construction, validation, and application of models" (p. 659). Therefore, the authors designed a cycle of different learning activities in which students' models undergo each of these phases. Hubber (2006) also addressed students' mental models in his teaching sequence by conducting classroom discussions about students' own mental models of light, based on what they learned in years 10 and 11. This resulted in student-generated models, which were evaluated throughout the year for their efficacy to explain the concepts of photons, interference, diffraction, and the photoelectric effect. This constant evaluation prompted students to consciously revise their own models and discuss them with their colleagues and teacher. As a recommendation in his study, Hubber (2006) stressed the need to 1) focus on students' mental models in science education and 2) make clear to students that models are representations of reality rather than reality itself.

Recommendation ix: address contexts and processes. When pointing out the limitations of interventions aimed at conceptual change, Duit and Treagust (2003) refer to an excessive focus on teaching isolated concepts, instead of on the process and context that involve these concepts. In this literature review, some researchers (e.g., Asikainen & Hirvonen, 2009; Bungum et al., 2015; Choudhary et al., 2018) provided context in their proposed sequences through a historical overview of wave-particle duality topics. According to Greca and Freire (2003), including a historical background when teaching quantum physics is a common practice. However, they add that the historical evolution of QM concepts is insufficient if used as a didactical strategy alone. Regarding practical contexts, McKagan et al. (2009) specified that the third lecture of their teaching sequence is used for discussing real-life applications of the photoelectric effect, such as "photomultiplier tubes, as well as details of how the electrons are bound in materials" (p. 88).

Recommendation x: consider affective components. Duit and Treagust (2003) also reported that conceptual change approaches might not consider affective components of instruction, such as a supportive learning environment. The Center for Curriculum Development (2005) exemplifies such environment as one where students are encouraged by their teacher to express their own ideas and ask questions. Therefore, this recommendation was addressed in the analysis of recommendation iv.

Recommendation xi: address social aspects. Similar to the previous recommendation, Duit and Treagust (2003) addressed the lack of focus on social aspects as a limitation of conceptual change strategies. This social aspect was also addressed in the analysis of recommendation iv.

6.2 Document Analysis

6.2.1 Dutch Curriculum

In the Dutch secondary school curriculum, it is defined that the wave-particle duality should be taught to students at the pre-university level (VWO). The topic is part of the "Quantum world" sub-domain of the Physics subject, which is mandatory for students who choose the study profile "Nature and Technology" (Natuur en Techniek). For students in the other profiles (i.e., Nature and Health, Economy and Society, and Culture and Society), Physics is an optional subject. Within the wave-particle duality scope, the curriculum defines that students should be able to: identify and explain the phenomenon of light as a wave, explain in which situations light diffracts, explain an intensity pattern in terms of constructive and destructive interference, apply the wave-particle duality to explain a) interference phenomena of electromagnetic radiation and particles and b) an electron microscope, make calculations with de Broglie's wavelength, describe and explain the meaning of the double-slit experiment, become familiar with the concept of probability distribution, and use the photoelectric effect to prove that electromagnetic radiation is quantized (concepts: photon, emission energy, energy of a quantum) (CvTE, 2017).

6.2.2 National Physics Exams

Dutch students in their last year of pre-university education need to take a standardized test to conclude this level of education. Each student takes the exams corresponding to the subjects from their study profiles. QM was introduced in the exam in 2016. In that year, three questions were categorized as pertaining to the "Quantum world" sub-domain (Cito, 2016). In the years of 2017 and 2018, this number of questions was respectively 2 and 3 (Cito, 2017 & 2018). The main statistics from these exams and their questions within the "Quantum world" sub-domain are displayed in Table 2. The retakes of these exams also comprise some questions concerning QM. Although it is possible to have access to these questions and their expected answers, no statistical analyses of the items are available. Therefore, only the topics of these questions are displayed in Table 3.

To understand how wave-particle duality topics were approached in the exams and how the items were related to the curriculum's learning goals, the correction sheets of each exam (including retakes) were analysed. The level of difficulty of the questions was analysed through their p values and through a comparison with the p value of the exam which contained the questions (when available). The p value is a measurement of how difficult an item is, and ranges from 0 to 1 (or 0 to 100%). A p value of 0 indicates that no students in the exam answered the question correctly, and 1 (or 100%) indicates that all students answered it correctly. In this study, the p values were interpreted as follows: $p < 30\%$ indicates a very

Table 2

Main statistical data from the physics national exams and questions within the "Quantum world" sub-domain

Year of Exam	*N*	Max. score	Average score	*SD*	*p* (%)	Question topic	Max. score	Average score	*SD*	*p* (%)
2016	12434	76	40.2	11	53	**Probability distribution**	3	1	1.0	34
						Infinite wells	3	0.8	1.0	28
						Uncertainty principle	2	1.4	0.9	67
2017	17165	73	46.1	9.2	63	Infinite wells, **de Broglie wavelength**	4	2	1.2	49
						Infinite wells	3	0.5	0.7	16
2018	18871	72	44	8.9	61	Tunnelling, **de Broglie wavelength**	3	1.6	1.2	52
						Tunnelling, **de Broglie wavelength**	2	1.5	0.7	72
						Tunnelling	2	1.2	1	57

Note. The topics within the wave-particle duality scope are displayed in **bold**.

Table 3

Question topics within the "Quantum world" sub-domain for national exam retakes

Question topics per year		
2016	2017	2018
Interference of light		**Interference of light**
De Broglie wavelength	Bohr's atomic model	**Photon energy**
Uncertainty principle		Infinite well

Note. The topics within the wave-particle duality scope are displayed in **bold.**

difficult item, 30% ≤ p ≤ 50%, indicates a difficult item, 50% < p ≤ 85% indicates a moderate item, and p > 85% indicates an easy item (Doran, as cited in Ding, Chabay, Sherwood, & Beichner, 2006; Carlson, Seipel, & McMaster, 2014). The following subsections categorize the analysis of the items based on their topics.

Interference of light and photon energy. Both retakes from 2016 and 2018 contained one question about light's interference. In 2016, students were first shown the pattern in a detection screen formed by a laser beam after it passed through one slit. The question explained the phenomenon of diffraction and asked why the pattern formed by the laser had two points where the intensity was zero. From the total score of three points, one point was given for each of the following competences: insight on the occurrence of path difference; perceive that the path difference should be half of a wavelength or that the phase difference should be half; and insight on the occurrence of destructive interference. In 2018, the question started by explaining how a dye laser beam is generated. Then, a drawing compared the representation of light waves from a regular light source and from a dye laser. The question asked the student to explain why the laser beam's intensity is stronger than the regular light source, even if the amplitudes from the individual waves are the same for both sources (see Figure 1). This question's total score of two points required students to perceive, from the given representation of waves, that the waves from the dye laser are in phase, and therefore constructive interference happens, whereas in the regular source it does not happen.

In figuren 2a en 2b zijn een aantal individuele lichtgolven geschetst van respectievelijk een gewone lichtbron en een laser.

figuur 2a **figuur 2b**

Ook als de amplitude van de individuele golven gelijk is, is de totale amplitude (en dus de intensiteit) van het laserlicht groter dan die van de gewone lichtbron.

11 Leg uit hoe dit komt aan de hand van de figuren 2a en 2b.

Figure 1. Question about interference of light from 2018's retake exam. From: "Examen VWO 2018 tijdvak 2" by Cito, 2018, p.8.

The next question from 2018's retake exam followed the context of the dye laser, explaining the formation of spectra of emission and absorption for a specific dye laser. The question contained a picture of these spectra, depicting that their peaks differed by 25nm, and asked the student to explain why the emission spectrum was shifted to the right. This question required, among other competences, the insight that $\Delta E = hf$ and therefore is inversely proportional to light's wavelength.

De Broglie wavelength. In both 2017 and 2018 exams, the concept of the de Broglie wavelength was treated in different contexts. The questions asked students to explain, in each context, how big was the chance of observing a quantum wave behaviour from an entity. In 2017, this entity was the electron, and in 2018, it was a hydrogen atom. The questions were evaluated for other competences such as the use of given formulas, but they all required students to conclude that the de Broglie wavelength had an order of magnitude which allowed quantum effects to be observed in each context. In 2018, this competence was further explored by the addition of a question where the nucleus of the hydrogen atom was replaced by a deuterium nucleus. These questions analysed if students could assess: the change in the de Broglie wavelength for a heavier atom; and the chance of observing quantum effects given the change in such wavelength.

The *p* value of 2017's question was 49%, meaning that the question is considered difficult. Additionally, the question's *p* value is below the exam's *p* value of 63%. However, it must be noted that the question also required the knowledge of infinite wells. Thus, it is not possible to know the influence of de Broglie's wavelength topic alone on the question's difficulty. In 2018, the *p* values of both questions about de Broglie's wavelength were 52% and 72% and are therefore considered as moderate. The difference between the question's *p* values and the test's *p* value (61%) is the same, indicating that the first question was relatively more difficult in the same way that the second question was easier. That is an interesting finding, considering that both questions required the same knowledge of the de Broglie wavelength.

Probability distribution. In the exam of 2016, one question covered the topic of probability distribution. The concept was applied in the context of a hydrogen iodide molecule, in which the hydrogen atom vibrated as a spring. A graph of the classical probability distribution of the hydrogen atom was given in function of the atom's displacement amplitude (see Figure 2). The question asked students to explain the reasons for the distribution's maximum and minimum values, and to explain what would happen to the distribution if the total energy of the system would increase. The competences required by this question were students' insight in: a) how the atoms' velocity changes in terms of its displacement and how that affects the probability; and b) how the increase in energy increases the amplitude of vibration and decreases the probability's maximum values. This question's *p* value (in percentage) was 34%, which can be considered as a difficult question and below the exam's *p* value of 53%.

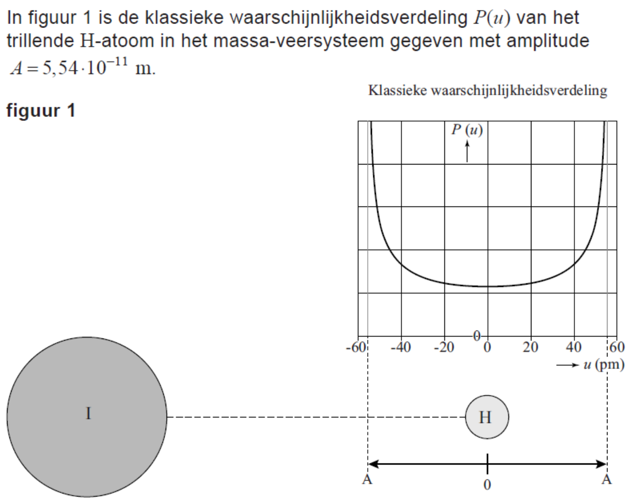


Figure 2. Representation of a hydrogen iodide molecule and the probability distribution of the hydrogen atom in 2016's national exam. From: "Examen VWO 2016 tijdvak 1" by Cito, 2016, p.11.

6.2.3 **Dutch School Books**

Regarding the analysis of school books, the main findings are displayed in Table 4. The following books were analysed: Bouwens, Doorschot, van Reisen, and Vennix (2012; hereafter Overal Natuurkunde); Van Bemmel and Koopman (2012; hereafter Nova); Biezeveld, Mathot, and Brouwer (2014; hereafter Stevin); Flokstra et al. (2015; hereafter Newton); Te Brinke et al. (2015; hereafter Pulsar); and Van Dalen et al. (2015; hereafter Systematische Natuurkunde). Generally, these books provided a historical background on the development of the wave and particle models of light as part of their introduction to the topic of wave-particle duality. In four books, a brief discussion about Huygens' and Newton's models of light was conducted. Some books also mentioned Planck's postulate of the quantized emission of electromagnetic energy.

All historical trajectories also contained Einstein's hypothesis of light as a quantized energy packet. Following the historical trajectories, all books presented Young's double-slit experiment to explore the phenomenon of interference with light. All analysed authors explained the formation of the interference pattern in terms of constructive and destructive interference and path or phase difference, with exception of Overal Natuurkunde, who conducted a qualitative explanation. Besides describing Young's experiment with light, Pulsar, Nova, and Newton also proposed analogies of the experiment with water or sound waves.

After providing proof of light's wave behaviour through the double-slit experiment, all authors also explored the particle nature of light. That was done through either recalling or introducing the concept of photons. Some examples of how the photon was defined or referred to are "packet of electromagnetic radiation" (Systematische Natuurkunde) and "energy packets". Newton also provided a sub-section called "About what light 'is'", in which the difficulty of observing electromagnetic radiation without promoting any changes in it was discussed. The particle character of light was further analysed by Newton, Overal Natuurkunde, Stevin, and Systematische Natuurkunde through the study of the photoelectric effect[1]. This was done through a brief explanation of the typical experimental setup used to measure the effect, of the dependence on light's frequency to release electrons from a metal, and of the energies involved in the process. Newton, Overal Natuurkunde, and Stevin also briefly analysed the Compton effect, even though it is not included in the Dutch curriculum. The dual properties of light led to the discussion of the wave-particle duality, in which light was approached as a wave and a particle phenomenon, and/or as an entity which behaves like a wave or a particle. Overal Natuurkunde also identified this dual behaviour as Bohr's complementarity principle.

The dual properties of electrons were also explored. The authors did so by exposing pictures of electron diffraction experiments and/or pictures of the outcome of the double-slit experiment when conducted with electrons. It is important to highlight that all authors initially treated the electrons as particles. Except for Newton, all books also covered the phenomenon of interference when electrons (or photons) are sent individually through the slits. Overal Natuurkunde and Nova added that, in this case, the electron interferes with itself. Additionally, the single-electron interference is used by Overal Natuurkunde to explore what happens if one would try to measure through which slit the electron passed (Newton also explores this, but not using single electrons). This matter was not thoroughly explained in both books, but it was mentioned that the interference pattern vanishes. Stevin and Newton also discussed the wave

[1]The books Nova and Pulsar introduced the photoelectric effect in their previous volumes, under the sections "electromagnetic radiation" for Nova and "atomic Physics" for Pulsar.

behaviour of electrons through de Broglie's interpretation of electrons as standing waves in Bohr's atomic model. Additionally, all books contained an explanation about the probability distribution of electrons or photons. This was done through an analysis of the interference pattern from the double-slit experiment (when displayed in the book) and/or an interpretation of the meaning of intensity (or amplitude) in a matter wave. Newton, Nova, Overal Natuurkunde, and Pulsar linked this probability distribution to the concept of a wave function.

When regarding analogies with classical physics, these were included in all analysed books and concerned various topics. For instance, Pulsar compared the three main properties of a classical wave (frequency, wavelength, and amplitude) with those of a matter wave. It concluded that the classical properties of frequency, wavelength, and amplitude are comparable to the properties of energy, momentum, and probability for matter waves. Nova Natuurkunde, before recalling the concept of quantized electromagnetic energy, made a comparison with how electric charge and mass are also quantized. Additionally, Pulsar, Nova, and Newton proposed analogies of the double-slit experiment with water or sound waves.

Conceptual change recommendations. As listed in sections 4.2 and 6.1, Vosniadou et al. (2001) and Duit and Treagust (2003) provided recommendations on how to support conceptual change when designing learning environments. Because teachers might become influenced by how school books approach subjects when planning learning activities (Lautesse et al., 2015), an analysis of recommendations for conceptual change was conducted for each school book. It was analysed whether each book contained the listed recommendations for supporting conceptual change, and how they are implemented. Additionally, this analysis was conducted only for sections addressing the wave-particle duality.

Recommendation i: focus on fewer key concepts. All books followed the content determined by the Dutch national curriculum.

Recommendation ii: address similarities between concepts. As previously stated, Van den Berg et al. (2018) found that students had difficulty in differentiating waves from particles and defining their correct properties. Therefore, the authors recommended that classical waves and particles and their main differences should be addressed before teaching students about the wave-particle duality. As commented, the books did present different wave and particle *behaviours* of entities, but none of the books presented the main differences between classical waves and particles.

Regarding the photoelectric effect, the literature review showed that students have difficulties to differentiate photon flux (related to intensity) from photon energy (related to frequency). From the six school books, Newton addressed the difference between photon flux and energy. Overal Natuurkunde, Stevin, and Systematische Natuurkunde did it partially, by

Table 4

Topics within the wave-particle duality covered per school book

Book	Classical physics analogies	Definition of photon	Definition of electron	Single electron or photon interference	Probability distribution	Wave Function	Photoelectric effect
Newton	Yes	As a wave packet	As a particle	No	Yes	Yes	Yes
Nova Natuurkunde	Yes	As energy packets	As a particle	Yes	Yes	Yes	Yes[a]
Overal Natuurkunde	No	As energy packets and as “quanta”	As a particle and as “quanta”	Yes	Yes	Yes	Yes
Pulsar	Yes	As light particles and quantum particles	As particles and quantum particles	Yes	Yes	Yes	Yes[a]
Stevin	Yes	As a wave packet	As a particle	Yes	Yes	No	Yes
Systematische Natuurkunde	No	Packet of electromagnetic radiation	As a particle	Yes	Yes	No	Yes

Note. [a] Treated in the previous volume of the book.

mentioning that the effect does not depend on the light's intensity, but not addressing the difference between flux and energy.

As mentioned in section 4.1.1, another common difficulty is the distinction between the representation of the photon as a wave packet (see Figure 3) and the photon's trajectory. Among several authors, Olsen (2002), McKagan et al. (2010), and Özcan (2015), reported that students mistake the photon's representation for the photon's trajectory. All books except Nova and Systematische Natuurkunde represent the photon (or a general wave packet) similar as in Figure 3, but none stresses the difference between the representation and the trajectory of the packet.

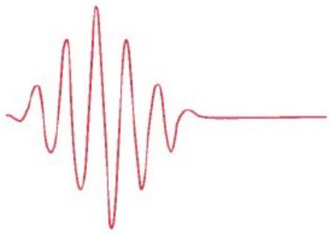


Figure 3. Representation of a wave packet. From: *Overal Natuurkunde*, by R. Bouwens, P. Doorschot, G. van Reisen, and A. Vennix, 2012, the Netherlands: Noordhoff Uitgevers B.V.

Recommendation iii: consider prior knowledge. As mentioned in the literature review, a source of misconceptions about the photoelectric effect is students' lack of prior knowledge about circuits and about the concept of voltage. To remedy such misconceptions, Knight (2002) suggested that students need to comprehend the role of each component of the experimental setup to be capable of comprehending the photoelectric effect. None of the analysed books presented a thorough explanation of the experimental setup, nor of the concept of voltage. Nonetheless, Systematische Natuurkunde revisited the concepts of voltage in a photocell and explored the behaviour of the current in function of such voltage with more detail.

As reported in section 4.1.2, students' prior understanding of photons and electrons influences how they reason about the double-slit experiment. Because this understanding is mostly classical when students are first introduced to the double-slit experiment, it might be necessary to address how this classical understanding does not apply to quantum objects. All analysed books addressed this issue when discussing the meaning of the probability distribution, stressing that it is not possible to determine the precise location of a photon/electron, but only their probability to be encountered.

Recommendation iv: promote metaconceptual analysis. According to Vosniadou (1994), practicing questions and exercises is a way to facilitate metaconceptual analysis. This was done in all books using not only quantitative but also qualitative exercises and in-text questions for students to evaluate their current knowledge of the subject.

Recommendation v: identify (counter)intuitive concepts to plan teaching strategy adequately. As mentioned in section 6.1, because QM topics are intrinsically counterintuitive, it is not necessary to differentiate between intuitive and counterintuitive concepts.

Recommendation vi: motivate with meaningful experiences. Presenting meaningful experiences to motivate students' revision of presuppositions through school books is challenging because books allow only for static visual and textual information. Nonetheless, all analysed books presented a variety of images or schemes of experimental outcomes, external links to videos, guides for students to perform experiments, and meaningful exercises. Figure 4 depicts an example from the analysed books in which the wave behaviour of electrons is proven by pictures of an experimental outcome.

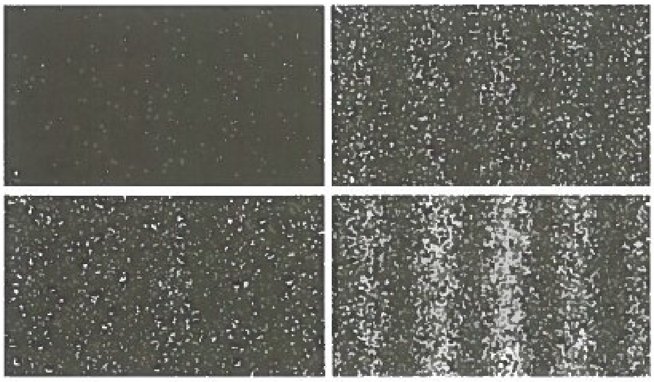


Figure 4. Depiction of the building of an interference pattern with electrons. From: *Overal Natuurkunde*, by R. Bouwens, P. Doorschot, G. van Reisen, and A. Vennix, 2012, the Netherlands: Noordhoff Uitgevers B.V.

Recommendation vii: avoid cognitive conflict as only strategy. None of the analysed books made use of cognitive conflict.

Recommendation viii: use model-based instruction. The books addressed different models throughout the discussion of topics within the scope of the wave-particle duality. Models of the atom, photoelectric effect, light as a wave (packet), and electron as a standing wave were depicted in images and explained through text. However, it could be argued that some models and their explanations do not aid students' conceptual change. For instance, Figure 5 shows the model used by Newton to explain the photoelectric effect. Its sinusoidal representation of light could strengthen students' idea of light as a wave, even though the photoelectric effect is presented as proof of light's particle behaviour. Additionally, as previously discussed, the model of a wave packet as a sinusoidal entity (see Figure 3) can also be detrimental to students' proper acquisition of knowledge if not properly explained and interpreted.

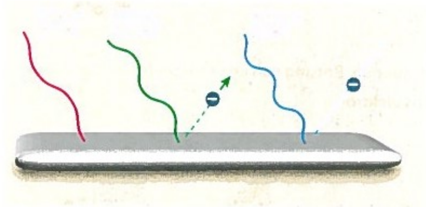


Figure 5. Representation of the photoelectric effect. From: *Newton*, by J. Flokstra, A. Groenewold, K. Hooyman, C. Kootwijk, K. Kortland, P. Over, and P. Siersma, 2015, the Netherlands: ThiemeMeulenhoff bv.

Recommendation ix: address contexts and processes. All books provided context through a historical overview of wave-particle duality topics. As stated in section 6.1, including a historical background when teaching quantum physics is a common practice, but insufficient as sole didactical strategy. Each book also provided additional contexts for different topics. For instance, Nova introduced the QM chapter by exploring the phenomenon of bioluminescence and Systematische Natuurkunde and Newton used solar panels to discuss the photoelectric effect.

Recommendations x and xi: consider affective components of the learning environment and social aspects. Not applicable to the analysis of school books.

6.3 TEACHER INTERVIEWS

This section contains the results on the analysis of the teacher interviews (see Appendix A for the complete interview scheme). The following subsections include an analysis of the teachers' input on specific topics about teaching the wave-particle duality. As mentioned in section 5.5, two of the interviewed teachers (A and C) had taught students who also took the post-test conducted by Van den Berg et al.'s (2018). In section 6.4.2, a comparison between the outcomes of the post-test from students of teachers A and C is conducted.

6.3.1 NUMBER OF LESSONS

The participants of the interview were first asked how many lessons they spend teaching the photoelectric effect, double-slit experiment, and de Broglie wavelength. In the Netherlands each school determines the number of lessons of a subject per week, as well as the duration of those lessons, and each teacher establishes how many lessons they want to dedicate to a topic. Therefore, the answers varied considerably among each interviewed teacher. Table 5 specifies the number of lessons per interviewed teacher.

Table 5

Number of lessons per topic per interviewed teacher

Teacher	Number of lessons per topic		
	Photoelectric effect	Double-slit experiment	De Broglie wavelength
A	3	6	1
B	3	2	1
C	2	2	1
D	1	1	1
E	1	2	1
F	2	2	1

6.3.2 TEACHING APPROACH TO THE PHOTOELECTRIC EFFECT

Teaching strategies. Four teachers introduce their lessons about the photoelectric effect using an electroscope. Teacher A uses a real-life electroscope and shines different kinds of lamps on it, while bringing attention to how they affect the electroscope's charge. He added that after the electroscope, he uses the PhET simulation of the photoelectric effect for visualization purposes. Teacher C also demonstrates the effect with a real-life electroscope, but when shining an ultraviolet lamp on it, he places a lens between the lamp and the electroscope's plate. This lens filters the ultraviolet radiation; therefore, the electroscope is not discharged, and the photoelectric effect is not observed. Teacher B and D introduce the experiment of the electroscope through a visual scheme (in a power-point presentation) and use this scheme to discuss how different kinds of lamps or metal plates change the outcome of the experiment. Teacher D commented that he used a hands-on experiment to demonstrate the photoelectric effect before, but it resulted to be too difficult for students. Teacher B added that, before teaching about the electroscope, he addresses the phenomenon of photosynthesis as an application of the photoelectric effect. Teachers E and F do not use the electroscope, but only the PhET simulation of the photoelectric effect. Teacher E specified that the simulation allows him to add lamps, so he explores such feature by first adding six to twenty red lamps in the simulation, analysing what happens, removing all lamps, and finally adding only one blue lamp. After the addition of the blue lamp, the simulation shows electrons flowing from one plate to the other.

After this introduction, all teachers explain the theory behind the photoelectric effect. From the theory, they follow to an analysis of two graphs related to the effect: kinetic energy *versus* frequency and current *versus* voltage. Teachers A, E, and F use the graphs shown in the PhET simulation as part of such analysis. Teacher B commented that he used to employ the simulation for analysing these graphs as well, but stopped because he noticed that one of the graphs differed from what was shown in his students' books. All teachers' instructions are then followed by quantitative exercises.

Regarding the discussion of the particle behaviour of light in the photoelectric effect, teachers A, B and D do not cover this content. Teacher A reported that he does not find the effect a convincing manifestation of the particle property of light himself, and therefore does not address it. He commented:

> *You can show the particle behaviour with [the photoelectric effect], but it's not quite convincing, I think. I am still searching a way to convince my pupils that this is one of the ways to show light has a particle behaviour. I am still myself not really convinced.*

On the other hand, teacher E stresses the particle behaviour of light in his instruction, and teacher F does not mention the word 'particle' but describes the photon as a package of energy. Teacher C also mentions the particle behaviour, without emphasizing it, but comments the following:

> *[The students] accept that light is a particle. They see it happens so there should be particles. They just accept it and don't really think about the implications.*

Finally, teachers B and C mentioned that their students also conduct an activity with LEDs as part of their instruction in the photoelectric effect. They explained that the activity is done independently by the students. Due to time constraints, it was not possible for the teachers to provide a detailed description of the activity during the interview.

Student difficulties. Teachers A and C believed that the photoelectric effect is abstract to students and needs a lot of different physical concepts to be understood. About that, teacher C commented:

> *It's quite abstract, they don't visualize it. And there are a lot of factors playing a role: the material, the colour, the voltage, the current... There is a lot of information, a lot to do with [this] information.*

Additionally, teachers A, E, and F reported that students show difficulties with the concept of voltage in the experiment. More specifically, teacher E stated that his students have difficulty understanding why the electrons' acceleration changes in terms of the voltage and how this process works. Teacher A added that students also struggle with interpreting a negative value of voltage.

Another difficulty, experienced by teachers B and F, is the interpretation of the graph of current *versus* voltage, and how it changes when the intensity or colour of light change. Finally, teacher D added that many of his students do not understand why the number of photons changes in the PhET simulation when the intensity or colour of light changes.

6.3.3 Teaching Approach to the Double-slit Experiment and Wave-Particle Duality

Teaching strategies. All teachers use different strategies and resources when giving instruction about the wave-particle duality. However, they all start by either recalling or introducing the phenomenon of diffraction. For instance, teacher A does so by demonstrating the phenomenon using a ripple tank with water going through one slit. He then explores the same phenomenon using a laser beam going through one slit. Teachers B and C also use a laser beam to show students the pattern formed with one slit. Following the phenomenon of diffraction, all teachers discuss the phenomenon of interference and its relation with the waves' path difference. The demonstrations with the ripple tank and laser beam are used again, but this time with two slits. All teachers use diffraction and interference to emphasize the wavelike character of light.

After exploring the wave property of light, teachers move on to the wave-particle duality. Teachers C and E make an analogy between the outcomes of the double-slit experiment with light and with macroscopic objects. For that, teacher C uses water from a hose and teacher E uses paint spray. They demonstrate the experiment using these materials and students compare the patterns between this experiment and the one with light. This comparison leads the teachers to question the students about which pattern would be observed if the experiment would be conducted with electrons. After receiving some answers from students, these teachers show two videos: one with the build-up process of the interference pattern formed by electrons[2], and one animation which explains the wave-particle duality phenomenon[3]. Teacher B uses a similar approach, in which he asks students to verbally describe the observed pattern when the double-slit experiment is conducted with bullets, water waves, and electrons. From that discussion, he also shows the video containing the build-up of the interference pattern formed by electrons. About the discussion of the video's content, he adds:

[2] Available at: https://youtu.be/jvO0P5-SMxk
[3] Available at: https://youtu.be/DfPeprQ7oGc

I try to discuss what is happening, so I hope someone will bring up that the electron is splitting up, things like that. But all the dots [in the video] are the same, there is not a half dot. I try to work the conclusion that the only option is that [the electron] goes through both slits.

Teacher A uses a different approach. After demonstrating the double-slit experiment with light, he builds a table with wave and particle properties of light, to be completed by him together with the students. Then, he asks about how that same table would look like for electrons. This is his starting point to show the same video used by teachers B, C and E. In addition to the video, he also uses an electron diffraction tube, so students can visualize the diffraction pattern formed by electrons. Once the teachers have discussed the phenomenon of electron interference, they introduce the concept of de Broglie's wavelength. Teachers A, D, and F add a derivation of de Broglie's wavelength formula from the interpretation of electrons as standing waves in Bohr's atomic model.

Some teachers also discuss the phenomenon of single-photon interference. Teachers A, E, and F do so by using the same single-photon interference experiment described in Van den Berg et al.'s (2018) article. They demonstrate the experiment for either the entire classroom or for groups of students. Teachers E and F added that before conducting the experiment, it is necessary to convince the students that the photons are going through the slits individually. In respect to that, teacher E commented:

What I found the most important is that you have to make sure [the students] understand that these photons are coming one by one. Because otherwise they think "laser is light, so it's obvious that there is interference, because it's a light wave."

Another resource which illustrates the phenomenon of single-photon or electron interference in the "quantum wave interference" simulation by PhET. Teachers A, C, and F make use of this simulation to help students visualize the phenomenon.

Teachers finalize the discussion about the wave-particle duality with an interpretation of the interference pattern formed by electrons or photons as a probability distribution, and how this probability distribution is described by a wave function. However, this is not deeply discussed or analysed by them. As stated by teacher B:

When I taught [the probability distribution] the first time, I made it very philosophical, but [the students] gave up because they thought it was very difficult.

Teacher F, after explaining how he approaches the discussion about probability distribution and wave function, also commented:

> *For most students [the instruction] works because they don't think it through. If they start thinking through, it gets wrong again. And I do tell them about wave function and about how a wave function collapses during the measurement, but… can you visualize it? (laughs) I know it works and I've come to accept that apparently that's how these things behave… but what an electron looks like while it's on the way somewhere without being detected, I have no idea. So I am not surprised that [the students] struggle with that.*

Student difficulties. Teachers C, D, and F mentioned that students find the wave-particle duality too abstract and therefore take it for granted, as another phenomenon that must be simply accepted. As explained by teacher F:

> *But after [the photoelectric effect], the double-slit experiment comes in and light is a wave again. In that moment duality comes in and they start to get a bit puzzled, but even then, they just accept it. They accept it to be dual, but I don't know if they really get to the point of what duality actually means. Some students do, but most don't.*

Besides this difficulty, each teacher also encountered different struggles faced by students: Teacher B noticed students struggling to apply the wave-particle duality to practical exercises; teacher E pointed out students' lack of prior knowledge about classical waves and particles; and teacher F stressed that, because the concept of momentum is only introduced to students together with de Broglie's wavelength, there is not much time for students to actually understand it.

6.3.4 STRENGTHS AND IMPROVEMENTS

Another goal of the teacher interviews was to identify factors which positively influence the teaching of the wave-particle duality. Two factors were mentioned by teachers: the variety of available teaching resources such as experiments, simulations, and videos, and the image which students have about QM. More specifically, they mentioned how students see QM as a strange and almost mystic topic, which triggers the interest of some students. As explained by teacher D:

> *I think that [the students] get a feeling that [quantum mechanics] is really modern Physics, that this is happening now. They understand that this is getting closer to the boundaries of my knowledge as a teacher, and they understand it. But they have a lot of questions, and I think the nice thing is that they also accept*

that I don't have all the answers. Some students like the discussions, like philosophizing about these matters.

Another goal of the interview was to know which educational improvements could help the participants to teach about the wave-particle duality. The answers comprise the following suggestions: more real-life examples which apply the wave-particle duality and are connected to other disciplines (e.g. Chemistry); more simulations, hands-on experiments, and analogies; opportunities to discuss about the topic with other Physics teachers; a website which gathers all the available digital resources for teaching QM; instructional videos for teachers about students' misconceptions in QM and how to address them; and improvement of exercises from books and national exam.

6.3.5 **CONTRIBUTIONS TO CONCEPTUAL CHANGE**

Similar to the analysis of literature review and school books, teachers' input was categorized based on Vosniadou et al.'s (2001) and Duit and Treagust's (2003) recommendations on how to promote conceptual change. However, given the limited time of the interviews, it was not possible to assess how teachers addressed all the recommendations.

Recommendation i: focus on fewer key concepts. This recommendation was proposed by Vosniadou et al. (2001) because students should be offered enough time to achieve a deeper knowledge about the key concepts of a certain topic. As displayed in section 6.3.1, the interviewed teachers spend a varied number of lessons in different topics. Therefore, it could be inferred that some of the interviewed teachers offer more time for students to acquire proper knowledge about the wave-particle duality than others, based on the total number of lessons spent on the topic by each teacher. Section 6.4.2 offers a detailed statistical analysis of this claim. Additionally, the findings of Van den Berg et al. (2018) seem to strengthen the claim, as the students participating in their study appeared to "insufficiently realize the meanings of wave, particle, probability distribution, and other classical and quantum concepts" (para. 8) after receiving instruction about the topic.

Recommendation ii: address similarities between concepts. It was not possible to clearly assess this recommendation through the interviews. However, teachers A and E do address the aforementioned difference between light's intensity and frequency. Teacher A does so by demonstrating the behaviour of an electroscope when different lamps with various intensities and colours are shone upon it. Teacher E, on the other hand, uses the simulation of the photoelectric effect to explore the experiments' outcomes as the number and colour of lamps vary.

Regarding the main differences between classical waves and particles, Teacher E's experiences supported Van den Berg et al.'s (2018) finding that students do not grasp such differences. It could be considered that the series of demonstrations of the double-slit experiment with different sources, conducted by some of the teachers, might address these differences. However, the recent findings of Van den Berg et al. (2018) suggest that teachers might have to treat the subject differently.

Recommendation iii: consider prior knowledge. In some cases, such as with teacher F, the concept of a photon or of interference was already taught to students before their instruction on QM. In these cases, teachers said that they recalled these concepts when teaching the wave-particle duality. Regarding prior knowledge about circuits and voltage, it was not clear how teachers addressed it during instruction on the photoelectric effect. However, teachers A, B, E, and F reported that students struggle with either the concept of voltage or the graphic of current *versus* voltage when learning about the photoelectric effect. Therefore, it could be argued that the prior knowledge of voltage and its role in the photoelectric effect experiment could have been explored in more depth.

Recommendation iv: promote metaconceptual analysis. All teachers reported that they discuss certain topics with the students during class or ask for the students' input on questions. Teacher B, for example, promoted a discussion with students about the outputs of the double-slit experiment with bullets, water waves, and electrons, and asked for students to explain their views on single-electron interference and how it happens. Another example is teacher A, who asked for students' input when completing a table about the wave and particle properties of light.

Recommendation v: identify (counter)intuitive concepts to plan teaching strategy adequately. Because QM topics are intrinsically counterintuitive, it is not necessary for teachers to differentiate between intuitive and counterintuitive concepts.

Recommendation vi: motivate with meaningful experiences. All interviewed teachers explored different resources such as simulations, experiments, hands-on activities, and videos to promote meaningful learning experiences to students.

Recommendation vii: avoid cognitive conflict as only strategy. None of the interviewed teachers used cognitive conflict.

Recommendation viii: use model-based instruction. It was not possible to clearly assess this recommendation through the interviews.

Recommendation ix: address contexts and processes. It was not possible to clearly assess this recommendation through the interviews, but it is known that teacher B starts his instruction about the photoelectric effect using the phenomenon of photosynthesis as a way to provide context.

Recommendation x: consider affective components of the learning environment. It was not possible to clearly assess this recommendation through the interviews.

Recommendation xi: address social aspects. The social aspect was addressed in the analysis of recommendation iv.

6.4 Student Interviews and Post-test

6.4.1 Student Interviews

This section contains the results on the analysis of the student interviews' transcripts. The following subsections include an analysis of the students' input about their learning of the wave-particle duality.

General remarks about quantum mechanics. When students were asked about what they think of QM, they classified the subject as abstract, vague, counterintuitive, and different, but also interesting. Some mentioned that classical mechanics is easier to grasp because it is more accessible. However, one student mentioned that his/her classes on QM had many more practical experiments than classes on other subjects of Physics. Regarding the comparison with classical mechanics, a student commented:

> *[Quantum mechanics] is very counterintuitive, especially tunnelling. You have to accept that it is like that. I am prepared to accept it, but it is much more difficult to think that it actually happens. You see with the effect that that indeed is the case. But with classical mechanics you see literally what happens and is all more acceptable. And I think that the physics you had for all those previous years, you build on what you have learned then, also in early high school. It builds on each other and every time it is a step further, so it is easier to keep up with. But that was a completely new subject and I could not compare it with anything.*

Additionally, another student added his/her thoughts on how to improve QM teaching using applications:

> *It is abstract, it is very complex, and you think "I will never see this again." But it is used everywhere. Maybe there could be more focus on that during class. Not that you need to go deep into it, but that you know that it exists.*

Similarly, another student commented about the use of the single-photon interference experiment (introduced to the students as ‘the suitcase experiment’, because the experiment is setup in a dark suitcase) during their wave-particle duality class:

> *I found the suitcase [experiment] more accessible. Quantum mechanics itself sounds difficult and it is also a bit complex, and then I myself imagine a big lab with people working with complex apparatuses, but in principle it can also happen with a little suitcase. That makes it more accessible.*

Conceptualization of the wave-particle duality and probability distribution. When asked about what wave-particle duality is, students’ answers followed a pattern in which they explained that a certain entity shows properties of waves and particles. This entity varied among students: in two interviews, the entity was “light”; in four interviews, it was “particles”; in two interviews, it was “a photon”; and in one interview, it was “a wave”. In two interviews, students did not provide a definition of the wave-particle duality. Additionally, the use of verbs in the explanation also varied. For instance, instead of saying that the entity “shows properties of waves and particles”, some students said “is a wave and a particle”, or “is a wave and has particle properties”, or “has wave and particle behaviours”. One of the students defined the wave-particle duality as follows:

> *It means that certain small particles actually are waves, as long as they are not detected. And when they are detected, they turn out or appear to have become particles. And the duality thus mean that they can have one of both phases, but not both at the same time.*

Regarding the probability distribution of quantum entities and how it is depicted in the interference pattern, four out of the eleven interviews contained this discussion. All students provided correct answers about the probability distribution and about the impossibility to know where a quantum object is with certainty. One student also added that the portrayal of a photon in the PhET simulation is a representation of the chance to find the photon. However, in all of these interviews, this subject was not deeply discussed after the students’ answer.

Examples of wave and particle characteristics. Some students were asked during the interviews about their views on a) differences of behaviour between classical waves and particles; and b) wave and particle characteristics of quantum objects. Out of the eleven interviews, four contained this question. When describing the classical behaviour of waves and particles, one of the students mentioned that waves can diffract, and provided sound waves as an example. Regarding particles, he/she mentioned that they cannot diffract, and cited the example of atoms and electrons. In another interview, conducted with a pair of students, one of them commented that classical particles have mass and classical waves do not. The other student added that classical particles exist in only one place, but classical waves propagate through space. In that same interview, these students were also asked to point out the wave and particle characteristics of quantum objects. One student said that, when showing wave behaviour, a photon can interfere with itself and goes through both slits at the same time in the double-slit experiment. Regarding the particle behaviour, this same student added that such behaviour is observed when the photon is detected. The other student also mentioned that quantum particles can collide. In another interview also conducted with pairs, the students' answers were similar to the previous ones. However, one of these last students pointed out that classical waves follow a certain direction, while classical particles can be everywhere. When prompted by the interviewer, who asked about the distribution of his voice and of his pen in space, this student understood his/her mistake and corrected him/herself. Finally, one last student was asked about the difference between the wave and particle characters of a quantum object. He/she took the single-photon interference as an example, first pointing out interference as a wave characteristic, and then indicating the existence of a single photon as a particle characteristic. Later, this student was asked again by the interviewer about these different characteristics:

> *I: Can you formulate a general rule for which sort of phenomenon is a wave character used and for which phenomenon is a particle character used?*
>
> *S: Yes, by the refraction of light you have the wave character and on the moment that you calculate the speed of light, then you also have a wave character. In our test … [a question] was about space and that you can know how long the light takes to travel and for that you take the wavelength or the speed, or the speed of light.*
>
> *I: And if we take electrons, when do you use the wave character for electrons and when do you use the particle character for electrons?*
>
> *S: Wave character for tunnelling and particle character on the moment that they're somewhere on … an electrical circuit.*

De Broglie wavelength and the 'through which slit' discussion. During the interview, students were also asked about why is the interference phenomenon observed for small particles but not for macroscopic ones. Out of the eleven interviews, five included this discussion. However, in two interviews, this matter was not deeply discussed, and students expressed that they had learned it but could not remember the proper reasoning or answer. Two other students provided the correct reasoning, applying de Broglie's wavelength to explain its' relation with the mass of the entity, and how the size of the entity compared to its de Broglie wavelength affects the observation of wave properties. In one of these interviews, the student explained his/her reasoning as follows:

> *S: We ourselves have a wavelength and I think each particle has a wavelength, but electrons and photons are so small that … this wavelength still has an effect. I think for protons and neutrons also a bit less, because they are a bit bigger.*
>
> *I: What is then the difference in wavelength of big particles and small particles?*
>
> *S: I think the wavelength of both is small, but because an electron itself is also very small, this wavelength is still noticeable. And because this wavelength for people also is still very small but a person is big, this wavelength is not really noticeable in a person.*

Another student, when first asked about the difference between the de Broglie wavelengths of an electron and a basketball, answered that the basketball's wavelength is much larger than the electron's. Then, the interviewer prompted the student to remember the formula of de Broglie's wavelength and reason about the mass of both basketball and electron. Thereafter, the student understood his/her mistake and provided the correct answer. He/she also derived correctly the reason for the impossibility to observe wave properties for the basketball.

Regarding the double-slit experiment with one photon at a time, the interviewer also asked some students about whether it is possible to determine through which slit the photon went. Six out of eleven interviews contained this discussion (superficially), and in five of them, all interviewed students answered that the photon goes through both slits. They added that if one tried to measure through which slit the photon went, the interference pattern would disappear. One student, however, provided a different reasoning (which was later corrected by the interviewer):

> *I: Can you tell through which slit [the photon] went?*
>
> *S: Yes, I think so. If it comes in the middle you don't know for sure because then it could have been through both slits, but if it comes all the way from the left, then you can say that it goes through the left slit, because the chance then is much bigger.*

6.4.2 **POST-TEST**

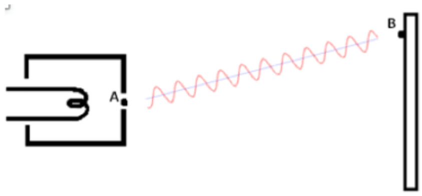
The multiple-choice post-test was taken by 112 students and covered the topics of wave-particle duality and tunnelling. The maximum score for the multiple-choice questions was 26 points and students' average score was M = 17.4 (SD = 3.9). Out of the 26 multiple-choice questions, 20 were about the wave-particle duality.

The difficulty of each item was assessed by Van den Berg et al. (2018) through *p* values. The analysis of the items and their difficulties was conducted in this study for two categories: items which contemplated the wave and particle properties of quantum objects (items 1, 3, 4, 6, 7, 10, 11-15, 18, 19) and items which covered the de Broglie wavelength (8, 9, 16, 17, 27). These categories were determined in an exploratory way, based on the content of the questions. Items 2 and 5 were not included in this analysis because it was later known that not every participating student had the content of these items during class.

Items about wave and particle properties. This subset contains items which seemed to be well understood by students. Out of the thirteen items in this subset, ten had *p* values ranging from 0.7 to 0.9. More specifically, the average percentage of correct answers was computed for all items which assessed knowledge about wave properties and particle properties. The average for items about wave properties was 77%, and for items about particle properties, 74%. The topics covered by these ten items are: wave behaviour of light (items 6 and 11), wave behaviour of electrons (item 3), protons (item 14), and molecules (item 15), particle behaviour of electrons when detected (item 7), particle behaviour of macroscopic objects (items 12 and 13), single-electron interference (item 18), and detection of the electron's trajectory in the double-slit experiment ('through which slit' discussion, item 19). For instance, item 14 required students to recall the concept of quantum interference with protons, which was correctly done by 91% of students. Similar to item 14, item 18 prompted students to recall the same concept, but with electrons. 88% of the students answered it correctly.

Three items had *p* values lower than 0.7. Item 1 asked students to identify the light's behaviour as a wave or particle behaviour in the photoelectric effect. 64% of the students answered it correctly. Similar to item 1, item 4 asked students to choose between the same two types of behaviour during the emission and absorption of electromagnetic radiation. The percentage of correct responses for item 4 was 54%. Finally, the most difficult item of this subset was item 10. It required students to recall the impossibility of determining the trajectory of an electron which is emitted by a source (see Figure 6). 47% of the students correctly chose that it is not possible to determine such trajectory. However, 32% chose the alternative which states that the electron moves in a sinusoidal trajectory, and 19% thought the electron moved in a straight line.

10. Een elektron wordt uitgezonden door een bron bij positie A, na verloop van tijd wordt het elektron waargenomen op een detectiescherm op positie B, zoals weergegeven in de onderstaande tekening. Hoe is het elektron van positie A naar positie B gegaan?

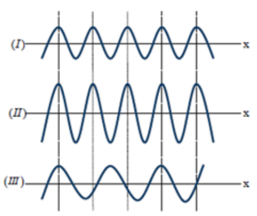


A. In een rechte lijn (zoals het blauwe, rechte pad)
B. Over een sinusvormige pad (zoals het rode, golvende pad)
C. Dat is niet te zeggen

Figure 6. Question of the post-test treating the trajectory of an electron.

Items about the de Broglie wavelength. All five questions in this subset evaluated the student's knowledge on how the de Broglie wavelength depends on the objects' momentum. The average percentage of correct answers for these questions was 55%. According to the reported *p* values, question 27 (see Figure 7) was the easiest question of the subset. It asked students to relate the speed of different electrons based on their wavelengths. 73% of students chose the correct alternative. Additionally, question 16 asked students how an interference pattern formed by electrons would change if these electrons' speed would be increased, which requires the application of the same knowledge from question 27. However, only 34% of students answered question 16 correctly, and most of the students (46%) answered that nothing would happen with the interference pattern. Similar to item 16, item 17 also asked what would happen with an interference pattern formed by electrons if they were substituted by heavier particles with the same speed, and 56% of the students answered correctly. Finally, item 8 asked why wave effects cannot be observed with a basketball. 48% of the students chose the correct alternative; 27% chose that the basketball is a classical particle, and therefore has no wavelength; 18% chose that the speed of the ball was too low and if it increased to 1000m/s, the effects would be observed; and 3% said that the ball was too light for the effects to be observed.

27. Drie elektronen bewegen in dezelfde richting. Hieronder zie je de deBroglie-golven behorend bij deze drie elektronen:



Hoe verhouden de snelheden van deze elektronen (I, II en III) zich tot elkaar?

A. $v_{II} > v_I > v_{III}$
B. $v_I = v_{II} > v_{III}$
C. $v_{II} > v_I = v_{III}$
D. $v_I = v_{II} = v_{III}$

Figure 7. Question of the post-test about de Broglie's wavelength.

Comparison between teachers. Two of the interviewed teachers (A and C) had taught students who also took the post-test. The interviews showed that the total number of lessons on the wave-particle duality differs for both teachers (10 lessons for teacher A and 5 lessons for teacher C). Because of this difference, it could be hypothesized that teacher A offered more time for students to acquire knowledge about the wave-particle duality than teacher C, which would be translated to higher total scores in the post-test.To determine whether a larger number of lessons resulted in a higher total score in the post-test, an independent samples T-test was conducted. Results were non-significant, with t (81) = .78, *p* = .22. Therefore, on average, students of teacher A (*M* = 13.0; *SD* = 2.4) did not obtain a higher total score than students from teacher C (*M* = 12.6; *SD* = 2.2). This means that there is no statistical evidence to suggest that the number of lessons spent by the teachers on the subject had an effect on the total post-test scores for these students. Table 6 displays the main statistics of these group of students.

Table 6

Main statistics of students from teachers A and C

Teacher	*N*	Average score in post-test (out of 18)	*SD*
A	20	13.0	2.4
C	63	12.6	2.2

Additionally, 22 students of teacher A answered the post-test. However, the results of two of these students were not considered for this analysis, because one of them answered only one question, and the other answered only one question correctly. These two cases were identified as extreme outliers (IBM Corporation, 2012) and removed from the analysis.

6.5 PILOT TEST

The pilot test consisted of four lessons of 45 minutes about the following topics, in chronological order: interference of light and general waves, photoelectric effect, definition of wave-particle duality, double-slit experiment, electron interference, and de Broglie wavelength. As mentioned in section 5.4, these lessons were scheduled as a revision, because the students had already learned about these topics previously (except for interference of electrons). Additionally, because the students would take a final exam shortly after the set of lessons, the teacher requested the researcher to narrow the focus of the pilot test to the relevant concepts for the students' exams. Nevertheless, it was possible to cover most of the intended topics in the pilot.

The discussion about the phenomenon of interference was interactive: the teacher asked students various questions about the phenomenon, and the students answered out loud.

Sometimes they also discussed with each other about the answers. All in all, the students explained the phenomenon in terms of constructive and destructive interference of waves and path difference. At the end of the discussion about interference, the teacher asked the students which character of light was shown through interference, and students answered that it was a wave character. From that, the teacher proceeded to the photoelectric effect. He displayed the PhET simulation of the effect and asked the students to describe the key parts of the experimental setup. After demonstrating the occurrence of the effect using the simulation, the teacher asked why electrons seemed to have different speeds, to which a student answered: "because the photons interact individually with one electron only and those electrons are in different places inside the metal." Later, the teacher asked students to draw how the graph of the maximum kinetic energy of electrons in terms of frequency of light would look like, if light was behaving like a wave during the occurrence of the effect. The students and the teacher talked about the degree of the function relating energy and frequency and about which graph was correct. With the teacher's help, students concluded that if light behaved like a wave, the graph should be a parabola. They also recalled that the empirical graph is, however, a straight line. The teacher then recalled the concept of photon and a student explained that a photon's energy is given in terms of hf. When asked about what a photon is, this student answered "a packet of electromagnetic energy". From that, the teacher recalled the phenomenon of wave-particle duality.

At that point, the researcher proposed three thought experiments, derived from Feynman et al. (1963) and previously described in section 6.1. First, students were asked to imagine a double slit experiment being conducted with 1) bullets, 2) water waves, and 3) electrons. Then, students were asked to draw how they depict each entity in the space before the slits, after the slits, and how the pattern formed by these entities would look like, when captured by a detection screen. Their drawings are presented in Figure 8.

Concerning the bullets, students had no objections and agreed that the bullets would arrive close to each other in the detection screen, forming an agglomerate of bullets which resembles both slits. Concerning the water waves, one student was first confused because she understood that the thought experiment was conducted with light. Then, the students and teacher discussed about the patterns that would be formed by light and water and whether these patterns would be different. The teacher used a PhET simulation of water waves interference to clarify the students' questions. Regarding electrons, one student explained her drawing (depicted in Figure 8h) as follows:

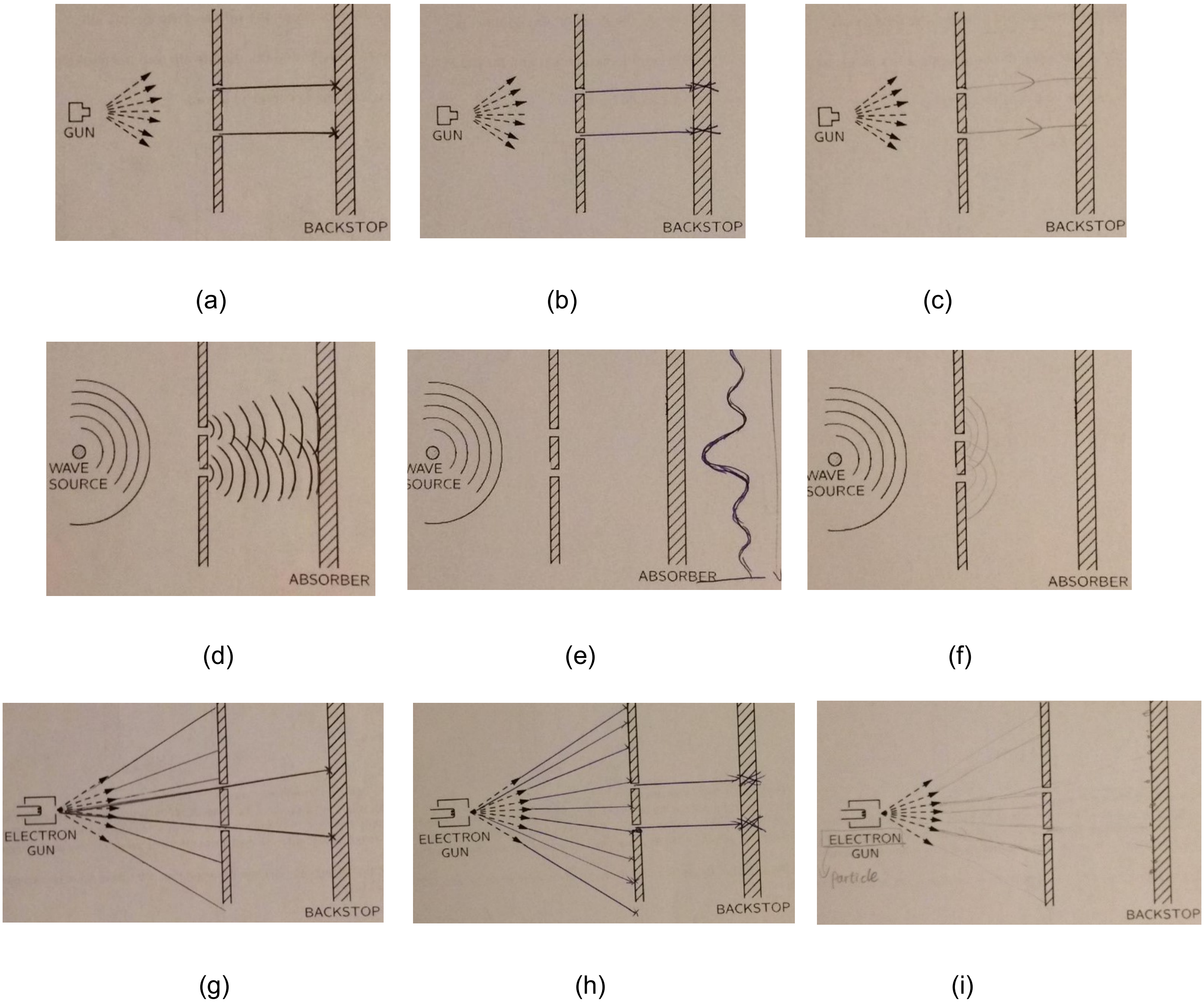


Figure 8. Students' depictions of the double slit experiment conducted with a-c) bullets, d-f) water waves, and g-i) electrons.

> *One electron only would be able to pass perfectly [through the slits] if it was aimed with a perfect angle, so if you are shooting electrons at random directions, then you would definitely hit the screen and they would stay there. At certain angles it gets a bit blurry, you may think that if you shoot it here (points to the edge of one of the slits) it might go through, but assuming that this fits just one electron, then it would hit the wall and it would not pass through. So only at a perfect angle an electron would be able to pass by, just like the bullets.*

She also commented about electrons changing direction after passing through the slits, which another student did not agree with by saying "the electron will continue in the same amount of motion, it's not like it will bounce inside the slits." At the end of the discussion, all students settled on the fact that the outcome of the experiment with electrons resembled the one with bullets. After that conclusion, the teacher showed the PhET simulation on electron interference, and asked: “what doesn’t make sense here?” to which a student answered, “it’s everywhere!”. Finally, one of the students also asked if what they saw in the simulation happened because electrons repelled each other, to which another student answered “but [the electron’s] velocity is so big that it doesn’t matter”. In the end, students agreed that the electrons formed an interference pattern. The teacher finalized the lesson series recalling the de Broglie’s wavelength and summarizing what was covered in the four lessons.

As mentioned in section 5.5, pre- and post-tests were conducted in the pilot and were analysed in an exploratory way. An interesting finding were the answers to question 4 of both tests: “True or false: in the absence of external forces, electrons move along sinusoidal paths”. According to McKagan et al. (2010), this question was elaborated to address students’ common misconception that the wave behaviour of electrons is manifested through a sinusoidal trajectory of movement. In this study’s pre-test, one student answered ‘false’ and two students answered ‘true’. However, in the post-test, the outcome was identical: all students answered the same as in the pre-test. Additionally, question 11 also provided interesting results. In this question, students were presented different patterns as a result of the double-experiment. They were then asked about which of these patterns would be seen if the experiment was conducted with electrons. Two students correctly chose an interference pattern in the pre-test, and one student chose a pattern with two bright vertical lines. However, when they were asked the same question through the thought experiment with electrons, all three students drew two lines, as previously explained. Due to time constraints, it was not possible to ask both students why they answered this question correctly in the pre-test. In addition, all students answered question 11 correctly in the post-test.

6.6 Summary of Results per Sub question

Because the previous sections described the results gathered by each instrument, it is also necessary to provide an answer to each sub question using these results. Therefore, the following sub sections offer a summary of the results and their contribution to each sub question.

6.6.1 Sub question 1 (Didactical Approach)

Sub question 1 was: What is the current didactical approach to the wave-particle duality from Dutch school books and high school Physics teachers, and how do these approaches promote conceptual change? The instruments used to answer it were the document analysis, teacher and student interviews, and post-test. Both Dutch national curriculum and school books approached the wave-particle duality concept using the dual behaviour of light. More specifically, light’s wave behaviour was introduced first, through the phenomenon of diffraction and interference. Light's particle behaviour was explored later through the concept of photon and/or through the photoelectric effect. Once both behaviours were presented, the dual properties of electrons were then explored. From the wave character of electrons, de Broglie's wavelength was introduced, as well as the concept of probability distribution. This approach from the curriculum and school books might be the reason why such similar approaches were identified in the practices of the interviewed teachers as well. Nonetheless, the teacher and student interviews showed that teachers made extensive use of different resources such as experiments, simulations, and videos. The experiments were used for teaching the photoelectric effect (electroscope), double-slit experiment (ripple tank, water hose, paint spray, and laser beam), and single-photon interference ('suitcase' experiment). Some teachers did not perform real-life experiments but used simulations instead. Others used simulations to complement the experiments. Videos were used for illustration of phenomena or proof of experimental outcomes (e.g., electron interference). Additionally, discussions about the concept of probability distributions were done by all teachers, and some also mentioned more advanced concepts such as the wave function and its collapse. Students' interviews and post-test also showed that some teachers discussed with students about a) the impossibility to know the slit through which a photon passed; b) the proportion between de Broglie's wavelength and the dimension of an object and how that influences the chance of observing wave behaviour from that object; and c) the act of measurement (detection) of an electron/photon as a particle property. However, it is not known how deep such discussions were.

Based on the previous results, a concept map of the wave-particle duality was elaborated specifically for the Dutch context (see Figure 9). The construction of this concept map considered how the topic was approached by the Dutch curriculum, school books, and interviewed teachers. The map's representation and elaboration process were inspired by the work of Mannila et al. (2001). In their work, a concept map was formed by connecting concepts of QM based on their properties. For this study, the elements (represented by the round shapes) were first defined by the national curriculum, and the connections between elements (represented by the arrows) were determined by the national curriculum and student and teacher interviews. More specifically, the connections were first determined by the verbs used in the national curriculum. Then, other elements and connections which were not present in the curriculum were added based on their occurrence in the teacher interviews and school books. For example, the analysis of school books showed that the wave function is taught as a way to describe the probability distribution of quantum particles. Therefore, the element "wave function" was added to the map.

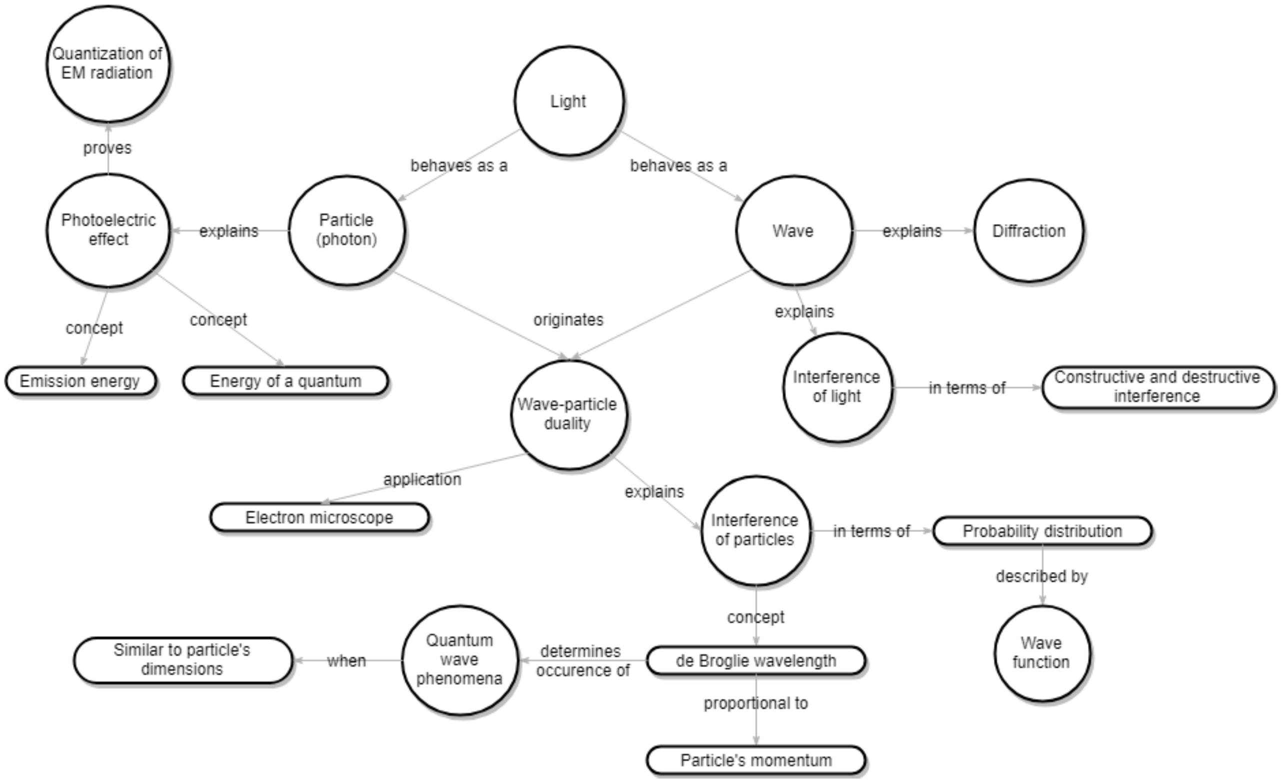


Figure 9. Concept map of the wave-particle duality as taught in the Dutch context.

Regarding the promotion of conceptual change, the analysed books and interviewed teachers promoted conceptual change using the following strategies: proposition of exercises, group activities, and classroom discussions; demonstrations of experiments; use of simulations, images of experimental outcomes, and videos; and contextualization using applications and historical background. An overview of the findings regarding conceptual change is shown in Table 7.

6.6.2 SUB QUESTION 2 (STUDENTS' CONCEPTIONS)

Sub question 2 was: What are the current conceptions of Dutch secondary school students about the wave-particle duality? The instruments used to answer it are: document analysis, teacher and student interviews, post-test, and pilot test (partially). The input from some of these instruments was used to create a concept map based on student understanding (Figure 10). The concepts and relations between them were first added to the map based on their presence in student interviews. Therefore, inputs from individual students were added to the map as elements (round shapes) or connections between the elements (arrows). Results from the post-test and national exams were then used to complement the map with other elements and connections which were not mentioned by students or asked in the interviews. For instance, the element "photoelectric effect" was added based on its presence in the post-test.

Table 7

Summary of findings on how school books and interviewed teachers addressed conceptual change recommendations

Recommendations for conceptual change	School books	Teacher interviews
Focus on fewer key concepts	N/A[a]	Time spent by some teachers in each key concept varies
Address similarities between		
Classical waves and particles	No, but differentiate wave and particle *behaviours*.	N/A
Photon flux and photon energy	Partially	Partially
Photon representation and photon trajectory	No	N/A
Consider prior knowledge of		
Voltage and circuits	No	N/A
Deterministic view of particles	Yes	N/A
Promote metaconceptual analysis	Yes, using quantitative and qualitative exercises	Yes, using classroom discussions and input from students
Identify (counter)intuitive concepts	N/A	N/A
Motivate with meaningful experiences	Yes, using pictures, links to videos, and guides to experiments	Yes, using simulations, experiments, videos, and hands-on activities
Avoid cognitive conflict as only strategy	No use of cognitive conflict	No use of cognitive conflict
Use model-based instruction	Yes, but model of light in the photoelectric effect might be detrimental	N/A
Address contexts and processes	Yes, using historical overview and practical applications	Yes, using practical applications
Consider affective components	N/A	N/A
Address social aspects	N/A	Yes, using classroom discussions and input from students

Note. [a]N/A is used when the recommendation is not applicable to the current instrument or when it was not possible to assess the recommendations from the intruments' input.

The occurrence of misconceptions in the map (shown in purple colour) was determined based on the percentage of students who answered a question from the post-test incorrectly. If 50% or more of the students answered an analysed question incorrectly, the concepts present in the incorrect alternatives were treated as a misconception. For instance, question 10 asked students about the trajectory followed by an electron between points A and B (see Figure 5). 47% of the students correctly chose that it was not possible to determine such trajectory, meaning that 53% of the students chose between either a sinusoidal or a straight trajectory. Therefore, the misconception that an electron has a definite trajectory was added to the map.

The concept map of students also depicts student understanding about the wave-particle duality topics using different colours. This understanding was evaluated as follows: First, it was determined which of the *connections* between elements in the map were covered by questions in the national exams. It was chosen to evaluate the connections because they show students' reasoning between the elements. The *p* values of the questions from the national exam were then used to determine the level of student understanding about the connections between the elements. It was considered that a question where $p \leq 20\%$ indicates poor knowledge, $20\% < p \leq 40\%$ indicates insufficient knowledge (represented in orange), $40\% < p \leq 60\%$ indicates partial knowledge (represented in yellow), $60\% < p \leq 80\%$ indicates sufficient knowledge (represented in blue), and $p > 80\%$ indicates good knowledge (represented in green). If more than one question from the national exams covered a same connection, an average of the *p* values of these questions was taken and used in the analysis. Second, it was determined which of the connections in the map were covered by questions in the post-test. The *p* values of these questions were used to determine the level of student understanding about the connections. When these connections overlapped with the ones from the national exams, only the *p* values from the national exams were considered, because of the national exam's sample representativity. The same criteria used for the *p* values of national exam questions were used to determine the level of student knowledge from post-test questions. Table 8 displays the questions from both instruments, the *p* values of these questions, and the level of knowledge based on these values. It is important to highlight that, because the student knowledge was assessed for the connections between elements, only the arrows between elements are coloured. Black arrows mean that such connections were not covered by the national exams or post-test.

Table 8

Questions and their p *values, used to assess student understanding of the concept map's elements.*

Concept map's components	Evaluating question	Question's *p* value	Average *p* value	Level of student understanding
Light behaves as a particle				
When absorbed/emitted	PT, Q4	54%		Partial
In the photoelectric effect	PT, Q1	64%		Sufficient
Light behaves as a wave				
In the refraction phenomenon	PT, Q6	79%		Sufficient
Explains interference of light	PT, Q11	83%		Good
Electrons behave as particles				
When detected	PT, Q7	79%	75%	Sufficient
	PT, Q19	71%		
Electrons behave as a wave				
Through interference phenomenon	PT, Q18	88%		Good
When propagating between a double slit and detection screen	PT, Q3	76%		Sufficient
Protons behave as a wave through interference phenomenon	PT, Q14	91%		Good
Interference phenomenon of protons/electrons forms an interference pattern, which is				
Influenced by the particle's speed	PT, Q16	34%		Insufficient
Influenced by the particle's mass	PT, Q17	56%		Partial
De Broglie's wavelength				
Is proportional to particle's speed	PT, Q27	73%		Sufficient
Is proportional to particle's mass	NE 2018, Q10	72%		Sufficient
Determines occurrence of quantum wave phenomena when similar to particle's dimensions	NE 2017, Q14	49%	58%	Partial
	NE 2018, Q9	52%		
	NE 2018, Q10	72%		
Macroscopic objects do not behave as waves	PT, Q12	87%	88%	Good
	PT, Q13	88%		
Because de Broglie's wavelength determines occurrence of quantum wave phenomena, when similar to particle's dimensions	PT, Q10	47%		Partial

Note. PT stands for post-test, NE stands for national exam, and Q stands for question.

The student map can be compared with the main concept map from the previous sub question (Figure 9). Below, the main concept map is repeated for convenience of the reader.

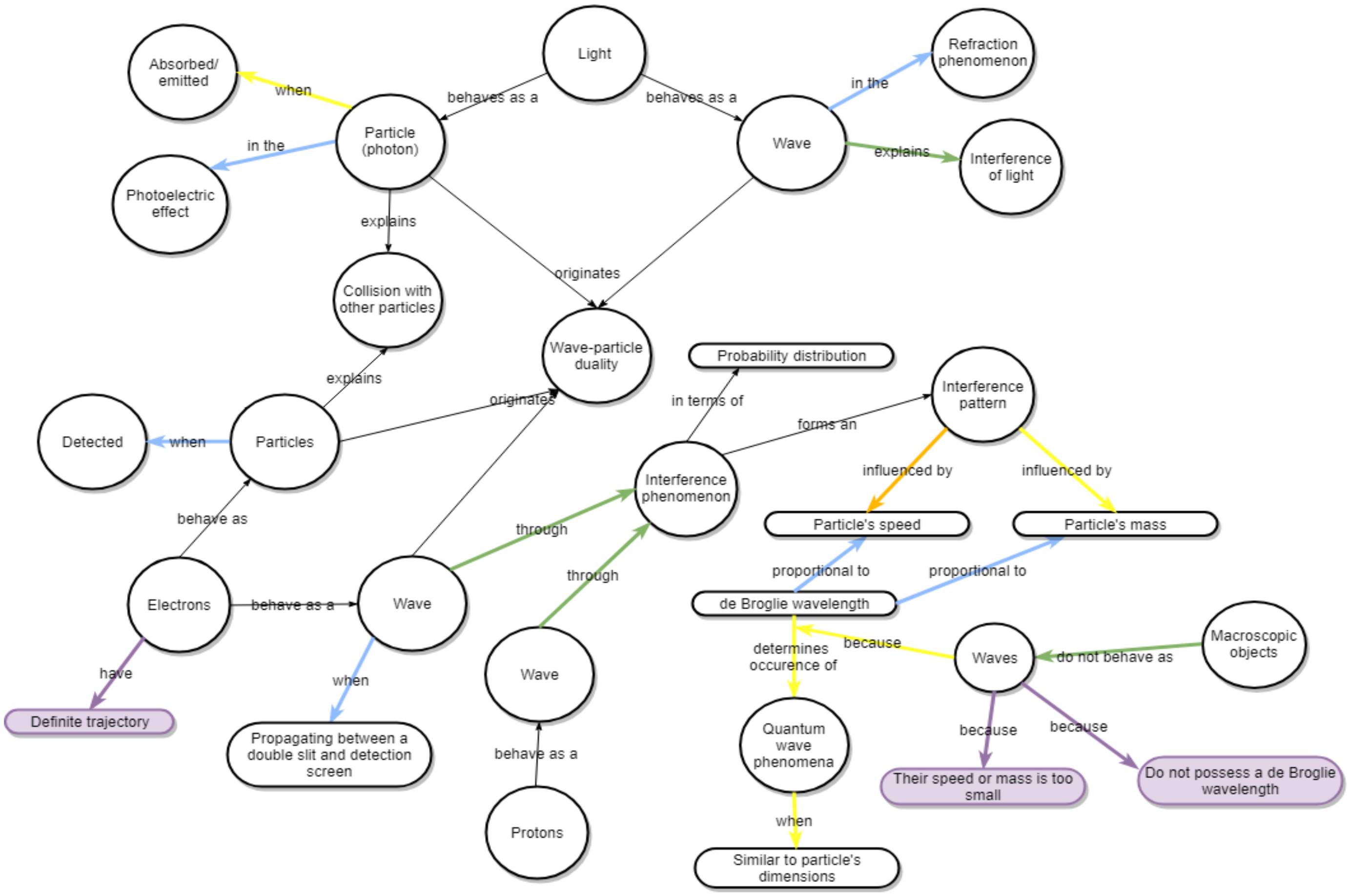


Figure 10. Concept map of the wave-particle duality as conceptualized by Dutch students. Elements are represented by round shapes and connections between them are represented by the arrows. The levels of student understanding about the connections are defined as: good (green colour), sufficient (blue), partial (yellow), and insufficient (orange). Student misconceptions are represented in purple.

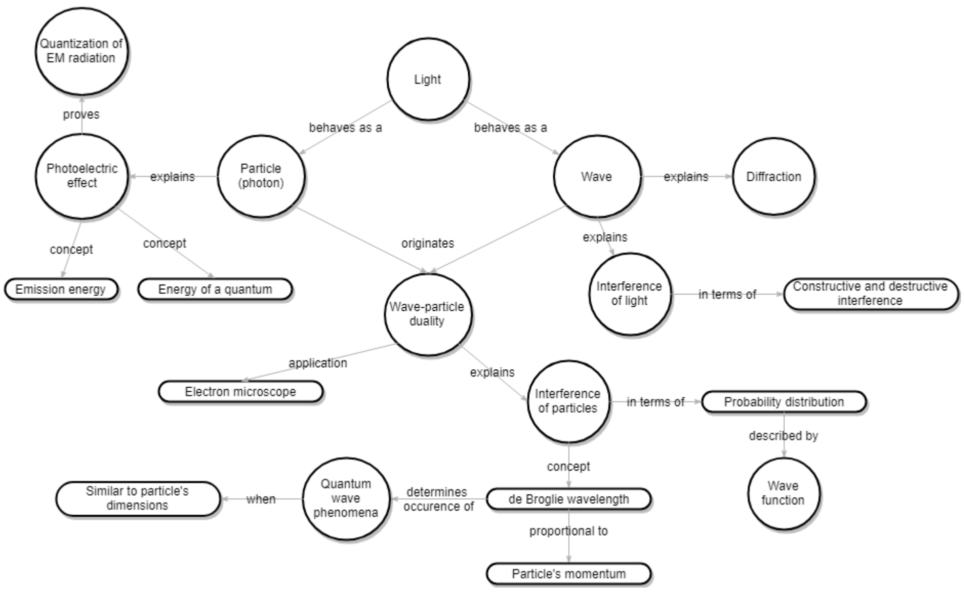


Figure 9 (repetition). Concept map of the wave-particle duality as taught in the Dutch context.

The student map depicts that students see the wave-particle duality not only as the co-existence of the dual behaviours of light, but also of electrons. The students map also shows the presence of additional concepts (e.g., electron's wave behaviour when detected) as well as the absence of other concepts (e.g. lights' interference in terms of constructive and destructive interference) when compared to the main concept map.

Additionally, teacher interviews suggested that students a) accept the wave-particle duality, instead of comprehending it; b) struggle with the photoelectric effect's dependence on various factors; c) have difficulty with understanding the influence of voltage, the current versus voltage graph, and the change of electron's acceleration in the photoelectric effect; d) lack prior knowledge of classical waves and particles; and e) struggle with the concept of momentum because it is introduced only when learning about de Broglie's wavelength. In addition, student interviews indicated that students a) think QM is counterintuitive, abstract, and interesting; b) define the wave and particle duality with both light and electrons as starting point; and c) grasped that a photon/electron is detected as a particle, and that the interference pattern represents a probability distribution. Van den Berg et al. (2018) added that the students who participated in the interviews and post-test also showed insufficient knowledge about the differences between classical waves and particles.

6.6.3 SUB QUESTION 3 (APPROACH'S SHORTCOMINGS)

Sub question 3 was: What are the shortcomings of the current didactical strategies? The instruments used to answer it were the document analysis, teacher and student interviews, and post-test.

From the analysis of school books and teacher interviews, it seemed that both teachers and school books a) did not sufficiently address the difference between photon flux and photon energy; and b) did not address students' prior knowledge about circuits and voltage in an adequate way. Specifically for school books, it was argued that the representation of the photon as a wave package or as a sinusoidal wave might confuse students and strengthen the common misconception that the representation is actually the photon's trajectory. Regarding the teachers, section 6.3.1 showed that they spend a varied number of lessons in different topics. Therefore, it was suggested that some of the interviewed teachers offered more time for students to acquire proper knowledge about the wave-particle duality than others, based on the total number of lessons spent on the topic by each teacher. However, an independent samples T-test with students from teachers A and C did not support this claim.

Finally, as previously mentioned for sub questions 1 and 2, students seemed to encounter difficulties with some concepts and form misconceptions about them. More specifically, the student map showed that students seemed to have a) an insufficient understanding about the influence of a particle's speed on the interference pattern formed by such particle and a partial understanding about the influence of a particle's mass on this same pattern; b) partial knowledge about why macroscopic objects do not display wave behaviours; and c) partial understanding about light's particle behaviour when absorbed or emitted. These difficulties suggest that the current teaching practices of these specific topics might be insufficient. Additionally, three misconceptions of students were identified: the belief that electrons move along definite paths and the belief that macroscopic objects do not behave as waves because they either do not have a de Broglie wavelength or because their speed or mass is too small.

6.6.4 SUB QUESTION 4 (TEACHING ALTERNATIVES)

Sub question 4 was: What alternatives are there to remedy these shortcomings? The instruments used to answer it were the literature review, teacher interviews, and pilot test. The following sub sections offer the alternatives categorized by shortcoming.

Photoelectric effect: Insufficient differentiation between photon flux and energy and focus on prior knowledge about circuits and voltage. An alternative is to consider McKagan et al.'s (2009) strategy, in which students explored the simulation of the photoelectric effect with focus on the difference between flux and energy. Books could propose a guided activity with the simulation and teachers could implement it. In this same strategy, students had an introductory lecture recalling the knowledge of circuits and voltage. This could be combined with a) Knight's (2002) suggestion that the role of each component in the experiment should be clear to students and b) McKagan et al.'s (2009) finding that the movement of electrons in the simulation facilitates the visualization of the voltage's effects.

Photon representation and trajectory. Even though different studies have reported students having the misconception that a photon (and electron, in some cases) travels through a sinusoidal trajectory, no specific strategies were reported to address the misconception. Nonetheless, both McKagan et al. (2010) and Özcan (2015) suggest that the source of the misconception might originate in books' representations of the photon as a wave package. Additionally, the results from the pre- and post-test given in the pilot test showed that two students answered, in both tests, that electrons have sinusoidal trajectories, even though such trajectories were not mentioned during their instruction. Therefore, school books and teachers could clarify the difference between the photon's trajectory and representation when depicting wave packets, and clarify that electrons also do not possess this type of tractory.

Difficulties with de Broglie's wavelength. Vokos et al. (2000) proposed a tutorial which specifically addresses students' difficulty in relating momentum and de Broglie's wavelength. In this tutorial, students are asked to predict and explain what would change in an interference pattern formed by electrons if these were slowed down. Then, students are given photographs which show the actual changes in the pattern and can resolve the inconsistencies between their predictions and observation. Additionally, the PhET simulation “Quantum Wave Interference” allows students to observe changes in the interference pattern of electrons when their velocity changes, or observe the interference pattern of protons and neutrons (and consequently the influence of mass in the interference pattern). Thus, the development of a tutorial which explores the relation between momentum and de Broglie wavelength (and, therefore, interference pattern) using the PhET simulation could be proposed. However, it must be considered whether the link between de Broglie wavelength and interference pattern would be appropriate in the Dutch context.

7 DISCUSSION AND CONCLUSION

This study analysed the current teaching practices and student understanding of the wave-particle duality in Dutch secondary schools to answer the question: *What is the current state of instruction on the wave-particle duality in Dutch secondary schools and how to promote the process of conceptual change in such context?* To answer the main question, four sub questions were formulated:

1- What is the current didactical approach to the wave-particle duality from Dutch school books and high school Physics teachers, and how do these approaches promote conceptual change?
2- What are the current conceptions of Dutch secondary school students about the wave-particle duality?
3- What are the shortcomings of the current didactical approaches to the wave-particle duality from Dutch school books and high school Physics teachers?
4- What alternatives are there to remedy these shortcomings?

The conclusions from and reflections on each sub question's findings are reported in the following sub sections.

7.1 DIDACTICAL APPROACH

The findings for the first sub question suggested that the current (and proposed) didactical approach to the wave-particle duality in Dutch high schools treats the wave and particle phenomenon of light separately, using analogies with classical physics, and defines their co-existence as the phenomenon of duality, which is followed by the explanation of wave properties of other objects such as electrons. The use of this didactical approach is common in secondary and undergraduate level (Lautesse et al., 2015) and has been suggested by other researchers as well (e.g., Weis & Wynands, 2003; Ayene et al., 2011). However, this study's literature review showed that the use of such approach is controversial: on one hand researchers argue that analogies with classical physics should be avoided as they delay students' contact with quantum phenomena (Ireson, 1999; Greca & Freire, 2003; Lautesse et al., 2015); on the other hand, researchers claim that such analogies facilitate interpretation, reduce abstractness and increase motivation (Didiş et al., 2014; Michelini et al., 2016).

Conceptual change seemed to be partially promoted by teachers and school books. The identified strategies which promote conceptual change included classroom and group discussions, exercises, demonstrations of experiments, use of simulations, images of experimental outcomes, videos, and contextualization using applications and historical background. The use of experiments, simulations, videos, applications, and historical context have also been advised by other authors (e.g., McKagan et al., 2008; Bungum et al., 2015; Krijtenburg-Lewerissa et al., 2017; Van den Berg et al., 2018). However, this study presented two limitations which might influence these findings about conceptual change. First, the teacher interviews were conducted with teachers who were involved with projects in quantum mechanics education at the University of Twente. Therefore, these teachers could have had more access to other didactical approaches and resources compared to other teachers. Additionally, the participants' presence in such educational projects might also suggest that they are more interested in how to improve their own practices than other teachers. Second, this study could not make a proper analysis of how metaconceptual analysis, models, and contexts were used during teachers' instruction about the wave-particle duality, because these strategies were not addressed during the interviews.

7.2 Student Understanding

Based on the results from the national exams and post-test, students' knowledge about the concepts within the wave-particle duality scope ranged from insufficient to good. More specifically, the results from the national exams and post-test suggested that students have the most difficulties with interpreting how the de Broglie wavelength influences the wave behaviour of (quantum) objects and the interference pattern formed by these objects. Vokos et al. (2000) reported the same difficulty in their study with undergraduate students. Additionally, the analysis of the post-test and pilot test showed the occurrence of the misconception that electrons move along definite (and sometimes sinusoidal) paths, which was also reported by Olsen (2002), McKagan et al. (2010), and Özcan (2015). Furthermore, Van den Berg et al. (2018) reported that the sample of students who participated in the post-test and interviews lacked knowledge of what differentiates classical waves and particles. Finally, the teacher interviews yielded that students might have difficulty with understanding the influence of voltage, the current versus voltage graph, and the change of electron's acceleration in the photoelectric effect, which is in line with McKagan et al.'s (2009) research.

The same limitation pointed out in section 7.1 applies to the sample of students analysed in this study. Because most of the participating students were pupils of teachers who were involved in Physics education programs at the University of Twente, this sample might have contained students who participated in more meaningful learning activities. Another limitation, which might have influenced the results from the post-test, is the fact that out of the 18 analysed multiple-choice questions, ten had only two alternatives, which increases the chances of students making correct guesses.

7.3 Shortcomings of Didactical Approach and Alternatives

The findings for the third sub question first suggested that teachers and school books did not sufficiently address a) the difference between photon flux and photon energy and b) students' prior knowledge about circuits and voltage. It could be argued that this happened because primarily the national curriculum addresses the photoelectric effect as a way to prove that electromagnetic radiation is quantized, which may imply that only a superficial knowledge of the effect is required. Therefore, teachers and authors of school books might believe that a deeper analysis of the effect is not necessary, and that is why the difference between photon flux and energy and students' prior knowledge about circuits and voltage seemed to not be sufficiently covered. However, the literature review suggested that addressing such difference and such prior knowledge is recommended when teaching the photoelectric effect. Therefore, it is advised for future researchers or practitioners to conduct a deeper analysis of the desired understanding of Dutch students about the photoelectric effect. Additionally, because such suggestion is solely based on input from teachers and on the analysis of school books and literature, an assessment of student understanding about the topics related to the photoelectric effect is recommended to offer better conclusions. Second, students' recurrent difficulties with a) the interpretation and application of de Broglie's wavelength and b) classical differences between waves and particles suggested that the current teaching practices of these specific topics might be insufficient. For the case of de Broglie's wavelength, one teacher pointed out that students might struggle with it because of the concept of momentum, which is not treated previously in classical mechanics classes and is introduced together with de Broglie's wavelength. Additionally, although the findings from literature have reported different solutions for these drawbacks, it should be considered that these shortcomings might be also related to the national curriculum's superficial approach to the topics, which was also suggested previously for the photoelectric effect. Therefore, the same suggestion for future researchers or practitioners to conduct a deeper analysis of the desired student understanding about the photoelectric effect could be extended for the de Broglie wavelength and for classical waves and particles.

Finally, it was considered that the representation of the photon as a wave package or as a sinusoidal wave in some school books might confuse students and strengthen the misconception that the representation is the photon's trajectory. This was also suggested by McKagan et al. (2010) and Özcan (2015), but no suggestions to address this misconception were found. Although this study advised teachers and authors of school books to clarify the difference between the photon's trajectory and representation when depicting wave packets, more research about how to address this misconception is recommended.

7.4 RECOMMENDATIONS FOR RESEARCH

This study has conducted an analysis of the Dutch context, which is the first of three phases of design-based research. However, the analysis conducted in this study included a sample of teachers who were involved with projects in quantum mechanics education, and a sample of students from some of these same teachers. Therefore, an analysis similar to the one conducted in this study should also be performed with a broader and preferably random sample of Dutch students and teachers. Additionally, the literature review in this study pointed out controversial opinions regarding the use of classical analogies when teaching quantum mechanics. Although the current didactical approach to the wave-particle duality used by Dutch books makes use of such analogies, such controversy could be firstly investigated through a meta-analysis, and later be tested with students.

This study also indicated the occurrence of drawbacks in teacher's practices and school books. It was suggested that certain concepts within the instruction of the photoelectric effect have not been sufficiently addressed by teachers and school books. However, because this claim is based on the input of teachers and school books, it is recommended to thoroughly investigate the knowledge of Dutch students about the photoelectric effect and its related concepts. In addition, students' recurrent difficulties with de Broglie's wavelength and classical differences between waves and particles suggested that teaching strategies of these topics also need improvement. Therefore, section 7.3 suggested future researchers or practitioners to conduct a deeper analysis of the desired student understanding about the photoelectric effect, de Broglie wavelength, and classical waves and particles.

7.5 IMPLICATIONS FOR PRACTICE

This research reported different didactical strategies to support students in the process of conceptual change when learning about the wave-particle duality. High school and university teachers, as well as developers of instructional books, could benefit from the strategies, best practices, and literature reported in this study. Furthermore, the insights in students' understanding and misconceptions might be useful to these practitioners as well. That is because these insights might help practitioners to identify such difficulties in their own students and address the misconceptions in a more appropriate way.

7.6 CONCLUDING REMARKS

The present study offered insights into the Dutch didactical approach to the wave-particle duality in secondary schools and how it promotes conceptual change. The results comprise the current practices from teachers, approaches from school books, insights from literature, and remarks on students' understanding about the wave-particle duality. These results revealed deficiencies in the analysed educational practices and provided suggestions on how to resolve them. Although several aspects were not covered in depth, this study provided further input for future researches about quantum mechanics instruction in Dutch secondary schools. Additionally, the results also aid teachers and developers of instructional materials, who can find in this study a compilation of best practices, students' (mis)conceptions, and suggestions for improving the instruction on the wave-particle duality. In that way, future students can benefit from an education on quantum mechanics which is not only effective, but also as fascinating as quantum mechanics itself.

8 REFERENCE LIST

Ayene, M., Kriek, J., & Damtie, B. (2011). Wave-particle duality and uncertainty principle: Phenomeno-graphic categories of description of tertiary physics students' depictions. *Physical Review Special Topics - Physics Education Research, 7*(2), 1-13. doi: 10.1103/PhysRevSTPER.7.020113

Asikainen, M. A. & Hirvonen, P. E. (2009). A study of pre- and inservice physics teachers' understanding of photoelectric phenomenon as part of the development of a research-based quantum physics course. *American Journal of Physics 77*, 658-666. Doi: 10.1119/1.3129093

Barab, S., & Squire, K. (2004). Design-based research: Putting a stake in the ground. *The Journal of the Learning Sciences*, *13*(1), 1-14. doi:10.1207/s15327809jls1301_1

Baser, M. (2006). Fostering conceptual change by cognitive conflict based instruction on students' understanding of heat and temperature concepts. *Eurasia Journal of Mathematics, Science and Technology Education, 2*(2), 97-114. doi: 10.12973/ejmste/75458

Biezeveld, H., Mathot, L. & Brouwer R. (2014) *Stevin Natuurkunde.* Hoorn, the Netherlands: Hoogland & van Klaveren.

Bouwens, R., Doorschot, P., van Reisen, J. & Vennix, A. (2012) *Overal Natuurkunde*. Groningen, the Netherlands: Noordhoff Uitgevers B. V.

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. *Nordic Studies in Science Education, 11*(2), 153-168. doi: 10.5617/nordina.2043

Carlson, S. E., Seipel, B., & McMaster, K. (2014). Development of a new reading comprehension assessment: Identifying comprehension differences among readers. *Learning and Individual Differences, 32*, 40-53. doi:10.1016/j.lindif.2014.03.003

Center for Curriculum Development (2005). *Doing Science: The Process of Scientific Inquiry*. Colorado Springs, CO: BSCS.

Choudhary, R. K., Foppoli, A., Kaur, T., Blair, D. G., Zadnik, M., & Meagher, R. (2018). Can a short intervention focused on gravitational waves and quantum physics improve students' understanding and attitude? *Physics Education, 53*, 1-16. doi:10.1088/1361-6552/aae26a

Cito (2016). Toets en Item Analyse VWO natuurkunde 2016 tijdvak 1 [Data file]. Retrieved from: https://www.cito.nl/onderwijs/voortgezet-onderwijs/centrale-examens-voortgezet-onderwijs/examenmateriaal-om-te-oefenen/vwo-2016/vwo-2016-tv1

Cito (2017). Toets en Item Analyse VWO natuurkunde 2017 tijdvak 1 [Data file]. Retrieved from: https://www.cito.nl/onderwijs/voortgezet-onderwijs/centrale-examens-voortgezet-onderwijs/examenmateriaal-om-te-oefenen/vwo-2017/vwo-2017-tv1

Cito (2018). Toets en Item Analyse VWO natuurkunde 2018 tijdvak 1 [Data file]. Retrieved from: https://www.cito.nl/onderwijs/voortgezet-onderwijs/centrale-examens-voortgezet-onderwijs/examenmateriaal-om-te-oefenen/vwo-2018/vwo-2018-tv1

College voor Toetsen en Examens vwo, havo, vmbo (2017). *Natuurkunde VWO – Syllabus voor central examen 2019*. Retrieved from: https://www.examenblad.nl/examenstof/syllabus-2019-natuurkunde-vwo/2019/vwo/f=/natuurkunde_2_versie_vwo_2019.pdf

Creswell, J. (2002*). Educational research: Planning, conducting, and evaluating Quantitative and Qualitative research*. Upper Saddle River, NJ: Merrill Prentice Hall.

Dangur, V., Avargil, S., Peskin, U., & Dori, J. D. (2014). Learning quantum chemistry via a visualconceptual approach: students' bidirectional textual and visual understanding. *Chemistry Education Research and Practice, 15*, 297-310. doi: 10.1039/c4rp00025k

DeVellis, R. (2012). *Scale Development: Theory and Applications*. New York, NY: Sage Publications.

Didiş, N., Eryılmaz, A., & Erkoç, S. (2014). Investigating students' mental models about the quantization of light, energy, and angular momentum. *Physical Review Special Topics - Physics Education Research, 10*(2), 1-28. doi:10.1103/PhysRevSTPER.10.020127

Dimitrova, T. L. & Weis, A. (2008). The wave-particle duality of light: A demonstration experiment. *American Journal of Physics, 76*, 137-142. doi:10.1119/1.2815364

Dimitrova, T. L. & Weis, A. (2010). Single photon quantum erasing: a demonstration experiment. *European Journal of Physics, 31*, 625-637. doi: 10.1088/0143-0807/31/3/020

Ding, L., Chabay, R., Sherwood, B., Beichner, R. (2006). Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment. *Physical Review Physics Education Research, 2,* 1-7. doi:10.1103/PhysRevSTPER.2.010105

Duit, R. & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, *25*(6), 671-688. doi:10.1080/09500690305016

Eisberg, R., & Resnick, R. (1985). *Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles*. New York, NY: John Wiley & Sons.

Feynman, R. P., Leighton, R. B., & Sands, M. L. (1963). *The Feynman lectures on physics*. Reading, Mass: Addison-Wesley Pub. Co.

Flokstra, J., Groenewold, A., Hooyman, K., Kootwijk, C., Kortland, K., Over, P., & Siersma, P. (2015). *Newton Natuurkunde voor de bovenbouw*. Amersfoort, the Netherlands: ThiemeMeulenhoff bv.

Greca, I. M., & Freire, O. (2003). Does an Emphasis on the Concept of Quantum States Enhance Students' Understanding of QM? *Science and Education*, *12*(5-6), 541-557. doi:10.1023/A:1-02535609694

Heisenberg, W. (1930). *The Physical Principles of the Quantum Theory.* Chicago, IL: University of Chicago Press.

Herrington, J., McKenney, S., Reeves, T. & Oliver, R. (2007). Design-based research and doctoral students: Guidelines for preparing a dissertation proposal. In C. Montgomerie & J. Seale (Eds.), *Proceedings of World Conference on Educational Multimedia, Hypermedia and Telecommunications 2007* (pp. 4089-4097). Chesapeake, VA: AACE.

Hewson, P. & Hewson, M. A. (1984). The role of conceptual conflict in conceptual change and the design of science instruction. *Instructional Science*, *13*, 1-13.

Hubber, P. (2006). Year 12 Students' Mental Models of the Nature of Light. *Research in science Education, 36*, 419-439. doi: 10.1007/s11165-006-9013-x

IBM Corporation (2012). Example: Boxplot. Retrieved from: https://www.ibm.com/support/knowledgecenter/en/SS3RA7_15.0.0/com.ibm.spss.modeler.help/graphboard_creating_examples_boxplot.htm

Ireson, G. (1999). A multivariate analysis of undergraduate physics students' conceptions of quantum phenomena. *European Journal of Physics*, *20*(3), 193-199. doi:10.1088/0143-0807/20/3/309

Ireson, G. (2000). The quantum understanding of pre-university physics students. *Physics Education*, *35*(1), 15-21. doi:10.1088/0031-9120/35/1/302

Johnston, I. D., Crawford, K., & Fletcher P. R. (1998). Student difficulties in learning QM. *International Journal of Science Education*, *20*(4), 427-446. doi:10.1080/0950069980200404

Kaur, T., Blair, D., Moschilla, J., & Zadnik, M. (2017a). Teaching Einsteinian physics at schools: part 2, models and analogies for quantum physics. *Physics Education*, *52,* 1-12. doi: 10.1088/1361-6552/aa83e1

Kaur, T., Blair, D., Moschilla, J., Stannard, W., & Zadnik, M. (2017). Teaching Einsteinian physics at schools: part 3, review of research outcomes. *Physics Education*, *52,* 1-7. doi:10.1088/1361-6552/aa83dd

Knight, R. D. (2002). *Five Easy Lessons: Strategies for Successful Physics Teaching*. New York, NY: Pearson.

Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A., & Van Joolingen, W. R. (2017). Insights into teaching QM in secondary and lower undergraduate education. *Physical Review Physics Education Research*, *13*(1), 1-21. doi:10.1103/PhysRevPhysEducRes.13.010109

Lautesse, P., Valls, A. V., Ferlin, F., Héraud, J-L., & Chabot, H. (2015). Teaching Quantum Physics in Upper Secondary School in France: ‘Quanton’ Versus ‘Wave–Particle’ Duality, Two Approaches of the Problem of Reference. *Science & Education, 24,* 937-955. doi: 10.1007/s11191-015-9755-9

Leone, C. J. & Oberem, G. E. (2004). Towards understanding student conceptions of the photoelectric effect. *AIP Conference Proceedings, 720*(85). doi: 10.1063/1.1807260.

Lévy-Leblond, J. M. (1988). Neither waves, nor particles, but quantons. *Nature*, *334*(6177), 19–20.

Mannila, K., Koponen, I. T., & Niskanen, J. A. (2001). Building a picture of students' conceptions of wave- and particle-like properties of quantum entities. *European Journal of Physics*, *23*(1), 45-53. doi: 10.1088/0143-0807/23/1/307

Marshman, E. & Singh, C. (2016). Interactive tutorial to improve student understanding of single photon experiments involving a Mach–Zehnder interferometer. *European Journal of Physics, 37,* 1-22. doi:10.1088/0143-0807/37/2/024001

Masshadi, A., & Woolnough, B. (1999). Insights into students' understanding of quantum physics: visualizing quantum entities. European Journal of Physics, 20, 511-516. doi:10.1088/0143-0807/20/6/317/

McKagan, S. B., Perkins, K. K., Dubson, M., Malley, C., Reid, S., LeMaster, R., & Wieman, C. E. (2008). Developing and researching PhET simulations for teaching QM. *American Journal of Physics*, *76*(4), 406-417. doi:10.1119/1.2885199

McKagan, S. B., Handly, W., Perkins, K. K., & Wieman, C. E. (2009). A research-based curriculum for teaching the photoelectric effect. *American Journal of Physics, 77*(1), 87-94. doi:10.1119/1.2978181

McKagan, S. B., Perkins, K. K., & Wieman, C. E. (2010). Design and validation of the QM Conceptual Survey. *Physical Review Special Topics – Physics Education Research, 6*, 1-17. doi: 10.1103/PhysRevSTPER.6.020121

McKenney, S., & Reeves, T. (2012). *Conducting Educational Design Research*. Florence, KY: Routledge.

Michelini, M., Santi, L., & Stefanel, A. (2016). Teaching modern physics in secondary school. *Proceedings of Science, 224*, 1-10. doi:10.22323/1.224.0231

Müller, R., & Wiesner, H. (2002). Teaching QM on an introductory level. *American Journal of Physics*, *70*(3), 200-209. doi:10.1119/1.1435346

Oh, J. Y. (2011). Using an enhanced conflict map in the classroom (photoelectric effect) based on lakatosian heuristic principle strategies. *International Journal of Science and Mathematics Education, 9*(5), 1135-1166. doi:10.1007/s10763-010-9252-1

Olsen, R. (2002). Introducing QM in the upper secondary school: A study in Norway. *International Journal of Science Education, 24*(6), 565-574. doi:10.1080/09500690110073982

Özcan, Ö. (2015). Investigating students' mental models about the nature of light in different contexts. *European Journal of Physics, 36*(6), 1-16. doi:10.1088/0143-0807/36/6/065042

Shiland, T. W. (1997). Quantum Mechanics and Conceptual Change in High School Chemistry Textbooks. *Journal of Research in Science Teaching, 34*(5), 535-545. doi: 10.1002/(SICI)1098-2736(199705)-34:5<535::AID-TEA7>3.0.CO;2-R

Sokolowski, A. (2013). Teaching the photoelectric effect inductively. *Physics Education, 48*(1), 35-41. doi:10.1088/0031-9120/48/1/35

Steinberg, R. N. & Oberem, G. E. (2000). Research-based instructional software in modern physics. *Journal of Computers in Mathematics and Science Teaching*, *19*, 115–136.

Te Brinke, L., van den Broeck, T., Buil, S., Van den Heuvel, E., Hoekzma, D., Jordens, H., … Zuurbier, P. (2015). *Pulsar*. Groningen, the Netherlands: Noordhoff Uitgevers B. V.

Van Bemmel, H. & Koopman, L. (2012). *Nova Natuurkunde*. ‘s-Hertogenbosch, the Netherlands: Malmberg.

Van Dalen, B., Van Dongen, J., de Jong, R., Keurentjes, A., Nijhof, E.-J., & Vink, H. (2015). *Systematische Natuurkunde*. Amersfoort, the Netherlands: ThiemeMeulenhoff bv.

Van den Berg, E., Van Rossum, A., Grijsen, J., Pol, H., & Van der Veen, J. T. (2018). *Teaching particle-wave duality with double slit single photon interference in Dutch secondary schools*. Manuscript submitted for publication.

Vokos, S., Schaffer, P. S., Ambrose, B. S., & McDermott, L. C. (2000). Student understanding of the wave nature of matter: Diffraction and interference of particles. *American Journal of Physics, 68*(7), S42-S51. doi:10.1119/1.19519

Vosniadou, S. (1994). Capturing and Modelling the Process of Conceptual Change. *Learning and Instruction, 4*(1), 45-69. doi:10.1016/0959-4752(94)90018-3

Vosniadou, S., & Brewer, W. F. (1992). Mental Models of the Earth: A Study of Conceptual Change in Childhood. *Cognitive Psychology, 24*(4), 535-585. doi:10.1016/0010-0285(92)90018-W

Vosniadou, S., Ioannides, C., Dimitrakopoulou, A., & Papademetriou, E. (2001). Designing learning environments to promote conceptual change in science. *Learning and Instruction, 11*(4-5), 381-419. doi:10.1016/S0959-4752(00)00038-4

Vosniadou, S. & Skopeliti, I. (2014). Conceptual Change from the Framework Theory Side of the Fence. *Science & Education, 23,* 1427-1445. doi:10.1007/s11191-013-9640-3

Walker, J., Halliday, D., & Resnick, R. (2011). *Fundamentals of physics*. Hoboken, NJ: Wiley.

Weis, A. & Wynands, R. (2003). Three demonstration experiments on the wave and particle nature of light. *Physik und Didaktik in Schule und Hochschule*, *2*, 67-73.

Wuttiprom, S., Sharma, M. D., Johnston, I. D., Chitaree, R., & Soankwan, C. (2009). Development and Use of a Conceptual Survey in Introductory Quantum Physics. *International Journal of Science Education, 31*(5), 631–654. doi:10.1080/09500690701747226

9 APPENDICES

9.1 APPENDIX A. TEACHER INTERVIEW SCHEME

1. How many 50-minutes lessons do you need to teach: the Photoelectric effect, double-slit experiment, and the de Broglie wavelength?
2. How do you teach them? Could you please walk me through your lessons on these three topics?
3. For each topic: Do you use other resources, such as simulations, videos, experiments…? What are the main difficulties when teaching this topic? What are students' most common difficulties when learning this topic?
4. Do you perceive any factors that help you when teaching the wave-particle duality? E.g., are students motivated, do they find it interesting…?
5. What could be done to help teachers regarding the teaching of the wave-particle duality? E.g., more workshops, different materials, experiments…?

9.2 APPENDIX B. MULTIPLE-CHOICE POST-TEST

Test by Van den Berg et al. (2018).

MEERKEUZE VRAGEN kies uit de 2 (A of B), 3 (A, B, of C), of 4 (A, B, C, of D) alternatieven

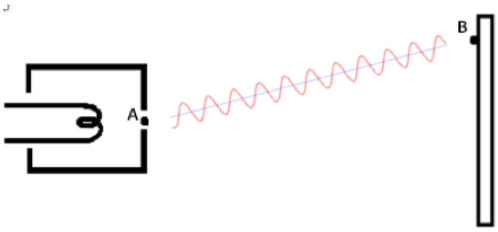
Opgaven 1-7: In sommige situaties domineert golfgedrag (antwoord A), in andere situaties deeltjesgedrag (antwoord B). Geef in de volgende situaties steeds aan of golfgedrag (A) of deeltjes gedrag (B) domineert:

1.	Foto-elektrisch effect.	A	B
2.	Compton effect.	A	B
3.	Voortplanting van elektronen via een spleet naar een scherm.	A	B
4.	Absorptie en emissie van elektromagnetische straling.	A	B
5.	Alfadeeltjes die de kernkracht overwinnen en uitgezonden worden.	A	B
6.	Breking van licht van lucht naar water of omgekeerd.	A	B
7.	Absorptie van elektronen door een scherm	A	B

8. Een basketbal met een massa van 0,4 kg beweegt met een snelheid van 10 m/s. Waarom kunnen we geen golfeffecten waarnemen?
   A. De snelheid is te klein, bij 1000 m/s zien we mogelijk wel golfeffecten.
   B. De golflengte van de bal is te klein om waar te nemen.
   C. De bal is te licht, bij zwaardere objecten zijn golfeffecten van materie gemakkelijker waar te nemen.
   D. Een basketbal heeft geen golflengte, want het is een klassiek deeltje.

9. Een elektron en een proton bewegen voort met dezelfde snelheid. Wat kan je zeggen over hun deBroglie-golflengten λ_e en λ_p?
   A. $\lambda_p > \lambda_e$
   B. $\lambda_p < \lambda_e$
   C. $\lambda_p = \lambda_e$
   D. **Je kan niets zeggen over hun deBroglie-golflengten.**

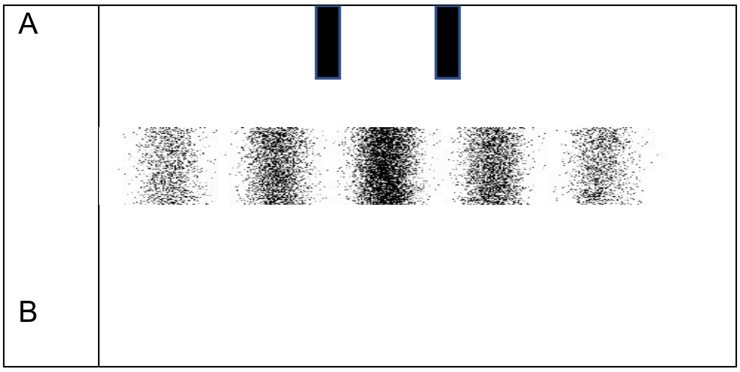
10. Een elektron wordt uitgezonden door een bron bij positie A, na verloop van tijd wordt het elektron waargenomen op een detectiescherm op positie B, zoals weergegeven in de onderstaande tekening. Hoe is het elektron van positie A naar positie B gegaan?



A. In een rechte lijn (zoals het blauwe, rechte pad)
B. Over een sinusvormige pad (zoals het rode, golvende pad)
C. Dat is niet te zeggen

Opgaven 11-15

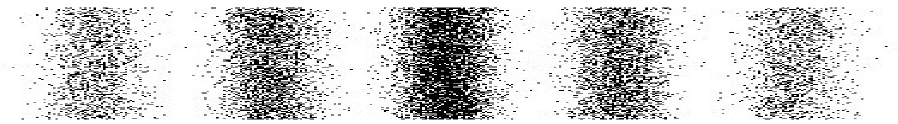
We laten materie of licht door een dubbele spleet gaan en zien op een scherm erachter figuur A of figuur B als uitkomst. De afmetingen van de spleet zijn van dezelfde orde van grootte als de objecten of golflengte van licht die we erdoor schieten. Het gebiedje waar materie of licht terecht komt op het scherm wordt aangegeven in zwart. Er wordt alleen bij het scherm gemeten.



Geef aan (omcirkel) welk van bovenstaande patronen (A of B) het meest waarschijnlijk is in de volgende gevallen:

11. We beschijnen de dubbele spleet met laserlicht. A B
12. We schieten kleine verfballetje door de dubbel spleet. A B
13. We schieten kleine (1 mg) kogeltjes door de dubbelspleet. A B
14. We schieten protonen door de dubbelspleet. A B
15. We schieten C_{60} moleculen (nano-afmetingen) door de dubbelspleet. A B

Opgaven 16 -20: Een onderzoeker voert het dubbelspleetexperiment uit. Eerst schiet hij een bundel elektronen op de dubbele spleet en kijkt hij waar deze op het scherm terechtkomen. Er ontstaat een interferentiepatroon zoals hieronder is weergegeven.



Kies voor opgave 16 – 19 steeds uit de volgende antwoorden:

A. Niets
B. De minima/maxima komen dichter bij elkaar liggen
C. De minima/maxima komen verder uit elkaar te liggen
D. Het interferentiepatroon verdwijnt, er ontstaan twee maxima recht achter de spleten

16. Wat verandert er aan het interferentiepatroon als de onderzoeker nu de elektronen sneller laat gaan? A B C D
17. Wat verandert er aan het interferentiepatroon als de onderzoeker de elektronen vervangt door deeltjes met een iets grotere massa en gelijke snelheid? A B C D
18. Wat verandert er aan het uiteindelijke interferentiepatroon als de onderzoeker de elektronen vervolgens één-voor-één door de dubbele spleet laat gaan in plaats van heel veel elektronen tegelijk? A B C D
19. Opnieuw worden elektronen één-voor-één door de dubbelspleet geschoten maar nu plaatst de onderzoeker een detector bij een van de spleten om te zien door welke spleet het elektron gaat. Wat verandert er? A B C D
20. Geef een korte uitleg voor je antwoord op vraag 19.

____

____

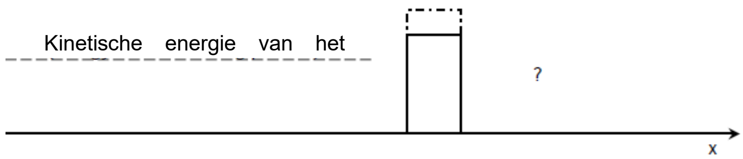
Tunneling

21. Een elektron tunnelt van links naar rechts door de onderstaande barrière:

Wat kan je zeggen over de verhouding van de kinetische energie van dit deeltje voor en na het tunnelen?

A. $E_{voor} > E_{na}$
B. $E_{voor} = E_{na}$
C. $1E_{voor} < E_{na}$

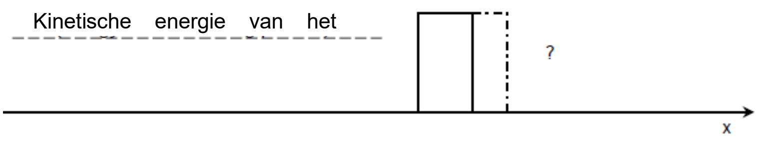
22. Een deeltje met een bepaalde energietoestand heeft kans om door een barrière te tunnelen. Dan wordt de barrière hoger gemaakt. Wat is het effect van het verhogen van



de barrière?

A. De kinetische energie van het doorgelaten deeltje wordt hierdoor kleiner.
B. De kans op tunneling wordt hierdoor kleiner.
C. A en B zijn allebei waar.
D. Geen van bovenstaande antwoorden is waar.

23. Een deeltje met een bepaalde energietoestand heeft kans om door een barrière te tunnelen. Dan wordt de barrière breder gemaakt. Wat is het effect van het verbreden van



de barrière?

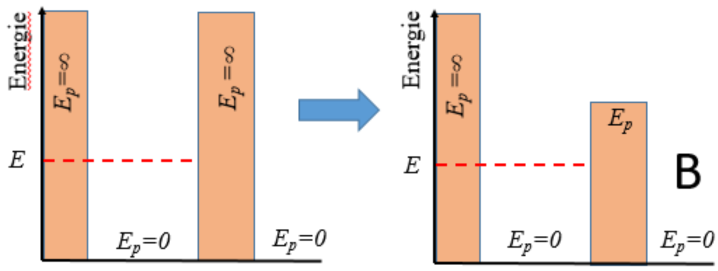
A. De energie van het doorgelaten deeltje wordt hierdoor kleiner.

B. De kans op tunneling wordt hierdoor kleiner.

C. A en B zijn allebei waar.

D. Geen van bovenstaande antwoorden is waar.

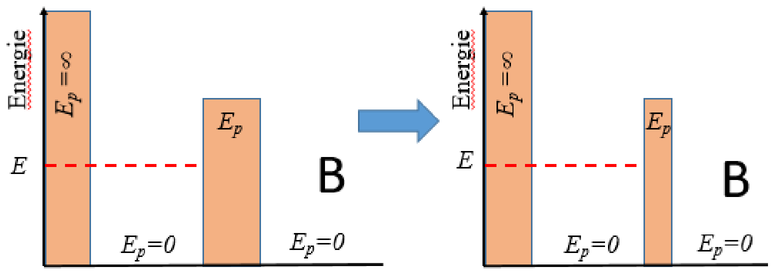
24. Een kwantum-deeltje-in -doos heeft kinetische energie E. De rechter energie barrière wordt verlaagd van oneindig naar $E_p > E$. Is er een kans om het deeltje in gebied B aan te treffen?



A. Nee, want $E<E_p$

B. Ja

25. Zelfde situatie als vorige vraag. Wat gebeurt er met de kans om het deeltje in gebied B aan te treffen als de barrière smaller wordt gemaakt?



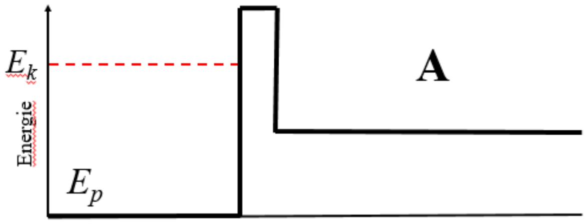
A. Kans neemt af

B. Kans blijft gelijk

C. Kans neemt toe

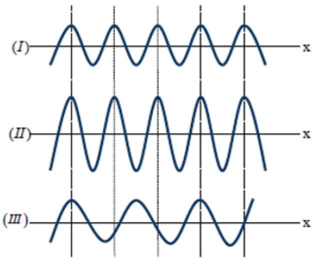
D. De kans blijft 0

26. Een kwantumdeeltje met kinetische energie E_k bevindt zich op tijdstip t_1 links van een energie barrière. Een tijdje later, op tijdstip t_2, wordt het deeltje gemeten aan de rechterkant in gebied **A**. Wat kun je zeggen over de verhouding van de *kinetische* energie van het deeltje op t_1 en t_2?



A. $E_k(t_1) > E_k(t_2)$
B. $E_k(t_1) = E_k(t_2)$
C. $E_k(t_1) < E_k(t_2)$

27. Drie elektronen bewegen in dezelfde richting. Hieronder zie je de deBroglie-golven behorend bij deze drie elektronen:



Hoe verhouden de snelheden van deze elektronen (I, II en III) zich tot elkaar?

A. $v_{II} > v_I > v_{III}$
B. $v_I = v_{II} > v_{III}$
C. $v_{II} > v_I = v_{III}$
D. $v_I = v_{II} = v_{III}$

KORTE UITLEGVRAGEN

28. Leg uit wat een golf is. Geef ook een voorbeeld. ______________________________
29. Leg uit wat een deeltje is. Geef ook een voorbeeld.

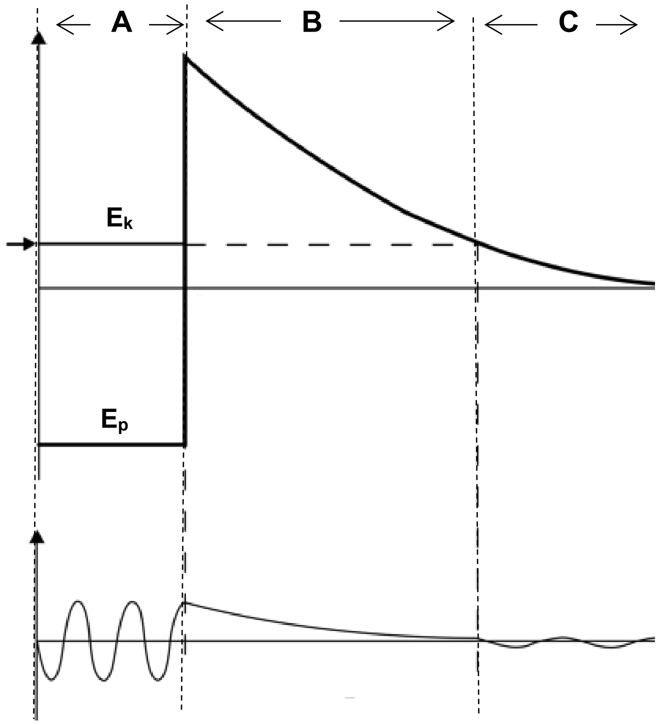
____

30. Wat zijn de belangrijkste verschillen tussen een golf en een deeltje?

____

____

31. In het bovenste deel van onderstaande figuur zie je de potentiële (E_p) en kinetische (E_k) energie van een kerndeeltje in een Uraniumkern, in het onderste deel van de figuur zie je de golffunctie van hetzelfde kerndeeltje.



Arno, Bram en Carla hebben een discussie over de energie van dit kerndeeltje en de kans om het kerndeeltje in de regio's A, B en C aan te treffen. Ze doen de volgende uitspraken:

a. Arno zegt dat het deeltje zich alleen in regio A kan bevinden,
b. Bram zegt dat het kerndeeltje alleen naar regio B of C kan gaan, als zijn (kinetische) energie tijdelijk hoger wordt dan de energie van de potentiaalbarrière,
c. Carla zegt dat de kinetische energie van het kerndeeltje kleiner is in regio C dan in regio A.

Geef voor een ieder (Arno, Bram en Carla) aan of hij of zij gelijk heeft. Geef bij elk antwoord een korte uitleg. Hierbij kun je gebruik maken van de volgende begrippen: *Amplitude, frequentie, waarschijnlijkheid, kinetische energie* en *potentiële energie*.

____

____

____

____

32. Stel we hebben een kern van een ander radioactief element X met een vrijwel gelijke barrière grafiek als in vraag 34, maar een hogere kinetische energie van het alfadeeltje in de kern. Wat is juist?
    A. De halfwaardetijd van element X is groter dan van Uranium.
    B. De halfwaardetijd van element X is kleiner dan van Uranium.
    C. De halfwaarde tijd van element X is gelijk aan die van Uranium.

    Beargumenteer je antwoord.

____

____

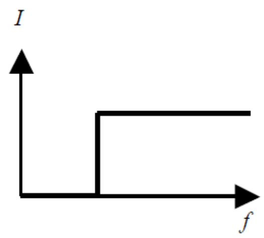
9.3 APPENDIX C. PRE- AND POST-TEST AND ACTIVITY USED IN THE PILOT TEST.

9.3.1 PRE- AND POST- TEST.

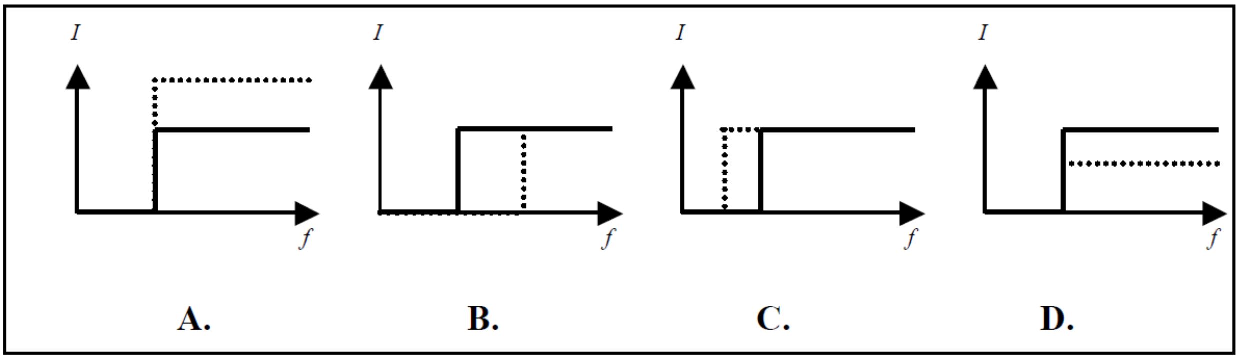
The results of this test will be used for research purposes only. They will not affect your grades in any way.

Circle or fill in the answers you think are correct. If you do not know the answer to a question, try your best guess. Please, do not leave questions unanswered.

Questions 1 and 2) In a hypothetical experiment to demonstrate the photoelectric effect, a light source of variable frequency is shone on a photosensitive surface. Ejected photoelectrons are collected by an anode. A graph of the resulting **photocurrent** *(I)* as a function of **frequency** *(f)* looks like this:



Select your answers to the questions below from these graphs:



Which graph would be **most appropriate** when:

1) The intensity of the light is increased? _______

2) The work function of the surface is increased? _______

Question 3) In an experiment to demonstrate the photoelectric effect, the following observations are made:

- Light of high frequency shone onto some materials causes electrons to be ejected;
- If the frequency of light is decreased (with any amplitude), a threshold frequency is observed.

These observations are believed to support a particle theory of light, rather than a wave theory. Which one of the statements is **inconsistent** with the previous observations?

A) In a particle theory, the ejection of electrons is explained by collisions with photons. Each collision can give a single electron enough energy to escape.
B) In a wave theory, the ejection of electrons is explained by the electromagnetic wave causing electrons to vibrate, which gives some electrons enough energy to escape.
C) In a particle theory, the threshold frequency is explained because at very low frequencies the photons have low energies and no individual photon has enough energy to eject and electron.
D) In a wave theory, the threshold frequency is explained because a very low frequency wave could not make the electrons vibrate energetically enough, even at high amplitudes.

Question 4) True or False: In the absence of external forces, electrons move along sinusoidal paths.

A) True
B) False

Question 5) An electron and a neutron are moving at the same speed. How do their wavelengths λ compare?

A) $\lambda_{neutron} > \lambda_{electron}$
B) $\lambda_{neutron} < \lambda_{electron}$
C) $\lambda_{neutron} = \lambda_{electron}$

Question 6-8) For each question, choose the most appropriate answer from A through C:

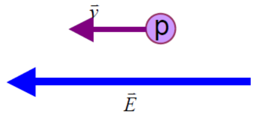
A) The de Broglie wavelength of the particle will increase.

B) The de Broglie wavelength of the particle will decrease.

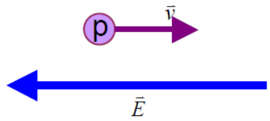
C) The de Broglie wavelength of the particle will remain the same.

What will happen when a positively charged particle is:

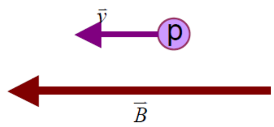
6) moving through an <u>electric field</u>, in the same direction as the field, and therefore is speeding up? _______



7) moving through an <u>electric field</u>, in the opposite direction as the field, and is therefore slowing down? _______

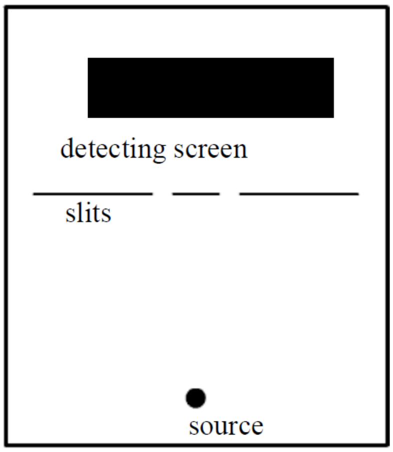


8) moving through a <u>magnetic field</u>, in the same direction as the field, and its velocity is therefore constant? _______



Questions 9-13) The following experiments are conducted:

- In the first one, *electrons* are travelling from a source to a detecting screen, through a double slit.
- In the second one, *light* is travelling from a source to a photographic plate, through a double slit.
- In the third one, *marbles* are travelling from a source to an array of collecting bins, through two slit-like openings, side by side.



The right-hand figure shows the experimental set-up and the figures below show roughly the possible patterns which could be detected on the various screens.

Possible patterns (not to scale)

A. **B.** **C.**

A through C represent some patterns which might be observed. If you think none is appropriate, answer D.

Which pattern would you expect to observe when:

9) light passes through the double slit? _____

10) marbles pass through the double opening? _____

11) electrons pass through the double slit? _____

12) light passes through the apparatus when one of the slits is covered? _____

13) electrons pass through the apparatus when one of the slits is covered? _____

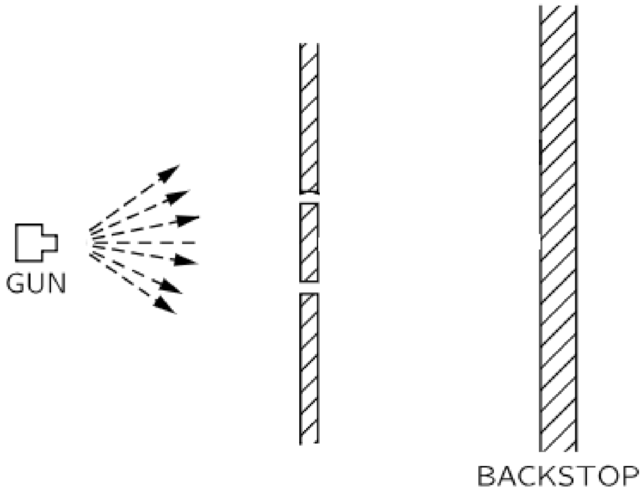
9.4 In-class Activity.

The figures in this activity were taken from Feynman et al. (1963).

Experiment 1 - Double-slit and bullets

Please **discuss with your pair** about the behaviour of the bullets in this experiment. Use these questions to help you: How do the bullets move? What happens after they pass through the slits? (you do not have to write down an answer to these questions, only discuss them).

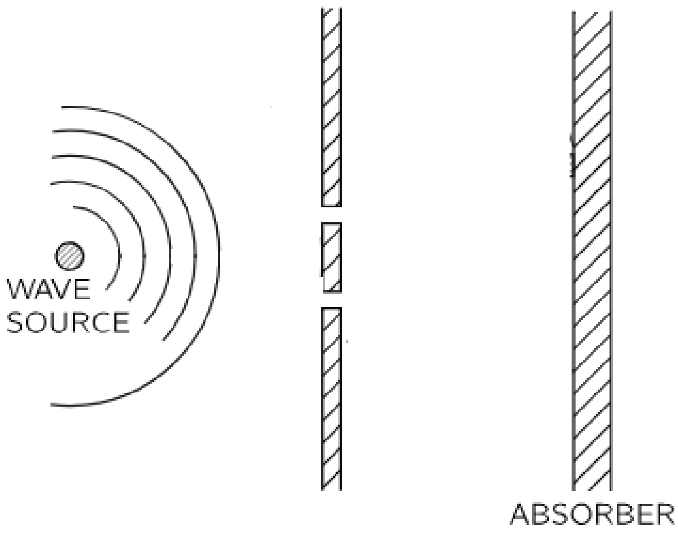
Then, **draw on the backstop below** where you think the bullets would be stored.



Experiment 2 - Double-slit and water waves

Please **discuss with your pair** about the behaviour of the water waves in this experiment. Use these questions to help you: How do the waves move? What happens after they pass through the slits? (you do not have to write down an answer to these questions, only discuss them).

Then, **draw on the absorber below** how the amplitudes of the wave would be recorded by the detector in the absorber.



Experiment 3 - Double-slit and electrons

Please **discuss with your pair** about the behaviour of the electrons in this experiment. Use these questions to help you: How do the electrons move? What happens after they pass through the slits? (you do not have to write down an answer to these questions, only discuss them).

Then, **draw on the image below:**

1) The **behaviour** of the electrons **between the gun and the double slit;**

2) The **behaviour** of the electrons **between the double slit and the backstop;**

3) **Where in the backstop** would the electrons be stored.