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Key topics for quantum mechanics at secondary schools: a Delphi study into expert opinions

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ABSTRACT
This article describes a Delphi study aiming to investigate which quantum mechanics topics experts consider to be important to teach at the secondary level, and what arguments these experts give. A series of three questionnaires was administered to experts in the fields of quantum physics, mathematics, chemistry and biophysics ($n = 17$, 12, 11 for the first, second, and third questionnaires, respectively; the number of participants changed due to attrition). Several experts from this group ($n = 9$) were also interviewed. Results show that there is consensus on the topics considered to be important, i.e. duality, wave functions and atoms. Experts mainly based their topic ranking on relations between concepts, and on what quantum mechanics topics they consider to be fundamental. The topics that were considered less important were often described as too difficult or too complex.

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Introduction

Quantum mechanics is an important theory underpinning many areas of physics research, and plays a vital role in current technologies, such as medical imaging, nanoscience, laser physics and semiconductor technology. Quantum mechanics is also the foundation for several emergent technologies including quantum computers, quantum encryption and quantum teleportation. Quantum mechanics has been an important part of university physics education for a long time. Traditionally, it has primarily been taught in a rather formal and mathematical way (Johnston, Crawford, & Fletcher, 1998). Because of its theoretical and practical importance, quantum mechanics has found its way into the secondary school curriculum. Because the mathematical skills of secondary school students fall short of what is needed for a more formal, mathematical approach, this introduction of quantum mechanics in secondary schools often aims for qualitative understanding. Such a qualitative approach has become more and more important in physics education (Duit & Treagust, 2003; Redish, 1994), and the currently available visualisation techniques and multimedia have made it possible to introduce complex and abstract topics, such as

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quantum mechanics, in a more qualitative way (Kohnle, 2015; Singh, Belloni, & Christian, 2006; Trindade, Fiolhais, & Almeida, 2002). Quantum mechanics has been part of the upper secondary school curriculum in England (Mashhadi & Woolnough, 1999; Ogborn, 2006), Germany (Müller & Wiesner, 2002), Italy (Michelini, Ragazzon, Santi, & Stefanel, 2000, 2007) and the USA (Escalada, Rebello, & Zollman, 2004) for several years. More recently, quantum mechanics has been incorporated in the Dutch (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo, 2010; Hoekzema, van den Berg, Schooten, & van Dijk, 2007), Norwegian (Henriksen et al., 2014) and French (Lautesse, Vila Valls, Ferlin, Héraud, & Chabot, 2015) secondary school curricula.

Because quantum mechanics entails fundamental changes in the way the physical world is understood and conflicts with students' classical thinking (Karakostas & Hadzidaki, 2005), there is need for a research-based instructional strategy that aims for conceptual understanding, comprising the key topics of quantum mechanics (Krijtenburg-Lewerissa, Pol, Brinkman, & van Joolingen, 2017). However, there is no generally accepted opinion on what to teach in introductory quantum mechanics courses, and a wide variety of topics has been explored for use in a more conceptual approach to quantum mechanics. Examples of introductory topics that have been used at the secondary and undergraduate level are: wave–particle duality (Lautesse et al., 2015; Müller & Wiesner, 2002; Olsen, 2002), entangled photons (Henriksen et al., 2014), the infinite potential well (Hoekzema et al., 2007), quantum states (Michelini, Ragazzon, Santi, & Stefanel, 2004, 2015), spin (Dür & Heusler, 2014), and path integrals (Malgieri, Onorato, & De Ambrosis, 2017). While the primary reason for using these topics in most cases was to find a way to introduce quantum mechanics conceptually and visually, the researchers also presented various other arguments for the use of these approaches, ranging from their importance for the understanding of quantum mechanics to their relevance for our daily life.

The current study was conducted in the context of the introduction of quantum mechanics in Dutch secondary schools, which is the result of a curriculum reform (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo, 2010) aiming to promote scientific literacy. More specifically, this reformed curriculum aims to promote scientific skills and thinking, and to give a good perspective on the relevance of science and technology in society and the interaction between scientific research and technological developments. This is in line with the current emphasis on scientific literacy and STS (science-technology-society) in secondary education (Aikenhead, 2005; Bybee, McCrae, & Laurie, 2009; DeBoer, 2000; Millar, 2006). Although many researchers investigating introductory topics for quantum mechanics often presume the chosen topics to be relevant, little systematic research has been done into the topics' relevance for development of a good perspective regarding the importance of quantum mechanics for science, technology and society.

According to Duit, Gropengießer, Kattmann, Komorek, and Parchmann (2012), investigation of the relevance of a topic is important in science curriculum design. They proposed the Model of Educational Reconstruction, which consists of three components: (1) clarification and analysis of science content, (2) research on teaching and learning, and (3) design and evaluation. The first step of this model includes the analysis of key topics, related applications, and their scientific and social implications. This knowledge, together with knowledge of students' preconceptions and difficulties, can provide a basis for the design of a curriculum (McDermott, 2001). Based on the Model of Educational Reconstruction, Laherto (2010) investigated the educational relevance of nanoscience in secondary education, and Sakhnini and Blonder (2015) used a Delphi study among teachers and experts in nanotechnology to explore key topics in nanoscience for secondary schools.

Following this lead, it becomes clear that research is needed on which subtopics of quantum mechanics are relevant for promoting scientific literacy. This article describes our investigation using the Delphi method to determine which subtopics of quantum mechanics (which will be called 'topics' throughout this article) experts consider relevant for teaching in secondary education, and an analysis of the experts' arguments. In contrast to the study by Sakhnini and Blonder (2015), we only consulted experts in quantum physics and related research fields, because teachers do not necessarily understand quantum mechanical topics (Asikainen & Hirvonen, 2009, 2014), and experts have more experience with scientific research and technological developments related to quantum mechanics.

Background

In this section, an overview is given of the existing research into what topics are important when teaching introductory quantum mechanics. The phrase 'scientific literacy' is also clarified, and a framework of goals for scientific literacy is presented. This framework gives an overview of all goals that can be addressed in curricula aiming for scientific literacy.

Research into key topics of quantum mechanics

In previous research, there have been attempts to determine which topics form the basis for quantum mechanics and should be taught in introductory courses. At the undergraduate level, McKagan, Perkins, and Wieman (2010) asked eight faculty members which three quantum mechanics topics were most important, in order to determine which concepts should be addressed in their concept test. These interviews resulted in a list of nine topics, but there was high variability in the faculty members' choices; the researchers noted that this list does not reflect a general opinion. Additionally, Wuttiprom, Sharma, Johnston, Chitaree, and Soankwan (2009) analysed university syllabi and consulted experts from a single university to identify important topics for their concept test. This yielded two main topics for their concept test: quantisation and uncertainty.

Both investigations were aiming at determining the important topics of quantum mechanics at the undergraduate level, but although the topics obtained were useful for developing concept tests, these topics did not reflect a general opinion. Furthermore, no emphasis was put on the educational relevance of these topics for promoting scientific literacy, which is an important reason for introducing quantum mechanics at the secondary level.

Scientific literacy

As we intend later to analyse reasons given for including aspects of QM in the school curriculum against the aim of promoting scientific literacy, it is necessary to consider in a little more depth what the term 'scientific literacy' might mean. Scientific literacy is a very popular term in contemporary science education. It refers to 'the public understanding of science' and has been used in very different contexts and perspectives, varying from awareness of the impact of science on society to understanding of the scientific method. Holbrook and Rannikmae (2009) stated that there are two points of view on scientific literacy; the first view regards scientific literacy as the fundamental ideas in science that everyone should know, while the second view considers scientific literacy to be the science-related knowledge and skills needed to function in society. For PISA 2006, a model was developed that included both points of view (OECD, 2006). In this model, scientific literacy is based on scientific knowledge, scientific competencies and attitude towards science. Scientific knowledge is defined as both knowledge *of* science and knowledge *about* science, scientific competencies are defined as the ability to identify scientific issues, explain phenomena scientifically and use scientific evidence, and attitude towards science is defined as a person's interest in and support for scientific inquiry. Table 1 gives an overview of the categories used in PISA 2006, which was used as the basis for the PISA assessment in 2006, 2009 and 2012.

For a broader overview of existing goals for scientific literacy, these three categories can be complemented with the different aspects of scientific literacy described by DeBoer (2000). In his review he showed that, historically, there have been nine separate goals that are related to scientific literacy:

1. Teaching and learning about science as a cultural force in the modern world;
2. Preparation for the world of work;
3. Teaching and learning about science that has direct application to everyday living;
4. Teaching students to be informed citizens;
5. Learning about science as a particular way of examining the natural world;
6. Understanding reports and discussions of science that appear in the popular media;
7. Learning about science for its aesthetic appeal;
8. Preparing citizens who are sympathetic to science;
9. Understanding the nature and importance of technology and the relationship between technology and science.

These goals, together with the goals developed for PISA 2006, give a good overview of the different aspects of scientific literacy, and can be used to analyse argumentation, development processes and curricula. Table 2 shows a framework based on the descriptions of aspects of scientific literacy by DeBoer (2000) and PISA (OECD, 2006). To create this framework, first the nine goals given by DeBoer were placed within the three main categories of PISA 2006. Then the descriptions in DeBoer (2000) and PISA 2006 were compared for overlaps. For the categories 'knowledge' and 'attitude', the goals mentioned by DeBoer (2000) were extensions refining the descriptions from PISA (OECD, 2006); therefore, five goals were placed beside the goals of PISA.

Table 1. The categorisation used by PISA 2006 (OECD, 2006).

Goals for scientific literacy		
Competencies	Knowledge	Attitude
Identifying scientific issues	Scientific concepts	Interest in science
Explaining phenomena scientifically	The nature of science	Support for scientific inquiry
Using scientific evidence		Responsibility towards resources and environments

Table 2. Overview of aspects of scientific literacy guiding the topic choice for a curriculum, based on OECD (2006) and DeBoer (2000).

	Aspects of scientific literacy	Description
Competencies	Identifying scientific issues	Enabling students to recognise scientific issues and key features of scientific investigation
	Explaining phenomena scientifically	Enabling students to apply scientific knowledge in a given situation, to interpret scientific phenomena and identify appropriate descriptions
	Being able to make informed decisions	Enabling student to identify, interpret and be critical about scientific evidence-related evidence in media and conversations, reflect on the societal implications and make informed decisions
Knowledge	Understanding of scientific concepts	Promoting knowledge and understanding of topic content and relations between topics which are considered fundamental for students to know
	Understanding the nature of science	Promoting the understanding of scientific inquiry, data analysis, scientific explanations and models, and limitations of scientific knowledge
	Knowledge of science as a cultural force	Promoting knowledge of the historical development of scientific ideas, current understandings in science and their effect on science and society
	Knowledge for future careers	Promoting knowledge about and needed for future careers or further studies in science
	Understanding the relationship between science and technology	Promoting understanding of the nature of technology and the interdependence of science and technology (e.g. technological applications based on scientific inquiry).
Attitude	Interest in science	Promoting students' engagement in science-related social issues, their willingness to acquire scientific knowledge and skills, and their consideration of science-related careers
	Support for scientific inquiry	Promoting students' appreciation of and support for scientific inquiry
	Responsibility towards resources and environments	Promoting students' sense of personal responsibility for maintaining a sustainable environment, and willingness to take action
	Seeing the influence of science in everyday life	Prompting students to see the applications of science in their daily lives, and have a more informed and intelligent experience with the natural world
	Appreciating the beauty of science	Promoting students' appreciation of and fascination for the natural world

Purpose of this study

For a systematic investigation into which quantum topics are considered important for secondary education for scientific literacy, a Delphi study was conducted among a number of Dutch experts in quantum physics and related research fields. The selection procedure and the expertise of the selected experts will be specified in the next section of this article. This research method is intended to find consensus among experts concerning the topics that are important within the Dutch context, in which the curriculum renewal aims to create a better understanding of the importance of science for research and technology. Therefore, the questions under investigation are:

1. In the view of experts, what are the essential topics that secondary school students need to learn in order to develop an appropriate image of quantum mechanics in terms of research, developments and applications?
2. What are the experts' arguments for choosing their topics and to what extent do these arguments correspond to the different categories and sub-goals for scientific literacy?

This article will give an overview of the research conducted and its results. First, the Delphi approach and the research method used in this study are explained, then an overview is given of the results and conclusions.

Method

The Delphi method is a systematic approach to researching expert opinions on a specific topic (Clayton, 1997; Okoli & Pawlowski, 2004) and is often used to exchange knowledge between experts, determine expert opinions, determine the assumptions leading to those opinions, find consensus, and create rankings of different alternatives.

This method uses multiple consecutive questionnaires in which experts can give their opinion together with their arguments. In this succession of questionnaires, the experts' previously stated opinions and arguments are summarised and shared. Before completing the current iteration of the questionnaire, the experts can read the different arguments and reconsider their previous response. This method is useful when opinions or predictions are being investigated, and when it is difficult to bring the experts together in person. It has the advantage that experts participate anonymously, which prevents group behaviour and places emphasis on their reasoning. The Delphi technique can be used for curriculum design (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; Reeves & Jauch, 1978; Rossouw, Hacker, & de Vries, 2010); in this specific study, it was used to explore expert opinions on the key topics of quantum mechanics that are suitable for developing the scientific literacy of secondary school students. Figure 1 shows the procedure used in this research, which is based on the approach described by Okoli and Pawlowski (2004).

Expert selection

First, we identified relevant research fields and institutions, related to research and technologies in which quantum mechanics plays a crucial role. Forty-eight experts from various Dutch universities and institutions were then invited to participate in this Delphi study. The responding experts were researchers in the field of quantum physics, quantum mathematics, quantum chemistry and biophysics, from eight different

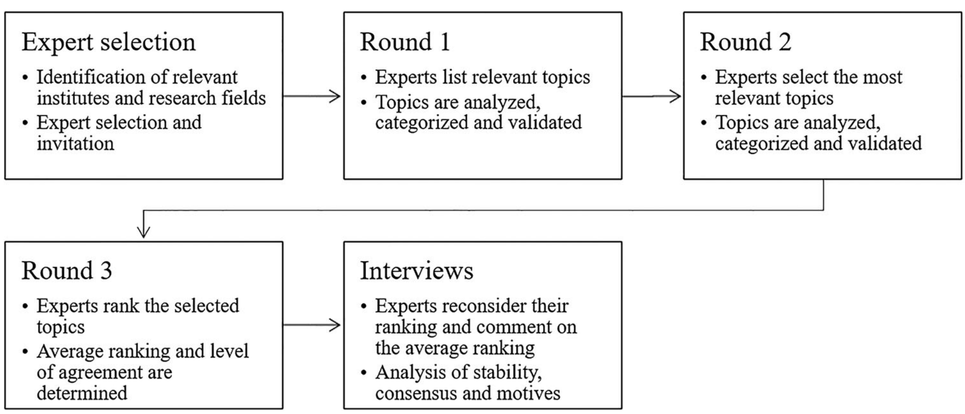

Figure 1. The procedure followed in this Delphi study.

Table 3. Overview of the experts' research fields.

Research field	Expertise	Number of experts round 1	Number of experts round 2	Number of experts round 3	Number of expert interviews
Physics	High energy physics	2	1	1	1
	Quantum physics	3	3	2	2
	Solid-state physics	2	2	2	2
	Particle physics	2	0	1	1
Mathematics	Quantum mathematics	2	2	1	1
Chemistry	Solid-state chemistry	1	1	1	1
	Polymer chemistry	1	0	0	0
Biophysics	Nano photonics	2	2	2	1
	Biophysics	2	1	1	0
Total		17	12	11	9

universities. There was some attrition; the number of respondents in every round, categorised for the various research fields, is listed in Table 3.

First round

In the first round, the responding experts completed an online survey. The experts were asked which quantum mechanics topics they considered necessary to address in order to give secondary school students an appropriate image of current research and technological developments. To ensure a connection with current technologies and everyday life, which is important for the Dutch curriculum renewal, we chose to explicitly ask for applications. Therefore, the experts were asked to give at least five concepts and five applications, together with a description of the chosen topics (concepts and applications), and an explanation of their topic choice. The responses were analysed and the coding was checked for interrater reliability ($\kappa = 0.81$) with the help of the second author. Then the codes were categorised in cooperation with the third author, who is an expert in quantum physics and nanophysics. The experts' descriptions of the topics (concepts and applications) in each category and the experts' argumentations were summarised and the third author verified that the content was correct and corresponded with the experts' responses.

Second round

The second round also involved an online survey. In this survey, the experts of round one were asked to read the summary of the descriptions of the topics in each category and the summary of the experts' arguments. Then the respondents were asked for each topic if they considered it considered appropriate for secondary schools. The responses were analysed and categorised. Topics that were chosen by at least two-thirds of the experts were used for the following round, together with a list of the experts' arguments.

Third round

In the third round, the experts were asked to rank the selected topics, from indispensable to dispensable. For this, the experts had to place each topic in one of the following categories: (1) indispensable, (2) desirable, (3) optional, or (4) dispensable. The number of topics that could be placed within each category was limited. Within each category the topics were also ranked. The experts' categorisation was analysed, the rankings were used to create an average ranking, and consensus was analysed using Kendall's *w*.

Interviews

After the third round, interviews were conducted with several experts of the previous round to investigate the stability and validity of the experts' rankings, and to explore the reasoning and arguments on which the experts based their rankings. Transcripts of the interviews were analysed for stability, consensus and the underlying arguments. For stability and consensus, the experts were asked if they would alter something in their individual ranking and if they agreed with the final ranking. For the analysis of the arguments, the arguments were compared to the goals of scientific literacy in Table 2.

Results

First round

In round one, the experts stated which five quantum mechanics topics and applications they considered necessary for scientific literacy. Their responses were analysed, which resulted in a list of 89 topics, accompanied by explanations and arguments. The 11 topics listed in Table 4 were proposed by more than 50% of the experts. Because of the large number of topics, the 89 topics were categorised. In cooperation with the third author, an expert in quantum physics, the topics with related content were grouped. Seven groups were formed: wave–particle duality, wave functions, atoms, subatomic particles, materials, nonlocality and history. These categories are shown in Table 5, together with a reduced summary of the experts' descriptions. Table 5 also shows the different aspects of scientific literacy which were used in the experts' arguments.

Second round

In the second round, the experts selected topics from the list of 89 topics and explained their choices, after reading the corresponding explanations and summaries. Analysis of their responses showed that experts often labelled the topics as concepts, examples and applications. This led to a change in categorisation, in the analysis and following

Table 4. The most frequently proposed quantum mechanics topics in round one (top 11 out of 89 items, $N = 17$).

Topic	Number of experts
Spectral lines	16
Tunnelling	12
Photoelectric effect	11
Probability	11
Wave–particle duality	11
Double slit experiment	10
Energy levels and quantisation	10
Hydrogen atom	10
Heisenberg's uncertainty principle	9
Lasers	9
Wave function	9

Table 5. The categories resulting from analysing the experts' responses in round 1.

Categories	Experts' descriptions	Experts' arguments
Wave–particle duality	A particle shows both wave and particle behaviour. Single photon detection, the double slit experiment, the photoelectric effect, and the delayed choice experiment can illustrate this dual behaviour	Understanding of scientific concepts, understanding the relation between science and technology, seeing the influence of science in everyday life
Wave functions	A particle can be described by a wave function Ψ. The wave function can be a superposition of all possible wave functions. Ψ^2 is a measure of the particle's probability distribution	Understanding of scientific concepts, understanding the nature of science, understanding the relation between science and technology, identifying and explaining scientific issues, seeing the influence of science in everyday life, appreciating the beauty of science
Atoms	Electron's energy levels are quantised, which determines spectra and colours of atoms. Quantisation can be explained with Bohr's atomic model, and with the quantum atomic model. The electron configuration also depends on Pauli's exclusion principle	Understanding of scientific concepts, knowing science as a cultural force, understanding the relation between science and technology, seeing the influence of science in everyday life
Subatomic particles	Subatomic particles have properties, which can be described by quantum numbers. An important property is spin, which is important in magnetism and electron configuration, and can be illustrated by the Stern–Gerlach experiment	Understanding of scientific concepts, understanding the relation between science and technology
Materials	Molecules and metals have energy bands and band gaps, which determine material properties such as strength, structure, colour and resistance	Understanding of scientific concepts, knowing science as a cultural force, understanding the relation between science and technology, seeing the influence of science in everyday life
Nonlocality	QM violates local realism, which can be illustrated by the fact that entangled particles, when separated, cannot be described independently. This phenomenon shows the counterintuitive character of QM and is important in information technologies	Understanding of scientific concepts, understanding the relation between science and technology
History	QM plays an important role in the history of science and was one of the most important scientific revolutions of the twentieth century. It shows the nature of science	Knowing science as a cultural force, understanding the relation between science and technology, seeing the influence of science in everyday life

rounds the topics were divided into three groups; concepts, examples and applications. The experts' arguments also showed some topics coincided; these topics were merged into one topic, which resulted in a list of 84 topics. Table 6 shows these topics, together with the number of experts who selected the listed concepts, examples and applications. From this table can be seen that the applications were considered less important for secondary education than the concepts and examples. The 37 topics chosen by at least eight experts were used in round three.

Third round

In the third round of the Delphi study, the experts placed the 37 remaining topics into categories going from indispensable to dispensable and ranked them, after reading the experts' arguments used in round two. Kendall's w was used to determine the average ranking, which is shown in Table 7, and the level of agreement on this ranking. The experts showed moderate to strong agreement (Kraska-Miller, 2013; Schmidt, 1997) on the exact ranking of the concepts ($w = 0.61$) and examples ($w = 0.58$), but there was no significant agreement on which applications should be treated in secondary schools to

Table 6. Overview of the topics selected by the experts in round two ($N = 12$), together with the number of experts who wanted the topics to be taught at secondary schools.

Concepts	Number of experts	Examples	Number of experts	Applications	Number of experts
'de Broglie' wavelength	12	Double slit experiment	12	Solar cells	9
Particle behaviour of light	12	Atomic structure	12	Quantum information	9
Probability	12	Periodic table	12	STM	8
Energy levels and quantisation	12	Spectral lines	12	Lasers	8
Wave–particle duality	11	Photoelectric effect	11	LEDs	8
Wave function	11	Hydrogen atom	10	Quantum computers	8
Heisenberg's uncertainty principle	11	Bohr's atomic model	10	Single photon detection	7
Tunnelling	11	Colour	10	Spectral analysis of stars	7
Pauli's exclusion principle	11	Magnetism	10	Transistors	7
Spin	11	Orbitals	9	Quantum cryptography	7
Momentum	10	Material properties	9	Atomic clock	6
Fermions and bosons	10	1D infinite well	8	Fluorescence	6
Superposition	8	Radioactive decay	8	Neon lamps	6
Time evolution	8	Schrödinger's cat	8	MRI	6
Quantum numbers	8	Bonds	8	IC's and chips	6
QM at a macroscopic scale	7	Semi-conduction	8	Quantum teleportation	6
Entanglement	7	Conduction	7	GPS	5
History of QM	7	Heat radiation	7	Microwaves	5
Complementarity	6	Polarisation	6	CCD	5
Zero point energy	6	Energy bands	6	Giant magneto resistance	5
Subatomic particles	6	Super-conduction	6	CT scan	4
Standard model	6	Chemical reactions	5	SEM	3
Bohr versus Einstein	6	Stern–Gerlach experiment	5	Random generators	3
Foundations of QM	6	Delayed choice Experiment	4	Single molecule microscopy	3
Schrödinger equation	5	Crystal structures	4	Flash memory	3
Stationary states	5			Bennet–Brassard protocol	3
Measurement	5			PET scan	2
EPR paradox	5				
Development of atomic models	5				
Free vs. localised particle	4				
Locality and causality	3				
Bell's inequalities	3				

Table 7. Mean expert ranking in the third round ($N = 11$) on the importance of the selected quantum topics for the secondary school curriculum. Rank 1 is considered most important.

Rank	Concepts	Mean rank	Examples	Mean rank	Applications	Mean rank
1	Wave–particle duality	2.10	Double slit experiment	2.10	Solar cells	2.70
2	Particle behaviour of light	3.50	Spectral lines	4.20	STM	3.10
3	Wave function	4.20	Photoelectric effect	4.30	LEDs	3.60
4	De Broglie wavelength	4.60	Atomic structure	4.60	Lasers	3.70
5	Probability	4.80	1D infinite potential well	6.00	Quantum information	3.90
6	Energy levels and quantisation	6.80	Hydrogen atom	6.30	Quantum computers	4.00
7	Heisenberg's uncertainty principle	7.40	Periodic table	6.60		
8	Superposition	9.10	Bohr's atomic model	8.20		
9	Spin	9.40	Radioactive decay	9.40		
10	Tunnelling	9.70	Bonds	11.40		
11	Pauli principle	10.60	Orbitals	11.60		
12	Momentum	11.20	Magnetism	11.70		
13	Quantum numbers	11.50	Schrödinger's cat	12.20		
14	Fermions/bosons	11.70	Colour	12.20		
15	Time evolution	13.40	Material properties	12.40		
16			Semiconductors	12.80		

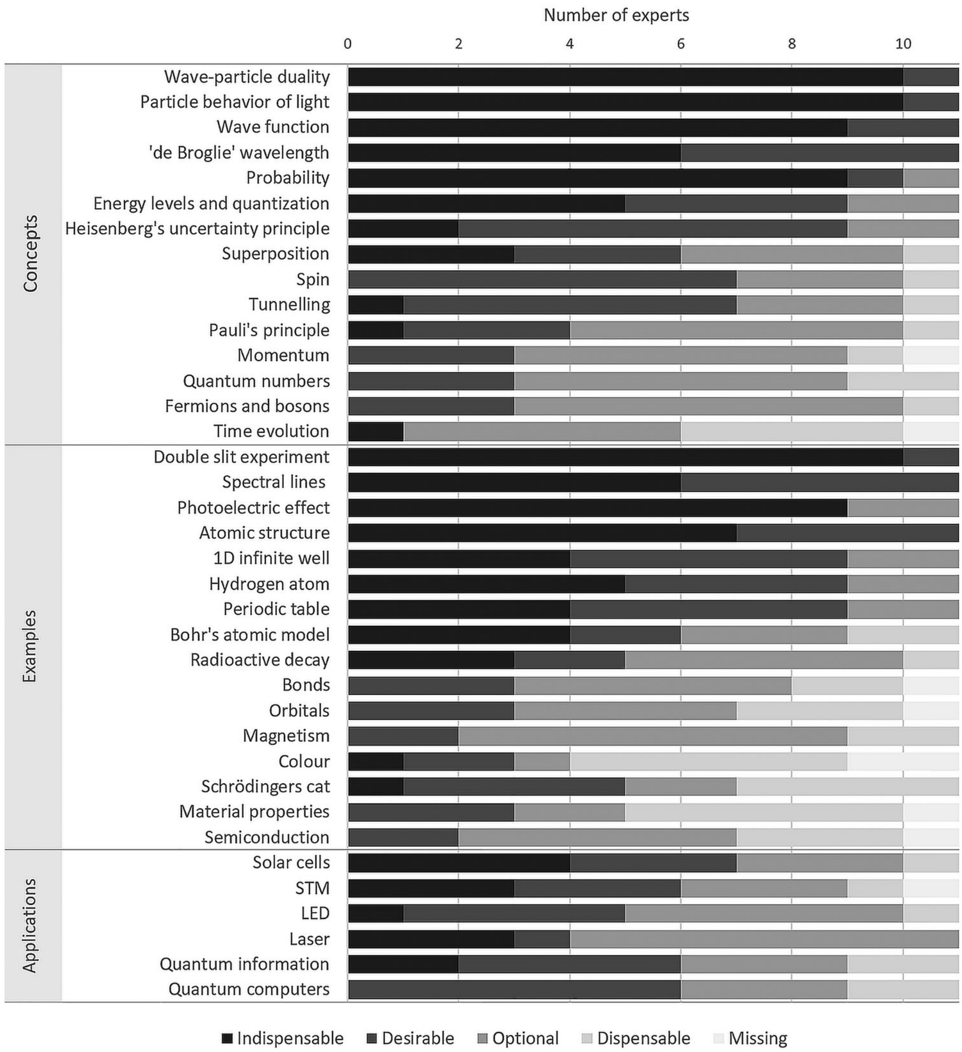

Figure 2. The number of experts in round three ($N = 11$) who considered the listed topics indispensable, desirable, optional or dispensable.

establish scientific literacy. The placement of the 37 topics within the four categories was also analysed. As can be seen in Figure 2, the first seven concepts and examples in Table 7 are considered indispensable or desirable by at least nine experts. Furthermore, none of the other experts considered these concepts and examples dispensable, which leads to the conclusion that there is a strong agreement on the importance of these 14 topics.

Interviews

After the third round, semi-structured interviews were conducted with nine experts from the previous round. The main objectives of the interviews were to investigate the stability of the experts' categorisations in the third round, the experts' level of agreement with the final rankings, and their underlying arguments.

To investigate the stability of the rankings, the experts were shown their own personal final rankings and were asked if there were topics they would change in rank or category. Seven experts proposed changes, but only two of these changes involved a change of category. These changes caused a slight change in the values shown in Figure 2 for superposition (a shift of from optional to indispensable) and the Pauli principle (a shift from dispensable to desirable). The changes also caused a slight change in the average ranking shown in Table 7 (spin and tunnelling are switched, and orbitals and bonds are switched). Still, these are minor changes and the ranking can be considered stable, especially the ranking of the topics which are considered indispensable.

The consensus was investigated by discussing the average ranking. The majority of the experts perceived the average ranking to be similar to their own ranking (six out of nine experts), especially the upper part of the ranking of concepts and examples.

> 'The first parts are almost exactly the same'

> 'They are a little … they are rather similar'

Two of the experts who did not mention that the average ranking was similar to their own ranking stated that they considered the average ranking sensible. The differences in ranking that were perceived as striking were mainly in the lower part:

> 'I think it is surprising that superposition is at position 8'

> 'The only thing that surprises me is the fact that Schrödinger's cat has a low position'

Only two topics from the upper part of the ranking were mentioned by an expert as showing a difference:

> ' … I ranked the photoelectric effect, I ranked it lower'

> 'I would not know what essential topics should be explained with the uncertainty principle … I don't think that it is essential'

The fact that the majority of the experts perceived the average ranking similar to their own ranking, especially the upper part of the ranking, demonstrates that there is a high level of agreement, especially for the topics that are considered essential and desirable. The level of agreement was also determined for the rankings based on the interviews ($w_{\text{concepts}} = 0.61$, $w_{\text{examples}} = 0.58$), and showed a moderate to strong agreement.

The arguments used by the experts were analysed using the goals for scientific literacy from Table 2 as codes. These codes were assigned to fragments in the transcripts, a fragment being a line of reasoning mainly addressing one single issue (e.g. a subtopic or category of quantum mechanics, a goal for scientific literacy or statement the expert wants to make). Table 8 gives an overview of the arguments used by the experts, together with the topics that were discussed. Since most experts did not distinguish between 'identifying scientific issues' and 'explaining phenomena scientifically', these two categories were merged into one category. The results showed that the experts based their rankings mainly on the understanding of scientific concepts, and that over 75% of the fragments are related to knowledge.

When looking to the arguments about understanding of scientific concepts in more detail, there were several underlying categories. Besides content reasoning based on

Table 8. The arguments regarding scientific literacy used by the experts ($N = 9$) during the interviews.

	Goals for scientific literacy	No. of experts	No. of fragments	Topics mentioned
Competencies	Identifying and explaining scientific issues	5	7	Heisenberg's uncertainty principle, energy levels and quantisation, Schrödinger's cat, quantum information, quantum computers
	Being able to make informed decisions	–	–	–
Knowledge	Understanding of scientific concepts	9	67	All
	Understanding the nature of science	3	4	Double slit, wave function
	Knowing science as a cultural force	4	4	Material properties
	Being aware of career opportunities	1	1	Quantum information, quantum computers
	The relationship between science and technology	2	2	Wave–particle duality, probability, semiconductors
Attitude	Interest in science	–	–	–
	Support for scientific inquiry	1	1	Quantum information, STM.
	Responsibility towards resources and environments	–	–	–
	Seeing the influence of science in everyday life	8	11	Wave–particle duality, 'de Broglie' wavelength, Heisenberg's uncertainty principle, quantisation and energy levels, tunnelling, atoms, 1D infinite potential well, radioactive decay, spin, fermions/bosons, material properties, lasers
	Appreciating the beauty of science	2	3	Wave–particle duality, spin, tunnelling, quantum information, quantum computers

what concepts the experts consider to be the fundamental concepts of quantum mechanics and the relation between these different concepts, experts also based their arguments on the conceptual complexity of the topic, and the extent to which a topic demystifies quantum mechanics. The complexity of the topic was addressed especially often (21 out of 67 fragments):

> 'I would like to introduce quantum information, but I think it is too abstract'

> 'I consider superposition to be a central element … but I do understand that it is too difficult to explain'

> 'Quantum computers … they are fascinating, but there is a lot of mathematics involved'

However, five of these experts also stated that students should have basic knowledge of complex topics in order to be able to interpret new developments presented in the media and distinguish fact from fiction in discussions. Some experts stated that you have to avoid the applications that cannot be explained to secondary school students, others stated you can refer to these applications, but should not try to explain them. This conflict between importance and difficulty may explain the lack of consensus for the applications, most of which are both complex and prominent in the media.

Eight of the experts used the argument that the chosen topics show students that quantum mechanics forms the basis for our everyday life:

> 'So everything, really everything is quantum'

> ' … they think it is fascinating, that something that fundamental, that it [radioactive decay] is a deep quantum mechanical phenomenon'

The experts stated that students should be aware that quantum mechanics is the foundation of everything we perceive, and that many technologies we use in our daily lives are based on quantum mechanics. During the interviews, the experts showed they were fascinated by the way quantum mechanics determines the natural world themselves and two experts explicitly stated that it is fascinating for students too. Other experts were not explicit, but used phrases that show they aim for more than being informed about quantum physics in our everyday life:

> 'as long as the message of quantum mechanics sinks in … that it is not a classical world, but a quantum world'

> 'But when you see that it [everyday life] is not at all self-evident, that a strange theory is needed to understand it … '

So, even though the goal 'appreciating the beauty of science' was not often mentioned specifically, this goal seems closely related to 'seeing the influence of science in everyday life'.

Other goals were mentioned less often, and the goals mentioned mainly focused on understanding and explaining of quantum mechanical concepts, but the understanding of physical models, the importance of quantum mechanics for technological developments and its impact on society were also mentioned. Even though the goals mentioned by the experts were mainly content based, Table 8 shows there are many topics of quantum mechanics considered appropriate for promoting scientific literacy; in particular, quantum information and wave–particle duality were mentioned often.

Conclusions

In this article, we presented an analysis of key quantum mechanics topics, which is the first step in developing a curriculum on quantum mechanics for the secondary level, based on an investigation of relevant topics, and students' preconceptions and difficulties. For this analysis we investigated: (1) which topics experts considered essential for obtaining an appropriate image of quantum mechanics in terms of research, developments and applications, and (2) what arguments experts used for choosing these key topics. In this section, we give an overview of the main conclusions that can be drawn based on the Delphi study and the interviews, together with recommendations for further research and curriculum development.

Key topics

In contrast to the results of McKagan et al. (2010), which showed no consensus on key topics, this study shows there is a moderate to strong agreement on what quantum mechanics topics are considered to be important. The Delphi study showed that the majority of the experts considered the following topics essential:

1. *Duality*: The wave–particle duality, the particle behaviour of light, the 'de Broglie' wavelength, Heisenberg's uncertainty principle, the double slit experiment and the photoelectric effect.
2. *Wave functions*: The wave function, probability and the 1D potential well.
3. *Atoms*: Energy levels, quantisation, atomic structure, spectral lines, the hydrogen atom and the periodic table.

These topics were considered important by a majority of the experts in rounds 2 and 3, and the interviews also showed that the experts considered the upper part of the average ranking similar to their personal ranking.

Arguments

The arguments used for the ranking were mainly based on knowledge, especially on 'the understanding of scientific concepts', for example, the relation between the different concepts and their position within quantum mechanics. This is in in accordance with the fact that the consulted experts were all academic scientists and researchers, who are more likely to embrace *wish-they-knew* and *need-to-know* science (Aikenhead, 2003; Stuckey, Hofstein, Mamlok-Naaman, & Eilks, 2013). The lack of addressing the other goals for scientific literacy may be partly due to the predominantly unstructured nature of the interviews, in which the different goals were not specifically mentioned. Moreover, the enquiry specifically emphasised research and technological developments, which is appropriate for the Dutch curriculum, but may have interfered with our focus on scientific literacy.

An important argument for finding a topic appropriate for secondary education was its complexity. Most topics that were described as too complex or abstract were considered less essential. Although the experts mainly reasoned about content knowledge, the goal of 'seeing the influence of science in everyday life' was also mentioned by the majority of the experts. Additionally, the interviews showed that there are various aspects of quantum mechanics that can be used to address the different goals for promoting scientific literacy.

Implications

The ranking of quantum mechanics topics found in this study is based on the opinions and expertise of academic scientists and researchers. These experts can be considered content experts, who have a good view of quantum mechanics and its position within the fields of research and development. Still, these experts are all part of a specific sub-group of academic scientists and researchers, which may have biased the outcomes; the results of this study are likely to be a sub-set of views on what students *need-to-know* and what we *wish-they-knew*. However, the knowledge of the general public, industry, policy-makers, and even secondary school teachers about quantum mechanics is rather limited, which makes it difficult to take their opinion into consideration without first teaching them the basics of quantum mechanics.

Since quantum mechanics is a rather new field for secondary school curriculum policy-makers and researchers in the Netherlands, this ranking provides a good starting point for the development of a research-based curriculum. Still, the ranking resulting from this study is rather unspecific, because the listed topics all consist of various subtopics and can be taught in many different ways. Also, the results of this study do not give insights into the experts' exact interpretation of the understanding of the chosen topics. For the development of a quantum mechanics curriculum, not only insights into what students should learn, but also knowledge of the feasibility of teaching these topics at secondary school level is needed. Therefore, there is a need for practice-based research into students' understanding of quantum mechanics, in which the feasibility of teaching the various subtopics of quantum mechanics to secondary school students is investigated. The knowledge of learning difficulties, underlying problems, and needs for prior knowledge obtained from this research into feasibility and students' learning difficulties can form the basis for the design of instructional materials.

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