



# Probing University Students' Pre-Knowledge in Quantum Physics with QPCS Survey

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## ABSTRACT

The study investigated the use of Quantum Physics Conceptual Survey (QPCS) in probing student understanding of quantum physics. Altogether 103 Finnish university students responded to QPCS. The mean scores of the student responses were calculated and the test was evaluated using common five indices: Item difficulty index, Item discrimination index, Item point biserial index, Kuder-Richardson Formula 21, and Ferguson's delta. The results show that QPCS is not well suitable for probing Finnish university students' understanding of basic ideas of quantum physics in its current form. Based on the calculated indices, QPCS was too difficult for the participating students as an introductory-level test. The discrimination ability of QPCS was also vague. There were numerous individual test items, which were both too difficult and poor discriminators. Particularly, the items of theme Waves and Particles seemed to be problematic because they required understanding of the Standard interpretation of quantum mechanics, which is not discussed in the Finnish upper secondary curriculum or in basic physics studies in the university. It seems that the QPCS may have potential as an instrument to probe Finnish students' understanding of quantum physics but only after some careful modifications.

**Keywords:** conceptual test, diagnostic test, QPCS, quantum physics, university students

## INTRODUCTION

In the history of physics, it took almost 30 years to develop the theories of quantum physics, but lectures of quantum physics often assume that students are able to grasp the basic ideas easily based on their upper secondary knowledge. The concepts of quantum physics are, however, abstract and counterintuitive, which makes them demanding to be understood profoundly (e.g. Singh, Belloni, & Christian, 2006, McKagan, & Wieman, 2006).

During last decades, the learning and teaching of quantum physics has received increasing interest among physics educators and physics education researchers. As a first step to develop quantum physics instruction has been developing conceptual tests which may be used to probe student understanding before and/or after instruction of quantum physics is given. Some promising tests have already been published for the undergraduate level.

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### **State of the literature**

- Diagnostic tests are widely used to probe student understanding in physics. There are validated tests for domains such as mechanics (FCI), electromagnetism (CSEM), and electricity (CSE) that can be used in different educational and cultural contexts.
- In quantum physics, the development of a suitable, generic diagnostic test is still ongoing. Some tests have been developed for different educational levels and for different purposes but the tests are mainly validated within the same culture and country.
- QPCS is a promising survey aimed at introductory level. It has been validated with Australian university students.

### **Contribution of this paper to the literature**

- In this study, QPCS is used and evaluated in Finnish context.
- The study gives information on the usability of QPCS in other cultural and educational context. QPCS is examined with the same indices than in the original study, therefore, the results help to validate the test further.
- The study also informs about the level of quantum understanding of Finnish university

Catoglu and Robinett (2001) introduced a test called Quantum Physics Visualization Instrument (QPVI) that concentrates on students' conceptual and visual understanding of quantum mechanics at intermediate or advanced level. The test covers topics such as the probabilistic interpretation of the Schrödinger equation, the properties of solutions of the Schrödinger equation, the uncertainty principle, and the Pauli Exclusion Principle. Almost all the test questions include visualizations. The QPVI consists of 25 questions and a student selects the correct response of given five choices. In addition, a student is asked to explain his/her answers with one or two sentences after each question. A student's confidence about his/her answer is probed with a four-scale very certain, somewhat certain, somewhat uncertain, very uncertain. The QVMI has been used to find out the development of quantum understanding of senior physics majors only a few studies, such as Belloni and Christian (2003).

Another test that is suitable for probing student quantum understanding at university level is Quantum Mechanics Conceptual Survey (QMCS) (McKagan & Wieman, 2006; McKagan, Perkins, & Wieman, 2010). It consists of 12 questions addressing the essential topics of quantum mechanics, such as wave function and probability, wave-particle duality, Schrödinger equation, the quantization of states, uncertainty principle, superposition, operators and observables, and tunnelling. The developer's original idea was to construct a test applicable at all the levels of university education to evaluate different instructional ideas used in the teaching of quantum mechanics. However, they realised that it is not possible to construct a test suitable for all educational levels because there is no consensus about the basic concepts of quantum mechanics. QMCS is the most suitable for sophomore-

level as a post-test (McKagan, Perkins, & Wieman, 2010), which makes its usability rather limited.

Chapman, Hunt and Walet (2013) recently described the development of a Quantum Mechanics Diagnostic Questionnaire for investigating third-year students' quantum understanding after their first quantum physics course. The questionnaire included both self-evaluation questions concerning confidence and understanding and questions about mathematics, time-dependence, and general topics of quantum physics. Unfortunately, the final version of the questionnaire has not been published yet.

It seems that there is only one diagnostic test available for the introductory quantum physics at the moment. Wuttiptom, Sharma and Johnston (2009) designed and validated a conceptual test entitled Quantum Physics Conceptual Survey (QPCS) that concentrates on conceptual understanding of the basic quantum concepts. The test covers five themes: photoelectric effect, waves and particles, de Broglie wavelength, double-slit interference, and uncertainty principle. The authors have used QPCS to discover quantum understanding of first and second year university students in Australia. Even if the test has not been used in other educational contexts, it seemed to be the most suitable for our teaching and research purposes.

In this study, the use of QPCS instrument in the Finnish university context was examined. The aim was to evaluate the use of QPCS in probing quantum understanding of Finnish university students in the beginning of an introductory level course on quantum physics. The following research questions were phrased:

1. What is the level of Finnish students' pre-knowledge in quantum physics in the beginning of the introductory course on quantum physics measured with QPCS?
2. How valid is QPCS in the context of Finnish university physics education?

The first research question is answered by examining the mean scores and the theme scores of the QPCS of the Finnish sample. The second question related to the validity of the QPCS instrument is responded by calculating five different indices commonly used in evaluating conceptual tests (Ding, Chabay, Sherwood, & Beichner, 2006; Ishimoto, Thornton, & Sokoloff, 2014). Wuttiptom, Sharma and Johnston (2009) have also used these indices in their study to validate QPCS.

By answering these questions, the applicability of QPCS in a new cultural context is evaluated, which has theoretical relevance. The practical relevance of this study is achieved if the results favour the use of QPCS as a diagnostic test in the beginning of Finnish quantum physics courses.

## METHOD

The Quantum Physics Conceptual Survey (QPCS) developed by Wuttiptom, Sharma and Johnston (2009) consists of 25 multiple-choice items that belong to five themes, see [Table 1](#). The developers of the test have chosen these themes because they consider them as the

**Table 1.** Items of QPCS in five themes

	<b>Theme</b>	<b>Items (questions)</b>
1	Photoelectric effect	1-3
2	Waves and particles	4-7
3	de Broglie wavelength	8-14
4	Double-slit interference	15-19
5	Uncertainty principle	20-25

basic concepts of quantum physics. The author and her colleagues translated the survey into Finnish for the purposes of this research. They all are experts in the field of physics education research and have already translated several conceptual tests into Finnish. The author performed the first translation and some occurring issues were discussed together to find the best possible way to formulate test items. Furthermore, a third physics education researcher evaluated the readability of the test.

Participants of the quantum physics course responded to the questionnaire in the beginning of the course in quantum physics. **Table 2** gives basic information about the participants. The participants were mostly majors of mathematics, physics, and chemistry. A majority of the participants were third-year students. All the students had taken the basic physics courses and traditional intermediate university courses in thermal physics, electromagnetism, and optics. The response time was approximately 30 minutes. The test was voluntary but all the participants attending the opening lecture of the course responded the test. A 5% bonus for the course exam was given to participating students.

Because the number of participants in the course varies between 35-45 students, the data was collected during three years (2012, 2013, and 2014) to get enough data for statistical analyses. The number of students who responded to the test was 29 in the first course, 37 in the second, and 37 in the third course, 103 in total.

The questionnaire data was analysed with the key of correct responses that was received from the developers of the test. First, it was ensured that there is no statistical difference between the mean scores of the three different course samples so treating them

**Table 2.** Basic information about the participants (N=103) of the quantum physics course

<b>Major subject</b>	<b>Teacher education program</b>	<b>Subject specialist program*</b>	<b>Other**</b>
Mathematics	40	9	
Physics	22	8	
Chemistry	4	8	
Other	4		8

\*Students qualify as a mathematician, physicist, or chemist

\*\*Some students studied in open university or in-service training

together is valid ( $df=2$ ,  $F=0.140$ ,  $p=.334$ ). This also showed that cohorts are similar in respect of their pre-knowledge, and therefore, the test really measures student understanding of quantum physics. Then, the mean scores of correct responses in each item and in five themes were calculated.

Furthermore, five indices were calculated to evaluate the difficulty and the discrimination of the test following Classical test theory (e.g. Engelhardt, 2009) commonly used in studies of this kind that aim to evaluate the reliability, validity, and discrimination a conceptual test (Ding, Chabay, Sherwood, & Beichner, 2006; Wuttiptom, Sharma, & Johnston, 2009; Ishimoto, Thornton, & Sokoloff, 2014). These indices were Item difficulty index (DiffI), Item discrimination index (DiscI), Item point biserial index (BisI), Ferguson's delta, and Kuder-Richardson Formula 21. With the help of an item analysis, it can be examined do the items function well or do they need to be reworked or edited (Engelhardt, 2009). These indices are introduced in detail in results section.

## RESULTS

### QPCS mean scores

The analysis of the data revealed that the mean score of the Finnish sample is  $45.9 \pm 13.6\%$ . It is almost identical with the mean score reported by the developers of the test. Wuttiptom, Sharma and Johnston (2009) studied first-year Australian physics students ( $N=95$ ) in the beginning of a technology-oriented introductory physics course in the study and received means score  $45.9 \pm 12.8\%$ . However, a theme-based examination revealed some similarities and differences between the Finnish and the original student samples, as can be seen from [Table 3](#).

**Table 3.** The mean scores and standard deviations by themes of the Finnish sample compared with the results of the original sample, derived from Wuttiptom, Sharma and Johnston (2009)

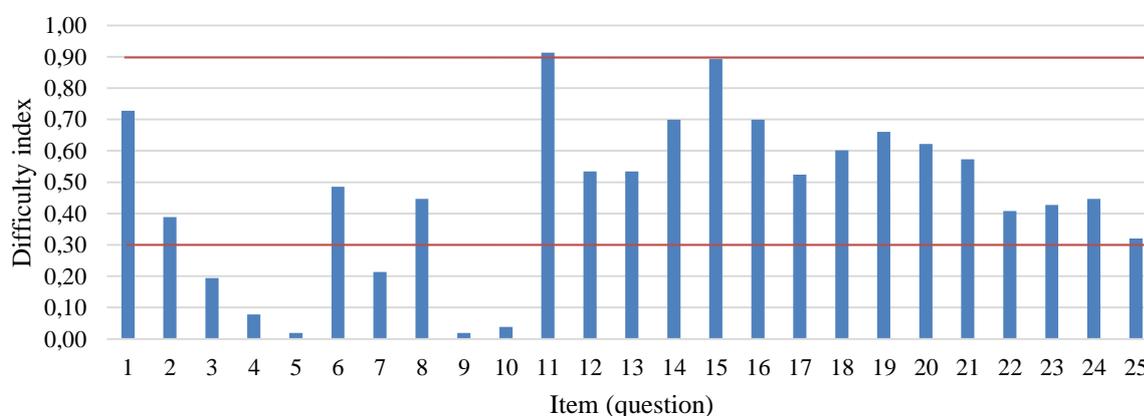
Theme	Mean score and standard deviation	
	Finnish sample	Original sample
<b>Overall</b>	45.9±13.6	45.9±12.8
1 Photoelectric effect	40	50
2 Waves and particles	20	23
3 de Broglie wavelength	43	54
4 Double-slit interference	63	56
5 Uncertainty principle	42	38

The mean scores were low in both the student groups but the comparison of mean scores shows that our results are well in line with the results by Wuttiptom, Sharma and Johnston (2009). The trend is similar in both student groups: same themes were easy or difficult for students. The students were the most familiar with the theme Double-slit interference and theme Waves and particles was the most difficult one for them.

### Item Difficulty

Item difficulty was evaluated by using Item difficulty index, which measures the proportion of students' correct responses item by item (Wuttiptom, Sharma, & Johnston, 2009; Ding, Chabay, Sherwood, & Beichner, 2006). The values are between 0 and 1. Values close to 1 mean that most of the respondents answered the item correctly and 0 that most respondents did not answer correctly (Engelhardt, 2009). Value  $<0.3$  is considered to mean that the item is too difficult whilst value  $>0.9$  indicates that the item is too easy. The optimum value of the mean of the indices is 0.5. The mean of the Item difficulty indices of the sample is near the optimum value, IDiff = 0.46~0.5.

As can be seen from **Figure 1**, there are six too difficult items for the Finnish students. The most worrying observation is that three of these items (4, 5, and 7, see Appendix) belong to the theme Waves and particles, which makes the validity of the whole theme questionable. Based on the Item difficulty index, there is only one item of this theme (item 6) is suitable for probing the level of student pre-knowledge. The effect of items 9, 10, and 11 is not so significant because that particular theme, de Broglie wavelength, also includes four other items that were acceptable based on the item difficulty index.



**Figure 1.** QPCS item difficulty indices based on a sample of 103 Finnish students' pre-test results. Optimum values lie between 0.3 and 0.9 (marked with red lines)

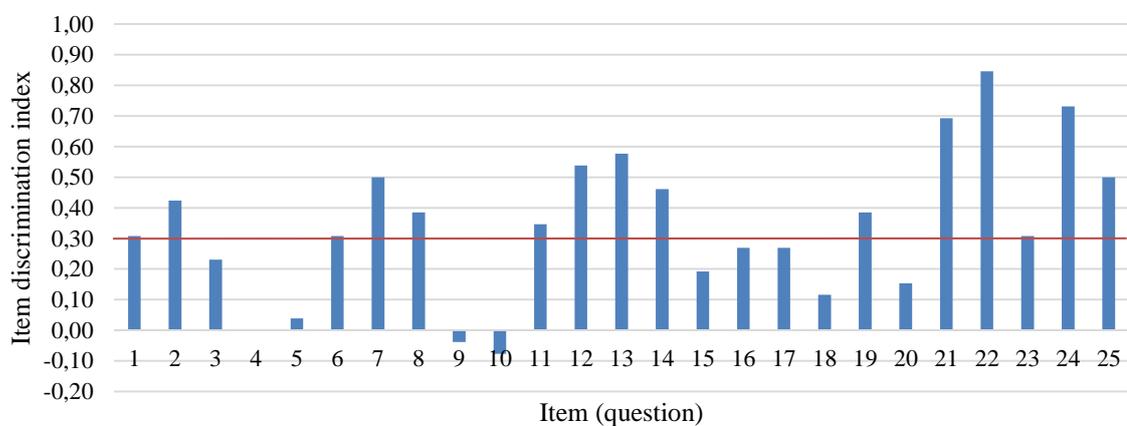
### Discrimination

Discrimination was evaluated with three different measures: Item discrimination index, Item point biserial coefficient, and Ferguson's delta. Items that discriminate well increase the variance and make the test more reliable (Engelhardt, 2009).

Item discrimination index measures the ability of a test to discriminate low-scoring and top-scoring students. It can be calculated as a difference of top 25% scorers and bottom 25% scorers who responded correctly (Wuttiptom, Sharma, & Johnston, 2009; Ding, Chabay, Sherwood, & Beichner, 2006). The range of possible values is between -1 and 1, and a value  $>$

0.3 indicates that the item discriminates well. The overall mean score of the Item discrimination index was 0.34, which is a little bit above the desirable value of 0.3.

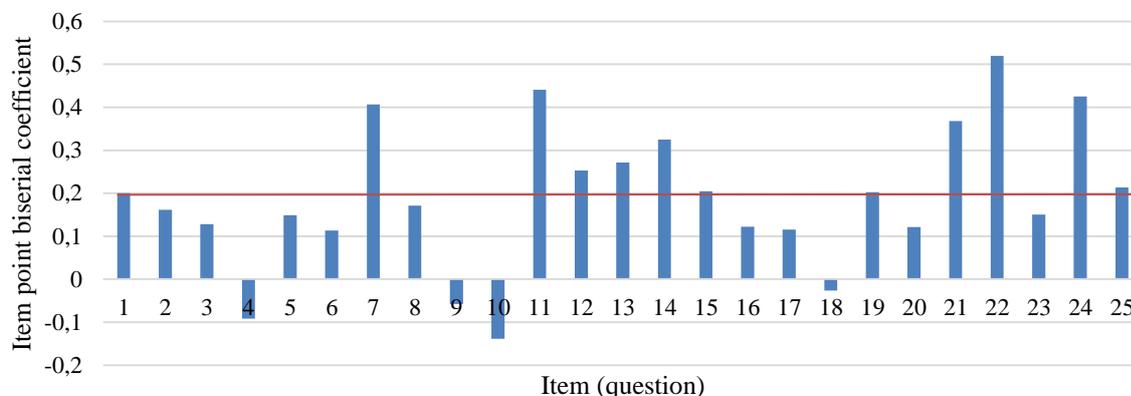
As **Figure 2** shows, ten items are poor discriminators. Again, items 4 and 5 belonging to the theme Waves and particles are of concern. In addition, items 9 and 10 related to de Broglie wavelength fail according to the item discrimination index. The most worrying items belong to the theme Double-slit experiment. Of the five items of the theme, only one item (19) discriminates students well.



**Figure 2.** QPCS item discrimination indices based on a sample of 103 Finnish students' pre-test results. Optimum values lie above 0.3 (marked with a red line)

Another calculated index was Item point biserial coefficient that measures the relationship between a student's correctness on the given item and his/her score on the overall test (Wuttiprom, Sharma, & Johnston, 2009). It is computed as a correlation coefficient between the item scores and the total scores (Ding, Chabay, Sherwood, & Beichner, 2006). The values lie between -1 and 1, and value  $>0.2$  is considered acceptable.

The results in **Figure 3** show that 13 items are poor discriminators in our sample. These items do not differentiate students appropriately. Several themes, such as Photoelectric effect, Waves and particles, and Double-slit experiment are problematic because most of their items are not good discriminators.



**Figure 3.** QPCS Item point biserial coefficients based on a sample of 103 Finnish students' pre-test results

### Self-consistency

Self-consistency of the test was evaluated using Kuder Richardson Formula 21 (KR-21). KR21 measures the self-consistence of the whole test and it is based on the covariances of dichotomously scored items (Engelhardt, 2009). The values lie between 0 and 1 (Ding, Chabay, Sherwood, & Beichner, 2006). The calculation gave 0.49, which is below the recommended value of 0.7.

### Comparison of problematic items

For a more detailed analysis of the problematic items, problematic items based on three indices, Item difficulty index, Item discrimination index, and Item biserial coefficient index, were cross-tabulated and compared with the results by Wuttiptom, Sharma and Johnston (2009), see [Table 4](#).

As can be seen from [Table 4](#), there are five items that fail in all the three indices, items 3, 4, 5, 9, and 10 (see Appendix). These items should definitely be re-considered to enhance the validity of the Finnish version of the QPCS. Four items that were unsuccessful in two indices (16, 17, 18, and 20) are also worrying and should be examined in more detailed. Items that fail in one index (3, 4, 5, 7, 9, 10, and 11) may have minor issues that cause their failure in the test.

Furthermore, there are eight items (3, 4, 5, 6, 7, 10, 11, and 20) that are problematic according to the results of this study and the results reported by Wuttiptom, Sharma and Johnston (2009). This observation may indicate that the validity of the original QPCS might be further improved by paying attention to these items.

**Table 4.** Cross-tabulation of problematic items by three indices in QPCS test in the Finnish and original samples. IDiffI = Item difficulty index, IDiscl = Item discrimination index, and IPBI = Item biserial coefficient index

Item	IDiffI		IDiscl		IPBI	
	Finnish sample	Original sample	Finnish sample	Original sample	Finnish sample	Original sample
1						
2					x	
3	x		x	x	x	x
4	x	x	x		x	
5	x	x	x		x	
6				x	x	x
7	x					x
8					x	
9	x		x		x	
10	x	x	x	x	x	
11	x	x		x		
12						
13						
14						
15			x			
16			x		x	
17			x		x	
18			x		x	x
19						
20			x	x	x	x
21						
22						
23					x	
24						
25						

## DISCUSSION AND CONCLUSIONS

The study examined the use of Quantum Physics Conceptual Survey (QPCS) in evaluating Finnish university students' pre-knowledge in introductory quantum physics. Based on the calculated indices, there are some concerns on the Finnish version of QPCS that should be taken into account before a wider use of the test as a pre-test in quantum physics.

The results showed that the Finnish students' mean score in QPCS was 45.9% that is exactly the same than the mean score by Australian first-year physics students in a study by Wuttiprom, Sharma and Johnston (2009).

The results also showed that QPCS was somewhat difficult for the Finnish students participating in the test. Especially the themes Waves and particles and de Broglie wavelength caused problems for the participants. The discrimination ability of the whole test, Ferguson's delta, was above the recommended value but the discriminatory power of its individual items was not very good. These contrasting results should be taken with caution because it has recently been claimed that Ferguson's delta is not a good measure of discrimination (Terluin, Knol, Terwee, & de Wet, 2009). Altogether six items out of 25 were problematic in three indices. In total, eight items have also been reported being problematic by Wuttiprom, Sharma and Johnston (2009). The measure of self-consistency, KR-21 index, was not satisfactory.

The moderate level of student understanding of quantum physics is not surprising, because the quantum pre-knowledge of the Finnish students participating QPCS is mainly based on their upper secondary school studies and basic physics courses at the university level. Our students are majors of mathematics, physics, or chemistry, and it is possible that their secondary studies do not include anything about quantum physics, because the course called Modern physics is a voluntary course for students and only a minority of upper secondary students finish it. It can be estimated that about a half of the students participated in this study have taken the course in the upper secondary school. The contents of the course are various because it covers the main ideas of modern physics from quantum physics, relativity, and particle physics. The themes photoelectric effect and waves and particles are explicitly mentioned in the national core curriculum (Finnish National Board of Education, 2004) but also de Broglie wavelength, double-slit interference, and uncertainty principle are discussed in upper secondary textbooks. It is probable that high school teaching does not often lead to profound understanding of these counterintuitive topics.

The basic university physics courses at our university discuss the topics of quantum physics during a tight timeframe and with rather lightweight style based on the book by Randall Knight (Knight, 2013). The double-slit experiment, de Broglie wavelength, waves and particles are briefly introduced, but the photoelectric effect has more weight in teaching. The photoelectric effect is also one topic of our students' intermediate laboratory work, which is recommended to be taken before the intermediate course on quantum physics. According to our knowledge, only a few students do obey the recommended structure of studies.

These factors may partly explain somewhat modest level of student quantum understanding. As Wuttiprom, Sharma and Johnston (2009) have stated, *"it seems that learning quantum physics at a higher level with standard instruction does not necessarily cement understanding of the introductory concepts."*

Some students also commented that they are not familiar with the Standard (Copenhagen) interpretation of quantum mechanics, which exist in six items of three different themes. Four of these items constitute the theme Waves and particles, which was

the most difficult theme for the students and which was shown to be a poor discriminator as well. The Standard interpretation of quantum mechanics is not discussed in the Finnish upper secondary textbooks and it does not include in the basic physics curriculum in our university. In the Finnish version of QPCS, this theme could be modified, ignored or replaced with another theme based on upper secondary quantum physics.

We also think that there is some contentual overlap between the themes Waves and particles (wave-particle dualism) and de Broglie wavelength, which makes these themes interrelated. Wave-particle dualism cannot be understood without understanding the concept of de Broglie wavelength and vice versa. This supports also the need for reformulating QPCS for our purposes.

These results suggest that QPCS has potential and it could be a valid instrument to monitor student understanding of quantum physics after some careful modifications that take the main domains of the Finnish upper secondary school syllabus into account. Our results suggest that in the current state, QPCS may not work well as a pre-test if students' pre-knowledge is vague or they have not been studied the themes of QPCS. Our study also verified some problematic items already noted by the developers of the test. The validity of the original QPCS can be further improved by paying attention to these items.

We encourage other users of QPCS to evaluate the test with their own samples before an implementation of the test. It is possible that there are differences in the amount and extent of quantum physics in the national syllabuses that may have an effect on the level of university students' pre-knowledge. This means that same test does not necessarily work as it is supposed to do in different cultural environments.

Next in this research project, a modified QPCS will be developed and tested. We hope that the novel version can be used as a more valid tool in probing student understanding of quantum physics both in the beginning and in the end of the course quantum physics in the Finnish universities.

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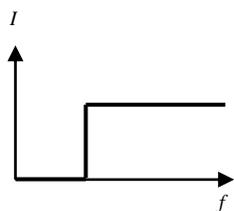
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## APPENDIX

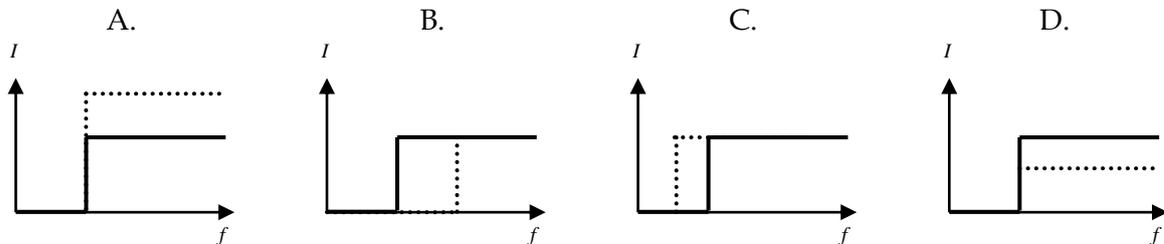
### Quantum Physics Conceptual Survey (QPCS) (Republished with a permission by the authors)

**Questions 1 through 3** refer to the following.

In a hypothetical experiment to demonstrate the photoelectric effect, a light source of variable frequency is shone on a photo-sensitive 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?

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; and
- if the frequency of light is decreased (with any amplitude) there is a cut-off frequency below which electrons are no longer ejected.

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 observations?

- A. In a particle theory, 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, ejection of electrons is explained by the electromagnetic wave causing the electrons to vibrate, which gives some electrons enough energy to escape.
- C. In a particle theory, the cut-off is explained because at very low frequencies the photons have very low energies and no individual photon has enough energy to eject an electron.
- D. In a wave theory, the cut-off is explained because a very low frequency wave could not make the electrons vibrate energetically enough, even at very high amplitudes.

Questions 4 through 7 refer to the following experiments.

- In one experiment electrons are traveling from a source to a detecting screen.
- In a second experiment light is traveling from a source to a photographic plate.

For each question, choose from A through D the most appropriate answer according to the standard (Copenhagen) interpretation of quantum mechanics.

- A. It is behaving like a particle.
- B. It is behaving like a wave.
- C. It is behaving like both a particle and a wave.

D. You cannot tell if it is behaving like a particle or a wave.

How is the particle/wave behaving when,

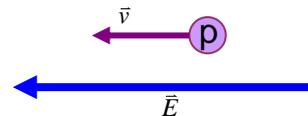
4. an electron travels from the source to the screen?
5. light travels from the source to the plate?
6. the electron interacts with the screen?
7. the light interacts with the plate?

For each question 8 through 10, choose the most appropriate answer from A through C.

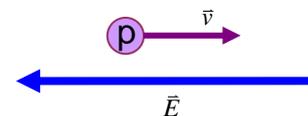
- A. The de Broglie wavelength of the particle will increase.
- B. The de Broglie wavelength of the particle will decrease.
- C. The de Broglie wavelength of the particle will remain the same.

What will happen when a positively charged particle is,

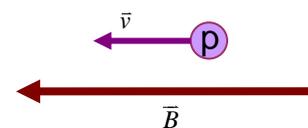
8. moving through an electric field, in the same direction as the field, and is therefore speeding up?



9. moving through an electric field, in the opposite direction as the field, and is therefore slowing down?



10. moving through a magnetic field, in the same direction as the field, and its velocity is therefore constant?

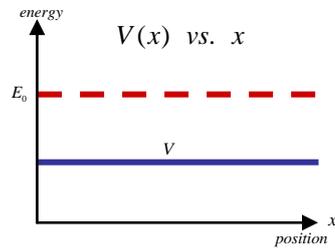


For each question 11 through 13, choose the most appropriate answer from A through C.

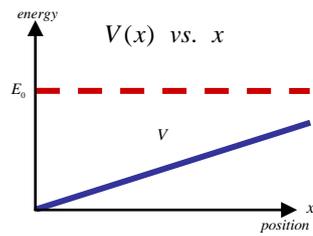
- A. The de Broglie wavelength of the particle will increase.
- B. The de Broglie wavelength of the particle will decrease.
- C. The de Broglie wavelength of the particle will remain the same.

What will happen when a quantum particle is traveling from left to right with constant total energy,  $E_0$ , in a region in which the potential energy is,

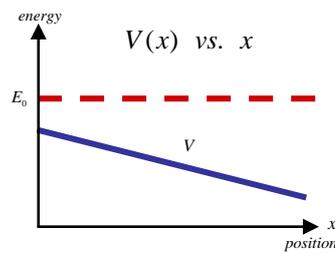
11. constant?



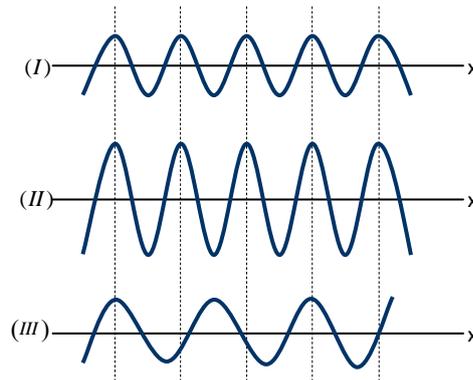
12. increasing?



13. decreasing?



14. Three particles of equal mass are traveling in the same direction. The de Broglie waves of the three particles are as shown.



Rank the speeds of the particles (*I*), (*II*), and (*III*) by circling one of these four possibilities.

A.  $v_{II} > v_I > v_{III}$

B.  $v_{II} > v_{III} > v_I$

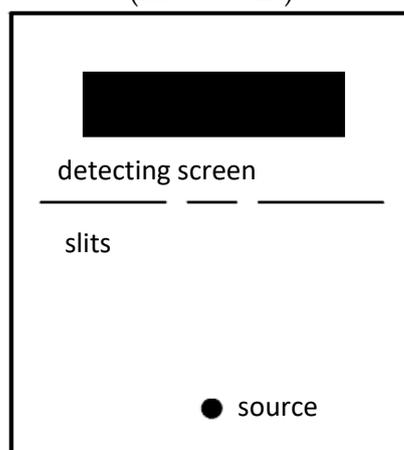
C.  $v_I = v_{II} > v_{III}$

D.  $v_{II} > v_I = v_{III}$

Questions 15 through 19 refer to the following experiments.

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

Top view of experimental set-up  
(not to scale)



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,

\_\_\_\_\_ 15. light passes through the double slit?

\_\_\_\_\_ 16. marbles pass through the double opening?

\_\_\_\_\_ 17. electrons pass through the double slit?

\_\_\_\_\_ 18. light passes through the apparatus when one of the slits is covered?

\_\_\_\_\_ 19. electrons pass through the apparatus when one of slits is covered?

In questions 20 and 21, circle the most appropriate statement.

20. According to the uncertainty principle, the more we know about an electron's position, the less we know about its,

- A. speed.
- B. momentum.
- C. kinetic energy.
- D. all of these.

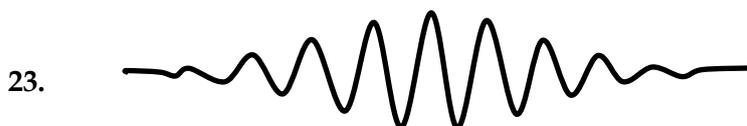
21. Choose the answer A through D which is most appropriate answer according to the standard (Copenhagen) interpretation of quantum mechanics?

The Heisenberg Uncertainty Principle is mostly applied to very small objects such as electrons and protons. Why don't we use the uncertainty relation on larger objects such as cars and tennis balls?

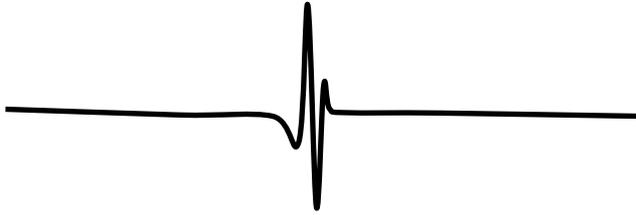
- A. The errors of measurement can always, in principle, be made smaller by using more sensitive equipment.
- B. Large objects at any instant of time have an exact position and exact momentum and with sufficient care we can measure both precisely.
- C. Large objects obey Newton's laws of motion, to which the uncertainty principle does not apply.
- D. Because it does apply to large objects, but the uncertainties are so small that we don't notice them.

For each question 22 through 24, choose the description from A through D which best describes the illustrated wave packet.

- A. Poorly defined position, well defined wavelength
- B. Well defined position, poorly defined wavelength
- C. Well defined position, well defined wavelength
- D. Poorly defined position, poorly defined wavelength



24.



25. For the double slit experiment with electrons, which one of the following statements is true according to the standard (Copenhagen) interpretation of quantum mechanics?
- A. It is, in principle, possible to measure which slit an electron went through and still see a multiple fringe pattern, if the technology is sophisticated enough.
  - B. Each electron must have gone through one slit or the other, but it is impossible to measure which slit any one particular electron went through.
  - C. It is possible to measure which slit an electron went through, but if you make this measurement, the beam of electrons will no longer form the multiple fringe pattern on the screen.

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