

Students' alternative conceptions in quantum mechanics: The case of one-dimensional potential quantum tunneling

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Abstract

Quantum mechanics is generally an abstract theory that challenges intuition since it cannot be understood using ordinary experiences. Quantum tunneling is one of the topics which is more counterintuitive and challenges students' conceptual understanding. The study was aimed at investigating if final year undergraduate quantum mechanics students have alternative conceptions regarding quantum tunneling phenomena after a full course of instruction. In this study, students' alternative conceptions are referred to as any student ideas related to the incorrect belief of scientific principles. Using the deep structured interviews involving 36 students who were registered in a quantum physics course from the University of Malawi, we found that some students hold on to the idea that the energy of a quantum tunneling electron is lost, the wave function graph depicts the physical wave, and the “potential step,” and “barrier” means a physical object/barrier. The study further established that the possible sources of these alternative conceptions emanated from students' experience with classical tunneling / classical mechanics, quantum mechanics lecturer notes, and previous quantum mechanics lessons. The findings of this study further portray that traditional pedagogy has its limitation in facilitating students' comprehension of quantum tunneling. We recommend that further research into the design of instructional technology for quantum physics should consider these students' alternative conceptions when designing visual, interactive, and mental models, which may help establish students' conceptual understanding of quantum mechanics.

Keywords quantum mechanics; classical mechanics; quantum tunneling; alternative conceptions

Introduction

Physics Education Research (PER) is a new branch of physics that is concerned with identifying students' challenges in teaching and learning physics. PER has found that both introductory and advanced level university physics students struggle to demonstrate an understanding of the basic concepts of quantum mechanics (QM) even after a full course of instruction (Singh et al. 2006; Singh

& Marshman, 2015). Moreover, even students from outstanding universities where there are more qualified teachers, and a repertoire of teaching and learning resources are relatively adequate still possess unscientific beliefs (alternative conceptions) (Morgan, Wittmann, and Thompson, 2003). Meanwhile, Marshman, (2016) reported that students have these alternative conceptions because the quantum theory is based on advanced

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mathematical and abstract philosophical principles which seem to contradict their experiences with the macro-universe. However, Anecdotal evidence has shown that most university quantum physics students go along with an experience of classical physics in which the approved knowledge has been learned as scientifically correct and absolute. Vygotsky (1978) found that the experience which learners obtain in their different contexts, helps them to make meaning to the new knowledge, however, when learners perceive their experiences as absolute knowledge, it gets hard for them to tune into what seems to contradict their prior experiences (Larsson et al., 2018).

From the study sites of this research, quantum tunneling is taught as a final course of the Physics/Education Science degree program hoping that students have acquired the necessary baseline knowledge, proper cognitive abilities, and suitable problem-solving skills which are relevant for students' comprehension of this topic (Carlone, 2004). However, this research established that up to the final year level when graduates are being furnished to practice their physics, they still hold on to several unscientific beliefs regarding quantum tunneling (QT) even after a full course of chalk and talk instruction. In the efforts to address such challenges, this research took advantage of the need to review students' alternative conceptions in QT so that further research can be integrated to cater to pedagogy that may improve student understanding of this topic.

Purpose of the Study

The main purpose of this research was to establish if students have some alternative conceptions in quantum tunneling after a full course of chalk and talk instruction and to establish the possible sources of their alternative conceptions.

Literature Review

A lot of studies on students' conceptual understanding of Quantum Mechanics have been done in introductory mechanics, however, a growing number of researchers such as Styre (1996), Ireson (2000), Cataloglu (2002), and Witman, Morgan, and Bao (2005) have invested their efforts in investigating issues related to student understanding of quantum mechanics in advanced undergraduate level and discovered that students always have several faulty and unscientific ideas regarding this subject matter (Singh, et al., 2006). For instance, Morgan (2006), Singh (2006), and Ozcan (2009) reported some shared students' alternative conceptions such as the idea that the energy of a quantum tunneling particle is lost. They attributed this problem to textbooks and lecturers drawing the energy and the wave function graphs on the same graph, meanwhile, we noted from this study that a similar student alternative conception of energy loss was attributed to students' overgeneralization of classical concepts on quantum mechanical concepts e.g., classical intuition about objects physically passing through obstacles, in which energy is usually dissipated. Other studies, for example, Muller, (2005) and McKagan and Wieman (2006) have reported that students have a 'Mistaken belief that reflection and transmission of a beam of particles are due to a range of energies of the particles in the beam'. They also referred to the quantity $U(x)$ as some kind of "external energy." These Alternative conceptions were attributed to textbooks and lecturers nearly always refer to "a particle in a potential" as if the potential is something external. Although most of these students' alternative conceptions are universal (Ozcan, 2009). It was noted from this study that the sources of these alternative conceptions can vary. We also noted some consistent results with Singh et al., (2006), that in some instances students who excel at solving technically difficult questions possess several

alternative conceptions when the qualitative understanding of the same questions is sought (Singh, 2010; Marshman & Singh, 2015). Some of these alternative conceptions persist even after students have completed the course and they are hard to break (Marshman & Singh, 2015). Since quantum physics is built on a paradigm different from classical mechanics, students technically struggle to reconcile these two theories, as such, some students struggle to capture the correct concepts of quantum mechanics. They mostly memorize for the exam just to get promoted to the next level. It is not surprising that students' alternative conceptions persist even at the graduate level (Carlone, 2004).

Meanwhile, a variety of pedagogical interventions have been put in place to enhance the conceptual understanding of QM phenomena. Boe, Henriksen, and angel (2018) suggested the use of history and philosophy of science (HPS) in QM lessons, Sayer, Marshman, and Singh (2016) deployed the use of the Just-in-time (JiTT) instructional strategy where students are assigned reading materials before the actual lecture and are required to fill the electronic pre-lecture assignment as a way of giving feedback to the instructor to exact points where students are having difficulties so that the instructor may make some adjustments to his lesson plan. Mason et al. (2013) suggested the use of Computer-based interactive simulations. Meanwhile, there is still an ongoing debate as

to which of these methods will facilitate conceptual understanding in quantum tunneling, as many of these methods have been explored at introductory levels and there are still ongoing studies investigating the effectiveness of these methods in the advanced level of undergraduate quantum mechanics' course (Höttecke, 2013). In the efforts to address such challenges, this research took advantage of the need to review students' alternative conceptions in QT and their sources so that further research can be integrated to cater to pedagogy that may improve student understanding of this topic. We have noted that some similar studies have mostly focused on sourcing the students' alternative conceptions and did not go beyond to find the sources of these alternative conceptions, for example, Ozcan, (2009). We believe that unless we find the source of the problem long-lasting solutions may not be found.

Study Design and Methodology

This study considered the mixed method approach to a scientific inquiry. As suggested by Tashakkori and Teddlie (2009), the quantitative design was embedded to provide a starting point for an in-depth study of students' misconceptions in QT (Creswell, 2014). We used a three-step approach as discussed by the structural model developed by Classen & Lopez (2006); see Table 1. Firstly, we developed a quantitative dataset by administering a written questionnaire. Later,

Table 1 Summary of the adopted research design.

Research design	The specific type of mixed methods	Procedure	Purpose	Level of Interaction	Priority
Mixed methods	Sequential explanatory	Quantitative followed by qualitative	Qualitative data was collected to explain the quantitative findings	Quantitative data frames qualitative data collection	Qualitative dominant

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interviews were used to collect qualitative datasets, then a meta-synthesis was deployed, such that the narrative data were categorized by conducting a thematic analysis, which involved sorting of groups of similar words or statement clusters based on the inductive and deductive analysis (Classen, 2006).

The study was guided by the one-dimensional time-independent Schrödinger equation to show the behavior of a one-dimensional quantum tunneling particle. The equation is shown in Equation 1.1.

$$E\Psi(x) = -\frac{\hbar^2}{2m} \frac{d^2}{dx^2} \Psi(x) + V(x)\Psi(x) \text{ Equation 1.1}$$

- where: \hbar is the reduced Planks constant, (d^2/dx^2) is the second derivative in space,
- $V(x)$ is the potential energy of the particle (measured relative to any convenient reference level),
- m is the particle mass, x represents distance measured in the direction of motion of the particle,
- Ψ is the Schrödinger wave function and E is the energy of the particle that is associated with motion in the x -axis (measured relative to V).

Participants

The participants of this study were final year students who were registered for a Quantum Mechanics course from the University of Malawi- Chancellor College(n=36), which was all composed of pre-service physics teachers, all students were male. The mean age was 25.32 ($SD = 3.50$), These participants were recruited through convenience sampling. All students had already attended to the topic of tunneling using the traditional chalk and talk method.

Data Collection

We first administered a written survey using a closed-ended questionnaire which was later

followed by semi-structured interviews which were designed to probe students' insights about their survey responses. The opening questions of the interviews were collected from the survey item. Students were called individually to justify their responses and explain why they thought that the other options were wrong. The questions in the survey that was used were adapted from the Quantum Mechanics Conceptual Inventory (QMCI) and the Quantum Mechanics Conceptual Survey (QMCS). Some questions were modified from the PhET teacher resources guide on QT. This developed tool was further thoroughly evaluated by

faculty members and tested in a pilot study. The reliability coefficient of this tool was calculated i.e., $\alpha = 0.87$ which interprets a good test design. The point bi-serial discrimination coefficient was between **0.3** and **0.8** for every individual question, which means a very good probing tool with proper item difficulty and discrimination index.

This research instrument was composed of four questions that were systematically selected as they deeply persuade the qualitative conceptual understanding of quantum tunneling. The items were selected based on the consistency in students' alternative conceptions of quantum tunneling as were presented by other researchers, for example, Wittman, (2005), McKagan, (2008), and McKagan, (2009). For instance, questions number one and two in the appendix were designed to measure students' understanding of the concept of probability of tunneling for a particle of known kinetic energy and appropriate potentials. Meanwhile, question one gave an extension of a physical instance in which quantum tunneling might occur giving students a mental model of the concept of tunneling. question three was adopted from the QMCS as it is effective in probing the most

common student's alternative conception of the energy loss of a quantum tunneling particle (McKagan, 2009). Question number four was aimed at probing students' understanding of the relationship between the amplitude of a wave function and its relation to probability, the wavelength, and its relation to energy. Since quantum tunneling is conceptually based on the understanding of the probabilistic nature of quantum mechanics. After validating the instrument with the pilot study, we found these questions necessary and sufficient to meet the desired outcome of the study.

The semi-structured interview consisted of two different categories of questions, the backbone questions which were the four opening questions that were built from the quantum tunneling questionnaire which was already administered. The follow-up

responses, quoting them directly to invoke students' insights about a given concept. The copies of these questions were only available to the researchers and were dictated to a student at a time with minimum interference from other participants.

Data Analysis

Data was qualitatively analyzed through the use of narrations and a careful analysis of the patterns that emerged from the interview transcripts. We used content analysis of written responses, interpretation of diagrams and sketches, and descriptions of student actions. In addition, the transcript of each student was analyzed as a single case (single case analysis) then, we identified some common themes that emerged from the interview transcripts (Strauss & Corbin, 1998). The thematic analysis also helped to

Table 2 Six phases of thematic analysis by Braun and Clarke, (2006)

Phases of Thematic Analysis	Means of Establishing Trustworthiness
Phase 1: Familiarizing with the data	<ul style="list-style-type: none"> • Data was read several times • Initial ideas of participants in the transcripts were noted down
Phase 2: Generating initial codes	<ul style="list-style-type: none"> • Peer debriefing • We made notes on the texts that indicated some potential patterns.
Phase 3: Searching for themes	<ul style="list-style-type: none"> • We organized the codes into potential themes
Phase 4: Reviewing themes	<ul style="list-style-type: none"> • The researchers read all the collated extracts for each theme to conclude if they formed a coherent pattern
Phase 5: Defining and naming themes	<ul style="list-style-type: none"> • Peer debriefing • Team consensus on themes • Documentation of theme naming
Phase 6: Producing the report	<ul style="list-style-type: none"> • Peer debriefing • This was the final stage for analysis and examples of vivid and compelling extracts were selected and further analyzed to reflect the research question and literature • Reporting on reasons for analytical choices throughout the study

questions were asked based on students' categorize narrative data by sorting the groups

of similar words or statements into clusters (Classen et al., 2007). Using such techniques, we were able to track the pattern of students' ideas about some scientific facts from where we could probe more to establish their alternative conceptions and their sources.

We repeatedly read the transcripts to gain familiarity with the text as a whole. Coding later followed. The codes were assessed for general themes or patterns. The identified themes were scrutinized to explore further relationships until data saturation had been reached and then possible conclusions and explanations were made (Nowell, 2017). The research supervisors from the department of curriculum and teaching studies helped in reviewing the codes which provided us with the necessary confirmation and modifications.

Results

In this section, we have first presented the quantitative results from the written survey, followed by qualitative results from the semi-structured interviews. The descriptive statistics of the results obtained from the written survey is presented in Table 3.

It can be noted from Table 3 that the participants had the average score (M = 36.56%; SD = 1.7967) A small value for

Table 3. Descriptive statistics for the written questionnaire

Number of students	Percent Mean Score	Std. Deviation	Std. Error Mean
36	36.56%	1.7967	.66680

standard deviation means that the data is clustered near the mean. This meant that most of the students failed the survey. Among other

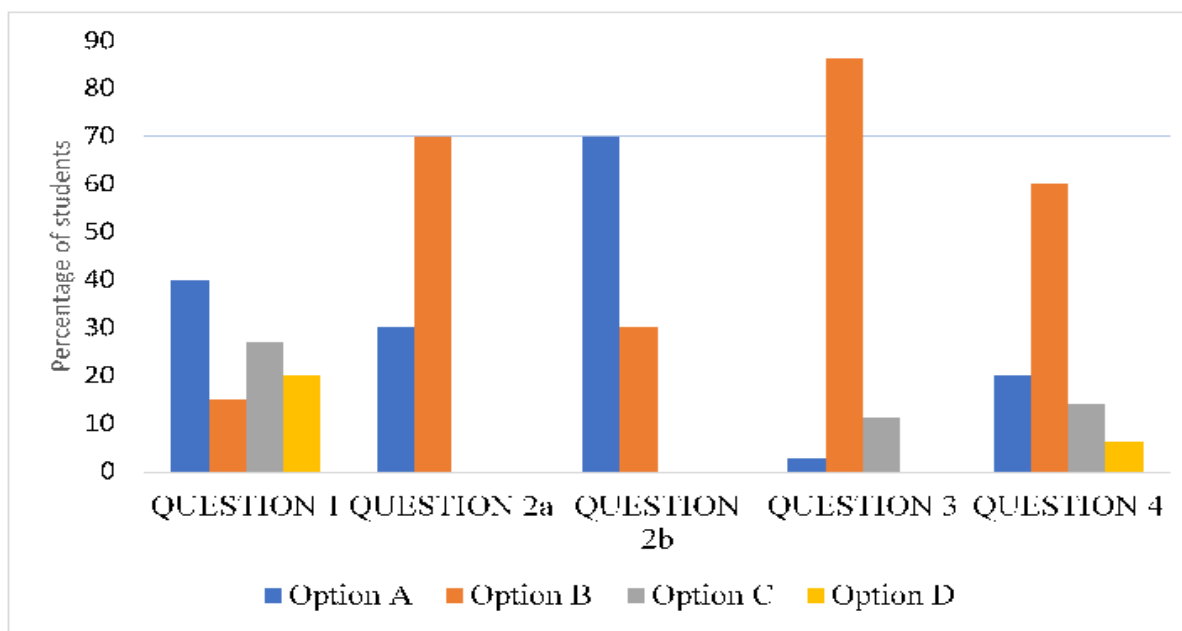


Figure 1 Percentage of selecting each option in some of the survey questions

To ensure a trustworthy thematic analysis, we adopted the six phases of thematic analysis as presented by Braun and Clarke, (2006). Table 2 is a description of the process.

reasons, we hypothesized that students failed the test because they were not informed to study the topic before the survey. We also assumed that since this survey was given a

semester after they learned the topic, some students had already forgotten the other concepts. Meanwhile, this was a good indicator for us of how our students returned the basic concepts of quantum tunneling. As reported by Bungum et al. (2015), in most cases, students' study for the exam, so that they can be promoted to the other level. Similarly, we noted from these results that the majority of students did not manage to return the basic quantum tunneling concepts that they learned in the previous semester. We plotted a graph to show how some destructors on the survey items were selected by the majority of students.

Figure 1 guided the researchers' interest to explore students' reasoning based on the pattern that immersed from the students' choices of the destructors. For instance, 20% of students selected the right option B from question number one, and 70% selected the right options in both questions 2a and 2b. 2.78% selected the right option A in question number 3, and 60% selected the right option B in question 4. This meant that some students had a similar pattern of thought in some questions.

Table 4. Distribution of students' responses to Question 3 on the written survey

Question Number 3 Options	Number of students selecting the option	Proportion of students
A. Energy is conserved	1	3%
B. Energy decreases exponentially	31	86%
C. Non- exponential energy loss	4	11%%

Meanwhile, we did not rely on this quantitative data as it could not give more insightful meaning to students' ideas. We opted for a qualitative approach which helped us gain more insightful meaning to students' reasoning. The qualitative results further demonstrated that our students have alternative conceptions which emanated from different sources as evidenced by the given interview transcripts.

Students Alternative Conceptions

In this study, students' alternative conceptions are referred to as any student ideas related to the incorrect belief of scientific principles. These ideas may emanate from various sources. The study sourced three different students' alternative conceptions namely: The wave function graph depicts the physical wave, the "potential step," and "barrier" means a physical object/barrier, and the energy of a quantum tunneling electron is lost.

The energy of a quantum tunneling electron is lost

Reference was made from students' questionnaire responses for question number three. It was noted that 86% of the participants failed to provide the correct response regarding the energy of a quantum tunneling electron. Table 4 shows the distribution of students' answers to this question. It can be observed from Table 4 that only one student got this question right. Considering that the topic of QT was already taught before the study, we noted that, that the energy concept challenged our students just as it has been reported in the literature (McKagan, 2010). We interviewed all 36 students to get an

insight into their understanding of the energy concept. The results revealed that the majority of students (33 out of 36) believed that the energy of a quantum tunneling electron is lost. We narrowed down the common themes, and the number of times these themes were used in the interview by the participants. The results recorded are presented in Table 5.

Table 5 Common themes and the number of times these themes were mentioned by respondents in the interview

Commonly used themes	Number of times theme mentioned	Number of respondents that mentioned the themes
Tunneling electron uses up some energy	86	36
Energy used up	18	6
Electron radiates energy	12	4
No energy loss	23	4
Exponential loss of energy	11	4

It can be observed from table 5 that energy loss was one of the most occurring themes. It was so worrying to observe that students who are to be certified as physics graduates held to the belief that the energy of a tunneling particle can be lost, having in mind that they have covered the topic of quantum tunneling and some fundamental concepts of QM. In an interview with one of the students whose QM scores were in the top percentile, we noted that this student was at the crossroads of building a model that will connect his understanding of classical mechanics to the QM phenomena. Find the idea of Student K regarding the energy of a quantum tunneling particle in the quote below.

Sir, energy, particularly from the first principles of mechanics it can never be lost, but since we're in quantum mechanics, anything can happen, I'm just not sure perhaps for a quantum system the energy of the electron may not be stable... maybe it can fluctuate with reference to the amplitude of the wave function (Student K)

From this quote, we see that **student K** is at the crossroads, thinking that perhaps quantum mechanics breaks the laws of nature, he knows classically it is impossible to lose energy using the law of conservation of energy. However, he is not sure if the law still applies to the case of quantum mechanics. Relating the amplitude of the wave function and the energy of the

particle could be one of the reasons student K held to a preconception that quantum mechanically, a tunneling electron loses energy.

Another interview with **student L** (his scores are in the bottom percentile) revealed that the student's idea of the energy loss of a tunneling electron was striking. We asked this student to explain why he selected option B (wrong answer to question 3), this is what he said:

A tunneling electron by all means uses up some of its energy in trying to overcome the potential barrier... as we know that doing work on a body say x will need some practical transfer of energy into the system...yeah... so that's what I think happens with the tunneling electron. [Student L, Interview Transcript].

A phrase like, energy is used up as used in the quote above may be synonymous with the phrase "energy loss," which might not be scientifically justifiable. With this idea in mind, we asked student **L** to explain his understanding of the two phrases as we wanted to see if it was just a problem of language or an alternative conception. This is what student **L** said:

Ummh. Well... about that, then all I can say is the electron loses its energy in the process of trying to tunnel through the potential barrier. Not sure

*where the energy goes afterward...
[Student L Interview Transcript].*

From his response, we found evidence that this student shared the energy loss alternative conception.

Further interview results revealed that the *energy loss* misconception persisted among several students, for instance, an interview with five students who got question number three right and five students who failed the same question reported that all but one student including those who selected the right item on the survey, failed to provide the correct reasoning of their respective answers. For instance, we asked the students who selected the option that *energy of a tunneling particle is lost* to justify their answers, and the common themes that appeared from their responses translated that energy is lost. Consider the following interview excerpt:

Interviewer (I): Why do you suggest that a tunneling quantum particle will lose energy?

Student (A): well...I think that's what we perceive in a natural world and...uh...it is well obvious in any sort of tunneling you'd register an energy loss...I mean energy will be used up whilst tunneling.

Student (B): in my understanding...umh... I think an accelerated electron will radiate some energy as it tunnels through a barrier...

Student (C): ...although it is from my class notes, there is an exponential decay of the energy of the particle inside the barrier...I mean it is just weird how the electron manages to get through the region³ without using up some energy.

The excerpt above provided a good direction for students' reasoning regarding their understanding of the concept of energy of a tunneling electron. It was noted that both students **A** and **B**'s reasoning was much

connected to their experience with the classical intuition of the concept of macroscopic tunneling. From student **C**, we noted that he did not have a clear understanding of the graph of a wave function $\Psi(x)$, it was not surprising that these students could interpret the wave function $\Psi(x)$ graph, as a graph of the energy of an electron.

The wave function (Ψ) graph depicts the physical wave

Present data suggest that some students who took part in this study think that the wave function depicts a physical wave. This is a worrying trend, especially since these are fourth-year students who are expected to demonstrate clear and logical thinking when articulating issues related to the behavior of different microscopic particles. What should be noted is that the scientific explanation of this phenomenon is that the plot of the wave function does not depict the physical wave, but rather a mathematical description of a quantum state of a particle as a function of momentum, time, position, and spin. By using a wave function, the probability of finding an electron within the matter-wave can be explained. This can be obtained by including an imaginary number that is squared to get a real number solution resulting in the position of a quantum particle for example an electron. Furthermore, the magnitude of the wave function is large in regions where the probability of finding the particle is high and smaller in regions where the probability of finding the particle is low. We realized that this was a confusing concept for some students, for instance, we asked students **X** and **Y** to explain their understanding of the meaning of the wavefunction. This is what they said:

The graph of the wavefunction as it is sinusoidal is like any form of a mechanical wave that has a wavelength, and say amplitude...moreover its changing

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amplitude tells us about the energy of the quantum particle like how the energy is distributed [Student X, interview transcript]

The wave function itself is a symbol that mathematically describes the particles' spatial and time coordinates... meanwhile, its graph is a wave that shows how the wavefunction travels as a result of whatever disturbance in its media. [Student Y, interview transcript]

It can be noted that both students X and Y hold to the idea that the sinusoidal representation of a wavefunction in a graph justifies that the wave is physical, i.e., phrases like “it travels upon disturbance”, and “just like any mechanical wave” shows that these students think that the wavefunction graph depicts a physical wave. It could be that they missed a point that we can use a sinusoidal wave to depict most periodic motions, such as moving in a circle or swinging a pendulum, which does not necessarily look wave-like when we consider the actual motion. It can also be seen that student X had a confounding idea that translated that the amplitude of the wave function represents the energy of the quantum particle, which is a result of holding on to the idea that the wave function graph depicts the physical wave.

Furthermore, we enquired about student (X)'s understanding of the relationship between the wave function and energy as shown in question number four of the tunneling questionnaire. It was noted that this student held the idea that the amplitude of the wave function represents the energy of the quantum particle such that increasing the particle's energy automatically increases the amplitude of the wave function. Consider the sample transcripts below:

Interviewer(I) Why did you choose option A in question number 4?

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Student (X) It is quite obvious to me that the amplitude must increase upon an increase in particle's energy, that's ideal for every typical wave...

Interviewer(I) Well, so what does the graph of the wavefunction mean?

Student (X) I'm pretty sure it's a wave sir... and the characteristics of describing the wave do not change... say... amplitude, wavelength... etc... so I suppose the interpretation should not change [Student(X), Interview Transcript].

From the quote above, the student is very confident about his understanding of a wave, moreover, by saying the characteristics of the wave are amplitude, wavelength, etc., he portrays a better understanding of what waves are. However, it is evident that he is generalizing that a wave function is a physical wave. Meanwhile, although both classical mechanics waves and quantum mechanics wave functions are sinusoidal, the difference comes in the interpretation of these distinct waves e.g., the probabilistic interpretation of the wave function. It can be observed that student (X) has a classical interpretation of a wave and misapplying it in the context of quantum mechanics, making him certain of his claim that the amplitude of the wavefunction represents the energy of the quantum particle.

Potential step,” and “barrier” mean a physical object/barrier

Both the survey and interview results pointed out that some students are of the view that the potential barrier or step is a physical barrier or a physical object. It is worth pointing out that these words are only analogies, they do not mean physical objects, for instance, a potential step/well/ barrier can be an air gap where there is no physical barrier. When we noted that one student had failed to answer question number two of the tunneling questionnaire (see

appendix), which was aimed at probing the student's understanding of the particles' probability of tunneling with respect to the height of the potential barrier, we asked him what the graphs in the question represented. His explanation was as shown in the quote below

In my understanding, a particle represented by the wave as shown in the question meets an obstacle that is bigger or... let me say higher than itself, so, the question is demanding us to say what will happen to the energy of this particle in case it tunnels through the barrier, secondly what is the possibility of this particle tunneling through the obstacle when the height of this obstacle increases. [Student Interview Transcript].

The use of words like “obstacle, bigger/higher” in this quote, can depict that this student pictures a potential barrier as a physical object which can be bigger or higher in size. As a result, this idea may technically lead one to think of the particle tunneling through this kind of barrier using and later losing some energy. As observed in this excerpt we noted from this student, that one alternative conception was capable of leading him into another alternative conception. For instance, thinking of quantum tunneling classically, where objects are penetrating a physical barrier in which case there is always dissipation, leads this student to embrace the idea that the energy of a tunneling electron is lost; A prevailing alternative conception that has already been discussed.

We also found that some students shared this alternative conception when dealing with step potentials as they do when dealing with potential barriers (rectangular potentials). For instance, we changed question number two by removing the potential barrier and replacing it with a step potential, then we asked one

student to describe the situation of the graphs in the question and this is what he said:

A high-energy stream of electrons runs through an obstacle like say a wall... then... it either must cross or bounce. [Student Interview Transcript].

Describing potential steps as walls or objects where electrons can run or bounce back shows that the student thinks of a step potential as a physical barrier. Such classical intuitions have the possibility of making a student directly relate the macroscopic experience to quantum systems.

Sources of Student Alternative Conceptions

Present data reveal that there are three main sources of students' alternative conceptions in QT. These are classical mechanics concepts, quantum mechanics previous lessons, and quantum mechanics lecturer notes. These sources of students' alternative conceptions were determined through the in-depth semi-structured interviews which gave some themes which directly pointed to the source.

Classical mechanics concepts

Interview data revealed that some students used classical physics ideas to generalize meaning to the quantum physics phenomena. This means that some students used ideas or models in classical mechanics to understand ideas in QM as shown in the quotes below:

Interviewer(I) Why did you choose option A in question four of the survey?

Student (S) It is quite obvious to me that the amplitude must increase upon an increase in particle's energy, that's ideal for every typical wave...

Interviewer(I) Well, so what does the plot of the wavefunction mean?

Student (S) I'm pretty sure it's a wave sir... and the characteristics of describing

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the wave do not change ... say... amplitude, wavelength... etc... so I suppose the interpretation should not change. [Student (S) Transcript].

It is evident from the quote above that this **student(S)** has a classical interpretation of a physical wave and misapplying it in the context of a wave function, making him certain of his claim that the amplitude of the wave function represents the energy of the quantum particle. Another student (**A**) was asked to explain why he thought the energy of a tunneling quantum particle is lost? It was also noted from the quote below that Student A's understanding of tunneling emanated from his experience with the classical mechanics' concepts on the topic of electromagnetism.

Student A: from my understanding of electromagnetism, it is well obvious that a particle or say an electron with energy (E)... must radiate upon any sort of acceleration...

Quantum mechanics previous lessons

The study also revealed that previous lessons on quantum mechanics contributed to the reported students' alternative conceptions in this study. For instance, an interview with five students revealed that some students had problems connecting some classical physics examples that were given in the class to a quantum mechanical situation. This was noted whilst probing students' understanding of the term potential barrier. This is what one student said.

I think of a potential barrier as something that has the energy that counteracts the motion of the electron, I remember when we were learning this topic, the teacher said think of a vehicle going through mt Everest, in fact, he also mentioned something like, imagine yourself walking through walls...well, ummh...

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I'm not sure what exactly this barrier can be in quantum mechanics, but it's something like what just blocks some sort of motion. [Student 2, Interview Transcript].

It can be noted from this quote that the student made reference to the previous QM lessons. For instance, the example of a car tunneling through mount Everest that was given in class had an implication on the student's conceptualization of the idea of quantum tunneling. It may be that the example was given to illustrate the concept but students made a different meaning out of it.

Quantum Mechanics Lecturer notes

Interview results further revealed that quantum mechanics books /lecturer notes contributed to some of the student's alternative conceptions noted in this study. When we enquired from some students about the basis of their current understanding of the behavior of energy of a quantum tunneling particle, this is what came out from them.

Interviewer: What is the basis of your current understanding of the behavior of energy of a quantum tunneling particle?

Student A: I just can't clearly say Sir, but I remember what I learned about the tunneling graphs it shows something like a wave...not sure though but it kind of decays

Student B: From what I saw in the notes there is a substantiated exponential decay in the quantum tunneling graph

Student C: I have seen it in the notes sir... the electron's wavefunction seemed to decay across the barrier...

Student D: I know it, sir, I read it somewhere, it was just not clear though [Interview transcript]

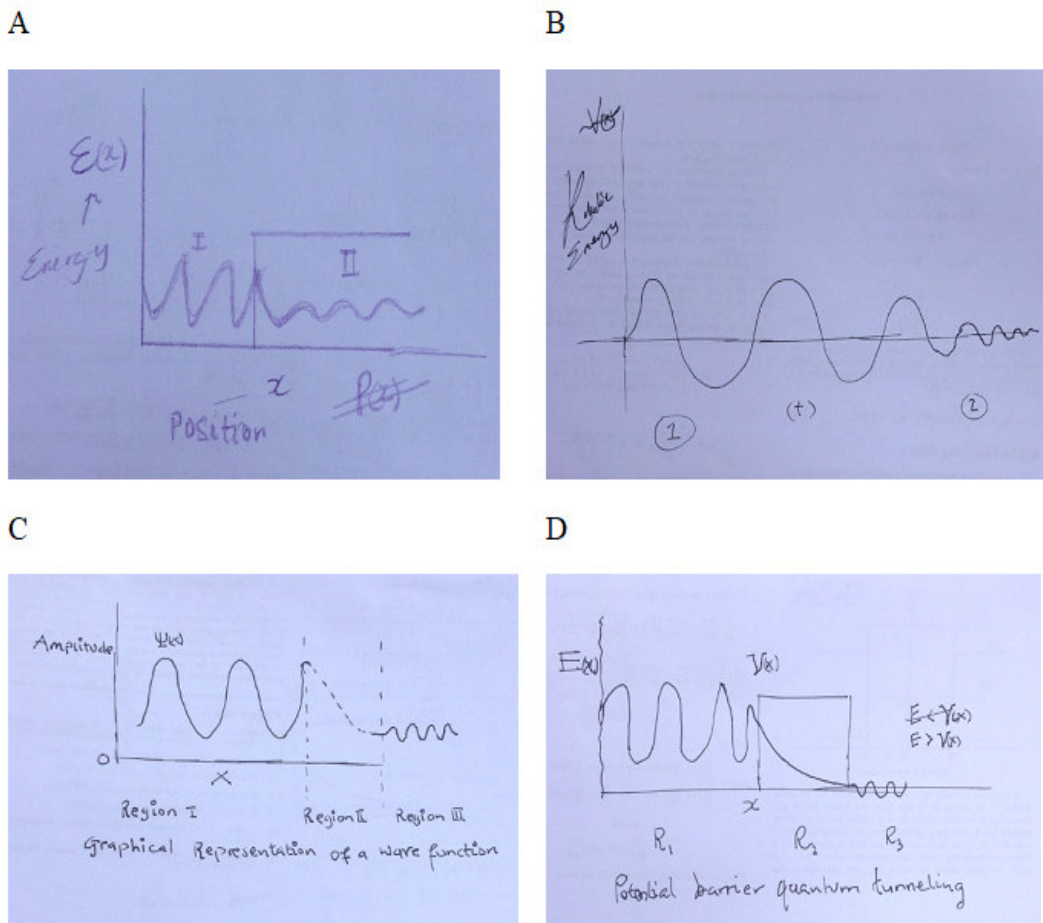


Figure 2. The set of students' sketches of the wave function

From this quote, we noted that students A, B, and C referred to what they saw in lecturer notes and what they learned in class. It must be noted that the books/lecturer notes that were used by our students gave a correct representation of the system, meanwhile, some of our students found it confusing to digest the information since the graphs were plotted on the same plane. For instance, reference can be made to the extract of the MIT lecturer notes that were used by our students.

To further the insight, we interviewed 7 students to provide sketches of all graphs associated with the QT phenomena based on what they have seen in books/lecturer notes or learned in class. six of the students managed

to provide reasonable sketches of the Potential, the Total energy, and $\Psi(x)$ when plotted on the same plane. Following what Wittman (2014) did in a similar study, we asked the six students to provide a plot of the $\Psi(x)$ on a separate plane, the results changed as only one student managed to provide a reasonable sketch. Consider the student sketches of the wave function in Figure 2

The notable similarity in the sketches is that all students managed to change the size of the wave function from various regions. Conversely, the labels of the axes are notably different. These four students whose sketches

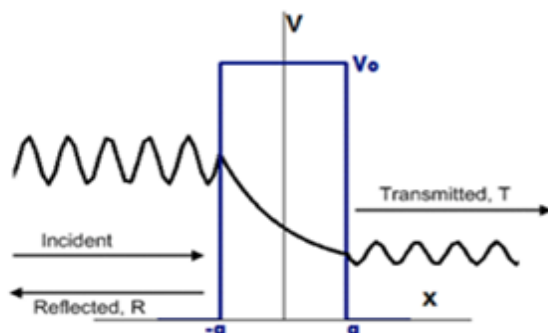


Figure 2. Sketch of tunneling
(adapted from 10.626 Electrochemical Energy Systems Spring 2014, page 4)

are shown above were then asked to justify the axis labels of their plots.

As seen in the sketches, Students **A** and **D** provided the graph of energy against the position and they reasoned that the wave function must have some energy so that it can probably tunnel through the potential barrier. This depicts an error in the understanding of the wave function. Student **B** reasoned that the wave function must have some kinetic energy that will be negative inside the barrier which over time will become constant. We noted that this student portrayed a surface understanding of the negative Kinetic Energy concept which is even a very useful concept in explaining why energy is not lost in QT. Student **C** managed to produce a fairly reasonable sketch of the $\Psi(x)$ and he reasoned that the $\Psi(x)$ does not tell us anything about the energy of the tunneling electron but the amplitude and position of the electron at some point. So much as we found some minor errors in his reasoning, student **C** managed to provide a logical understanding of the $\Psi(x)$.

We further requested the same four students, to interpret their graphs in terms of the energy of the tunneling quantum particle. It was not surprising to observe that students **A**, **B**, and **D** portrayed the energy loss alternative

conception since they used the changing amplitude of the $\Psi(x)$ graph to justify the energy loss. Exceptionally, student **C** described the $\Psi(x)$ graph as a map of the probable positions of finding the electron in space and has nothing to do with the energy of the electron.

From these interviews, it was observed that lecturer notes as they provided sketches of several graphs on a single axis made some students get confused about the meaning of the graphs. In our further

research, we have proposed the use of Physics Education Technology Simulations (PhET) in instruction since these graphs were sketched separately and there is the flexibility of changing some parameters.

Discussion

The present data points that traditional pedagogy did not facilitate some students with the enhanced conceptual understanding of this subject matter as evidenced by the persistence of some misconceptions even after a full course of instruction. We noted from this study that traditional pedagogy focused much on the mathematical formulation of quantum tunneling leaving students with no proper visualization that could advance their conceptual understanding of this topic. This was evidenced by the case of some students who got the right answers in the written survey but failed to give a correct scientific justification for their responses. This is in line with the results that were reported by Wieman et al., (2008), and McKagan (2008). We suggest that QM instructors should consider instruction strategies that focus on giving students some mental models as they would help them to make sense of the idea of tunneling.

The most prevailing students' alternative conception that was observed in this study was the students' belief that the energy of a tunneling electron is lost. It was observed that students' classical intuition of classical tunneling influenced this alternative conception. The closest idea of a macroscopic tunnel prompted students to think that the energy of a quantum tunneling particle will be lost upon tunneling. Morgan, Wittmann, and Thompson (2003) suggested several explanations for why students might believe that energy is lost in tunneling. One explanation is that some textbooks and lecturers draw the energy and the wave function on the same graph, leading many students to confuse the two, believing that the energy, like the wave function, decays exponentially during tunneling. This study reports similar findings. In addition, a summary of topics, methods, and common student difficulties in modern physics was prepared by Mckagan (2006), and Wieman (2009), who reported that the energy loss misconception is the most frequently reported misconception in literature. As we already pointed out, Singh (2006) similarly argued that this student's misconception about the energy loss of a tunneling electron is mostly based on teaching methods that do not provide a proper qualitative understanding of the learned concepts. We suggest teaching strategies that will be able to give students proper mental models of quantum tunneling phenomena. For example, the use of computer simulations (Erinosho, 2013).

Another prevailing challenge was for students to distinguish classical tunneling from quantum tunneling, we noted that students had incorrect overgeneralizations of concepts of tunneling based on their macroscopic understanding of the process of tunneling. As such, it was prone for them to think that the "potential step," and "barrier" mean a physical object/barrier and that the energy of a quantum tunneling electron is lost. According to these

findings, we recommend that instructors should provide separate sketches of the wave function and energy graphs when teaching this topic. Modern instruction technology such as computer simulations should also be built by taking into consideration these student difficulties. Emphasis should also be given to the qualitative understanding of the process of tunneling as similarly suggested by Witman (2014).

As suggested by Singh (2001), Singh (2006), Witman (2014), and Bungum (2018) we recommend further research into the use of modern technology and ICT to provide visual and interactive support in teaching which may help to establish students' conceptual understanding of quantum mechanics.

Recommendations

According to these findings we recommend that emphasis should also be given to the qualitative understanding of the process of tunneling. Most importantly, further research into teaching strategies that will give students effective models for learning QM concepts should be established as ICT and modern technology has the possibility of providing visual and interactive support in teaching which may help establish students' conceptual understanding of quantum mechanics.

Implication of the Results

These results of this study have the possibility of reforming and improving the quantum physics curriculum. Eliciting explicit instruction that may help to address the conceptual difficulties that students have with quantum tunneling. Identifying students' misconceptions can help to guide the development of research-based instructional materials for addressing these misconceptions.

Conclusion

With the help of the objective conceptual survey and the open-ended interviews, the

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study managed to come up with three different sets of students' alternative conceptions regarding quantum tunneling. which are, the student's belief that the “potential step,” and “barrier” mean a physical object/barrier, the belief that the wave function graph depicts the physical wave, and the belief that the energy of a quantum tunneling electron is lost. The study established that the sources of these alternative conceptions emanated from students' experience with classical tunneling, quantum mechanics lecturer notes, and previous quantum mechanics lessons. Since the concept of quantum tunneling cannot be physically perceived by both students and teachers, moreover, there are no proper models that may help instructors to demonstrate this concept to students. There is a need of developing research-based instructional materials that may help to facilitate students learning of quantum mechanics.

Ethical Policy

The research was conducted following the principles embodied in accordance with local statutory requirements. All participants (or their parent or legal guardian in the case of children under 16) gave written informed consent to participate in the study. The University of Rwanda College of education's directorate of research and innovation confirmed that this research adheres to ethical standards and policies.

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Appendix Quantum Tunneling Questionnaire

Instructions

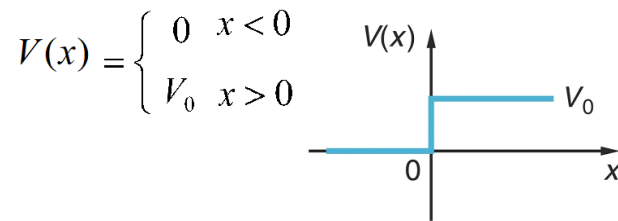
Time allowed: 20 Minutes

- i. Circle only one right option.
- ii. In case you do not know the right answer leave the question blank

I. An electron is traveling through a very long wire, approaching the end of the wire



The potential energy of this electron as a function of the position is given by:



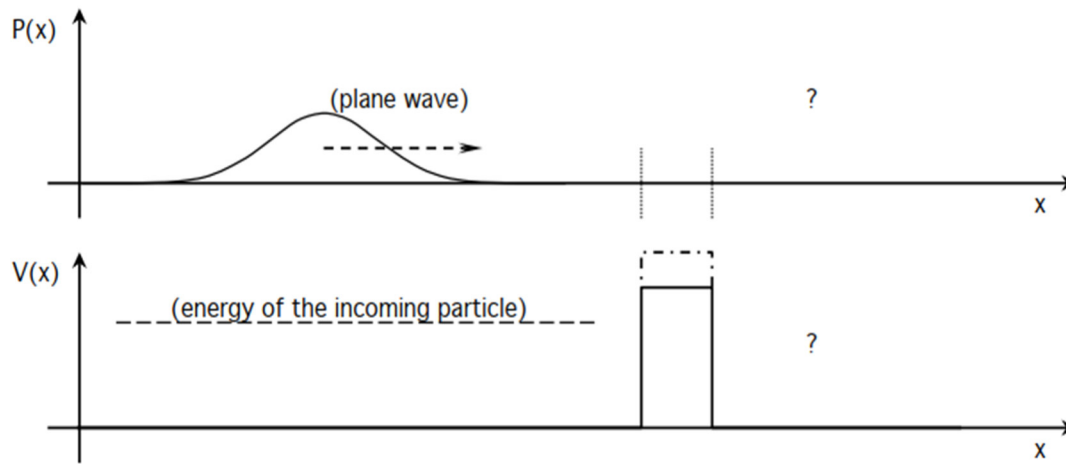
If the total energy E of the electron is **GREATER** than the work function of the metal, V_0 , when the electron reaches the end of the wire, it will?

- A. stop.
- B. be reflected.
- C. exit the wire and keep moving to the right.
- D. either be reflected or transmitted with some probability.

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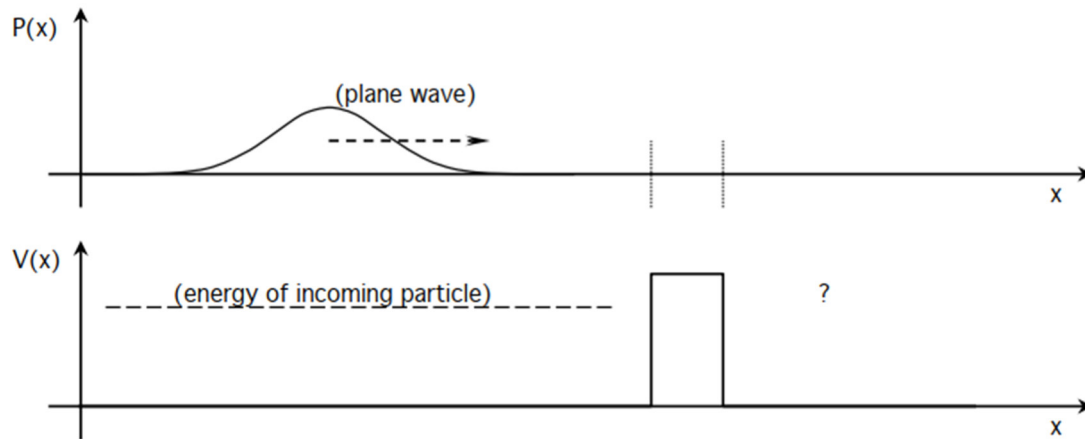
2.



An incoming plane wave encounters a potential barrier. The corresponding particle may tunnel through the barrier. How will the probability of tunnelling and the possibly transmitted particle's energy be affected if the barrier is *higher*?

- true false a) The energy of a transmitted particle decreases.
 true false b) The probability of tunnelling decreases.

3.



Some students are discussing energy loss when tunnelling. Who do you agree with the most?

- Alice: "A particle does not lose energy when tunnelling."
- Bob: "The energy for a particle that tunnels decreases exponentially with respect to the width of the barrier."
- Cedric: "There is energy loss, but not exponentially as Bob says."

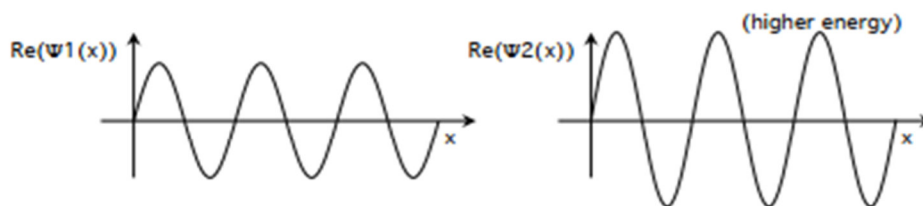
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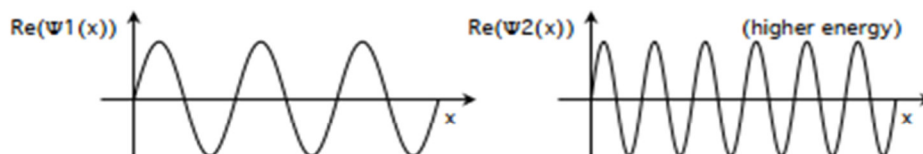
4.

$\Psi(x)$ describes a plane wave. Some students are discussing the relation between Ψ and the particle's energy. Who do you agree with the most? Choose one alternative only.

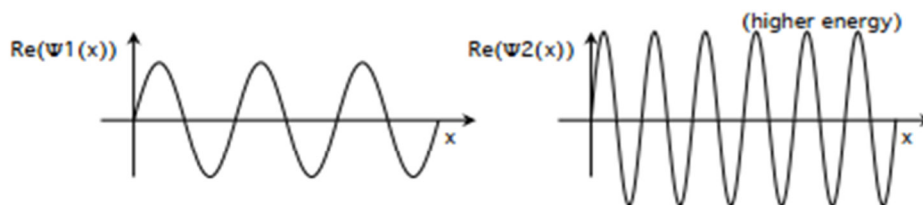
Alice: "For a particle with higher energy, Ψ will be greater in amplitude."



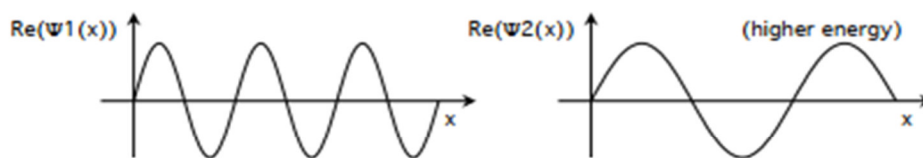
Bob: "For a particle with higher energy, the frequency of Ψ will be higher."



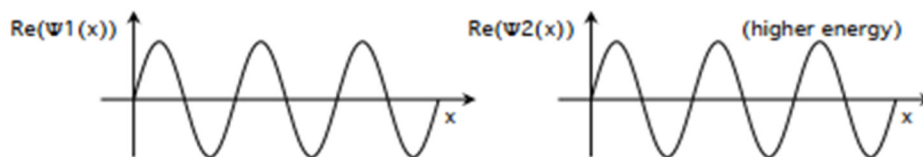
Cedric: "For a particle with higher energy, Ψ will be higher in both amplitude and frequency."



Daniel: "For a particle with higher energy, the wavelength of Ψ will be greater."



Eve: "Two particles with different energy can have the same wave function Ψ ."



SEMI-STRUCTURED INTERVIEW QUESTIONS

The copies of these questions were only available to the researchers and were dictated to a student at a time with minimum interference from other participants.

Backbone questions

1. What makes you feel that option (A, B, C, or D) is the correct answer for question number (1, 2, 3, 4)?
2. Explain why the other three options are not correct answers to this question?
3. Describe in your own words what the question is asking you to find.
4. Explain the meaning of the parameters (for example, symbols, graphs,) used in this question.

Follow up questions

Based on students' responses they will be asked to:

1. Explain further a concept
2. Explain where they got that idea from
3. Explain the connection between 'that concept' and quantum tunneling