Clicker Questions

Modern Physics

Chapter 6: "Unbound States"

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by Gary Felder and Kenny Felder

Instructions

- These questions are offered in two formats: a deck of PowerPoint slides, and a PDF file. The two files contain identical contents. There are similar files for each of the 14 chapters in the book, for a total of 28 files.
- Each question is marked as a "Quick Check" or "ConcepTest."
  - Quick Checks are questions that most students should be able to answer correctly if they have done the reading or followed the lecture. You can use them to make sure students are where you think they are before you move on.
  - ConcepTests (a term coined by Eric Mazur) are intended to stimulate debate, so you don't want to prep the class too explicitly before asking them. Ideally you want between 30% and 80% of the class to answer correctly.
- Either way, if a strong majority answers correctly, you can briefly discuss the answer and move on. If many students do not answer correctly, consider having them talk briefly in pairs or small groups and then vote again. You may be surprised at how much a minute of unguided discussion improves the hit rate.
- Each question is shown on two slides: the first shows only the question, and the second adds the correct answer.
- Some of these questions are also included in the book under "Conceptual Questions and ConcepTests," but this file contains additional questions that are not in the book.
- Some of the pages contain multiple questions with the same set of options. These questions are numbered as separate questions on the page.
- Some questions can have multiple answers. (These are all clearly marked with the phrase "Choose all that apply.") If you are using a clicker system that doesn't allow multiple responses, you can ask each part separately as a yes-or-no question.

6.1 Math Interlude: Standing Waves, Traveling Waves, and Partial Derivatives

Which of the following describes the evolution of a standing wave over time? (Choose one.)

A. The amplitude and the wavelength both change.

B. The amplitude changes but the wavelength doesn't.

C. The wavelength changes but the amplitude doesn't.

D. Neither the amplitude nor the wavelength changes.

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B. The amplitude changes but the wavelength doesn't.

C. The wavelength changes but the amplitude doesn't.

D. Neither the amplitude nor the wavelength changes.

Solution: B

A standing wave starts out in the form $y = 3\cos(2x)$. If you watch that standing wave over time, which of the following never changes? (Choose one.)

A. The x-intercepts.

B. The y-intercept.

C. The area under one wavelength's worth of the curve.

D. None of the above.

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D. None of the above.

Solution: A

If you watch a traveling wave over time, which of the following never changes? (Choose one.)

A. The x-intercepts.

B. The y-intercept.

C. The area under one wavelength's worth of the curve.

D. None of the above.

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A. The x-intercepts.

B. The y-intercept.

C. The area under one wavelength's worth of the curve.

D. None of the above.

Solution: C

Let $u(x, t)$ be the temperature along a rod. If the temperature is the same everywhere on the rod, and it's steadily getting hotter all over the rod at the same rate, which of the following is true? (Choose one.)

A. $(\partial u/\partial x) > (\partial u/\partial t)$

B. $(\partial u/\partial x) = (\partial u/\partial t)$

C. $(\partial u/\partial x) < (\partial u/\partial t)$

D. There's not enough information to tell.

Let $u(x,t)$ be the temperature along a rod. If the temperature is the same everywhere on the rod, and it's steadily getting hotter all over the rod at the same rate, which of the following is true? (Choose one.)

A. $(\partial u/\partial x) > (\partial u/\partial t)$

B. $(\partial u/\partial x) = (\partial u/\partial t)$

C. $(\partial u/\partial x) < (\partial u/\partial t)$

D. There's not enough information to tell.

Solution: C

If $f(x,t) = 2x^2 \sin(3t)$, which of the following is $\partial f/\partial x$? (Choose one.)

A. $4x$

B. $4x \sin(3t)$

C. $6x^2 \cos(3t)$

D. $12x \cos(3t)$

If $f(x,t) = 2x^2 \sin(3t)$, which of the following is $\partial f/\partial x$? (Choose one.)

A. $4x$

B. $4x \sin(3t)$

C. $6x^2 \cos(3t)$

D. $12x \cos(3t)$

Solution: B

What is the period of the function $f(t) = 2\sin(4t) + 3\sin(2t)$? (Choose one.)

A. 2

B. 4

C. $\pi/2$

D. π

E. This function doesn't have a well-defined period.

What is the period of the function $f(t) = 2\sin(4t) + 3\sin(2t)$? (Choose one.)

A. 2

B. 4

C. $\pi/2$

D. π

E. This function doesn't have a well-defined period.

Solution: D. Period is defined as the time it takes for the function to return to its original value and start repeating. The first sine has period $\pi/2$ and the second one has period π. After $t = \pi/2$ the first one will start repeating but the second one will be halfway through its period. After $t = \pi$ both sines will be back where they started, so that's when the whole function will start repeating.

The function $f(x, t)$ has the following two properties.

- If you look at the entire function at any particular moment in time, you see a sine wave in x.
- If you follow the function at any particular x-value, you see it oscillating sinusoidally in t.

Choose one.

A. This function is neither a standing wave nor a traveling wave.

B. This function might be a standing wave, but it is not a traveling wave.

C. This function might be a traveling wave, but it is not a standing wave.

D. This function might be a traveling wave, or it might be a standing wave.

E. This function could be both a traveling wave and a standing wave, because they are two mathematical forms for expressing the same motion.

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D. This function might be a traveling wave, or it might be a standing wave.

E. This function could be both a traveling wave and a standing wave, because they are two mathematical forms for expressing the same motion.

Solution: D

A curve is changing over time, so its height is given as a function $y(x,t)$. The partial derivative $\partial^2 y/\partial x^2$ is, in general…(Choose one.)

A. A constant.

B. A function of x but not t.

C. A function of t but not x.

D. A function of both x and t.

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A. A constant.

B. A function of x but not t.

C. A function of t but not x.

D. A function of both x and t.

Solution: D

A curve is changing over time, so its height is given as a function $y(x,t)$. At one particular place and time, the following "mixed partial derivative" is positive.

$$\frac{\partial}{\partial t}\left(\frac{\partial y}{\partial x}\right)$$

What does that tell you about the curve at that place and time? Choose one.

A. The slope of the curve is positive.

B. The curve is moving upward.

C. The concavity of the curve is positive.

D. The curve is accelerating upward.

E. The slope of the curve is getting higher over time.

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D. The curve is accelerating upward.

E. The slope of the curve is getting higher over time.

Solution: E. $(\partial y/\partial x)$ is the slope, and $\partial/\partial t$ of anything tells you how that thing is changing over time, so this tells you how the slope is changing.

6.2 Free Particles and Fourier Transforms

Why isn't it possible for a particle to have the following wavefunction?

$$\psi(x) = Ae^{ik_1 x} + Be^{ik_2 x}$$

(Choose one.)

A. It's not continuous.

B. It's not differentiable.

C. It's not normalizable.

D. It's not a solution to the time-independent Schrödinger equation.

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C. It's not normalizable.

D. It's not a solution to the time-independent Schrödinger equation.

Solution: C

The functions $\psi_\pi(x) = e^{i\pi x}$ and $\psi_{-\pi}(x) = e^{-i\pi x}$ represent...
(Choose one.)

A. Two different eigenstates of a free particle, representing two different energy levels.

B. Two different eigenstates of a free particle, both representing the same energy level.

C. The same eigenstate of a free particle, expressed in two different ways.

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(Choose one.)

A. Two different eigenstates of a free particle, representing two different energy levels.

B. Two different eigenstates of a free particle, both representing the same energy level.

C. The same eigenstate of a free particle, expressed in two different ways.

Solution: B

A Fourier transform is a mathematical technique for. . . (Choose one.)

A. Finding the complex exponential function that most nearly approximates a given function $f(x)$.

B. Writing a function $f(x)$ as a series of complex exponentials.

C. Writing a function $f(x)$ as an integral over complex exponentials.

D. Writing a function $f(x)$ as a polynomial.

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D. Writing a function $f(x)$ as a polynomial.

Solution: C

If you evaluated $\int_3^7 \frac{\sin(kx)}{e^{kx} - 2} dk$, you would end up with... (Choose one.)

A. A constant

B. A function of x

C. A function of k

D. A multivariate function of both x and k

If you evaluated $\int_3^7 \frac{\sin(kx)}{e^{kx}-2}dk$, you would end up with... (Choose one.)

A. A constant

B. A function of x

C. A function of k

D. A multivariate function of both x and k

Solution: B

True or false? If you know $\hat{\psi}(k)$ you can find the position probabilities for a particle.

True or false? If you know $\hat{\psi}(k)$ you can find the position probabilities for a particle.

Solution: True. From $\hat{\psi}(k)$ you can find $\psi(x)$, which gives the position probability density.

The integral $\int_0^{k_1} \left|\hat{\psi}(k)\right|^2 dk$ represents. . . (Choose one.)

A. The probability of finding a free particle's energy between 0 and $\hbar^2 k_1^2/(2m)$.

B. *Half* the probability of finding a free particle's energy between 0 and $\hbar^2 k_1^2/(2m)$.

C. Neither of those things.

The integral $\int_0^{k_1} \left|\hat{\psi}(k)\right|^2 dk$ represents... (Choose one.)

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B. *Half* the probability of finding a free particle's energy between 0 and $\hbar^2 k_1^2/(2m)$.

C. Neither of those things.

Solution: C. The probability of finding the particle's energy between 0 and $\hbar^2 k_1^2/(2m)$ is $\int_{-k_1}^{k_1} \left|\hat{\psi}(k)\right|^2 dk$, but there's no guarantee that the lower half of that integral is equal to the upper half, so just going the upper half doesn't necessarily give you half the probability.

If you follow the function $e^{i(kx-\omega t)}$ over time, you will see that... (Choose one.)

A. At any given x-value, the function rotates in a circle around the complex plane.

B. The entire function keeps its shape but moves at constant speed along the x-axis.

C. Both A. and B. are correct; they are actually saying the same thing in this case.

D. Neither A. nor B. is correct.

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C. Both A. and B. are correct; they are actually saying the same thing in this case.

D. Neither A. nor B. is correct.

Solution: C. You can plot a complex function of x in three dimensions by plotting the real and imaginary parts of the function in the y and z directions. If you do, this function at any moment will spiral around the x axis. As it moves to the right each point on the x axis rotates. (Picture a barber pole.)

6.3 Momentum Eigenstates

Suppose $\hat{\psi}(3) = 1/3$ and $\hat{\psi}(5) = 1/5$. Which of the following are true? (Choose all that apply.)

A. The probability of measuring a position of 3 is $1/9$.

B. The probability of measuring a momentum of $3\hbar$ is $1/9$.

C. The probability of measuring a momentum between $3\hbar$ and $5\hbar$ is $\int_3^5 \hat{\psi}(k)\, dk$.

D. The probability of measuring a momentum between $3\hbar$ and $5\hbar$ is $\int_3^5 |\hat{\psi}(k)|^2\, dk$.

E. The particle is more likely to have a momentum very near $p = 3\hbar$ than very near $p = 5\hbar$.

F. The particle is more likely to have a momentum very near $p = 5\hbar$ than very near $p = 3\hbar$.

Suppose $\hat{\psi}(3) = 1/3$ and $\hat{\psi}(5) = 1/5$. Which of the following are true? (Choose all that apply.)

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F. The particle is more likely to have a momentum very near $p = 5\hbar$ than very near $p = 3\hbar$.

Solution: D and E

The function Ce^{ikx} is… (Choose all that apply.)

A. An eigenstate of energy, but only for a free particle.

B. An eigenstate of energy for any particle.

C. An eigenstate of momentum, but only for a free particle.

D. An eigenstate of momentum for any particle.

E. A physically impossible wavefunction that no particle could ever actually have.

The function Ce^{ikx} is... (Choose all that apply.)

A. An eigenstate of energy, but only for a free particle.

B. An eigenstate of energy for any particle.

C. An eigenstate of momentum, but only for a free particle.

D. An eigenstate of momentum for any particle.

E. A physically impossible wavefunction that no particle could ever actually have.

Solution: A, D, and E

Rewriting a wavefunction $\psi(x)$ in the form $A\int \hat{\psi}(k)e^{ikx}dk$ makes it easier to…(Choose one.)

A. Find the probability density associated with different values of the momentum.

B. Find the probability density associated with different values of the position.

C. Find the relationship between the position and the momentum.

D. Normalize the wavefunction.

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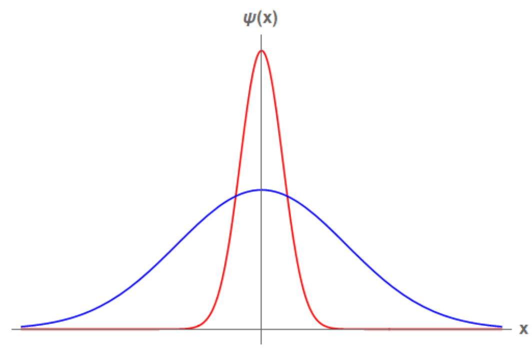
D. Normalize the wavefunction.

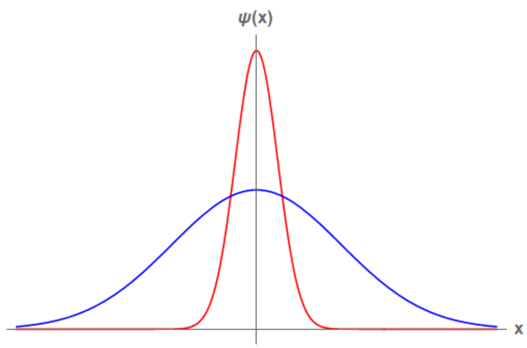
Solution: A

The figure shows two wavefunctions.



1. Which particle is more likely to be found with position very close to zero, the red or the blue?
2. Which particle is more likely to be found with momentum very close to zero, the red or the blue? *Hint:* Both of their momentum probability distributions peak at $p = 0$.

The figure shows two wavefunctions.



1. Which particle is more likely to be found with position very close to zero, the red or the blue?

   Solution: red

2. Which particle is more likely to be found with momentum very close to zero, the red or the blue? *Hint:* Both of their momentum probability distributions peak at $p = 0$.

   Solution: blue

Particle 1 has wavefunction $\psi_1(x) = Ae^{-c^2x^2}$ and Particle 2 has wavefunction $\psi_2 = Be^{-2c^2x^2}$. Which of the following describes their momentum probabilities? (Choose one.)

A. Particle 1 is more likely than Particle 2 to be found with momentum $0 < p < \hbar c$.

B. Particle 2 is more likely than Particle 1 to be found with momentum $0 < p < \hbar c$.

C. They are equally likely to be found with momentum $0 < p < \hbar c$.

D. You don't have enough information to determine which is more likely.

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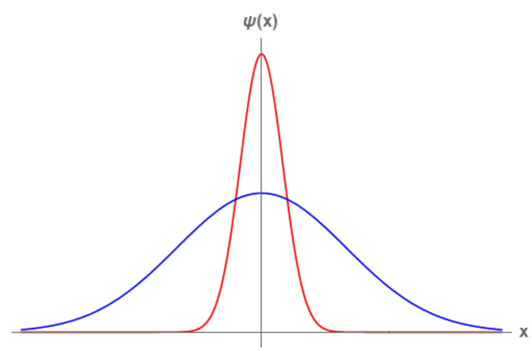
D. You don't have enough information to determine which is more likely.

Solution: A. If you graphed those two functions, you would find that $\psi_2(x)$ is thinner than $\psi_1(x)$. That means its $\hat{\psi}(k)$ function is wider, so it has less likelihood of being found near the center (0) and more further out.

Particle 1 has wavefunction $\psi_1(x) = Ae^{-(x/L)^2}$. The probability of measuring $-\hbar/L < p_1 < \hbar/L$ is 68%. Particle 2 has wavefunction $\psi_2(x) = Be^{-(4x/L)^2}$. (The figure shows ψ_1 in blue and ψ_2 in red.) Which of the following is true of the momentum probabilities for Particle 2? (Choose one and explain your choice.)



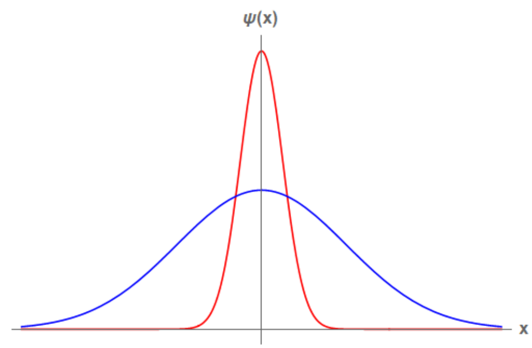
A. There's an 17% chance of finding $-\hbar/L < p_2 < \hbar/L$.

B. There's a 68% chance of finding $-4\hbar/L < p_2 < 4\hbar/L$.

C. Both A and B

D. Neither A nor B

Particle 1 has wavefunction $\psi_1(x) = Ae^{-(x/L)^2}$. The probability of measuring $-\hbar/L < p_1 < \hbar/L$ is 68%. Particle 2 has wavefunction $\psi_2(x) = Be^{-(4x/L)^2}$. (The figure shows ψ_1 in blue and ψ_2 in red.) Which of the following is true of the momentum probabilities for Particle 2? (Choose one and explain your choice.)



A. There's an 17% chance of finding $-\hbar/L < p_2 < \hbar/L$.

B. There's a 68% chance of finding $-4\hbar/L < p_2 < 4\hbar/L$.

C. Both A and B

D. Neither A nor B

Solution: B

When you see that the wavefunction $\psi_1(x) = Ae^{-(x/L)^2}$ gives a momentum probability of 68% of measuring $-\hbar/L < p_1 < \hbar/L$, that result is independent of what L is. It would work with any length.

So we can rewrite $\psi_2(x)$ as $Be^{-[x/(L/4)]^2}$ and the same math must work with the new length $L/4$. That is, there must be a 68% probability of finding $\hbar/(L/4) < p_2 < \hbar/(L/4)$.

The Example on p. 274 gave you the wavefunction of a free particle and found that the probability you would measure the particle's energy to be greater than $\hbar^2/(mL^2)$ was 16%. What is the probability that you would measure its momentum to be between $-\sqrt{2}\hbar/L$ and $\sqrt{2}\hbar/L$?

A. 16%

B. 8%

C. 32%

D. 84%

E. 42%

The Example on p. 274 gave you the wavefunction of a free particle and found that the probability you would measure the particle's energy to be greater than $\hbar^2/(mL^2)$ was 16%. What is the probability that you would measure its momentum to be between $-\sqrt{2}\hbar/L$ and $\sqrt{2}\hbar/L$?

A. 16%

B. 8%

C. 32%

D. 84%

E. 42%

Solution: D

From $E = p^2/(2m)$ we see that those momentum values both correspond to $E = \hbar^2/(mL^2)$. So any momentum between those two values gives you an energy *less* than $\hbar^2/(2m)$. So the probability is 100% minus the 16% calculated in that example. You can also see this if you look at the example, where the probability we're asking about here is the *unshaded* part of the image.

6.4 Phase Velocity and Group Velocity

A proton, currently experiencing no forces, shoots through space at 1 million miles/hour. Which of the following are true? (Check all that apply.)

A. The proton's wavefunction can be expressed as a discrete sum of energy eigenstates:

$$\Psi(x,t) = \sum_{k=-\infty}^{\infty} C_k e^{i(kx-\omega t)}$$

B. The proton's wavefunction can be expressed as an integral over energy eigenstates:

$$\Psi(x,t) = \int_{-\infty}^{\infty} C_k e^{i(kx-\omega t)} dk$$

C. Each individual eigenstate is moving through space at approximately 1 million miles/hour.

D. The eigenstates combined have a "group velocity" of 1 million miles/hour.

E. For this proton's energy eigenstates, $d\omega/dk \approx 1$ million miles/hour.

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D. The eigenstates combined have a "group velocity" of 1 million miles/hour.

E. For this proton's energy eigenstates, $d\omega/dk \approx 1$ million miles/hour.

Solution: B, D, E

Alice is holding one end of a rope and gives it a quick shake, which sends a bump moving along the rope. The velocity of that bump is a . . . (Choose one.)

A. Phase velocity

B. Group velocity

C. Neither phase velocity nor group velocity

D. Both, because these are two different ways of describing the same thing

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A. Phase velocity

B. Group velocity

C. Neither phase velocity nor group velocity

D. Both, because these are two different ways of describing the same thing

Solution: B

Which of the following is true about a sum of two cosines? (Choose one.)

A. Group velocity is always faster than phase velocity.

B. Group velocity is always equal to phase velocity.

C. Group velocity is always slower than phase velocity.

D. Group velocity can be faster than or slower than phase velocity.

Which of the following is true about a sum of two cosines? (Choose one.)

A. Group velocity is always faster than phase velocity.

B. Group velocity is always equal to phase velocity.

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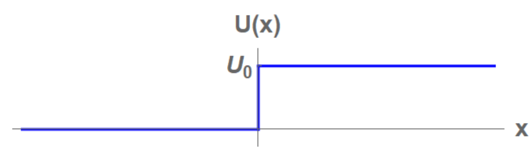
D. Group velocity can be faster than or slower than phase velocity.

Solution: D. Based on the equations $v_p = \omega/k$ and $v_g = \Delta\omega/\Delta k$, it could go either way.

6.5 Scattering and Tunneling

The figure shows a "potential step": $U(x) = 0$ for $x < 0$, and $U(x) = U_0$ for $x \geq 0$.



What does this step represent in terms of forces? (Choose one.)

A. There is no force anywhere except for a leftward-pointing force at (or very near) $x = 0$.

B. There is no force in the $x < 0$ region, but a constant force for all $x \geq 0$.

C. There is no force in the $x < 0$ region, but a force in $x \geq 0$ that linearly increases with x.

D. The potential graph does not contain enough information to describe the forces.

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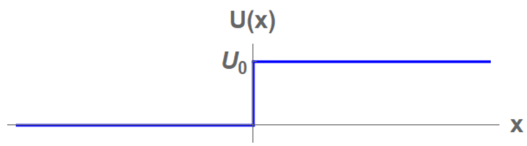

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C. There is no force in the $x < 0$ region, but a force in $x \geq 0$ that linearly increases with x.

D. The potential graph does not contain enough information to describe the forces.

Solution: A

A particle with energy E approaches a potential step of energy U_0. (Choose one.)

A. The particle has some chance of bouncing back and some chance of continuing on, regardless of the energies.

B. The particle will always bounce back, regardless of the energies.

C. If $E < U_0$ the particle will always bounce back, and if $E > U_0$ it will always continue on.

D. If $E < U_0$ the particle will always bounce back, and if $E > U_0$ it will have some chance of bouncing back and some chance of continuing on.

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A. The particle has some chance of bouncing back and some chance of continuing on, regardless of the energies.

B. The particle will always bounce back, regardless of the energies.

C. If $E < U_0$ the particle will always bounce back, and if $E > U_0$ it will always continue on.

D. If $E < U_0$ the particle will always bounce back, and if $E > U_0$ it will have some chance of bouncing back and some chance of continuing on.

Solution: D

An energy eigenstate (or part of an energy eigenstate) of the form Ce^{-ikx} for positive k represents which of the following? Assume $E > 0$. (Choose one.)

A. A wave moving at constant speed to the right.

B. A wave moving at constant speed to the left.

C. A wave that only exists for a particle moving to the right.

D. A wave that only exists for a particle moving to the left.

E. None of the above.

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C. A wave that only exists for a particle moving to the right.

D. A wave that only exists for a particle moving to the left.

E. None of the above.

Solution: B

In Equation 6.16 (p. 298) we left out a term of the form e^{-ikx} in the region $x > 0$ because ... (Choose one.)

A. That term can't be normalized.

B. That term is part of an energy eigenstate, but it doesn't appear in the particular scenario we are considering.

C. That term is not part of an energy eigenstate.

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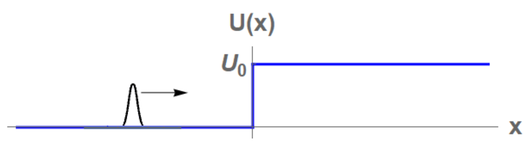
Solution: B

The figure represents the wavefunction of a particle.



Suppose this particle is moving at 30 m/s. This tells us that... (Choose one.)

A. All the pieces of this particle's energy eigenstates are moving at or near 30 m/s.

B. The incident waves are moving at or near 30 m/s, but the other parts of the eigenstates may not be.

C. The group velocity of the wave packet is 30 m/s.

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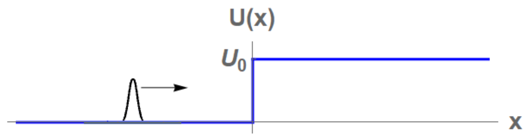

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C. The group velocity of the wave packet is 30 m/s.

Solution: C. The waves that make it up can all be moving at different velocities, but the group velocity corresponds to the observed motion of the particle.

In Equation 6.15 on p. 296, the constant A... (Choose one.)

A. must be determined by boundary conditions, but for any given particle, is a constant.

B. could have a different value for every value of x.

C. could have a different value for every value of t.

D. could have a different value for every value of E.

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Solution: D. A wave packet is a superposition of energy eigenstates, each with a different energy and a different amplitude.

When a classical particle hits a potential barrier with $E > U_0$, the particle continues to the right slower than its original speed. What does that suggest about the behavior of a quantum mechanical wavefunction in the same situation? (Choose one.)

A. The eigenstates on the right side of the barrier, which represent traveling waves, will move more slowly than the eigenstates on the left side of the barrier.

B. The individual eigenstates will not move more slowly, but their group velocity will be slower.

C. Neither of these is necessarily true.

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B. The individual eigenstates will not move more slowly, but their group velocity will be slower.

C. Neither of these is necessarily true.

Solution: B

6.6 The Time-Dependent Schrödinger Equation

Which of the following are separable functions? (Choose all that apply.)

A. $f_1(x, y) = x^3 \sin(3y)$

B. $f_2(x, y) = x^3 + \sin(3y)$

C. $f_3(x, y) = \sin(3x^3 y)$

D. $f_4(x, y) = \sin(x^3 + 3y)$

E. $f_5(x, y) = 17$

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E. $f_5(x, y) = 17$

Solution: A and E

Suppose $f(x, y) = g(y, z)$ for all values of x, y, and z. What can you conclude? (Choose one.)

A. The function f depends on z.

B. Both functions f and g are constants.

C. Both functions f and g can depend on y, but not on x or z.

D. You can't conclude any of those things without knowing more about the functions.

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Solution: C

The time-dependent Schrödinger equation can be used to derive which of the following facts? (Choose all that apply.)

A. The probability density distribution for a particle with wave-function $\psi(x)$ is $|\psi(x)|^2$.

B. The momentum eigenstates of a particle are of the form Ce^{ikx}.

C. The solutions to the time-independent Schrödinger equation evolve through time by multiplying by $e^{iEt/\hbar}$.

D. Some cats are both alive and dead at the same time.

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C. The solutions to the time-independent Schrödinger equation evolve through time by multiplying by $e^{iEt/\hbar}$.

D. Some cats are both alive and dead at the same time.

Solution: C

True or false? All solutions to the time-dependent Schrödinger equation are separable.

True or false? All solutions to the time-dependent Schrödinger equation are separable.

Solution: False. Every solution can be built as a linear combination of separable solutions, but those combinations themselves do not have to be separable. (The function x is separable, and the function t is separable, but the function $x+t$ is not.)

Which of the following represent separable functions? Choose all that apply.

A. $f_1(x, y) = (x + y)^2 - (x - y)^2$

B. $f_2(x, y) = e^{2x+3y}$

C. $f_3(x, y) = \left(e^{2x}\right)^{3y}$

D. $f_4(x, y) = \ln(xy)$

E. $f_5(x, y) = \sin(x + y)$

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Solution: A, because it simplifies to $4xy$.
B, because it simplifies to $e^{2x}e^{3y}$.
None of the others can be simplified into a product of a function of x times a function of t.