Clicker Questions

Modern Physics
Chapter 7: “The Hydrogen Atom”
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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.

7.1 Quantum Numbers of the Hydrogen Atom

Which of the following are possible hydrogen atom eigenstates? (Choose all that apply.)

A. $\psi_{1,1,1}$

B. $\psi_{2,1,1}$

C. $\psi_{2,1,-1}$

D. $\psi_{2,1,-2}$

Which of the following are possible hydrogen atom eigenstates? (Choose all that apply.)

A. $\psi_{1,1,1}$

B. $\psi_{2,1,1}$

C. $\psi_{2,1,-1}$

D. $\psi_{2,1,-2}$

Solution: B and C

For each of the following, say whether it is possible for a hydrogen atom eigenstate.

1. $|\vec{L}| = \hbar$
2. $L_z = \hbar$
3. $L_z > |\vec{L}|$

For each of the following, say whether it is possible for a hydrogen atom eigenstate.

1. $|\vec{L}| = \hbar$

   Solution: impossible

2. $L_z = \hbar$

   Solution: possible

3. $L_z > |\vec{L}|$

   Solution: impossible

Recall that the “degeneracy” of an energy level refers to how many independent quantum states correspond to the same energy. What is the degeneracy of the energy level $n = 2$ for a hydrogen atom? (Choose one.)

A. 0

B. 1

C. 2

D. 3

E. 4

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A. 0

B. 1

C. 2

D. 3

E. 4

Solution: E

Which of the following is definitely specified in a hydrogen atom eigenstate ψ_{nlm_l}? (Choose all that apply.)

A. Energy

B. The z-component of linear momentum

C. The z-component of angular momentum

D. The magnitude of linear momentum

E. The magnitude of angular momentum

F. The speed

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B. The z-component of linear momentum

C. The z-component of angular momentum

D. The magnitude of linear momentum

E. The magnitude of angular momentum

F. The speed

Solution: A, C, and E

Of the five hydrogen atom eigenstates listed below, which two represent different states with the same energy?

A. $\psi_{5,2,1}$

B. $\psi_{4,2,1}$

C. $\psi_{4,2,2}$

D. $\psi_{3,0,0}$

E. $\psi_{2,0,0}$

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B. $\psi_{4,2,1}$

C. $\psi_{4,2,2}$

D. $\psi_{3,0,0}$

E. $\psi_{2,0,0}$

Solution: B and C

Which of the following are true of the quantum number n for a hydrogen atom eigenstate? (Choose all that apply.)

A. It can never be bigger than $\hbar$.

B. It must always be an integer.

C. It can never be a prime number greater than 2.

D. It must be between the quantum numbers m_l and l.

E. It tells us the energy of the electron state.

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D. It must be between the quantum numbers m_l and l.

E. It tells us the energy of the electron state.

Solution: B and E

Suppose a hydrogen atom is in the state $\psi_{3,2,1}$. You measure L_z, then measure L_x, and then measure L_z again. Are you guaranteed to get the same answer for L_z both times?

Suppose a hydrogen atom is in the state $\psi_{3,2,1}$. You measure L_z, then measure L_x, and then measure L_z again. Are you guaranteed to get the same answer for L_z both times?

Solution: No. They have an uncertainty relationship, so certain knowledge of one destroys certain knowledge of the other.

The function $(1/2)\psi_{4,3,1}+(\sqrt{3}/2)\psi_{4,1,0}$ is an eigenstate of energy, but not of angular momentum magnitude. Is it possible to have the reverse: an eigenstate of angular momentum magnitude that is not an eigenstate of energy?

The function $(1/2)\psi_{4,3,1} + (\sqrt{3}/2)\psi_{4,1,0}$ is an eigenstate of energy, but not of angular momentum magnitude. Is it possible to have the reverse: an eigenstate of angular momentum magnitude that is not an eigenstate of energy?

Solution: Yes, for example $(1/2)\psi_{4,1,1} + (\sqrt{3}/2)\psi_{3,1,0}$. In general, any superposition of states with the same l but different n will work.

7.2 The Schrödinger Equation in Three Dimensions

If the function $\psi(x, y, z)$ is constant over some small sphere in space, how do you find the probability that the particle is inside that sphere? (Choose one.)

A. Multiply $|\psi|$ by the radius of the sphere.

B. Multiply $|\psi|^2$ by the radius of the sphere.

C. Multiply ψ by the volume of the sphere.

D. Multiply $|\psi|^2$ by the volume of the sphere.

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B. Multiply $|\psi|^2$ by the radius of the sphere.

C. Multiply ψ by the volume of the sphere.

D. Multiply $|\psi|^2$ by the volume of the sphere.

Solution: D

The general solution to the equation $X''(x) = -k^2 X(x)$ is $X(x) = A\sin(kx) + B\cos(kx)$. When we solved for the eigenstates of the particle in a box, why did we only use a sine and not a cosine? (Choose one.)

A. The cosine does not fit the differential equation.

B. It was arbitrary; we could have gone the other way, as long as we were consistent.

C. The cosine fits the differential equation, but not the boundary conditions.

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A. The cosine does not fit the differential equation.

B. It was arbitrary; we could have gone the other way, as long as we were consistent.

C. The cosine fits the differential equation, but not the boundary conditions.

Solution: C

Which of the following are true about the quantum numbers a, b, and c in a given eigenstate ψ_{abc}? (Choose all that apply.)

A. They must be positive integers.

B. No two of them can be the same.

C. You need to know all three of them to know the state that ψ_{abc} describes.

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A. They must be positive integers.

B. No two of them can be the same.

C. You need to know all three of them to know the state that ψ_{abc} describes.

Solution: A and C

Which of the following *best* describes why our solution to the three-dimensional particle in a box involved discrete (as opposed to continuous) energy levels? (Choose one.)

A. The math led to continuous solutions, and then we introduced quantization because it's one of the rules of quantum mechanics.

B. The general solution to Schrödinger's equation with $U = 0$ is quantized.

C. The general solution is not quantized, but the boundary conditions led to quantized energy levels.

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B. The general solution to Schrödinger's equation with $U = 0$ is quantized.

C. The general solution is not quantized, but the boundary conditions led to quantized energy levels.

Solution: C

Why does the constant at the front of ψ_{abc} have to equal $\sqrt{8/L^3}$? (Choose one.)

A. It wouldn't solve Schrödinger's equation for any other constant.

B. It wouldn't match the boundary conditions for any other constant.

C. The position probabilities wouldn't be normalized for any other constant.

D. All of the above

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A. It wouldn't solve Schrödinger's equation for any other constant.

B. It wouldn't match the boundary conditions for any other constant.

C. The position probabilities wouldn't be normalized for any other constant.

D. All of the above

Solution: C

If a particle in a box is in the state $\psi(x, y, z) = c_{1,2,1}\psi_{1,2,1} + c_{2,3,1}\psi_{2,3,1}$ then the two constants must satisfy $|c_{1,2,1}|^2+|c_{2,3,1}|^2 = 1$ because… (Choose one.)

A. Otherwise $\psi(x, y, z)$ wouldn't solve Schrödinger's equation.

B. Otherwise $\psi(x, y, z)$ wouldn't match the boundary conditions.

C. Otherwise the energy probabilities wouldn't make sense.

D. All of the above

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A. Otherwise $\psi(x, y, z)$ wouldn't solve Schrödinger's equation.

B. Otherwise $\psi(x, y, z)$ wouldn't match the boundary conditions.

C. Otherwise the energy probabilities wouldn't make sense.

D. All of the above

Solution: C

Given the equation $f(x, y) = g(x, t)$, which of the following can you conclude? (Choose one.)

A. This equation is impossible for any functions.

B. Both sides can be functions of x, but not of y or t.

C. Both sides can be functions of y and t, but not of x.

D. Both sides must equal a constant.

E. None of the above.

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B. Both sides can be functions of x, but not of y or t.

C. Both sides can be functions of y and t, but not of x.

D. Both sides must equal a constant.

E. None of the above.

Solution: B

Box A contains a particle in the state $\psi_{1,2,1}$ and Box B contains a particle in the state $\psi_{1,3,1}$. In which box, A or B, are you more likely to find the particle very close to $y = L/2$?

Box A contains a particle in the state $\psi_{1,2,1}$ and Box B contains a particle in the state $\psi_{1,3,1}$. In which box, A or B, are you more likely to find the particle very close to $y = L/2$?

Solution: Box B.

Here are the two wavefunctions.

$$\psi_{1,2,1}(x, y, z) = \sqrt{\frac{8}{L^3}} \sin\left(\frac{\pi}{L}x\right) \sin\left(\frac{2\pi}{L}y\right) \sin\left(\frac{\pi}{L}z\right)$$
$$\psi_{1,3,1}(x, y, z) = \sqrt{\frac{8}{L^3}} \sin\left(\frac{\pi}{L}x\right) \sin\left(\frac{3\pi}{L}y\right) \sin\left(\frac{\pi}{L}z\right)$$

Looking at the middle factor (where the y-dependence lives) we see that at $y = L/2$ the two functions give 0 and -1, respectively. Since probability goes like $|\psi|^2$, we know that $\psi_{1,3,1}$ has much higher probability.

You have two cubical boxes, each containing a particle in its ground state. Box A is 1 meter across and Box B is 2 meters across. In which box is $|\psi|^2$ larger in the middle of the box? (Choose one.)

A. Box A

B. Box B

C. They are equal

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A. Box A

B. Box B

C. They are equal

Solution: The answer is A.

Because $|\psi|^2$ is probability *per unit volume* and Box B has more volume, it must on average have a smaller $|\psi|^2$, so it's larger in Box A. You can check this by looking at the formula for the eigenstate and noting that in both boxes $\psi = \sqrt{8/L^3}$ in the middle of the box for the ground state. Since L is bigger in Box B, ψ and $|\psi|^2$ are bigger in Box A.

Which of the following are possible wavefunctions for a particle in a 3D cubical box of side length L? Choose all that apply. (Assume the constants A and B are chosen to normalize the functions correctly.)

A. $\psi(x, y, z) = A\sin(\pi x/L)\sin(\pi y/L)\sin(\pi z/L)$

B. $\psi(x, y, z) = A\sin(\pi x/L)\sin(\pi y/L)\sin(\pi z/L) + B\sin(\pi x/L)\sin(2\pi y/L)\sin(\pi z/L)$

C. $\psi(x, y, z) = A\sin(\pi x/L)\sin(\pi y/L)\cos(\pi z/L)$

D. $\psi(x, y, z) = A\sin(\pi x/L)\sin(\pi y/L)z(z - L)$

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C. $\psi(x, y, z) = A\sin(\pi x/L)\sin(\pi y/L)\cos(\pi z/L)$

D. $\psi(x, y, z) = A\sin(\pi x/L)\sin(\pi y/L)z(z - L)$

Solution: Parts A, B, and D all match the boundary conditions and are therefore possible. Part C does not go to zero at $z = 0$, so it is not possible.

Recall that a particle doesn't have to be in an energy eigenstate. But any valid state can be written as a sum of energy eigenstates. So even though it doesn't look like it you are guaranteed that (d) can be written as a sum of those sine wave functions. (The method for doing that, which you may or may not have encountered yet, is called "Fourier series.")

7.3 Math Interlude: Spherical Coordinates

Can r ever be less than x for a point? (Assume r is positive.)

Can r ever be less than x for a point? (Assume r is positive.)

Solution: no

For each Cartesian point (x, y, z) below, choose which set of spherical coordinates (r, θ, ϕ) matches it. You should be able to answer by picturing where each point is, rather than by plugging into formulas.

1. $(3, 0, 0)$
   - A. $(3, 0, 0)$
   - B. $(3, \pi/2, 0)$
   - C. $(3, 0, \pi/2)$
   - D. $(3, \pi/2, \pi/2)$
2. $(0, 0, -2)$
   - A. $(0, 0, -2)$
   - B. $(2, \pi/2, 0)$
   - C. $(-2, \pi, 0)$
   - D. $(2, \pi, 0)$

For each Cartesian point (x, y, z) below, choose which set of spherical coordinates (r, θ, ϕ) matches it. You should be able to answer by picturing where each point is, rather than by plugging into formulas.

1. $(3, 0, 0)$

   A. $(3, 0, 0)$
   B. $(3, \pi/2, 0)$
   C. $(3, 0, \pi/2)$
   D. $(3, \pi/2, \pi/2)$

   Solution: B

2. $(0, 0, -2)$

   A. $(0, 0, -2)$
   B. $(2, \pi/2, 0)$
   C. $(-2, \pi, 0)$
   D. $(2, \pi, 0)$

   Solution: D. (Technically ϕ doesn't matter on the z axis, so $(2, \pi, \text{anything})$ would be valid.)

For each spherical point (r, θ, ϕ) below, choose which set of Cartesian coordinates (x, y, z) matches it. You should be able to answer by picturing where each point is, rather than by plugging into formulas.

1. $(5, 0, \pi/4)$
   A. $(5, 0, \pi/4)$
   B. $(5/\sqrt{2}, 5/\sqrt{2}, 0)$
   C. $(5/\sqrt{2}, 0, 5/\sqrt{2})$
   D. $(0, 0, 5)$
2. $(\sqrt{2}, \pi/2, \pi/4)$
   A. $(\sqrt{2}, \pi/2, \pi/4)$
   B. $(1, 1, 0)$
   C. $(1, 0, 1)$
   D. $(0, 0, \sqrt{2})$

For each spherical point (r, θ, ϕ) below, choose which set of Cartesian coordinates (x, y, z) matches it. You should be able to answer by picturing where each point is, rather than by plugging into formulas.

1. $(5, 0, \pi/4)$
   - A. $(5, 0, \pi/4)$
   - B. $(5/\sqrt{2}, 5/\sqrt{2}, 0)$
   - C. $(5/\sqrt{2}, 0, 5/\sqrt{2})$
   - D. $(0, 0, 5)$

   Solution: D

2. $(\sqrt{2}, \pi/2, \pi/4)$
   - A. $(\sqrt{2}, \pi/2, \pi/4)$
   - B. $(1, 1, 0)$
   - C. $(1, 0, 1)$
   - D. $(0, 0, \sqrt{2})$

   Solution: B

7.4 Schrödinger's Equation and the Hydrogen Atom

We approach the hydrogen atom in spherical coordinates rather than Cartesian because… (Choose one)

A. The potential energy function is simpler.

B. The boundary conditions are simpler.

C. The normalization condition is simpler.

D. The limits of integration are finite rather than infinite.

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A. The potential energy function is simpler.

B. The boundary conditions are simpler.

C. The normalization condition is simpler.

D. The limits of integration are finite rather than infinite.

Solution: A

One part of $\psi_{nlm_l}(r, \theta, \phi)$ is called $R(r)$. This part of the function tells us. . . (Choose one.)

A. How ψ depends on distance from the nucleus.

B. How ψ depends on orientation (what direction you head from the nucleus).

C. Sometimes A, sometimes B, and sometimes both, depending on the values of n, l, and m_l.

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C. Sometimes A, sometimes B, and sometimes both, depending on the values of n, l, and m_l.

Solution: A

One part of $\psi_{nlm_l}(r, \theta, \phi)$ is called $\Theta(\theta)\Phi(\phi)$ (also known as "spherical harmonics"). This part of the function tells us. . . (Choose one.)

A. How ψ depends on distance from the nucleus.

B. How ψ depends on orientation (what direction you head from the nucleus).

C. Sometimes A, sometimes B, and sometimes both, depending on the values of n, l, and m_l.

One part of $\psi_{nlm_l}(r, \theta, \phi)$ is called $\Theta(\theta)\Phi(\phi)$ (also known as "spherical harmonics"). This part of the function tells us... (Choose one.)

A. How ψ depends on distance from the nucleus.

B. How ψ depends on orientation (what direction you head from the nucleus).

C. Sometimes A, sometimes B, and sometimes both, depending on the values of n, l, and m_l.

Solution: B

Every eigenstate $\psi_{nlm_l}(r, \theta, \phi)$ contains a factor $e^{-r/(a_0 n)}$. One of the effects of this factor is. . . (Choose one.)

A. It makes the probability of finding the electron increase as you start to head away from the nucleus.

B. It makes the probability of finding the electron change as you rotate from the positive z-axis down to the xy plane.

C. It makes the probability of finding the electron near zero far away from the nucleus.

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A. It makes the probability of finding the electron increase as you start to head away from the nucleus.

B. It makes the probability of finding the electron change as you rotate from the positive z-axis down to the xy plane.

C. It makes the probability of finding the electron near zero far away from the nucleus.

Solution: C

Label each statement about the hydrogen atom as "True" or "False."

1. In any energy eigenstate the electron is equally likely to be found at any angle ϕ.
2. The energy eigenstates of the hydrogen atom are independent of ϕ.
3. It's impossible for a hydrogen atom to be in a state where it is more likely to be at some values of z than others.
4. It's impossible for a hydrogen atom to be in a state where it is more likely to be at some values of x than others.

Label each statement about the hydrogen atom as "True" or "False."

1. In any energy eigenstate the electron is equally likely to be found at any angle ϕ.

   Solution: True

2. The energy eigenstates of the hydrogen atom are independent of ϕ.

   Solution: False

3. It's impossible for a hydrogen atom to be in a state where it is more likely to be at some values of z than others.

   Solution: False

4. It's impossible for a hydrogen atom to be in a state where it is more likely to be at some values of x than others.

   Solution: False

All but one of the following statements about the energy eigenstates of the hydrogen atom are true. Which one is false?

A. Given sufficient energy a hydrogen atom can be arbitrarily large.

B. At any given angle the probability density $|\psi|^2$ always gets smaller as r gets larger. (In math terms, this is called a "monotonically decreasing" function of r.)

C. For any given energy there are only a finite number of possible values of the total angular momentum.

D. For any possible energy the angular momentum can be exactly zero.

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C. For any given energy there are only a finite number of possible values of the total angular momentum.

D. For any possible energy the angular momentum can be exactly zero.

Solution: B

Label each of the following as "possible" or "impossible" for a hydrogen atom in one of the eigenstates ψ_{nlm_l}. If there is any eigenstate in which the statement would be true you should answer "possible."

1. The probability distribution is independent of time.
2. The probability distribution is independent of ϕ.
3. The probability distribution depends on ϕ.
4. The electron is more likely to be at positive x than at negative x.
5. The probability per unit radius of finding the electron in a given range of radii is highest at $r = 0$.

Label each of the following as "possible" or "impossible" for a hydrogen atom in one of the eigenstates ψ_{nlm_l}. If there is any eigenstate in which the statement would be true you should answer "possible."

1. The probability distribution is independent of time.

   Solution: possible

2. The probability distribution is independent of ϕ.

   Solution: possible

3. The probability distribution depends on ϕ.

   Solution: impossible

4. The electron is more likely to be at positive x than at negative x.

   Solution: impossible

5. The probability per unit radius of finding the electron in a given range of radii is highest at $r = 0$.

   Solution: impossible

7.5 Spin

Which of the following was demonstrated by the Stern-Gerlach experiment? (Choose all that apply.)

A. The electrons in a silver atom have nonzero angular momentum.

B. The component of electron angular momentum in the direction they measured is quantized.

C. The energy of electrons in silver atoms is quantized.

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A. The electrons in a silver atom have nonzero angular momentum.

B. The component of electron angular momentum in the direction they measured is quantized.

C. The energy of electrons in silver atoms is quantized.

Solution: A, B

Which of the following is a possible value for S_z, the z component of the spin angular momentum of an electron? (Choose one.)

A. 0

B. 1/2

C. $\hbar/2$

D. $\hbar$

Which of the following is a possible value for S_z, the z component of the spin angular momentum of an electron? (Choose one.)

A. 0

B. 1/2

C. $\hbar/2$

D. $\hbar$

Solution: C

How many electron states with $n = 2$, $l = 1$ are possible in a hydrogen atom? (Choose one.)

A. 2

B. 3

C. 6

D. 8

E. None of the above

How many electron states with $n = 2$, $l = 1$ are possible in a hydrogen atom? (Choose one.)

A. 2

B. 3

C. 6

D. 8

E. None of the above

Solution: 6

Spin is… (Choose one.)

A. The quantum mechanical version of angular momentum.

B. One of the properties that is specified—sometimes exactly, but usually probabilistically—by a particle's wavefunction ψ.

C. A property that is *not* specified by a particle's wavefunction ψ.

Spin is… (Choose one.)

A. The quantum mechanical version of angular momentum.

B. One of the properties that is specified—sometimes exactly, but usually probabilistically—by a particle's wavefunction ψ.

C. A property that is *not* specified by a particle's wavefunction ψ.

Solution: C

7.6 Spin and the Problem of Measurement

A stream of silver atoms passes through an x-oriented Stern-Gerlach apparatus. The ones that come out $\rightarrow$ are discarded and the ones that come out $\leftarrow$ are passed through a y-oriented apparatus. What fraction will come out as positive in the y direction?

A. 0

B. 1/2

C. 1

D. There's not enough information to know.

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A. 0

B. 1/2

C. 1

D. There's not enough information to know.

Solution: B

A Stern-Gerlach apparatus oriented in the z direction…(Choose one.)

A. Changes the spin z-component of all incoming atoms to be the same.

B. Sends incoming atoms in two different directions, depending on their spin z-components, while leaving the spin x and y components unchanged.

C. Sends incoming atoms in two different directions, depending on their spin z-components, while destroying all information about their spin x and y-components.

A Stern-Gerlach apparatus oriented in the z direction…(Choose one.)

A. Changes the spin z-component of all incoming atoms to be the same.

B. Sends incoming atoms in two different directions, depending on their spin z-components, while leaving the spin x and y components unchanged.

C. Sends incoming atoms in two different directions, depending on their spin z-components, while destroying all information about their spin x and y-components.

Solution: C

The x and z components of an atom's spin. . . (Choose one.)

A. Have no correlation.

B. Must always be in a state where both are known, or neither is known.

C. Must always be in a state where one is known and the other is not.

D. May both be simultaneously unknown, but cannot be simultaneously known.

The x and z components of an atom's spin... (Choose one.)

A. Have no correlation.

B. Must always be in a state where both are known, or neither is known.

C. Must always be in a state where one is known and the other is not.

D. May both be simultaneously unknown, but cannot be simultaneously known.

Solution: D

A million $\uparrow$ silver atoms passes through an x-oriented Stern-Gerlach apparatus, and then all the ones that came out positive are passed through a z-oriented apparatus. Roughly how many come out as $\downarrow$?

A. A million

B. Half a million

C. A quarter million

D. None

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Solution: C

7.7 Splitting of the Spectral Lines

If an atom is in an external magnetic field pointing in the positive z direction … (Choose one.)

A. that will cause higher m_l states to have more energy than lower m_l.

B. that will cause lower m_l states to have more energy than higher m_l.

C. the atom's energy will still be independent of m_l.

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Solution: A

A magnet is in a uniform magnetic field. Its energy depends on . . . (Choose one.)

A. its position.

B. its orientation.

C. both its position and its orientation.

D. neither its position nor its orientation.

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Solution: B

Each of the following shows the initial and final quantum numbers (n, l, m_l) of an electron transition. Which are allowed by the selection rules? (Choose all that apply.)

A. $(2, 0, 0)$ to $(1, 0, 0)$

B. $(3, 1, 0)$ to $(1, 0, 0)$

C. $(3, 2, 0)$ to $(2, 1, 1)$

D. $(4, 3, 3)$ to $(2, 2, 1)$

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B. $(3, 1, 0)$ to $(1, 0, 0)$

C. $(3, 2, 0)$ to $(2, 1, 1)$

D. $(4, 3, 3)$ to $(2, 2, 1)$

Solution: B and C

Ignoring spin, how many spectral lines does the $n = 6$ to $n = 3$ transition split into as a result of an external magnetic field? Explain. (Choose one.)

A. 2

B. 3

C. 4

D. 5

E. > 5

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A. 2

B. 3

C. 4

D. 5

E. > 5

Solution: B. The normal (without spins) Zeeman effect depends on Δm_l and the selection rules say Δm_l can only take on the values -1, 0, and 1.

An electron is in a state with $l = 1$, $m_l = 1$, and $m_s = 1/2$. Which of the following effects does spin-orbit coupling have on the state? (Choose one.)

A. It increases the state's energy.

B. It decreases the state's energy.

C. It doesn't change the state's energy.

D. The answer depends on n.

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D. The answer depends on n.

Solution: B.

From $m_l = 1$ we get $L_z = \hbar$, and from $m_s = 1/2$ we get $S_z = \hbar/2$. (Don't know all that off the top of your head? That's probably OK; keep Appendix G handy.) The point here is that the two spins are pointing in the same direction, which is the preferred, i.e. energy-lowering, state.

True or False? If you want to predict a hydrogen atom's energy levels to about 1% accuracy in the absence of an external magnetic field, you only need to consider n.

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Solution: True. The biggest adjustment is the fine structure, which is about 20,000 times smaller than the uncorrected energy levels—in other words it's less than a 1% correction.

Which spectral line is wider? (Choose one.) *Hint*: This section discussed why each spectral line can be higher or lower than you would naively expect, but didn't talk about their widths. What would cause a particular spectral line to have nonzero width?

A. $n = 2$, $l = 0$ goes to $n = 1$

B. $n = 2$, $l = 1$, $m_l = 0$ goes to $n = 1$

C. These two lines are equally wide.

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C. These two lines are equally wide.

Solution: B

To first approximation these lines should all be infinitely thin because they each have exact energies. But we know from the energy-time uncertainty principle that a state with *exactly* defined energy would have to live forever. More generally, we said that the shorter-lived a state is the larger the uncertainty in its energy must be. Since $n = 2$, $l = 0$ lasts many orders of magnitude longer than the $n = 2$, $l = 1$ states, the $l = 0$ state has a more exactly defined energy and a thinner spectral line. (The $n = 1$ state does last essentially forever and has an effectively exact energy.)