Module 2 Student Answers

Before watching the video, consider these questions:

- If there is no intrinsic magnetic moment that allows electrically neutral atoms to interact with a magnetic field, what would you expect to see on the screen?

  Ans: a straight, undeflected beam

- If there is an intrinsic magnetic moment that allows electrically neutral atoms to interact with a magnetic field and the atoms in the atomic beam have random orientations of that property with respect to the magnetic field, what would you expect to see on the screen?

  Ans**:** one beam spreading out along the direction of the magnetic field

Spin Quantum Number - Guided Inquiry Questions

1. How many different allowed spin states does a spin-2 particle have? What are the m_s values for these states?

   Ans: 2(2)+1=5

   -2, -1, 0, 1, 2

2. How many different allowed spin states does a spin-3/2 particle have? What are the m_s values for these states?

   Ans: 2(3/2)+1=4

   -3/2, -½, ½. +3/2

3. Quantum particles that behave effectively as spin-zero particles (s = *0*) are sometimes said to occupy a singlet state and spin-1 particles (s = *1*) are sometimes said to occupy a triplet state. What do you think the reasoning is behind those names?

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Ans: Due to m_s, there is only 1 possible spin state for s = 0 and there are 3 different states of spin when s=1, they are -1, 0, 1. It makes some sense to call the single s=0 state a singlet and the triple s = 1 states a triplet.

4. Given the observations made in the Stern-Gerlach experiment shown above, what would be the effective spin quantum number *s* of the neutral silver atoms? How did you come to that conclusion?

   Ans: *s* = ½ There are clear two spin states after the silver atoms pass through the magnetic field, so $2 = 2s + 1$, and solving for *s* gives you ½.

Potential Sources For Magnetic Resonance - Guided Inquiry Questions

5. Use the Pauli exclusion principle, Aufbau principle, and Hund's rule to give the electron configuration of the six electrons of a carbon atom in its lowest energy atomic state.

   Ans: Electron Configuration of carbon is $1s^2 2s^2 2p^2$, and the Aufbau principle explains how those orbitals are filled.

   $1s^2$: ↑↓ $2s^2$: ↑↓ $2p^2$: ↑_ ↑_ __

   The electrons (as fermions) will spread out through the 2p states so that it 'maximizes the total spin quantum number for the electrons in the open subshell' according to Hund's rule.

6. Protons and neutrons are each made up of three quarks which each carry spin-1/2. Use the information provided above about finding the total spin of multiple spin-1/2 particles to explain why the three spin-1/2 quarks add together to give a total spin of 1/2 for both protons and neutrons.

   Ans: Both protons and neutrons are made up of three up and down quarks, giving it a half-integer spin. A spin-up pairs with a spin-down to contribute zero spin and then you are leftover with a spin-½ quark so the total spin is ½.

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Nuclear Spin - Guided Inquiry Questions

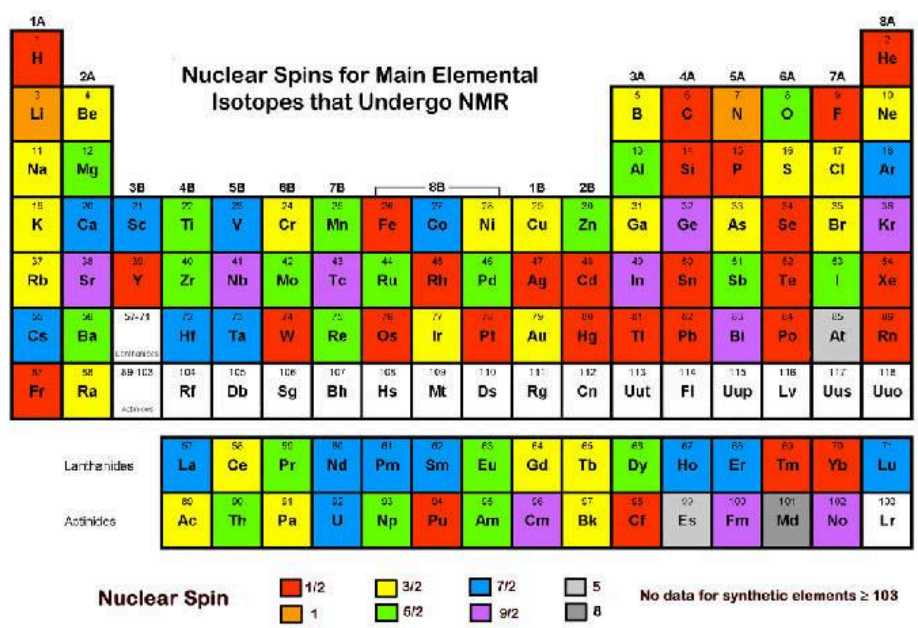
Use the tables shown below along with this [PhET simulation] to answer the questions in this section.

Spin Quantum Number of Common Nuclei

Element	^{1}H	^{2}H	^{12}C	^{13}C	^{14}N	^{16}O	^{17}O	^{19}F
Atomic Number	1	1	6	6	7	8	8	9
Atomic Mass (u)	1	2	12	13	14	16	17	19
Natural Abundance (%)	99.98	0.0115	98.93	1.07	99.636	99.757	0.038	100
Nuclear Spin Quantum No. (I)	1/2	1	0	1/2	1	0	5/2	1/2
Number of Spin States (2 I +1)	2	3	0	2	3	0	6	2

The most abundant isotopes of C and O do not have nuclear spin

The common nuclei used in NMR is due to its stability and possession of nuclear spin



7. Using the simulation to check out different isotopes of the same element, what appears to cause a nucleus to become unstable? Why do you think it is important to use stable nuclei for magnetic resonance experiments?

   Ans: Having either too few or too many neutrons can cause a nucleus to become unstable (having around the same number of neutrons and protons seems to be

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the most stable). Stable nuclei are more commonly found in nature and then you won't risk your sample radioactively decaying while you are measuring it.

8. By far the most common nucleus used for NMR is that of hydrogen-1 (essentially a single proton). What are the advantages of choosing to use this particular isotope of hydrogen?

   Ans: Hydrogen-1 is spin-½ and the most abundant isotope of hydrogen in nature, making it a very useful nucleus for NMR.

9. Why is carbon-12 *not* a good choice for NMR, despite its large natural abundance? *Hint: use the rules above to determine the nuclear spin of this carbon isotope.* Which spin-1/2 carbon isotope do you think is then referenced in the periodic table above? *Hint: we want the isotope to be stable as well!*

   Ans: Carbon-12 has an even number of protons and neutrons, so it has zero nuclear spin and NMR cannot be used. Since the spin of the carbon isotope referenced in the periodic table above is ½ then it is most likely that the number of protons and neutrons is odd which almost guarantees that the carbon referenced above is carbon-13. A drawback is that it is only 1% naturally abundant.

10. Which spin-1/2 fluorine isotope do you think is referenced in the periodic table above? *Hint: look at different isotopes of fluorine and determine the nuclear spin using the rules above.* What are the advantages of choosing this particular isotope?

    Ans: The isotope of fluorine would be fluorine-19. This would give it a ½ spin. The advantages of this isotope are that NMR is most often done with a ½ spin, and this isotope is 100% naturally abundant.

Reflection Questions

1. Why might learning more about quantum spins be considered important?

   Ans: Learning about quantum spins could be important because it can help us further understand how the fundamental particles at the basis of all known forms of matter work, and we can then harness this knowledge to develop more quantum-based technologies.

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2. Use what you learned about the Aufbau principle and the simplified explanation of how spin-1/2 particles get added together to provide some justification for the rules given above for finding the nuclear spin of an isotope. *Check out this YouTube video if you want a more thorough explanation of how nuclear spin gets calculated: https://www.youtube.com/watch?v=pcyfvwnHddA*

   Ans: If we assume only protons can pair up with other protons and neutrons can pair up with other neutrons (as the video implies), then those rules naturally follow. Even numbers of protons or neutrons contribute 0 to the total nuclear spin because they are all paired up. Odd numbers of protons or neutrons contribute a half-integer spin to the total nuclear spin. So if both protons AND neutrons are even, you get a total nuclear spin of 0. If the total number of protons and neutrons is odd, then you have an even number of one (contributes 0) and an odd number of the other (contributes a half-integer) so the total nuclear spin will be half-integer. If BOTH protons and neutrons are odd, then they both contribute a half-integer spin but cannot pair up with each other, so the total nuclear spin will be an integer (and non-zero).

3. For each of the following nuclear isotopes, provide your assessment of whether they may be useful for NMR or not. (Look for non-zero nuclear spin, stability, relative abundance, etc.)

   a. Phosphorus-31 (^{31}P)

      This is the most abundant isotope for phosphorus and has ½ spin so may definitely be useful for NMR

   b. Carbon-15 (^{15}C)

      This is an unstable isotope and, therefore, may not be useful for NMR

   c. Helium-3 (^{3}He)

      This is a spin-½ isotope, but not very naturally abundant, so it may not be as useful for NMR.

   d. Silicon-29 (^{29}Si)

      This is a spin-½ isotope that is stable with good natural abundance, so it would be useful for NMR.

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