Module 11 Student Questions

Observation Experiment - Individual Reflection

1. Do these results support the wave-like nature of light?

   Ans: Yes, light produces an interference pattern when shown through two slits, similar to waves in a liquid such as water.

2. Do these results support the particle-like nature of light?

   Ans: Yes, because only a single dot is made on the senor for each single photon, just like a single particle hitting the sensor.

3. What can these experimental results tell us about the quantum nature of light?

   Ans: Light can be modeled both as a wave and a particle.

Observation Experiment - Small Group Discussion

4. What aspects of quantum superposition have you seen in the study of NMR already?
   Ans: The vector positions on the Bloch sphere are superpositions of the $|\alpha\rangle$ and $|\mathscr{B}>$ states.

5. Is the quantum behavior of spins necessary for understanding and analyzing NMR data?
   Ans: Yes, to understand what the decay times tell us about the local magnetic environment we need to know how the environment affects the behavior of the spins, and spins are inherently quantum mechanical.

6. We have seen that interactions with the environment can cause the relaxation of quantum spins so that they are no longer in a superposition state. Provide a possible explanation of why we do *not* observe objects in a state of superposition outside of the quantum realm.
   Ans: Macroscopic objects are made up of lots of quantum particles that are all interacting with each other and causing those individual quantum particles to relax and lose any superposition. The environment of quantum spins outside of

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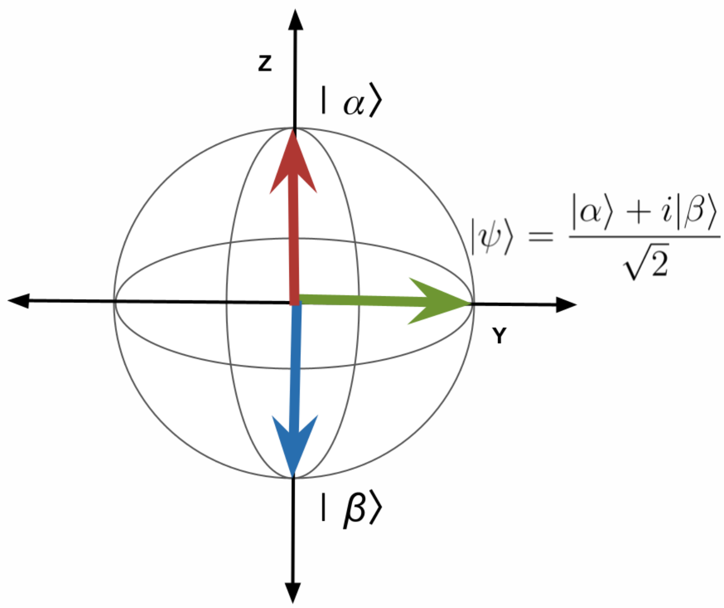
the quantum realm is so complex that keeping quantum superposition is nearly impossible.

Relating the Postulates of Quantum Mechanics to NMR - Guided Inquiry Questions

7. Do the spin-1/2 state vectors represented on the Bloch sphere reside in a real or complex vector space? Explain your reasoning.

   Ans: The spin-1/2 state vectors reside in a complex vector space because the states can use complex numbers (for example, a superposition state in the Bloch sphere), so the vector space those states occupy must inherently be complex.



8. Consider the three spin-1/2 quantum states shown in the Bloch sphere above. Which states would be considered stationary states? Explain your reasoning.

   Ans: The |α⟩ and |**β**> states correspond to stationary states.

9. What observables are associated with the stationary states you identified in the previous question?

   Ans: The |α⟩ and |**β**> states are the two states related to observables of $m_s = +½$ or -½, respectively.

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10. If you wait a long time, what state would you predict the spin-1/2 particle to be in? Explain.

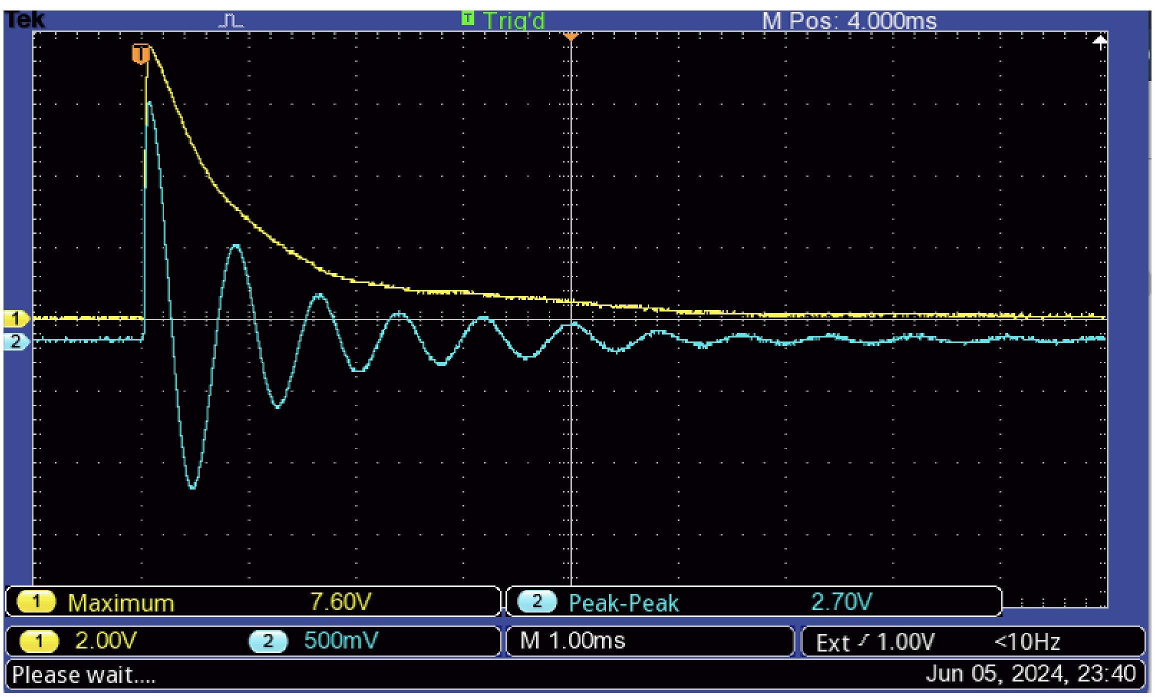
    Ans: If you wait a long time, the spin 1/2 particle should relax back into the stationary |α⟩ state.

11. If you apply a 180-degree pulse to a spin initially in |α⟩, what state would you predict the spin to be in after the pulse?

    Ans: I would predict the spin to be in the |β> state.

12. Provide a pulse sequence you could use to put a spin initially in |α⟩ into a superposition state like |Ψ⟩ in the Bloch sphere above.

    Ans: The easiest way to get the spin into a superposition state like |Ψ⟩ would be to apply a 90-degree pulse. You could also apply a 90-degree pulse plus a 360-degree pulse.



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13. The figure above shows the result of a free induction decay (FID) experiment of protons in a sample of mineral oil. Is this an example of decoherence? Why or why not?
    Ans: Yes, it is an example of decoherence. The signal decays because the spins interact with their local magnetic environment, changing their position on the Bloch sphere.

14. How does the time-varying nature of a precessing quantum spin suggest that the spin is *not* in a stationary state, but instead in a superposition state? Does this agree with which states we know will and will not precess in the Bloch sphere representation?
    Ans: A precessing quantum spin is constantly changing its quantum state with time, so it cannot be in a time-independent stationary state. We know that the stationary states, $|\alpha\rangle$ and $|\beta\rangle$, do not precess, but any superposition state will. This agrees with stationary states being time-independent and non-varying.

15. Physicists use multiple-pulse sequences like the Hahn echo or CPMG to "increase the coherence time". What do you think they mean by that? Why might that be useful?
    Ans: To "increase the coherence time" means to increase the amount of time before the spins relax back into the stationary $|\alpha\rangle$ state due to interacting with the local magnetic environment. This is helpful because it extends the time that you can measure a signal from the precessing quantum spins.

Heisenberg Uncertainty Principle - Guided Inquiry Question

16. Stationary states are not time-varying, so we know that the quantum system will stay in those states until acted upon ($\Delta t \rightarrow$very large). What does the energy-time uncertainty principle then tell us about our uncertainty in the energy of a stationary state?

    Ans: According to the energy-time uncertainty principle, a state with a very large Δt should have a very small ΔE, so the uncertainty in the energy of a stationary state should be relatively small.

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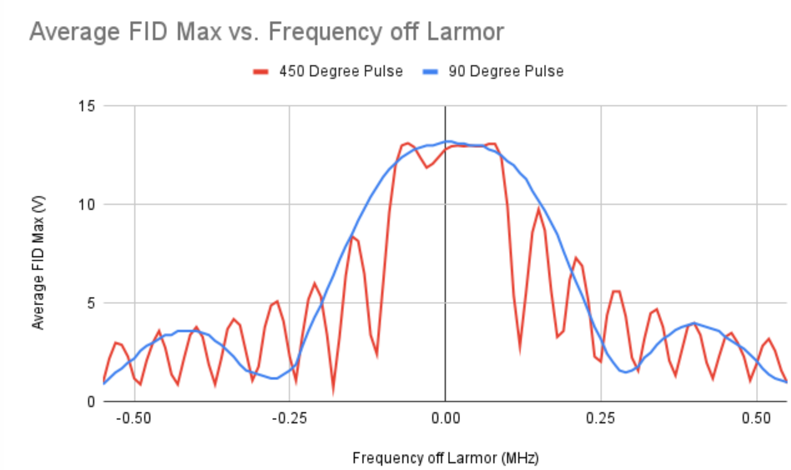
Testing Experiment - Guided Inquiry Questions

17. Thinking about the dynamics of spins along the Bloch sphere using the Bloch simulator, do you expect the MR signal amplitude to be different if you use a 450-degree pulse instead of a 90-degree pulse? Explain your reasoning.

    Ans: No, there shouldn't be a difference. Both a 90-degree pulse and a 450-degree pulse put the spins into the same position on the Bloch sphere since 450 = 90 + 360.

18. The Bloch simulator pulses assume the pulses are sent at the Larmor frequency of the spins (often called "on-resonance"). But now we will be deliberately driving the spins "off-resonance" to see the resonance curve. Using the energy-time uncertainty principle, do you expect the width of the resonance peak (directly proportional to Δf) to increase or decrease when you use the 450-degree pulse instead of the 90-degree pulse?

    Ans: When you use the 450-degree pulse, you are increasing Δt, so the energy-time uncertainty principle would suggest that ΔE would then need to decrease. Since E is directly proportional to f, then you would predict that Δf must decrease as well. That would mean the width of the resonance peak should be smaller when you use the 450-degree pulse instead of the 90-degree pulse.



19. Check out the results of the experiment [here] or view the frequency-domain curves above. Does this agree with the energy-time uncertainty principle?

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Ans: Yes, it agrees with the energy-time uncertainty principle because for the 450-degree pulse, which corresponds to a larger Δt, the resonance peak is narrower, which corresponds to a smaller ΔE.

Reflection Questions

1. Provide three examples of how elements of NMR we have studied directly connect to important postulates of quantum mechanics.

   Ans: The representation of quantum spins as vectors on the Bloch sphere relates to the State Vector Rule Postulate of quantum mechanics, which states that quantum states can be represented by vectors. We've seen the collapse of the quantum state into the stationary states $|\uparrow\rangle$ and $|\downarrow\rangle$ through the Stern-Gerlach experiment. The Bloch sphere is an example of probability since a vector in the upper hemisphere indicates a higher probability of finding the spin in the $|\alpha\rangle$ state, and a vector in the lower hemisphere indicates a higher probability of finding the spin in the $|\beta\rangle$ state. Quantum decoherence can be seen when the spins relax to the stationary state due to interactions with the local magnetic environment.

2. Write a short response in agreement or disagreement to the following statement: "The fact that quantum mechanics is probabilistic and the predictions inherently uncertain means that it is an inferior theory to classical mechanics where predictions are deterministic and exact."

   Ans: I would disagree with this statement because, as stated in the text, the experiments all support the probabilistic nature and inherent uncertainty of quantum mechanics. This suggests it more closely matches what actually occurs in nature, even though its predictions are not deterministic.

3. NMR is one application of quantum theory that has made an important scientific impact. Check out other technologies that have come out of our understanding of quantum mechanics here. Pick one of these technologies and briefly describe its scientific and/or cultural impact.

   Ans: Can choose from lasers and telecommunications, atomic clocks and GPS, and MRI, which all play an important role in scientific research and/or our technology-focused culture.

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