**Module 3 - Questions**

## The Spinning Aspects of Quantum Spin - Guided Inquiry Questions

1. Many people use ‘spin’ to refer to either the spin quantum number or the spin angular momentum vector. If I were to tell you the spin of a particular electron is ℏ/2, which aspect of spin am I talking about?
2. Draw a picture of a spin rotating in the opposite direction to the one shown above. *Make sure to draw the S vector pointing in the correct direction using the right-hand rule!*
3. Based on the behavior observed in our physical model of a quantum spin, do you think it is safe to say that it has some angular momentum and that angular momentum is an important factor in explaining the dynamical behavior observed?

## Testing Experiment: What causes the quantum spin to interact with the magnetic field? - Guided Inquiry questions

1. Describe (using both words and pictures) what you observe of the behavior of both the white cue ball and gyroscope in the presence of a magnetic field without any spinning.
2. List some different explanations for why our physical model of a quantum spin (white cue ball) can interact with a magnetic field. *Some explanations may seem more plausible than others, but list all the explanations you can think of since we don’t know what the correct answer may turn out to be, and it may not be the most obvious one!*
3. For your list of explanations (this will become your different *hypotheses*), design an experiment whose outcome you can predict using all the hypotheses that you constructed. *Note that when there are multiple explanations, the best-designed experiment will give different predicted outcomes, allowing us to determine which explanation best explains the observed phenomenon*.
4. For each different hypothesis: write down what you would predict to observe if you performed your chosen experiment and that particular hypothesis were correct. For example, "If [hypothesis] is correct and we perform [experiment], then we would predict [predicted outcome for that hypothesis]."
5. If you ultimately observed something different than your prediction for a particular hypothesis, what would that tell you about that hypothesis?
6. Perform your experiment and/or watch some of the videos of the different experiments students have performed. Write down a brief description of the experiment being performed, and the observed results of that experiment. Based on the experimental results, what is your judgment about your different hypotheses?
7. Based on the experimental results, is there a particular hypothesis that provides the best explanation of why the white cue ball interacts with a magnetic field? Please explain by referencing the experimental results.

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## Spin Magnetic Moment - Guided Inquiry Questions

1. In the visualization of a quantum spin given above with both the spin magnetic moment (as a bar magnet) and the spin angular momentum, is the gyromagnetic ratio positive or negative? How can you tell?
2. Draw your own visualization of a quantum spin with a negative gyromagnetic ratio. *Feel free to have it rotate in any direction, but make sure to draw the S vector pointing in the correct direction using the right-hand rule!*

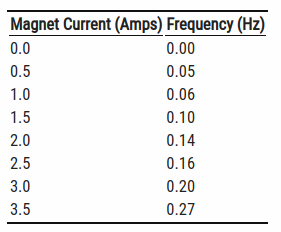
## Exploratory Experiment - What determines the frequency of precession of a quantum spin? - Guided Inquiry Questions

1. Consider the different possible ways we can set up precessional motion of our physical model of a quantum spin (the white cue ball), including the different apparatus controls highlighted in the diagram given in the **Background Information section**. List all the possible variables you can think of that might influence the precession frequency of our physical model of a quantum spin.
2. Perform some experiments and/or watch some of the videos of the different experiments students have performed. *Try to only change one variable at a time! If a particular variable is hard to reliably reproduce, then test that particular variable first so you can potentially rule out its influence on future experiments.* For each experiment, write down what independent variable was being changed and your observations of the impacts on the precession frequency.
3. Based on the experiments above, what variables influence the precession frequency?

## Larmor Precession - Guided Inquiry Questions

1. In the apparatus we have been using, the magnet current in the magnet coils are directly proportional to the magnetic field strength (e.g. if you took the current value and multiplied it by a particular constant, you would get the magnetic field strength, B.) If you doubled the magnet current, what would you expect to happen to the magnetic field strength? What would happen to the precession frequency?
2. Do your conclusions from your precession experiments above appear to agree with the Larmor precession frequency equation given for a quantum spin? Explain.
3. Are there any differences between the behavior of our physical model of a quantum spin and the theoretical quantum behavior given by the Larmor precession frequency equation? What does this suggest about the possible limitations of our physical model?
4. What precession frequency would you expect for 1H in a 2-T magnetic field? What precession frequency would you expect for an electron in the same magnetic field? What does the negative sign mean?
5. If you observed a Larmor frequency of 80.1 MHz in a 2 T magnetic field, which nucleus are you likely observing?

## Reflection Questions

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1. What is the independent variable (i.e. the variable the experimenter was controlling) in the data given? What is the dependent variable (i.e. the variable that was measured)?
2. What experiment was being performed?
3. Neatly plot the data, with the independent variable on the x-axis and the dependent variable on the y-axis.

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1. What type of relationship do these variables appear to have with each other (e.g. completely independent from each other, linear dependence, or some other dependence?)
2. Does this data match what we expect given the equation for the Larmor precession of a quantum spin? Why or why not?

**Follow this rubric to assess your work for this module:**

| **Scientific Ability** | **Adequate** | **Needs improvement** | **Inadequate** | **Missing** |
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| **Is able to describe what is observed without trying to**  **explain, both in words and by means of a picture of the**  **experimental setup.** | Clearly describes what happens in  the experiments both verbally and  with a sketch. Provides other  representations when necessary  (tables and graphs). | A description is complete, but  mixed up with explanations or  pattern. The sketch is present but  is difficult to understand. | The description is incomplete.  No labeled sketch is present.  Or, observations are adjusted  to fit expectations. | No description is  mentioned. |
| **Is able to design a**  **reliable experiment**  **that tests the**  **hypothesis** | The experiment tests the  hypothesis and has a high  likelihood of producing data  that will lead to a conclusive  judgment. | The experiment tests the  hypothesis, but due to the nature  of the design there is a moderate  chance the data will lead to an  inconclusive judgment. | The experiment tests the hypothesis, but  due to the nature of the design it is likely  the data will lead to an incorrect  judgment. | The experiment  does not test the  hypothesis. |
| **Is able to make a**  **reasonable judgment about the**  **hypothesis** | A judgment is made, consistent  with the experimental outcome,  and assumptions are taken into  account. | A judgment is made, is consistent  with the outcome of the  experiment, but assumptions are  not taken into account. | A judgment is made but is not consistent  with the outcome of the experiment. | No judgment is  made about the  hypothesis. |