Module 3 - How Do Quantum Spins Behave in a Magnetic Field?
Instructor's Manual

Suggested Prior Modules

Module 2.

Particular prior knowledge from Module 2 that students are expected to have already learned:

- Spin is an important property of elementary particles and has its own quantum number
- Spins interact with a magnetic field

If you do not have time to do the entirety of Module 2, The Discovery of Quantum Spin section should suffice as preparation for this module and could potentially be done as a pre-reading assignment for Module 3. You may want to have students complete a short assessment to verify they have the necessary prior knowledge listed above.

Particular prior knowledge from other courses that students are expected to have seen already:

- Vectors (basics, no need to know how to break them up into components)
- Magnetic moment, angular momentum, torque (at the level often taught in introductory physics classes or honors-level high school physics classes)
- Helpful prior knowledge, but it is not critical for achieving primary objectives: vector cross-products, the right-hand rule, precession of a gyroscope

If students have *not seen* some of these topics or need a refresher, having some assigned pre-reading from the Supplemental Reading at the end of the module or any introductory physics textbook should suffice. It is helpful if students have a simple conceptual understanding of these topics so they are not seeing it for the first time in this module.

Note about this module: This is the first module that primarily aims to introduce basic scientific abilities (using the ISLE rubrics) while developing a classical model for quantum spin that will be used throughout the rest of the modules. We highly suggest students write out answers to the module questions in a laboratory notebook, as the questions guide students to write down detailed notes of their design process, predictions, and analyses that we hope can serve as a model for writing up future experiments in their laboratory notebook as the scaffolding is taken away in future modules.

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Suggested Use:
This module covers a lot of ground, and is **best broken up over two 1.5-hour sessions**. We suggest starting the second portion with *Exploratory Experiment - What determines the frequency of precession of a quantum spin?* If doing it all in one day, provide plenty of short breaks between sections and have the student groups summarize the main point of each section before moving on to the next.

Expected Learning Outcomes

At the end of this module, students should be able to...

1. describe what is observed without trying to explain, both in words and by means of a picture of the experimental setup (Scientific Ability B5)
2. design a reliable experiment that tests the hypothesis (Scientific Ability C2)
3. make a reasonable judgment about a given hypothesis based on experimental data (Scientific Ability C8)

(Optional) Introductory Activity

(15 minutes)

Even if students have seen angular momentum before, it may be helpful to do a quick review and pull out your favorite angular momentum demonstrations where there is no external torque acting on the system (spinning top or gyroscope standing straight up so no gravitational torque) and then show what happens when there is a torque (a top or gyroscope that isn't perfectly aligned with the vertical). These are related to the examples given in the activity but will help prime the students to notice the interesting properties of spinning objects compared to their non-spinning counterparts.

Background Information

(5 minutes)

Suggested activity: Read aloud the short text - which essentially summarizes the aims of this module and introduces the magnetic torque apparatus that will be utilized.

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Observation Experiment - What does spin have to do with it?

(5 minutes)

You can use any available gyroscope or toy top for the observation experiments. First, just try to balance the gyroscope on its tip without spinning and have students write down their observations. (Do not worry about actually balancing it, the fact that it is hard to balance and will inevitably fall is the point!) Then repeat after spinning the gyroscope.

As stated in the text, this is the opportunity for students to practice making observations without hopping to conclusions, acting as scientists viewing this phenomenon for the first time. *This is the first learning objective.*

Class-Wide Discussion
Go through the *Class-Wide Discussion* questions as a class. If students use any physics jargon in their explanations (e.g. some students who have recently studied rotational motion might mention angular momentum or torque) ask them to clarify what they mean by going back to what they observe. Students with no prior experience in rotational motion have an advantage in writing these observations, which helps level the field for everyone.

The Spinning Aspects of Quantum Spin

(15 minutes)

Suggested activity: Have students take turns reading aloud this section. Feel free to pause to explain further the different boldfaced words that may require more clarification and use your favorite rotational motion demonstrations to help students practice using the right-hand rule.

You can do a quick think-pair-share for students (perhaps using small whiteboards) to complete the guided inquiry questions using the provided information for about 5 minutes.

Testing Experiment - What causes the quantum spin to interact with the magnetic field?

(30 minutes)

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If you do not have access to a magnetic torque apparatus to show what happens to the white cue ball when the applied magnetic field is increased and decreased, you can show this video.

For the guided inquiry questions, students can individually do question 4 (write down observations) and you can have students share and see if anyone has anything else to add. Question 5 is good for a class-wide question to try to generate as many possible explanations as possible.

The most common explanations are:

- The white cue ball is 'magnetic' in some way - I try to refine this into it either (1) being made of a strongly magnetic material OR (2) containing a permanent magnet (essentially the difference between a fridge magnet and the fridge itself, both interact with permanent magnets but the fridge doesn't generate its own magnetic field).
- The white cue ball is electrically charged. This might come up if people recall electricity and magnetism are related in some way, know that circulating electric charge produces a magnetic moment, or seen some explanations of electrons as a spinning ball of charge. You would need the ball to be spinning in order for this to be a possible explanation for the behavior we see, but if it comes up, I am happy to let it stand since it is an easy explanation to test (and disprove) in this case. (And later when we see the classical model of an electron as a spinning negative charge generating its own magnetic moment, you can refer back to this hypothesis not being too far off for an actual quantum spin, if not the actual explanation for the cue ball.)

The provided experimental videos provide experiments to differentiate between these different hypotheses.

Some uncommon explanations and how to address them:

- Students may also propose that there is an electromagnet instead of a permanent magnet inside the white cue ball, and technically we wouldn't be able to tell the two apart with the experiments given. However, the fact that there is no clear power source for the electromagnet and we are not cooling the cue ball down for some sort of superconductor to be involved makes the permanent magnet a more likely solution.
- There is some sort of Faraday induction happening. This technically wouldn't explain the behavior, because induction would try to counter the applied magnetic field and dampen any motion in the magnetic field, but I would praise students for recalling these concepts from electromagnetism (even if they are not applying them completely correctly!)

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- Some sort of demon pushing the magnet. These are always fun to include to point out that science cannot rule anything supernatural out. However, you can explain to students that this would not be a good *scientific hypothesis* since this explanation would not be testable.

Guided inquiry questions 6 - 10 can then be done in small groups, as they walk students through designing an experiment/s to test these different possible explanations and performing those experiments (or analyzing the provided experimental videos) to ultimately come to a conclusion on which explanation is best to explain the behavior.

You should try to avoid implying that students got the 'correct' answer, because in science, we do not know what the correct answer is, we only know what our experimental data suggests may be the best explanation. (In this case, I am fairly certain there is a permanent magnet inserted in the white cue ball because of these different tests, but I haven't cracked it open to check!)

The Magnetic Aspects of Quantum Spin

(15 minutes)

Suggested activity: Have students take turns reading aloud this section. Feel free to pause to explain further the different boldfaced words that may require more clarification. If you have time, it is fun to talk about the limits of classical models to explain quantum spin by referencing the *Fun Fact* in the margin of the *Spin Angular Momentum* section.

You can do a quick think-pair-share for students (perhaps using small whiteboards) to complete the guided inquiry questions using the provided information for about 3 minutes.

This is a good place to take a break and review everything you have discovered about our physical model of quantum spin. The remaining part of the module can easily take up another 1.5 hours to allow time for students to perform their own experiments (which we highly suggest you do!)

Exploratory Experiment - What determines the frequency of precession of a quantum spin?

(60 minutes)

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Suggested activity: Have students take turns reading aloud the text of this section. Feel free to pause to explain further the different boldfaced words that may require more clarification and make use of your favorite rotational motion demonstrations to help students make sense of precession. It's alright if they don't fully understand the vector cross product involved, mainly they should understand that because there is an applied torque perpendicular to the angular momentum, the angular momentum will precess in a circle. This is true for both the spinning top in a gravitational field and a quantum spin in a magnetic field, the source of the torque is just different in each case.

You may also want to review how to measure frequency by measuring the period, and suggest students use multiple cycles to get a rough estimate of the fractional uncertainty in their period measurements (and this can be assumed to roughly give the fractional uncertainty in their calculated precession frequencies.) Since the experiments they will perform in this section involve comparing the measured precession frequency when different parameters are changed, students will need to be aware of the size of the uncertainty to determine which frequency measurements are effectively the same within experimental uncertainty or different.

If students are performing experiments themselves, I would *not* recommend multiple trials where students repeat the experiment by stopping the ball and spinning it again since it is very hard to replicate spin speeds (though certainly let us know if you or your students find a way to do so!) Ideally, all experiments should be done with only one initial spin to the cue ball, unless you are explicitly testing different spin speeds as your independent variable.

The guided inquiry questions can be completed in small lab groups and will encourage students to perform several experiments (and/or view the linked videos) so they can determine what parameters appear to affect the observed precession frequency. The bulk of the time in this section should be students playing with the apparatus, taking data, and trying to make sense of what they are seeing. This is a great opportunity for them to explore and be scientists to try to understand this new physical phenomenon!

If you do not have access to a magnetic torque apparatus have students view some of the videos that students performed using the magnetic torque apparatus.

> Experiment #1 Varying different spin speeds, students should observe as the spin speed increases, the precession frequency decreases.

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Experiment #2 Varying the angle of the axis of rotation relative to the vertical, students *might* observe the precession frequency change slightly with the angle (but pretty small effect).

Experiment #3 Varying the magnet current (magnetic field strength), students should observe as the magnet current increases, the precession frequency increases. This is the most important finding. If there is time, the data can be plotted (precession frequency versus magnet current) to show a nice linear plot.

Experiment #4 Varying the magnetic field direction, students should observe the precession frequency does not change, but the direction of the precession (i.e. clockwise or counterclockwise) does change.

If you are short on class time: The class can decide on the different independent variables and experiments that should be performed and then assign each group to be responsible for performing one of the experiments and presenting their findings to the rest of the class. Students should share the answers to the following questions after analyzing the results of their experiment: (1) Does the precession frequency change with variation of the independent variable? (2) If the precession frequency does change with variation of the independent variable, how does it change? For example, they can fill in the sentence "As the [independent variable] increases, the precession frequency [increases or decreases]."

Check out this Module 3 - Example Experiment for an idea of the type of experiments, data analysis, and conclusions students can perform in this module.

Students should be able to give a fairly conclusive answer that the magnet current (magnetic field strength) clearly affects the precession frequency (and that the higher the magnet current, the shorter the period, and thus the higher the precession frequency). **This is the main experimental result we want them to observe,** the other observations are extra frosting on the cake that either matches with the theory or hints at where this physical model is limited compared with an actual quantum spin. The magnetic field direction will only cause the direction of precession to change, but not change the precession frequency. **This matches well with the theory explored in the next section.**

There is also a slight spin dependence, but reliably spinning the ball at different speeds without causing extra wobbling can be a challenge. If done correctly, students should observe that high spin speeds (higher angular momentums) lead to smaller precession

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frequencies. **This can seem pretty counterintuitive but *does* match the theory.** By increasing the spin speed, we are effectively *decreasing* the gyromagnetic ratio by increasing angular momentum while keeping the magnetic moment constant. (Check out the answers to the student questions for more details).

There also appears to be a very slight angular dependence on the precession frequency (though much smaller than all the other parameters). This is not something that matches the theory and is a mysterious phenomenon noticed in this apparatus that is mentioned in the instructor's manual. I suspect that it is due to the center of mass not being directly in the center of the cue ball so a little bit of gravitational precession is happening and this would depend on the angle of the true center of mass relative to the vertical, but this is certainly something that would be fun to explore further if a student is interested!

Larmor Precession

(20 minutes)

Suggested activity: Have students take turns reading aloud this section. Feel free to pause to explain further the different boldfaced words that may require more clarification. The main point is to see that for a quantum spin, the interaction with the magnetic field provides the torque that causes the spin to precess. You need both the magnetic aspect of spin (the magnetic moment interacting with the field) along with the angular momentum aspect of spin to fully explain the precession of a quantum spin in a magnetic field.

Most of the time for this section should be dedicated to having the students in small groups discuss the guided inquiry questions, particularly questions 17 and 18 about the similarities and differences of this physical model compared with Larmor's theory.

Reflection Questions

(Any Remaining Time)

Suggested activity: In any remaining time you can choose some or all of the questions as a small group or individual reflection activity. These are good questions for being completed outside of class as homework. They can help assess individual students' data interpretation, plotting, and analysis skills.

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In the last 5 minutes of class: Give the students some time in class to assess themselves on the learning objectives using the provided rubric in the student worksheet, copied on the next page.

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Follow this rubric to assess your work for this module:

Scientific Ability	Adequate	Needs improvement	Inadequate	Missing
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.

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