Module 4 - How Can We Control Quantum Spins?
Instructor's Manual

Suggested Prior Modules

Modules 2 and 3.

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

- Energy-level representation for quantum spin states
- Energy level splitting for quantum spin states in the presence of a magnetic field.
- Quantum numbers: s and m_s

If you do not have time to do the entirety of Module 2, the [Spin Quantum Numbers] section should suffice as preparation for this module and could potentially be done as a pre-reading assignment for Module 4. You may want to have students complete a short assessment to verify they have the necessary prior knowledge listed above.

Particular prior knowledge from Module 3 that students are expected to have already learned:

- Quantum spins precess in the presence of a magnetic field.
- The frequency of precession of the spins (called the Larmor frequency) is determined by the gyromagnetic ratio of the spin, γ, and the strength of the external magnetic field, B.

If you do not have time to do the entirety of Module 3, the [Larmor Precession] section should suffice as preparation for this module and could potentially be done as a pre-reading assignment for Module 4. You may want to have students complete a short assessment to verify they have the necessary prior knowledge listed above.

Suggested Use:
The instructions below are suggestions to help students engage with the material in class and were implementations of the materials that the developers used in their classes. However, *all* sections and questions in this module can successfully be done asynchronously online to serve as a pre-reading assignment in preparation for class or lab.

Expected Learning Outcomes

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

1. identify two primary ways scientists can control quantum spins
2. explain the importance of resonance in controlling quantum spins

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3. construct new Bloch sphere representation from previous representations (modified Scientific Ability A2)

(Optional) Introductory Activity

(30 minutes)

Suggested activity: Introduction to Resonance Activity

We highly suggest this small group activity to help students develop a definition for resonance based on a hands-on example and apply their understanding of resonance to explain several different examples of resonance occurring in the physical world.

Background Information

(10 minutes)

Suggested activity: Have students take turns reading aloud each paragraph of the text - which essentially provides a nice overview of all the information we want students to recall from previous modules. This is a good opportunity to demonstrate interrogative reading, by asking questions like “How do we know this is true?” or “Does this match what we have seen previously?” after every paragraph or so. Ideally, asking questions of this sort will become a habit for students reading scientific texts.

Class-Wide Discussion
Go through the *Class-Wide Discussion* questions as a class. It is very important to take time going over these questions, as they introduce key elements in the module.

Desired answers:
- Scientists can control spins using electromagnetic radiation or magnetic fields.
- The natural frequency for quantum spins in the presence of a magnetic field would be the Larmor frequency, γB_0.

For the third question, if students have completed the optional introductory activity suggested above, then you can have students compare the definition they developed of resonance with the one given by the text. If students have not completed the optional introductory activity, it would be helpful to show some examples of resonance and walk through how the definition of resonance applies (something like the final “Application” part of Introduction to Resonance Activity).

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Introducing the Bloch Sphere Representation for Two-Level Quantum Systems

(10 minutes)

Suggested activity: Have students take turns reading aloud this section. Feel free to pause to go over the definition of quantum superposition in the margin, which may require more clarification.

These guided inquiry questions are well-suited for quick polling of the class to make sure they understand the basics of the Bloch sphere representation. Ideally, everyone should be able to answer these questions fairly easily. If some students appear confused or are answering wrong, letting students talk with their neighbors for a few minutes before re-polling should help clear up any confusion.

Quantum Spin Control

(Up to 1 hour to complete all subsections)

Initializing Spin States *(10 minutes)*

> **Suggested activity:** Students can take 5 minutes to read this section and answer the questions individually, then give students 2 minutes to discuss their answers with a partner, and then take 3 minutes to have different pairs share their answers for the guided inquiry questions to make sure everyone has correct and adequate logical explanations for their answers. As some of these are more open-ended questions, this is a good opportunity to ask students to share if they have anything to add or a different explanation than the one shared with the class.

Getting Started with the Bloch Simulator *(30 minutes)*
In this subsection, students are introduced to the Bloch simulator.

> **Suggested activity:** Students can pair up with one person running the simulator and one person recording their answers to the guided inquiry questions. (The instructor can clarify that it is fine if students have the same answers for these questions, but also encourage students to write down who they were working with to give proper attribution that it was a shared effort.) *Students should swap roles for the next section.*

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Controlling Transitions Between Spin States *(25 minutes)*
In this subsection, the goal of the guided inquiry questions is to help all students ultimately discover for themselves how an applied additional magnetic field oscillating in the xy-plane at the Larmor frequency enables them to do a complete spin-flip and provides the final element necessary for quantum control.

> **Suggested activity:** This is a good point to have everyone reconvene briefly to read through the paragraph together and ensure everyone understands what is meant by a spin-flip. Then students can continue working through the guided inquiry questions using the Bloch simulator. Students working in pairs should swap roles from the previous section.

This portion of the module using the Bloch simulator can easily be completed outside of class, so if there is not enough time to finish this section AND the following Nutation and Pulses section, we suggest having students finish up this section as homework so then students can complete the Nutation and Pulses section in the following class.

Nutation and Pulses

(15 minutes)

Suggested activity: Have students take turns reading aloud this section. Feel free to pause to read about I.I. Rabi in the margin or discuss the differences between precession and nutation as shown in the figure.

These questions are good for think-pair-sharing. The last question is open-ended, so this is a good opportunity to ask students to share if they have anything to add or a different opinion and explanation than the one shared with the class. If the consensus leans toward pulses *not* providing control of the quantum state, it might be worthwhile for the instructor to point out that this is as good as it gets in terms of control of a quantum state. In this case, the students' definition of 'control' may not be feasible due to the probabilistic nature of quantum mechanics.

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. Often these are good open questions that provide an opportunity for students to reflect on everything they have learned in this

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module. These questions can be completed outside of class as homework and used to assess students' comprehension of the material.

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 and copied below.

Follow this rubric to assess your work for this module:

Scientific Ability	Adequate	Needs improvement	Inadequate	Missing
Is able to identify two primary ways scientists can control quantum spins	Can identify two ways scientists can control quantum spins.	Can identify one way scientists can control quantum spins.	Cannot provide a correct answer to how scientists can control quantum spins.	No attempt is made to address this objective.
Is able to explain the importance of resonance in controlling quantum spins	Can accurately explain the importance of resonance in controlling quantum spins.	Can somewhat explain the importance of resonance in controlling quantum spins.	Cannot accurately explain the importance of resonance in controlling spins.	No attempt is made to address this objective.
Is able to construct new Bloch sphere representation from previous representations	Bloch sphere representation is constructed with all given (or understood) information and contains no major flaws.	Bloch sphere representation is created without mistakes, but there is information missing, i.e. labels, variables.	Bloch sphere representation is attempted, but uses incorrect information or the representation does not agree with the information used.	No attempt is made to construct a different representation.

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