Module 11 - What Can NMR Teach Us About the Quantum Realm?
Instructor's Manual

Suggested Prior Modules

Modules 4, 5, 6, 7

Particular prior knowledge from Module 4 that students are expected to have already learned:

- The Bloch sphere representation for two-level quantum systems
- Using the Bloch simulator, including spin initialization and applying pulses
- Nutation and pulses, particularly how longer pulses cause more rotation of the spins on the Bloch sphere

This is the most important prior module to have students do in preparation for Module 11. *If you do not have time to complete the entirety of Module 4 in class, then this module can be used as a longer, interactive assignment completed outside of class. It is estimated to take about 1.5 - 2 hours for students to complete asynchronously.*

Particular prior knowledge from Module 5 that students are expected to have already learned:

- The free induction decay (FID) experiment, and what causes the observed dephasing of the spins.

If you do not have time to do the entirety of Module 5, then assigning the More Realistic NMR Signal section should suffice as a pre-reading for students to learn the necessary relevant material from this module.

Particular prior knowledge from Module 6 that students are expected to have already learned:

- Basic understanding of T_1 and T_2 as relaxation processes in MR.

The T_2 Relaxation and T_1 Relaxation sections should suffice as preparation for this module and could be done as part of a pre-reading assignment in preparation for this module.

Particular prior knowledge from Module 7 that students are expected to have already learned:

- Use of the Hahn echo or CPMG pulse sequence to measure T_2 relaxation times.

This is only required for answering Guided Inquiry Question 15. *The Hahn Echo Theory and Can We Find T_2 Using a Single Experiment and More Pulses? sections should suffice as preparation for this module and could be done as part of a pre-reading assignment. Alternatively, you can simply have students skip Question 15.*

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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 an excellent entryway for introductory science students to be introduced to the postulates of quantum mechanics through NMR examples.

Expected Learning Outcomes

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

1. *Connect important postulates of quantum mechanics to what we know about NMR*
2. *Interpret NMR experiments using quantum mechanics terminology*
3. *Predict how the resonance lineshape changes with longer pulses using the uncertainty principle*

[Brief History of Quantum Mechanics]

(20 minutes)

Suggested activity: Have students take turns reading aloud the text, along with the information in the margin. Give the students at least 3 minutes to answer the individual reflection questions to help them fully appreciate the 'weirdness' they are observing. The subsequent text can also use a good reflective break after each paragraph for students to absorb what is being said, and potentially question it! Eventually, with the help of the instructor, they will conclude that a pure particle or wave representation is not satisfactory to explain the observations made. The small group discussion questions will help students get back on more solid ground as they consider what aspects of quantum superposition they have already seen in previous NMR modules.

[Relating the Postulates of Quantum Mechanics to NMR]

(40 minutes)
Suggested activity: This section is the bulk of the content for this module, and each postulate can be expected to take about 10 minutes for students to read and respond to the guided inquiry question. We suggest having students work through this section in small groups. For reading the text out loud as a group or individually silently. After taking time to individually think about the guided inquiry questions at the end of each postulate

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section, the groups should discuss their answers before moving on to the next section. The instructor can hover around the groups and answer any student questions.

Heisenberg Uncertainty Principle

(20 minutes)

Suggested activity: The class can be brought back together to go through the content of this section, with instructor guidance. Have students take turns reading aloud the text. (The biographical information in the margin about Werner Heisenberg is unnecessary for understanding the content and can be skipped if there is limited time. If you have students read the biographical information in the margin, you can do that first before reading the main text, to provide some historical context for the material.) You can have the class do think-pair-share to answer guided inquiry question 16 and then have the class return to their small groups to read through and answer the guided inquiry questions for the Testing Experiment section. The experiment described in this section can be performed on any NMR spectrometers that allow users to change the pulse length or pulse angle and the frequency of the pulses to drive the system off-resonance deliberately. Having students perform this experiment is a great extension experiment that can be performed after completing this module. Check out the example experiment posted in the instructional materials for Module 11 to get more information.

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. The first reflection question asks students to recall and write down some of what they have learned in this module. This question can be a useful assessment of students' comprehension of the material presented in the module. The second and third reflection questions aim to help students consider the relevance of quantum mechanics as a scientific theory and its cultural impact. These questions can all be completed outside of class as homework if class time is limited.

In the last 5 minutes of class: Give the students time at the end of 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:

Learning Outcome	Adequate	Needs improvement	Inadequate	Missing
Is able to connect important postulates of quantum mechanics to what we know about NMR	Can provide NMR examples for all four postulates of quantum mechanics introduced in the module.	Can provide NMR examples for most of the four postulates of quantum mechanics introduced in the module.	Struggles to provide NMR examples for most of the four postulates of quantum mechanics introduced in the module.	Cannot provide NMR examples for any of the four postulates of quantum mechanics introduced in the module.
Is able to interpret NMR experiments using quantum mechanics terminology	Can easily use quantum mechanics terminology correctly to explain NMR experiments.	Can utilize most of the quantum mechanics terminology correctly to explain NMR experiments.	Struggles to use the quantum mechanics terminology correctly to explain NMR experiments.	Does not attempt to use quantum mechanics terminology to explain NMR experiments.
Is able to predict how the resonance lineshape changes with longer pulses using the uncertainty principle	Can accurately predict how the resonance lineshape changes with longer pulses using the uncertainty principle.	Makes a prediction of how the resonance lineshape changes with longer pulses, but the prediction has some errors or doesn't correctly use the uncertainty principle.	Makes a prediction of how the resonance lineshape changes with longer pulses, but does not use the uncertainty principle in making this prediction.	Does not attempt to make a prediction of how the resonance lineshape changes with longer pulses.

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