Module 9 Student Questions

Observation Experiments: Magnetic Moment Motion Impact on Local Magnetic Environment - Guided Inquiry Questions

Experiment 1

Procedure

- Set up a small grid of compasses separated by 3 - 4 inches in a location where the local magnetic field appears to be largely homogeneous - most likely, the compasses are just aligning with the Earth's magnetic field.

- Randomly place the small magnets in and around the grid of compasses and keep the magnets stationary.

1. What phase of matter would be the closest analogue of this experimental setup?

   Solid because the magnets are not moving around.

2. How does the magnetic field appear to vary over different regions of space (i.e. is it more or less homogeneous than before the magnets were added)?

   Less homogeneous than before the magnets were added.

3. Would you expect a sample that is analogous to this experimental setup to have a long or short T_2 relaxation time constant? Why?

   I would expect a short T2 relaxation time constant for a sample analogous to this experimental setup. There is a lot of different local magnetic fields being felt by the spins in the sample, so spins will precess at different frequencies and in different directions and cause signal decay.

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Experiment 2

Procedure

- Multiple students should move the magnets around. This motion should include rotating the magnets along with moving the magnets around the region of space where the grid of compasses has been set up.

- Other students observe the response of the compasses.

4. What phase of matter would be the closest analogue of this experimental setup?

   Liquid because the magnets are moving around, similar to the magnetic spins in a liquid sample moving around.

5. How does the (time-averaged) magnetic field appear to vary over different regions of space? Does it seem to depend on how fast the magnets are moving? How so?

   The time-averaged magnetic field tends toward zero for all the spins. The faster the magnets are moving, the more averaging occurs over the entire space so that the time-averaged local magnetic fields go towards zero. This causes more homogeneity in the time-averaged local magnetic fields.

6. Would you expect a sample that is analogous to this experimental setup to have a longer or shorter T_2 relaxation time constant compared with Experiment 1? Why?

   I would expect a long T2 relaxation time constant for a sample analogous to this experimental setup. The time-averaged local magnetic fields being felt by the spins in the sample are homogeneous, so there will be less spin dephasing and signal decay.

Testing Experiment: Molecular Motion Effect On T_2 - Guided Inquiry Questions

Based on the previous observation experiments, Alice and Sayed came up with the following hypothesis to explain how molecular motion may impact the T_2 relaxation time:

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Hypothesis: The faster the molecular motion in the sample, the more homogeneous the spin magnetic environments, and the longer the T_2 relaxation time.

7. Design an experiment that can be used to test the hypothesis given above. Include a pulse sequence diagram and explain your choice in the timing values you would use (e.g. τ, TR, etc.)

   We can choose samples with different known molecular motions (a liquid versus soft-solid sample or a sample that we heat up to cause more molecular motion) and then do a CPMG experiment to compare the T_2 decay times. We would want to use a long TR time so that signal amplitude differences aren't primarily due to T1 relaxation. We would want to use relatively short τ times so that we can see the exponential decay curve. (If the τ time is too long, the signal will have decayed before we get to see the echo.)

8. For your designed experiment, what would you predict to see in the resulting time-domain signal and frequency spectrum if the hypothesis above is correct? *Feel free to include rough sketches of your predictions!*

   If the hypothesis is correct and we perform the experiment outlined above, I would predict to see a faster decay (shorter T2 time) for the sample with slower molecular motion compared with the sample with faster molecular motion. This would correspond to a broader peak in the frequency spectrum for the sample with slower molecular motion compared with the sample with faster molecular motion.

9. Perform your experiment - or look at the provided experimental data that Alice and Sayed collected - and use these results to make a reasonable judgment about the hypothesis.

   After performing the above experiment, it looks like our predictions were confirmed. We can confidently say that the hypothesis has not been disproven and lives on for potential further testing.

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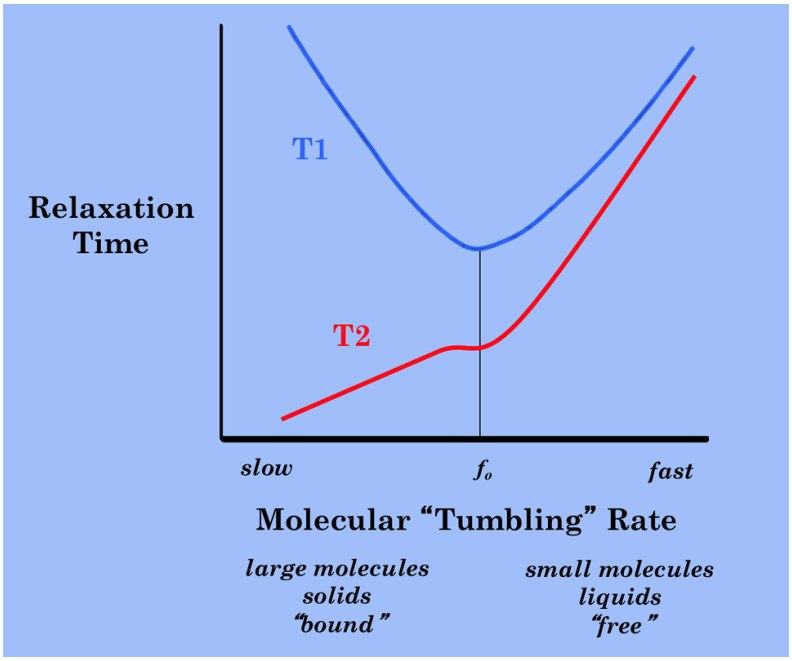
How Does Molecular Motion Impact Relaxation Time Constants? - Guided Inquiry Questions



10. Does the plot for the T_2 relaxation time versus molecular "tumbling" rate match with your experimental conclusions?

    Yes, our experimental conclusions also showed a longer T_2 time for samples with faster molecular "tumbling" rates.

11. Note that the correspondence of T_1 in response to molecular "tumbling" rate is not quite as straightforward. It is actually minimal when the tumbling rate is equal to the Larmor frequency. Provide a possible explanation given what we know about resonance (e.g., that using resonance gives the most efficient energy transfer between systems) and the fact that T_1 is related to the energy transfer between the environment and the quantum spins.

    Since T_1 is related to the energy transfer between the environment and the quantum spins, and this energy transfer is most efficient when matching the natural frequency of the system (the Larmor frequency for our quantum spins), then it makes sense that if the molecular tumbling rate matches the Larmor frequency, resonance occurs that causes more energy transfer and thus a shorter T_1 relaxation time.

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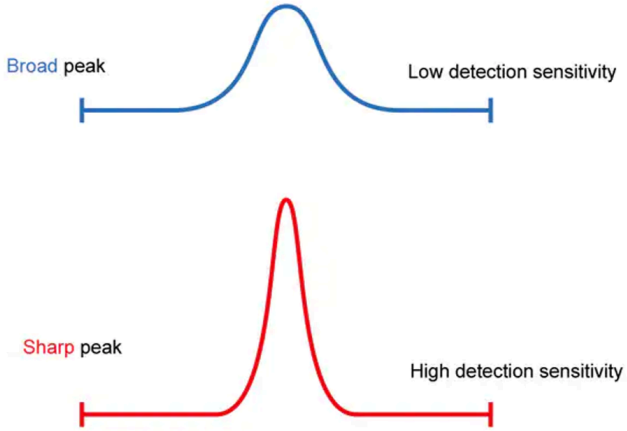
12. In the ideal MR experiments, we would have the longest possible T_2 time - so our signal lasts longer and we get sharper spectral peaks - and the smallest possible T_1 time - so we can repeat our experiments faster. Explain, using the diagram above, why solid-state NMR leads to non-ideal MR experiments.

    Solids are on the left side of the plot and thus have short T2 times and relatively long T1 times - so the exact opposite of the ideal MR experiments described.

Reflection Questions



1. In MR experiments, having narrow peaks helps both with detection sensitivity - signal strength - and spectral resolution - how easy it is to see distinct, individual peaks in the frequency spectrum. Both are very important for identifying peaks in the frequency spectrum and having higher resolution in imaging. One common way to get narrower peaks in solid-state NMR is to do magic angle spinning, where the sample is spun at frequencies up to 130 kHz about an axis that is tilted at the magic angle of 54.74° with respect to the magnetic field. (The magic angle comes from the mathematical formula for the spin-spin coupling causing the short T_2, which is beyond the scope of this module.) Why might rotating the sample help narrow the spectral peaks, given what you have learned in this module?

Rotating the sample effectively causes the time-averaging of the effect of local magnetic field interactions by physically changing the orientation of the spins relative to each other in space. (Effectively, each spin sees the other spins ‘circulating’ about it.)

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2. From the experiments above, we have seen that faster molecular motion leads to longer and longer T_1 and T_2 relaxation time constants. So you should presumably get much narrower spectra from doing NMR of gases. However, doing NMR on gases is even less common than on solids. Can you think of some other possible reasons why gases are not as commonly used for NMR experiments? *Hint: Another important factor is detecting the NMR signal, which is directly proportional to the number of spins we have in our sample volume.*

Gases are much less dense than liquids or gases, so it is harder to get enough spins inside our sample volume to get a detectable signal. (People get around this issue by using hyperpolarized gas, so that instead of just interacting with a few parts per million of spins in a sample, they can get signal from up to 60% of the spins in the gas sample to make up for the lack in total number of spins inside the sample volume.)

Tissue	T1 (msec)	T2 (msec)
Water/CSF	4000	2000
Gray matter	900	90
Muscle	900	50
Liver	500	40
Fat	250	70
Tendon	400	5
Proteins	250	0.1- 1.0
Ice	5000	0.001

3. Looking at the table above, we see that water and cerebrospinal fluid have the longest T_2 time out of the tissues listed. Using what you learned about molecular tumbling rate and its impact on the T_2 relaxation time, explain why this makes sense.

All the other tissues are soft-solids or solids, so they would have much slower molecular tumbling rates than water or cerebrospinal fluid and thus much slower T_2 times.

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4. In MR imaging (MRI), the brightness of the individual voxels (3D pixels) in the 3D image is related to the amount of MR signal one detects in that region of space, along with how quickly that signal decays as the signal is being acquired. Suppose we were doing an ^{1}H MRI of a human head, which has a layer of fat outside the skull and cerebral spinal fluid and gray matter inside. Which of these tissues would show up as the brightest voxels in the image (i.e., have the most signal)? Which of these tissues would show up as the darkest voxels?

Assuming a long enough TR so that all spins are at their maximum magnetization, cerebral spinal fluid would show up as the brightest voxels in the image, because it has the longest T_2 time. The skull would show up as the darkest voxels, since it presumably has T_2 time more similar to ice (another hard solid with slow molecular motion), and then fat would be the next darkest, then gray matter (just going from shortest to longest T_2 times).

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