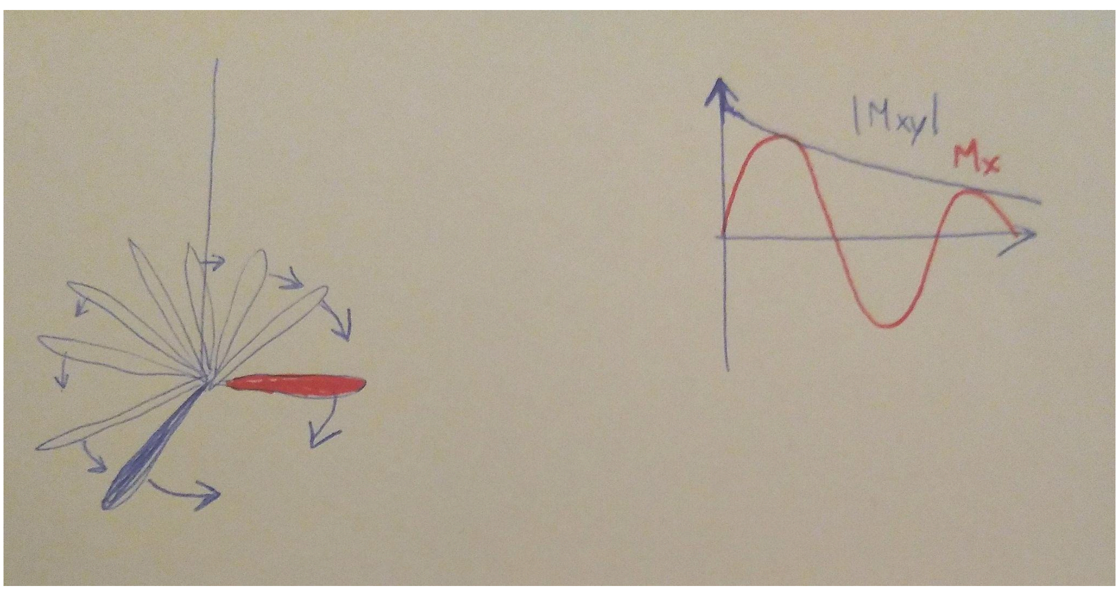
Module 7 Student Answers

Observation Experiments: Spin Echoes - Guided Inquiry Questions

Set up the Bloch simulator to use 'Inhomogeneity' (an option in the 'Equilibrium' menu) so that we will see multiple spins responding to an inhomogeneous external magnetic field. We can leave relaxation off for now to make any echo appear more obvious. Let's hop into the rotating frame (set frame to 'B0') to help clarify what we see.

1. After setting up the simulator as described above, knock-down the spins with a hard-90°$_x$ pulse and draw a sketch and write a description of what you see. Add some arrows to your sketch showing which spins are precessing clockwise and which are precessing counterclockwise in the rotating frame. Recalling how we set up the simulation, what is causing the spins to dephase from each other? What relaxation time would characterize the resulting MR signal decay?



Once the spins are knocked down into the transverse plane, 9 cylinders start 'fanning' out (the ones on the right moving clockwise and the ones on the left moving counterclockwise). The plot of $|M_{xy}|$ and M_x is decaying exponentially as the spins dephase.

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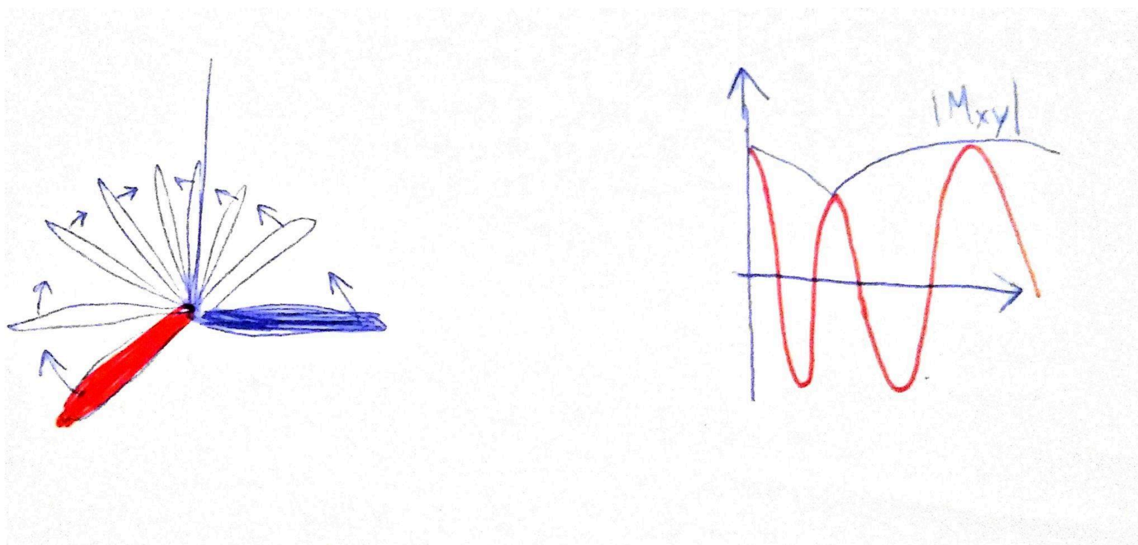
The spins are dephasing from each other because we have added magnetic field inhomogeneities. The relaxation time that would characterise the MR signal decay would be T_2*.

2. Start the spins at equilibrium again (by clicking on 'Inhomogeneity'), knock down the spins with a hard-90°$_x$ pulse, and after some time, apply a 180°$_y$ pulse. Draw a sketch and write a description of what you see after the 180°$_y$ pulse is applied. Keep track of the direction of the spins precession in the rotating frame before and after the 180°$_y$ pulse. Does the direction of each individual spin's precession change with the pulse? Does this make sense, considering the direction of the external magnetic field has not changed?



After the 180-pulse is applied, the 'fanning' spins appear to come back together again, and the signal builds up until all the spins are aligned and then start fanning out again.

I highlighted the most dephased spins on either side before the 180-pulse, and then afterwards they swap places. The direction of precession for each of the spins does NOT change. This makes sense because the external magnetic field direction hasn't changed, so the spins' precession direction shouldn't change.

3. It is helpful to have a physical model in your head to make sense of the spin dynamics on the Bloch sphere that lead to spin echoes - some favorites are racers on a race track or opening/closing a folding fan. Choose your favorite physical model and explain what causes the echo you observe, in your own words.

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I prefer the ‘fan’ physical model, as the many spins in the Bloch sphere representation in the rotating frame look like a fan opening when they are dephasing, and then the motion during the 180-pulse is just like a ‘pancake flip’ of the fan (so the bottom side of fan is now facing up and what was on the rightside of the fan is now on the left and vice versa). The fan then appears to close as the spins move towards each other (even though they are still moving in the same ‘sense’ as before), and the signal returns to a maximum when they are maximally aligned. The fan opens up again as the spins continue precessing at slightly different frequencies and dephase once more.

4. Does the phase of the pulses (that is, whether they are applied in the x- or y-direction) appear to determine whether you see an echo or not? Apply different combinations of pulses on the simulator and your physical model to settle on your answer.

   No, the phase of the pulses does not appear to determine whether you see an echo or not. I tried different combinations of x- and y-pulses for both the 90- and 180-pulses in the simulator. Occasionally, the spins would realign on the opposite side of the transverse planes to the original alignment (when the two phases were the same for both pulses), but it would still result in an echo. I also had fun flipping the fan around in different ways, but always kept my red spins going CW and my blue spins going CCW, and the echo would always appear as well.

5. If the time between the 90° and 180° pulses is τ, how long after the 180° pulse do you expect to see the peak of the echo? Use the simulator and your physical model to settle on your answer.

   Since we let our spins dephase for τ, then due to the symmetry of the observed motion, it takes another τ after the 180-pulse for the spins to realign and cause the peak of the echo. The appears to indeed be the case in the simulator and my physical model if I am careful to open and close the fan at the same rates (which would make sense, because that rate is just determined by the external magnetic field, which isn't changed at all throughout these pulse sequences).

Hahn Echo Theory - Guided Inquiry Questions

6. What relaxation time constant should the Hahn echo experiment enable you to measure?

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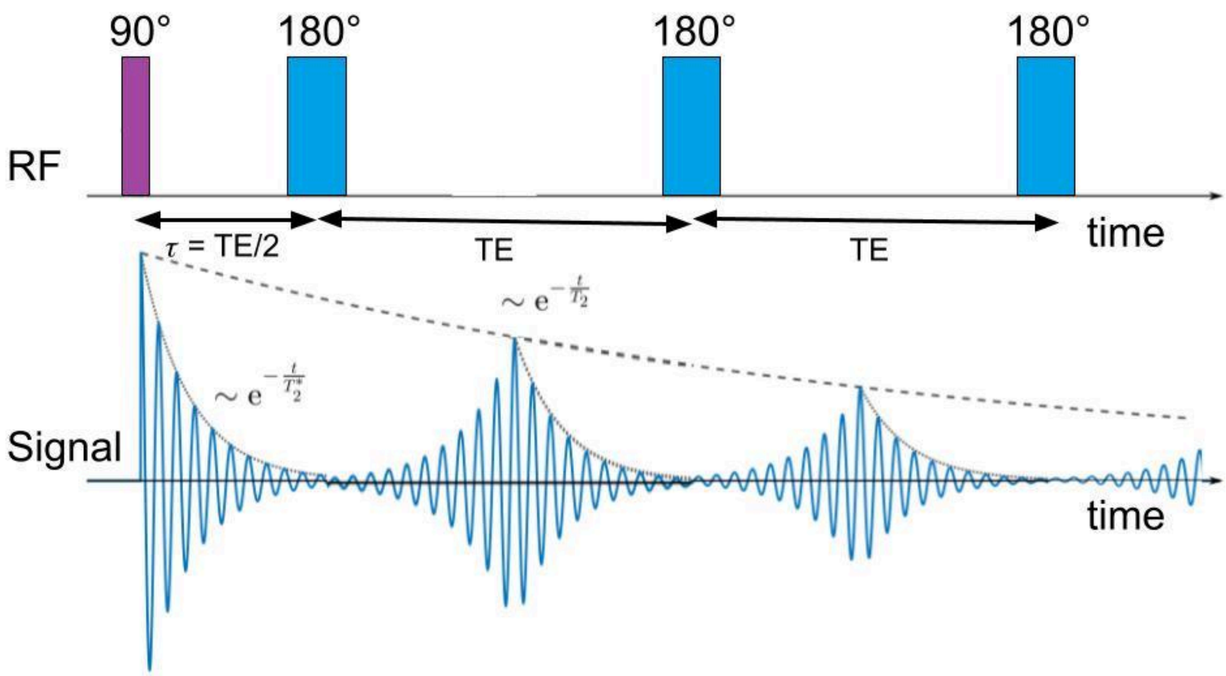
T_2, because it gets rid of the dephasing of spins due to any inhomogeneity in the external magnetic field, so only spin-spin interactions are left, which are the primary cause of T_2 relaxation.

7. Describe an experimental procedure that you could use to measure this relaxation time constant.

   As the animation shown in the module suggests, we can repeat the Hahn echo experiment with different τ times and plot the peak of the Hahn echo versus τ and this would give the T_2 exponential decay curve. Once you have that curve, you can look at the time where the amplitude is 37% of it's peak amplitude (the peak of the FID) and that would give you the T_2 relaxation time constant.

Can We Find T_2 Using a Single Experiment and More Pulses? - Guided Inquiry Questions



8. How does the CPMG pulse sequence compare with the experimental procedure you developed in the previous question?

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The CPMG pulse sequence just repeatedly applies 180-degree pulses, and then the decay of the echo amplitudes versus time gives you the T_2 exponential decay curve.

9. TE is the shorthand for the 'echo time' or the time spacing between consecutive 180° pulses. Why does it make sense that the time between the initial 90° pulse and the first 180° pulse is TE/2?

   TE/2 is essentially the τ time in the Hahn echo experiment, and then you have to wait another τ (TE/2) time for the echo to peak. So it makes sense that from one echo peak to another, you need to wait 2*τ, which would be TE.

10. What are some advantages to using the CPMG pulse sequence instead of just the standard Hahn echo pulse sequence to measure T_2?

    It is nice that you can get lots of data points for the T_2 exponential decay curve all in a single experiment (so a single TR, or repetition time) instead of having to repeat the Hahn echo pulse sequence multiple times to acquire essentially the same data.

11. Describe how you would go about determining the T_2 relaxation time constant for a sample if given data from a CPMG experiment.

    I would plot the peak of the Hahn echoes versus time (so each subsequent echo is at a time that is some integer multiple of TE), and this would give the T_2 exponential decay curve. Once you have that curve, you can look at the time where the amplitude is 37% of its peak amplitude (the peak of the FID), and that would give you the T_2 relaxation time constant.

Reflection Questions

1. Below is some ^{1}H CPMG data collected using a heavy mineral oil sample and very short echo times (TE). Estimate the TE time that is being used to collect this data. What parameter, $|M_{xy}|$ or M_x, is being plotted along the y-axis?

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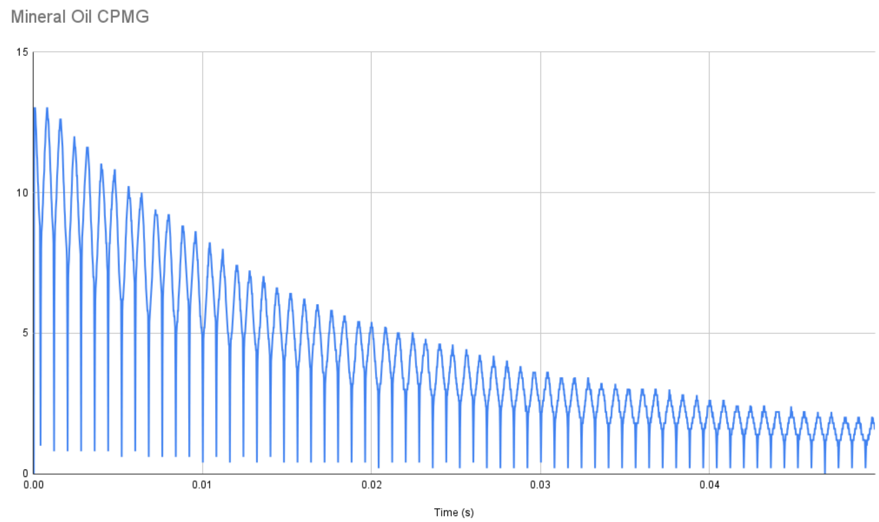
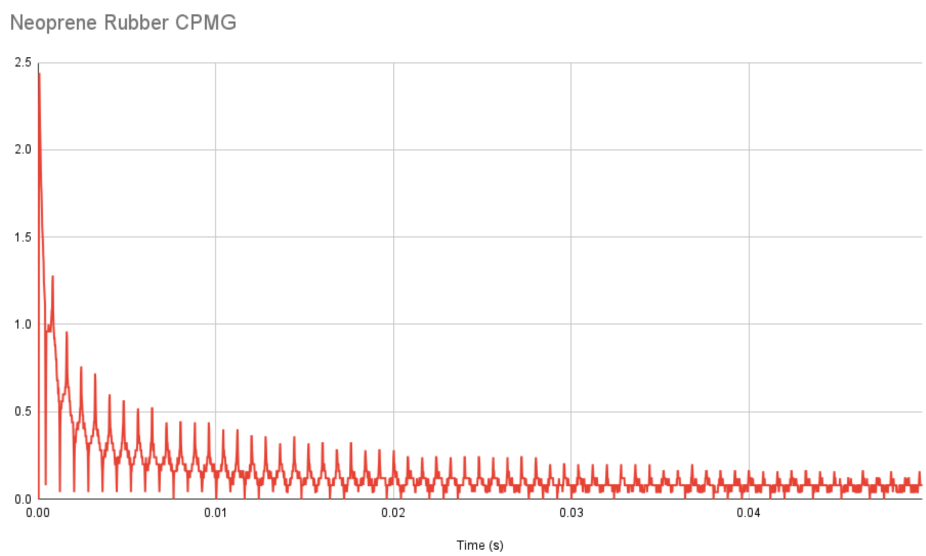


Looks like the y-axis is plotting the amplitude $|M_{xy}|$ for the acquired MR signal (presumably in Volts) from a CPMG pulse sequence using an echo time (TE) about equal to 0.0008 s (since there are about 25 echoes in 0.02 s).

2. Below is some ^{1}H CPMG data collected from a neoprene sample. Estimate the T_2 relaxation time constant.



Vpeak ~ 2.4 so 0.37*2.4 ~ 0.88.That looks to be near the peak of the second echo peak, which should be at 2*TE = 0.0016 s, so T_2 would be around 1.6 ms.

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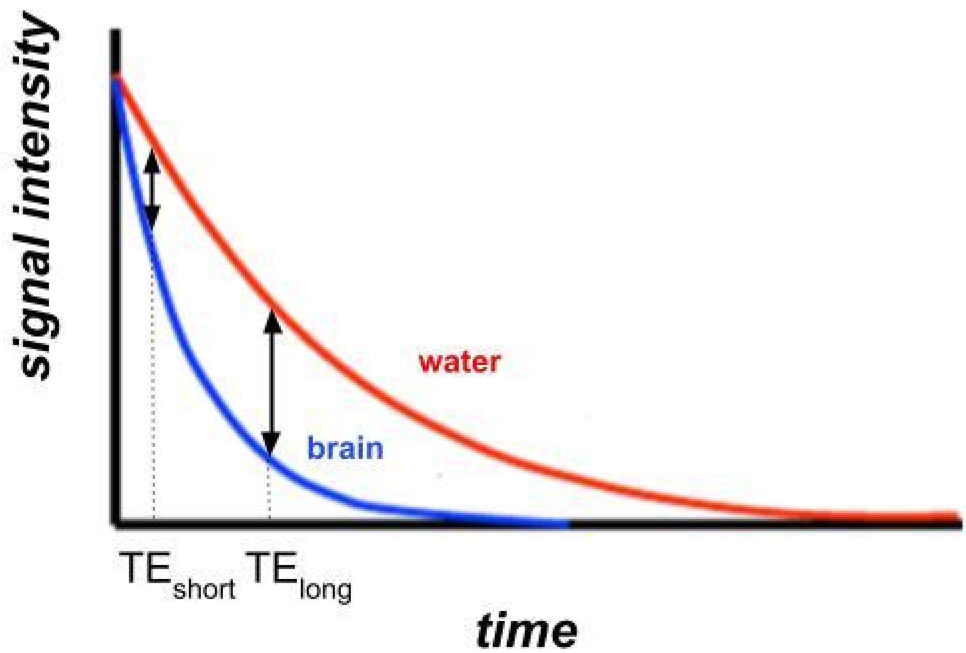
3. From the T_2 time constants for the two samples above, what can you say about the local magnetic environment of neoprene rubber as compared with mineral oil (e.g., is it more or less homogeneous)?

   The local magnetic environment of neoprene must be less homogeneous, causing more spin-spin relaxation and a shorter T_2 time.

4. Design an experiment that can test the hypothesis that the Hahn echo effectively gets rid of the effect of any external magnetic field inhomogeneities. Write a prediction of the results you would expect to see if you performed your experiment and this hypothesis was correct.

   Check out the Module 7 - Example Experiment document for one possible experiment that can be performed.

Below is a plot of the T_2 curves for brain tissue compared with water. You should use this plot to answer the following questions.



5. Which has the longer T_2 time, brain tissue or water?

   Water has a longer T_2 time than the brain tissue because it is decaying slower as shown in the figure above.

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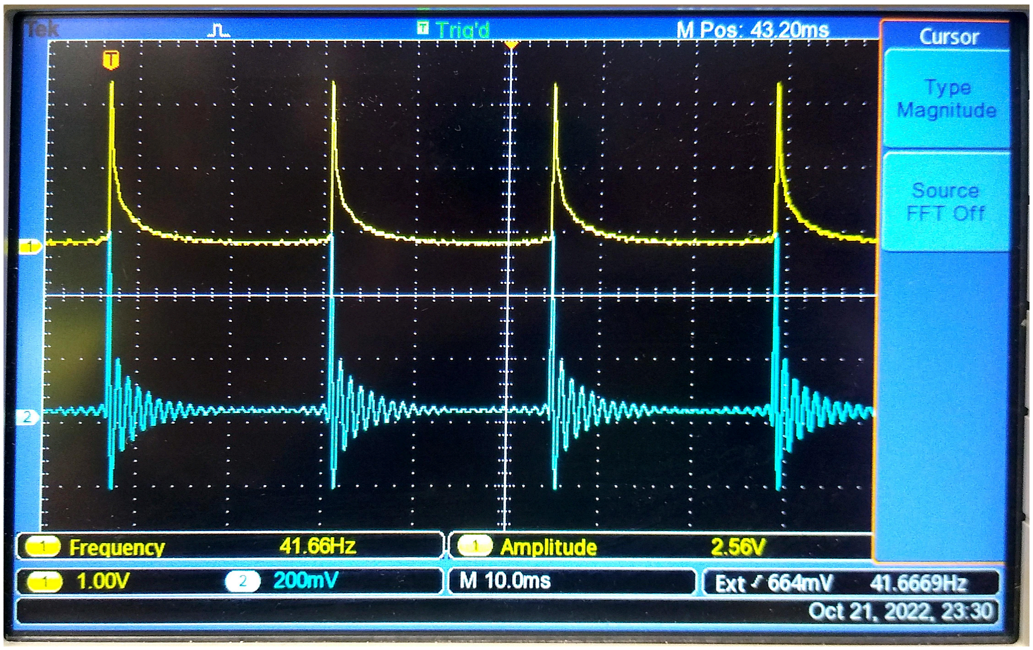
6. You are designing a T_2-weighted MRI pulse sequence that needs to highlight any water in the brain. Looking at the T_2 curves provided, which of the TE times (TE_{short} or TE_{long}) would be a better choice? Why?

   TE_{long} would be the better choice because for that TE time the difference between the two T2 curves is greatest, with the water signal being higher and so showing up brighter in the MR image.

Check out [this link] to help answer the following questions about the mysterious NMR signal below that was collected repeating an FID experiment with a short TR time.



7. Using whichever representation or model you prefer, explain a possible source for the small signal we see right before each subsequent 90° pulse. Why does it make sense that it appears to peak at the time the next pulse occurs?

   This sequence of repeated FIDs happening with a short TR is basically like a multiple-pulse sequence of repeated 90° pulses. The reading shows the 'eight-ball' echo occurring some time τ after two 90° pulses that are separated by τ. Following the CPMG example, we would then expect a small echo to peak right at time τ after each subsequent 90° pulse, but that is also when we are applying the next 90° pulse, so it makes sense that they coincide.

8. Provide a pulse sequence and an experimental procedure to test your hypothesis for the source of the signal.

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If this signal is indeed being caused by something akin to the ‘eight-ball’ echo, we can test this by doing a 2-pulse sequence with only two 90° pulses (separated by time τ that equals the TR time that was used in the above experiment. If our hypothesis is correct, we would predict to see an echo that peaks some time τ after the second pulse.

If we do see an echo after the two-pulse sequence, in order to confirm that echos would still form after multiple (> 2) pulses we can slowly increase the number of repeated 90° pulses by 1 and look for an echo after the last pulse. I would be interested to see if the echo amplitudes decay with the number of pulses used. If this is essentially a less ideal version of the Hahn echo, I would predict that the decay time constant should also be T_2.

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