**Module 4 - Student Questions**

## Bloch Sphere - Guided Inquiry Questions

1. If the quantum spin is in the green state shown in the figure and then is measured along the z-direction (meaning it can be found in either α or β), which state will it more likely be found in?
2. If the quantum spin is in a quantum state represented by an arrow aligned with the +y axis and then is measured along the z-direction (meaning it can be found in either α or β), what is the percent probability of it being found in α? Being found in β? Hint: Since there are only two allowed states, the percent probability of being found in α plus the percent probability of being found in β must equal 100%.

## Initializing Spin States - Guided Inquiry Questions

1. A common initialization state for quantum experiments would be the lowest energy level of the system. Give an argument for why you think that is a common choice.
2. For our spin-½ particles in the presence of an external magnetic field, what spin state would be the lowest energy level?
3. If we wanted to initialize our spins into the lowest energy state, what do you suggest we do?

## Getting Started with the Bloch Simulator

1. Open the Bloch Simulator (<https://www.drcmr.dk/BlochSimulator/>).
   1. Describe what you see.
   2. What motion do you think is being depicted?
   3. What is being shown in the plot in the upper right hand corner?
2. Is there a magnetic field being applied? If so, what direction is this magnetic field being applied?
3. In the upper left corner there are several drop down menus for changing different parameters of the simulation. Click on the dropdown arrow for ‘Fields’. B0 is typically reserved for the large external magnetic field being applied in the +z direction. Observe what happens when you increase or decrease B0. Does this match with what we saw happen with our physical model of quantum spin?
4. Click on the dropdown arrow for ‘Frame’ and change from ‘Stationary’ to ‘B0’. Describe what you observe now. What is happening when you switch from ‘Stationary’ to ‘B0’? In NMR, scientists often reference the ‘lab frame’ and the ‘rotating frame’. Which of the possible frames in the simulator do you think would correspond to the lab frame? Which do you think would correspond to the rotating frame?
5. Try clicking on the red ‘Equilibrium’ button in the lower left hand corner. Describe what happens. What quantum state is the spin put in?

(Note: This is a good way to initialize the simulator so that the system starts in a known quantum state!)

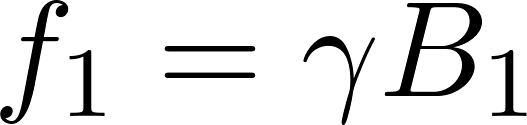
## Controlling Transitions Between Spin States - Guided Inquiry Questions

1. Consider how the dynamics of the Bloch Simulator are very similar to the dynamics of the physical model of quantum spin we saw in the previous module. If we were to introduce another magnetic field to cause a spin-flip, what direction of the magnetic field should we be using (e.g. should the additional magnetic field be oriented in the X, Y, or Z direction?) Would you want the additional magnetic field to remain ‘on’ indefinitely, or would you need to turn it ‘off’ at some point? Explain your reasoning.

(Hint: Consider the spin-flip has a precession that only goes half-way around.)

1. In the Bloch Simulator, initialize the quantum state (using ‘Equilibrium’ button) and turn off all the ‘Fields’ to 0 (B0, B1, and B1Freq). Under the menu ‘View’ you can **check** the checkbox next to ‘B1’ to show the B1 direction and **uncheck** the checkbox next to 'Torque/B1eff'. Now increase the B1 field and observe what happens to the quantum state in the lab frame. Describe what happens. What direction is the B1 field pointing in? Will this potentially be helpful for causing a spin-flip?
2. For actual NMR experiments, we cannot simply turn off the large external field B0, so make B0 nonzero as well (but keep B1Freq set at 0) and observe what happens to the quantum state in the lab frame. Can you explain why that might be happening?
3. Now keep B0 and B1 at some non-zero value and observe what happens when you increase B1Freq. Explain what you think B1Freq is controlling.
4. Your goal is to try to replicate a spin-flip (starting from the spin-up state) with a non-zero B0 using B1. You can play with any of the settings in the ‘Fields’ menu. Record the values that you use in order to replicate a spin-flip. **When you think you have a possible solution, show it to your instructor!**
5. In order to induce a spin-flip using B1, did you have to change B1Freq? What did you have to do to get the desired result? The units in the simulator are dimensionless, simply numbers showing the relative strength of the different variables. In actual NMR experiments, what do you think the frequency of B1 would be (if you know the strength of the B0 field and the gyromagnetic ratio of the spin)? *Hint: MR experiments are making use of* ***resonance*** *and the natural frequency of spins in a external magnetic is the Larmor frequency.*
6. In order to induce a spin-flip using B1, is the field B1 ‘on’ for a limited time? Usually the sources of these B1 fields in NMR are called ‘pulses’ and the different lengths of pulses are labeled by the angle of rotation they will cause the quantum state to undergo and the axis about which they will rotate the quantum state. For example, 90°y would provide a short-lived B1 field in the y-direction that causes a 90° rotation about the y-axis. in the bottom row, to the right of the ‘Equilibrium’ button, you will see some options of ‘hard’ and ‘soft’ pulses. Try some of them out and observe what happens to the B1 field during the pulse and the resulting motion of the spin. What is the difference between ‘hard’ and ‘soft’ pulses?
7. Scientists typically like to view the spin dynamics in the rotating frame. View some of the pulses in the rotating frame. Why might looking at the spin dynamics in this frame be more convenient?

## Nutation and Pulses - Guided Inquiry Questions

1. Scientists typically consider a very short pulse duration as a ‘hard’ pulse. What parameter would you adjust in order to generate a ‘hard’ pulse? Give an explanation for your answer using the nutation frequency, [](https://www.codecogs.com/eqnedit.php?latex=f_1%20%3D%20%5Cgamma%20B_1#0).
2. With the addition of pulses, do we have the ability to effectively ‘control’ the quantum state? Why or why not?

## Reflection Questions

1. Why might scientists prefer the Bloch sphere representation for two-level quantum systems instead of the energy-level representation?
2. How is utilizing resonance an important aspect of quantum spin control?
3. View [this video](https://www.youtube.com/watch?v=zNFDAEOLGqg) using the magnetic torque apparatus from our previous module. Explain what you think is going on.
4. Write down the pulse sequence that led to [this video](https://www.youtube.com/watch?v=E-ZMaCq9Q3A).

(Note: this video was taken in the rotating frame, so you want to use that frame when trying to replicate this pulse sequence using the simulator!)

**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. |