Nuclear Magnetic Resonance: The Foundation of Magnetic Resonance Imaging

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1 Motivation

I have been interested in physics for a while, but the only physics I have been exposed to has been basic classical physics, acting as an introduction and laying the foundation for further study. I have studied mechanics, electromagnetism, optics, fluid mechanics and some thermodynamics, but not any modern physics or quantum mechanics. I was interested in going beyond the physics encountered in my classrooms, so I have been doing some reading on my own about current physics experiments and some of the theory behind quantum mechanics. Dr. Dann was aware of this, so when he bought a Magnetic Resonance Imaging (MRI) machine this year, he suggested I do some experiments with it for my second semester project, as this would teach me a lot about quantum mechanics (as MRIs work using quantum interactions) and introduce me to the world of experimental physics.

The project will explore how atoms of different elements interact with one another at the quantum level. In essence, it will be taking pictures of chemical reactions to see whether chemists' theories for how elements and chemicals interact with each other are correct. I will be able to do this by imaging a single element and determining at what frequency resonance occurs, repeating this process for another element, and then imaging a chemical composed of the two elements. When this third image is taken, the two resonant frequencies of the two elements can be seen, but then at least one more resonant frequency peak can be seen, which represents the quantum interference of the two elements. It is the quantum mechanical effect of the electron wave functions of one atom interfering with those of another.

This paper was written for Dr. James Dann's Applied Science Research class in the spring of 2009.

This idea was first carried out by Robinson et al., [1] where the authors used two-dimensional Nuclear Magnetic Resonance (NMR) spectroscopy to obtain spectra of trifluoroethanol and para-difluorobenzene and observed the interference effects of the electron wave functions. MRI imaging is a vital aspect of diagnostic medicine, as it is a noninvasive procedure that allows doctor to see soft tissue. Functional MRI (or fMRI) is also a key tool in brain and cognitive research, as it allows investigators to observe blood flow to different sections of the brain in real time.

2 Theory

All elementary particles have an intrinsic quality called spin. Although it behaves similarly to angular momentum (hence the name), some particles that have spin (like electrons), are point particles and therefore cannot literally spin. Instead, the spin is due to a "circulating flow of energy in the wave field" [2]. Spins can have either half or full integer values. Additionally, every particle can be in a spin up or spin down state, which correspond to slightly different energy levels, causing their spin values to be positive or negative. The spin of a particle also gives rise to its magnetic moment, another intrinsic quality. But more than just elementary particles can have spins. Nuclei can as well, for example. In that case, spin is the part of the angular momentum of the nucleus that is separate from the motion of the center of mass.

The particle most MRIs interact with is the proton, as it constitutes the entire nucleus of the hydrogen atom. So when protons, which each have a spin of either +1/2 or -1/2, are placed in a strong magnetic field, a process called spin polarization occurs. This means that while most of the protons' spins are randomly aligned, there is a slight net alignment in the direction of the magnetic field. A +1/2 spin is the lower energy state of protons and is the state they are in when they are placed in the magnetic field with no other interactions occurring. The energy of a particle in a particular spin state is given by the following equation (where m = 1/2 corresponds to spin up and m = -1/2 corresponds to spin down.

$$U = -g \frac{m_i e\hbar}{2m_p}$$

$$m_I = I, I\text{-}1, \dots 1\text{-}I, \text{-}I$$

The small net alignment is due to the thermal energy of the particles (as they are at room temperature). This energy causes some of the particles to be in the higher energy spin down state. The net magnetization has a direction and is referred to as the bulk magnetization vector. This vector lies in the direction of the static magnetic field, in this case Earth's field. The spins of each proton precess around this vector, resulting in one component of the magnetic moment in the direction of the bulk magnetization vector and one in the transverse plane, as illustrated below.

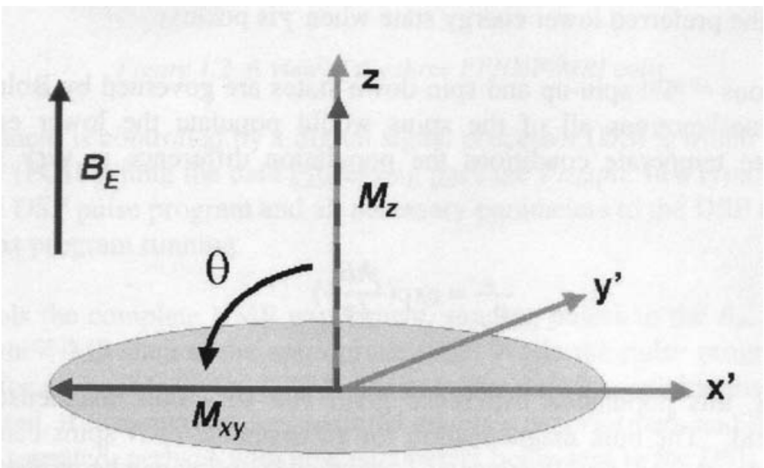


Figure 1: *Magnetization*

The B_E vector is Earth's magnetic field (the static magnetic field), the disc represents the transverse plane, M_Z is the component of the magnetic field in the direction of the bulk magnetization vector, and M_{XY} is the component of the magnetic moment in the transverse plane. The direction of M_{XY} for every proton is randomly distributed, however, so they all end up canceling out, resulting in a net magnetization in the z direction only.

NMR experiments control the bulk magnetization vector by applying an alternating electromagnetic field to the sample. If the frequency of this pulse matches the frequency at which the spins are precessing (the resonant frequency), then this energy induces a spin transition. The energy difference between levels is given by the following equation:

$$\Delta U = \frac{ge\hbar\mathcal{B}_0}{2m_p}$$

And the Larmor frequency, the resonant frequency of the protons, is given by this equation:

$$f = \frac{\Delta U}{h} = g\frac{e}{4\pi m_p}\mathcal{B}_0$$

When the electromagnetic pulse is sent through the sample, it tips the bulk magnetization vector from being in the z-direction into the transverse plane by some angle θ. As this new bulk magnetization vector is excited, it precesses about B_E. The B_1 coil (the pickup coil) can detect the MXY component, as it induces a current in the coil. This current is only induced when the precessing magnetization vector's frequency matches the resonant frequency of the pickup coil, which is set by the user. Through a Fourier transform, the MRI machine can determine where the resonant frequency is. This can then be plotted on the y-axis with position (x) or k-space (1/x) on the x-axis to create a one-dimensional plot.

One important measurement to make when conducting MRI experiments is the T1 relaxation time. This is a measurement of how long it takes for an equilibrium magnetization to be reached. In essence, it is a measurement of a transfer of energy, in this case the energy transfer between the spins of the sample and the surrounding material (referred to as the lattice). This T1 time, along with the T2 time, a similar measurement but in this case of the energy transfer between neighboring spins, provides a more unique signature to a particular MRI signal, allowing for more accurate imaging in the body. One can compare the different T1 and T2 times and tell more accurately where in the body the signal is coming from.

3 Results

In order to get clear results from MRI and NMR experiments, there must be no large disturbances in the magnetic field, in this case Earth's field. This is partially because the homogeneity of the field is very important in determining where the protons are located. An unexpected spike or dip in the magnetic field means that the Larmor frequency will be changed (either up with a spike or down with a dip), which means that the frequency picked up by the MRI will be wide, resulting in an inaccurate picture. A magnetic field with a known gradient, on the other hand, can be used to take 2D images. Additionally, magnetic field interferences can prevent the spin alignment from happening as it should, which then prevents any sort of accurate picture from being produced, as the production of many different frequencies can drastically reduce the signal-to-noise ratio.

The classroom where the EFNMR is located happens to have many sources of magnetic noise. There are multiple other science and engineering projects being carried out in the room, many of which include the use of extremely strong magnets. Additionally, the fluorescent lights used to light the room produce noise, as do the many computers located around the classroom. These, along with other factors, produce a background noise of about 50 μV. In order to get clear pictures, the noise level must be below 10 μV, and below 5 μV for the best results. This is because the signal induced in the pickup coil is usually no more than 50-70 μV, and the signal-to-noise ratio must be at least 5:1 to get a significant signal. Therefore, in order to get a better picture, it proved necessary to reduce the ambient noise. This was accomplished by building a Faraday Cage (albeit one with two open sides).

The first cage constructed was built out of thin aluminum sheet metal about 1.5 mm thick. The four sides of the cage were connected using 30 cm wide strips of aluminum bent into L-joints and screwed into two sides of the cage, four for each joint. This cage reduced the noise by about a factor of two, but there was still too much noise to proceed with any experiments. The next cage was built out of aluminum as well, but was about 13 mm thick and with the four sides welded together, forming a much better electrical connection along the corners. The added thickness provides far more insulation against electric and magnetic fields, both of which can interfere with NMR experiments.

This new cage lowered the noise far enough to conduct experiments (about 4 μV). However, the strong magnetic pulse induced eddy currents in the shield, which need to die down before a signal can be picked up. Finding the right delay is tricky, however, and took a while, especially because the shield being used in this experiment is thicker than the shield Magritek designed, so the delay must be longer than they advise. Finally, the correct delay was determined to be 130 ms. With the shield, this yielded a good result. (See Appendix A.) The resonant frequency of protons in Earth's magnetic field in the classroom is about 2100 Hz, and with the shield the experiment yielded a signal-to-noise ratio of about 60:1.

While the shield dispels magnetic and electric fields very effectively, the same principle means that when there is a large magnetic pulse in the MRI machine, there is an induced current in the shield. The MRI machine creates a magnetic field running through the center of the solenoid. Normally this would not induce a current in the shield, but due to fringing effects there is magnetic flux through the shield. According to Faraday's Law, the time derivative of magnetic flux is equal to the induced emf ($d\varphi/dt = \varepsilon$) and the magnetic flux is the integral of $B \bullet dA$. So as the magnetic pulse in the MRI machine changes in intensity, the derivative is non-zero and there is an induced emf, resulting in eddy currents. Luckily, these eddy currents die down very quickly, but until they do the interference they create makes it impossible to pick up an MRI signal, necessitating a longer delay.

The final experiment I attempted was a measurement of the T1 relaxation time for Earth's magnetic field. At first I was having difficulty getting a reading with a reasonable margin of error. The process works by creating a magnetic pulse to get an MRI signal, measuring the amplitude of the signal after a constantly increasing amount of time, and then integrating along the best fit line. This provides the T1 time. When I started the time interval at 300 ms after the pulse instead of 0 seconds, I was able to get a good signal with only about a 10% margin of error. My T1 time from Earth's magnetic field was 2600 ms +/- 300, and my T1 time from the polarization magnetic field was 2500 ms +/- 265. ●

4 Appendices

4.1 Appendix A: PulseAndCollectMacro

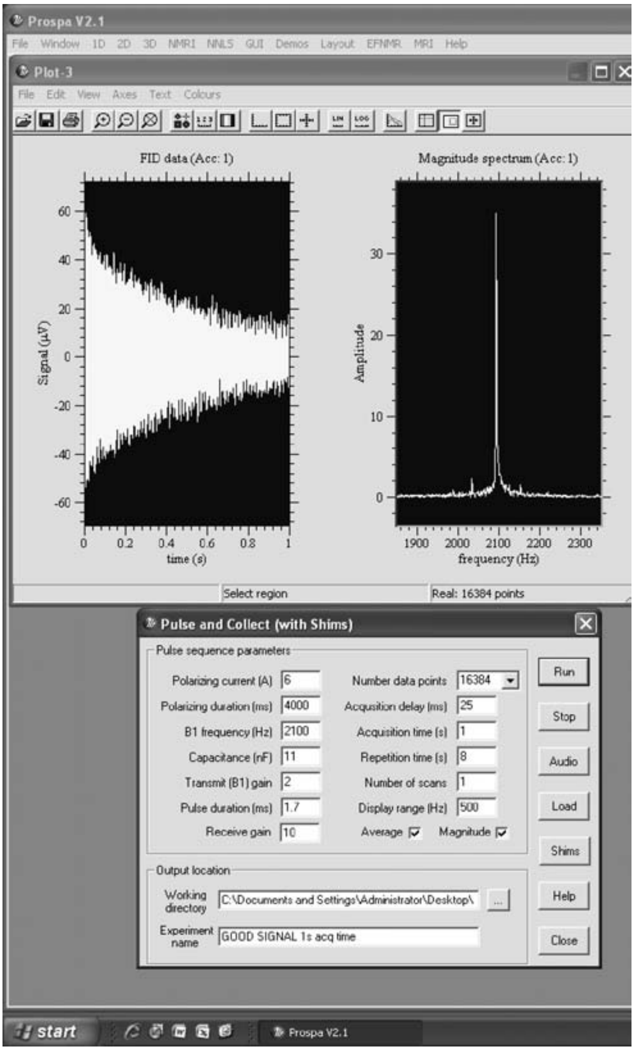
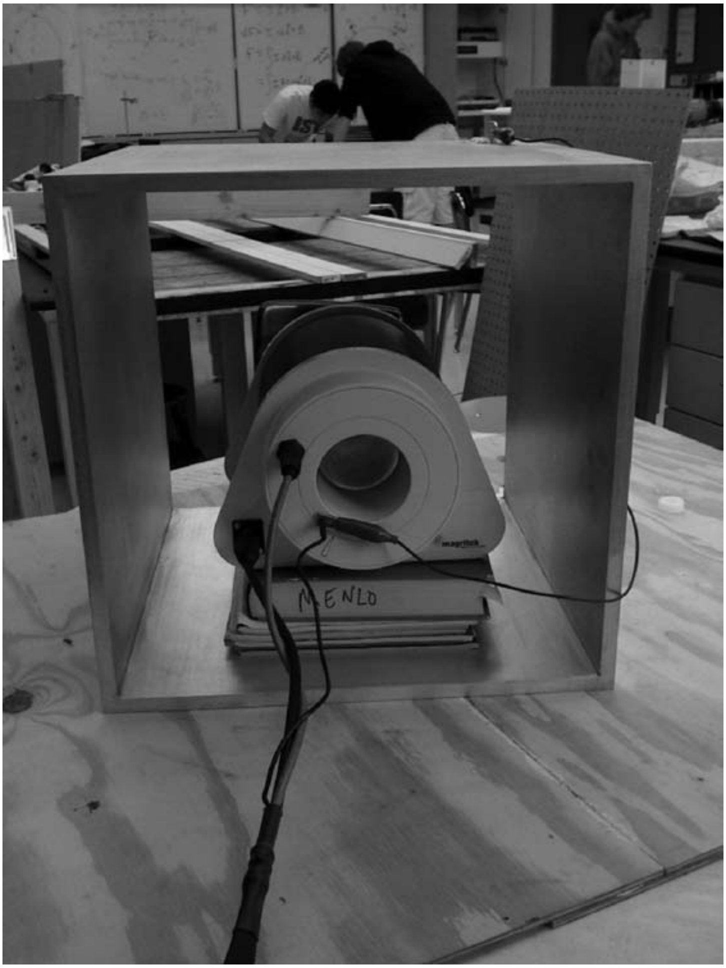


Figure 2: *Screenshot of the results of the PulseAndCollectMacro. This screenshot shows both the FID graph (upper left), and the frequency amplitude graph(generated from a Fourier Transform). The FID signal is an oscillatory decaying signal, with a max amplitude of about 60 μV. The bottom of the screenshot shows the parameters used to get the signal.*

4.2 Appendix B: Photos

A



B

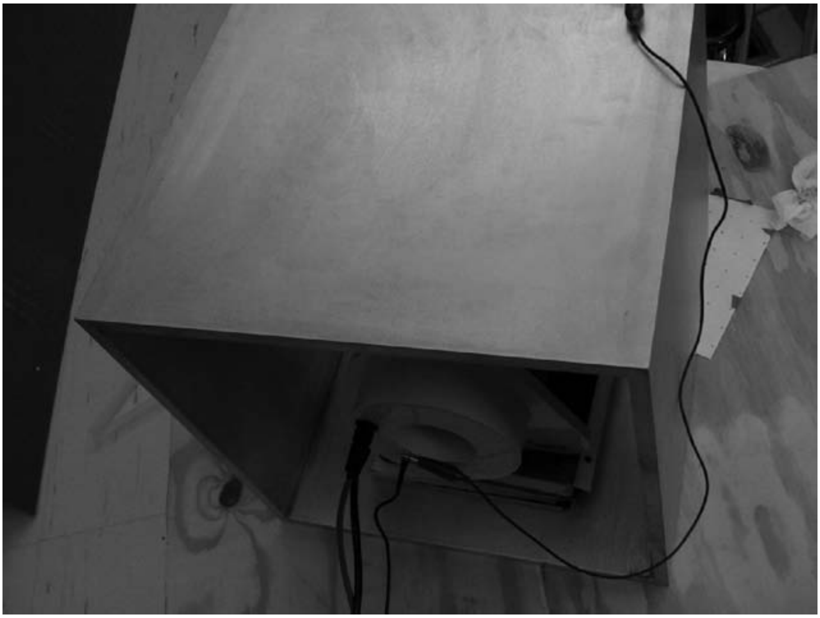


Figure 3: *Photos of the experimental setup from multiple angles. A: A side view of the setup. The MRI machine is visible inside the shield. The polarization coil is visible on the outside of the MRI and the ground can be seen connecting the shield to the ground of the MRI machine. B: A top view with a better view of the shield and the ground.*

5 Bibliography

1. Robinson, Jeremy, et al, Journal of Magnetic Resonance 182 (2006) 343.

2. Ohanian, Hans. (1990). *Principles of Quantum Mechanics*. Prentice-Hall (Englewood Cliffs, NJ).

3. Halse, Meghan. (2006). *Terranova-MRI EFNMR Student Guide*. Magritek Limited (New Zealand).