Physics 220, Spring 2009
Lab 12, Nuclear Magnetic Resonance in the Earth's Magnetic Field

Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI) are both generally based on the manipulation and observation of the effects of the magnetic moment of protons in a magnetic field. The nucleus of the hydrogen atom is simply a proton, meaning that any hydrogen-containing molecules (including water) contain protons that can be manipulated and observed in this way.

Because the proton has intrinsic spin, it has a magnetic moment given by $\mu = 2.79\frac{e}{m_p}S$.
(The 2.79 comes from considering the objects that make up the proton: the quarks and gluons.) With the proton being a spin-one-half particle, if it is placed in an external magnetic field B, the energy associated with the interaction of the magnetic moment with the magnetic field is $U = -\mu \cdot B = \mp 2.79\frac{e\hbar}{2m_p}B$, where the minus sign goes with the state with spin "up" and the plus sign goes with the state with spin "down." The quantity $\frac{e\hbar}{2m_p} = \mu_N$ is known as the nuclear magneton and its value (in eV/T) can be found in tables of constants.

If a proton's spin flips in a magnetic field, a photon may be emitted (if energy is released by the spin flip) or absorbed (if energy is required to flip the spin). Detecting the emission or absorption of these photons is the key to NMR and MRI.

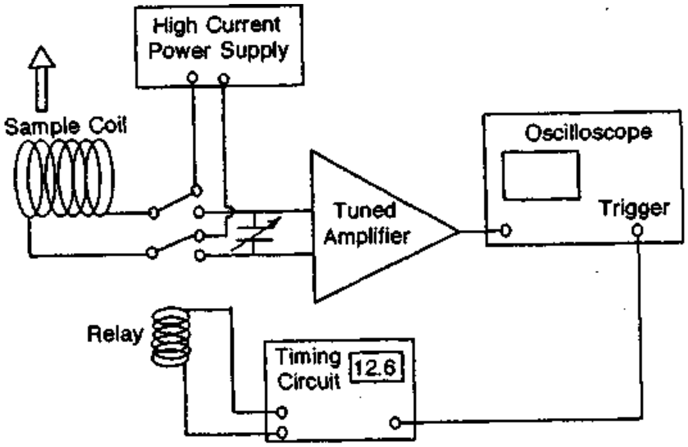
With most NMR instruments, it is not possible to observe the effects of a single proton's magnetic moment. Suppose, however, that we use 125ml of water as a sample. This contains about 10^{25} hydrogen nuclei (protons). If all those protons were aligned with their magnetic moments pointing in the same direction and they were all to remain aligned, then our signal would be 10^{25} times as large as from a single proton! Polarizing even a small fraction of the available protons will still produce a measurable signal.

The degree of alignment in a sample is referred to as the polarization or as the magnetization, M. Quantum physics tells us that there are only two possible magnetic states for the proton to reside in: spin along B, or spin opposed to B. The magnitude of proton magnetization is proportional to the difference between the number of protons with spin along B and opposed to B.

Lab question: The Earth's magnetic field varies by location, but a typical value is 50 μT.
a) For a proton in the Earth's magnetic field, calculate the difference in energy (in eV) between spin "up" and spin "down."
b) If the proton makes a transition between these two states, what's the energy, wavelength, and frequency of the photon given off (or absorbed)? In what part of the electromagnetic spectrum is this photon?

The Earth's field NMR apparatus allows you to apply an external magnetic field from a coil of wire to achieve some amount of polarization of the protons in a sample of water. When the external magnetic field is turned off, the Earth's magnetic field remains, and some of the protons will reorient themselves to align with the Earth's field. This produces a radiofrequency signal that we can detect using the same coil that produced the original magnetic field.

Overview of the Apparatus



See the simplified block diagram at right. The sample coil surrounds a 125ml plastic bottle filled with distilled water, or another liquid to be investigated. The sample is placed in a uniform part of the local Earth's magnetic field with the **axis of the coil perpendicular to the Earth's field.** At the beginning of the experiment, the electronic timers and relays connect the sample coil to the external dc power supply. The current from this external supply produces the so-called "Polarizing Magnetic Field." This polarizing field is perpendicular to the Earth's magnetic field and **much** larger in magnitude. The time the sample coil remains connected to this supply is set by the rotary switches on the electronic controls.

After some time of "soaking" the nuclei in this large polarizing magnetic field, the polarizing current is disconnected from the coil, the stored magnetic energy in the coil is quickly dissipated, and the coil is connected to the tuning capacitors and the amplifier. The polarizing magnetic field is removed so quickly that the nuclei remain polarized along the direction of the polarizing field. With the polarizing magnetic field turned off, the changing nuclear magnetization produces a time varying flux through the sample coil, which creates a time varying voltage at the terminals of the tuned circuit. This voltage is amplified, and then is directed to an oscilloscope.

In this apparatus, the initial signal amplitude is proportional to the magnetization of the sample. You can use to explore two parameters that might control the magnitude of the magnetization, the strength and the duration of the polarizing magnetic field Both the polarizing field and the polarizing time are under your control.

The Six Main Parts of the Apparatus

1. Coils
   - The inner coil is the sample coil. It has two functions: First, it provides a large (and variable) magnetic field to polarize (magnetize) the nuclear spins. Then it generates a signal voltage from the nuclear spins.
   - The larger outer (halo) coil reduces the pickup from external electromagnetic noise fields. (To further reduce noise, turn off fluorescent lights and incandescent lights that are on dimmer switches. Dimmers usually produce significant noise fields.)
2. Support stand for coils.

   This nonmagnetic stand allows the coils to be placed in a region of uniform Earth's magnetic field. If the nuclear moments in the sample find themselves in different magnetic fields the frequency of the transitions will be different. It is usually best to place the coils away from walls, tables with steel parts, off the floor where iron drain pipes may be buried and away from steel support columns. Small spatial adjustments, even just a few inches, can often make a significant difference in the observed decay time of the precession signal.
3. Electronic Controls
   a. Timing Circuits. These circuits provide the various timing functions.

- The length of polarizing time, which is set by the thumbwheel switches on the panel. This is variable in steps of 0.1 s, from 0.1 to 99.9 seconds.
- Various delay times, such as a 5 second delay after every experimental cycle, an 80 millisecond delay after switching off polarizing current to allow voltage transients to die out, and a delay time equal to polarization time to keep duty cycle to under 50%.
- Synchronizing pulses for oscilloscope triggering. For NMR signals, the scope should be set to trigger on a negative pulse, negative slope, at minus one volt.
- Manual Start. A push button switch that starts the entire sequence.
- Wait Light. Tell the experimenter that the instrument is still going through its cycle and the operator needs to wait before pushing the start button again.

b. Amplifier

It is essential to tune the sample coil to the frequency of the radiation produced by the changing magnetization. Since this frequency is uniquely determined by the local Earth's magnetic field in your laboratory, the student must experiment with the controls to determine the proper tuning. There are two outputs on the amplifier, one marked preamplifier and the other NMR signal. First adjust the tuning capacitors to maximize the output of the preamplifier. (Note. Use AC coupling on the oscilloscope since the preamplifier has a dc offset imposed on the signal from the electronics). The NMR output comes from the second stage amplifier. This is a tunable bandpass amplifier, which can be tuned by the 10 turn counter dial.

c. Amplitude Detector

The signal available at the NMR SIGNAL OUTPUT is also connected internally to an Amplitude Detector, the output of which is the average value of the full-wave rectified signal. For a full-wave rectified sinusoidal signal, the average value is $2/\pi$ of the peak value. Thus, the output of the NMR AMPLITUDE DETECTOR has the same shape as the envelope of the free-precession signal, but the amplitude is about 2/3 as large. This signal is particularly useful for signal averaging of repetitive experiments. It can enhance the signal to noise ratio for weak signals.

d. Audio Amplifier and Speaker.

The radiation frequency for both protons and fluorine nuclei in a typical local Earth's magnetic field is about two thousand cycles per second. This is in the audible frequency range. This instrument has a volume controlled audio amplifier connected to an internal speaker. You can hear the signal generated by the changing magnetization in the sample. If you are lucky to have a particularly uniform field in your lab you might hear the sound for several seconds.

4. Brick-on-a-Rope (power supply for electronics)

This is the dc regulated power supply that provides ± 15 volts and $+5$ volts to operate the electronics. The supply (brick) plugs directly into the ac power line and the dc outputs are connected by cable (rope) to the rear panel of the control box. It is best to leave the dc line plugged into the rear panel and remove the supply from the power line when you have completed the experiments. There is no on-off power switch.

5. External Power Supply for polarizing magnetic field

This power supply provides the direct current for the polarizing magnetic field. The polarizing field is changed by adjusting the output current. Ask your instructor to explain how you adjust the supply for current regulation to keep the current and thus the polarizing field constant. Do not run the experiment with less than 0.5 amperes or more than 3.5 amperes.

DO NOT GROUND EITHER SIDE OF THE EXTERNAL POWER SUPPLY. This supply must be floating!

DO NOT TURN THE POLARIZING CURRENT ON UNTIL THE INSTRUMENT ITSELF HAS

BEEN POWERED BY THE BRICK-ON-A-ROPE.

6. Oscilloscope

A 20 MHz scope is more than sufficient for these measurements. However, "aliasing" can be a problem (your instructor can explain this concept). One simple test for incorrect data presentation due to aliasing is to change the sweep time to a faster sweep by one unit and observe the same signal. If the signal changes appropriately, it is not aliasing, but if the scope presents significantly different data, then the first data should be ignored.

Setting up the instrument:

The instrument should be set up and then tuned to the resonant frequency of protons in water. Follow the instructions for Initial Setup on pages 16 through 22 of Student Manual #2. (Some of the steps have been already done for you—simply verify them in that case).

Objectives for the Experiments

Discuss with your instructor how you plan to measure each of these before actually making the measurements.

1. Measure the magnitude of your local Earth's magnetic field by determining the frequency of precession of the protons in a water sample. Also determine an uncertainty. Is your result reasonable?

2. Does the degree of polarization (magnetization) of the protons depend on the strength of the magnetic field they are placed in? If so, what is the mathematical relationship between the polarizing magnetic field and the polarization?

3. Does the polarization occur instantaneously? What is the mathematical description of the time dependence of the polarization? What is the value of the time constant for this polarization?