Spin Resonance and the Proton g-Factor

Name: Felix Martinez

Partners: Seth Kim, Jack Harrison

Date: 03/26/21

I. INTRODUCTION

The purpose of this lab is to understand spin resonance, both nuclear and electronic, and to measure the g-factor of the electron and proton. We will also be introduced to the gyromagnetic ratio of a charged spinning body, and how the g-factor relates to it.

Homogeneous classical bodies have a g-factor of 1. Relativistic quantum theory predicts that charged spin-1/2 particles have a g-factor of 2. When the gyromagnetic ratio of the proton was first measured and its g-factor was found to differ from 2 to 5.5. This was proof that the proton was a composite particle, and not an elementary particle like the electron.

II. LAYOUT AND EQUIPMENT

We will be taking measurements using a Tel-Atomic, Inc. CWS 12-50 cw NMR/ESR spectrometer. Below is an itemized list of all of the equipment we will be using in this experiment.

Fig. 1: Equipment we will be using for the NMR/ESR experiments courtesy of Tel-Atomic Incorporated.

The setup for the equipment in the experiment can be seen below. The first experiment we will be conducting tis the NMR experiment using a glycerin sample. The NMR experiment uses the Electromagnet as seen in figure 2. We will also be conducting the ESR experiment using the TCNQ sample. The ESR experiment uses the Helmholtz coil also seen in figure 2.

Fig. 2: The setup for our lab equipment courtesy of Tel-Atomic Incorporated.

Tel-Atomic Inc. also has data processing software (CW NMR/ESR Spectrometer) that we will be using to take measurements for this experiment, below is a screenshot of the software in action along with a detailed description over what tools are in the software.
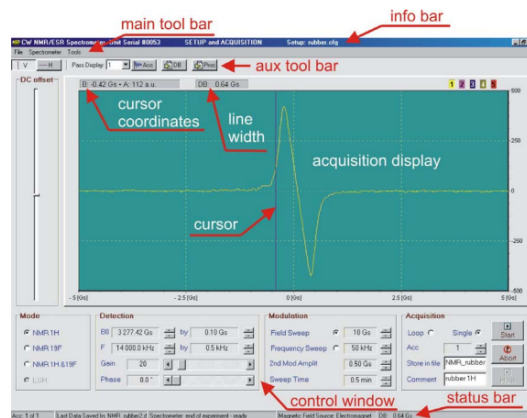

Fig. 3: A detailed analysis over the NMR/ESR Spectrometer software courtesy of Tel-Atomic Incorporated.

III. Procedure

We will begin our procedure by turning on our spectrometer, ensuring that the serial-USB adapter from the spectrometer is connect to the computer. To set up the software, we must choose the "Spectrometer" menu option, choosing "Comm Port" and then "COM2", then, from the Spectrometer menu, choose "Connect". This should enable communication between the software and the spectrometer.

As we are attempting to measure the precession frequency of tiny spins in an applied magnetic field for both protons and electrons, we will be using radio-frequency detection in the vicinity of 13-15 MHz, as this is a fairly quiet spectrum that is straightforward to detect.

A. NMR Experiment

Using the glycerin sample and the Electromagnet (putting the Helmholtz coil to the side for now), we must set up our apparatus as shown in figure 2.

To start measuring data, we must first turn the magnetic field (B0) as low as it would go, roughly 3073 Gauss, and set the control to increase the field by 1 Gauss. We must now increase the magnetic field by roughly 10 Gauss (or 10 clicks if the control was set correctly) to around 3083 Gauss. We must also set the RF frequency (F) to around 13160 kHz, with its control set to 10 kHz. To finish this setup we will also choose the "Field Sweep" option, setting it to 15 Gauss, alter the "Second Modulation Amplitude" parameter to 1.5 Gauss, "Gain" to 100, and "Phase" to zero.

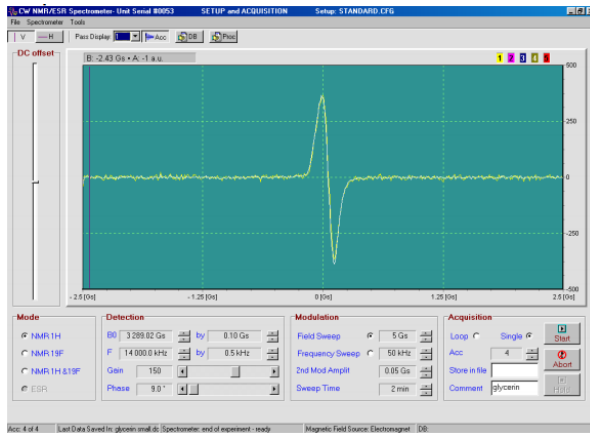Now we must perform a scan, our goal is to achieve a scan as shown below:

Fig. 4: Ideal Glycerin NMR Scan, courtesy of Tel-Atomic Incorporated.

However, due to our initial conditions, we will likely not achieve this scan and that is okay. We must adjust the frequency by roughly 10 kHz at a time to find the resonance occurring. Once we have the resonance line appearing on our software, we must optimize it. To do this we must take note the magnetic field at the resonance and the frequency and calculate the ratio. We can use this ratio to estimate what value to set the frequency so that the resonance appears roughly 1/4 of the way through the scan. We want to do this to save time when taking our data, instead of having to wait the full 30 seconds for each scan, we will only need to wait a fraction of that.

Now we must adjust the "Gain" until the resonance is large. We must then alter the "2nd Mod Amplit" to a value that is less than about 1/4 of the full linewidth. Finally, we must adjust the "Phase" setting, we want to have the phase control roughly $90°$ from the correct value, this will minimize the resonance and distort the resonance severely from figure 4. Once we find the minimum of the resonance, we must add another $90°$ to the phase to have a resonance that is $180°$ off our true maximum, this is okay as we are measuring the intercept of our wave as it coincides with an amplitude of zero, this will be the phase we will be taking our measurements on.

To take our first data point, we must let a full scan finish to allow a purple vertical line appear on the display. We can then drag this line to the center of the resonance, the point where the wave crosses from positive to negative (or negative to positive depending on your phase), and record the offset. The magnetic field at this point is just the B0 setting plus this offset, this is our first data point.

Our goal is to find the resonance frequency for as many different values of the RF as we can. To do this we must note the ratio of the frequency to the magnetic field, for example if our ratio is 3100 G/13.2 MHz, = 0.23 G/MHz, and we increase the frequency by 20 kHz, then we must increase the magnetic field by $20\times 0.23 \approx 5$ G.

After we receive 8-10 data points, we must preform a 2-parameter fit to get the gyromagnetic ratio γ, this value will be our slope. We can convert the gyromagnetic ratio to the proton g-factor (g_p) by using the below equation.

$$\gamma = g\frac{Q}{2M} \tag{1}$$

Where g is our g-factor, Q is our charge, and M is the mass of our particle. We must compare this to the true proton g-factor that is $g_p = 5.585694713(46)$.

B. ESR Experiment

We will now replace the Electromagnet and the glycerin sample with the Helmholtz coil and the TCNQ sample for the ESR experiment. This section is conducted using

the same steps as described in the NMR experiment, so we will repeat the same procedure as described in the section above with the only change coming from our g-factor becoming the electron g-factor (g_e). We will also compare this to the true electron g-factor that is $g_e = -2.0023193043622(15)$.

IV. DATA/ANALYSIS

A. NMR Experiment

When conducting this experiment, we found the minimum phase to be $76.5°$, resulting in our maximum phase being $166.5°$. This phase is $180°$ off our true maximum, but as we discussed in the procedure section, this is okay as we are measuring the intercept where our wave has an amplitude of zero between the two peaks, this is the phase we took our data in. We took a total of 7 measurements ranging from 13,100 kHz to 13,700 kHz, our results can be seen below.
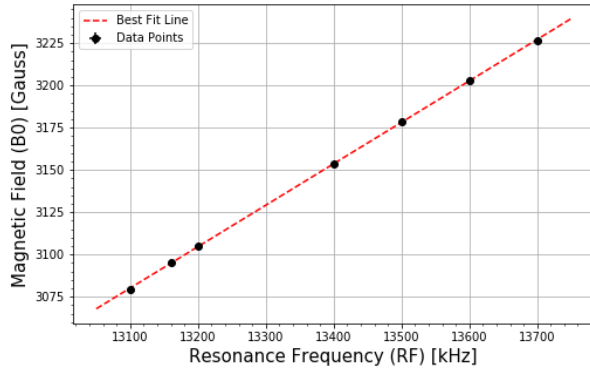

Fig. 5: Our NMR data showing Magnetic field vs. frequency, plotted alongside our best fit line.

When we were finding the slope of our best fit line, we also found the residuals of our data. These can be seen in the figure below.
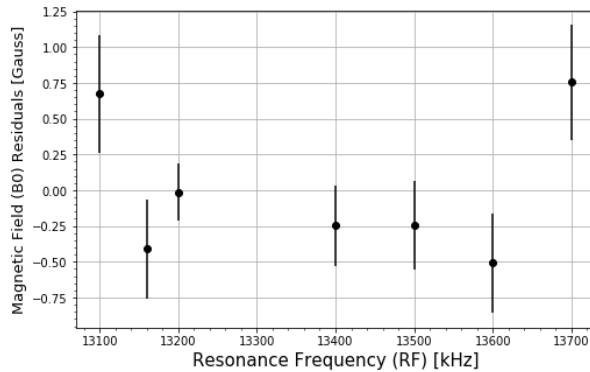

Fig. 6: The residuals of our data for our NMR Experiment.

Using equation 1 and defining our γ as the slope of our best fit line, we were able to find our proton g-factor to be:

$$g_p = 5.11412129(98) \tag{2}$$

This measurement is 8.44% less than the known quantity of the proton g-factor ($g_p = 5.585694713(46)$).

B. ESR Experiment

When conducting this experiment, we found the minimum phase to be $31.5°$, resulting in our maximum phase to be $121.5°$ ($180°$ off the true maximum). We took a total of 13 data points spanning 49,000 kHz to 51,000kHz, our results can be seen below.
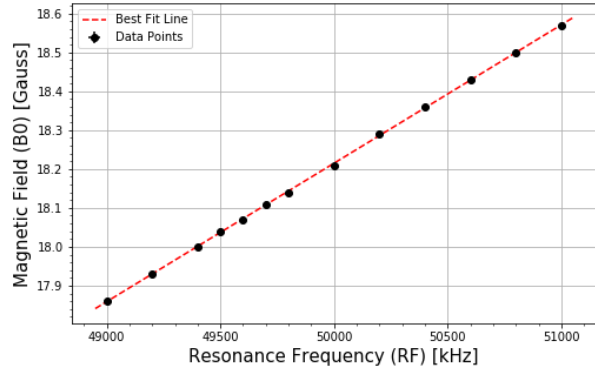

Fig. 7: Our ESR data showing Magnetic field vs. frequency, plotted alongside our best fit line.

When we were finding the slope of our best fit line, we also found the residuals of our data. These can be seen in the figure below.
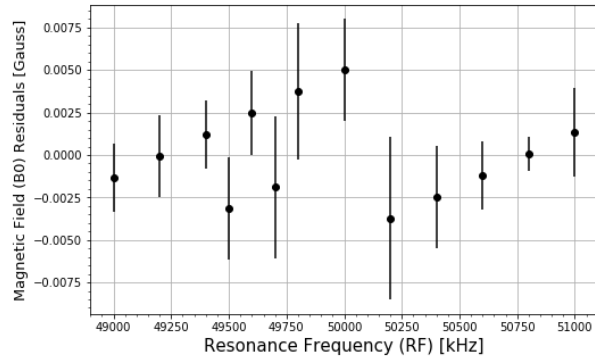

Fig. 8: The residuals of our data for our ESR Experiment.

Just like the NMR section, we used equation 1 to find the electron g-factor while defining our γ as the slope of our best fit line:

$$g_e = -2.544606084(79) \tag{3}$$

This measurement is 79.76% less than the known quantity of the electron g-factor ($g_e = -2.00231930436(15)$).

V. Conclusion

As can be seen by our results, our electron g-factor has much greater error than that of our proton g-factor. Unfortunately this is the result of us faultily implementing the procedure for the ERS experiment. While we were adjusting our frequency to find our resonance points, we failed to alter the magnetic field as well, such as was done in the NMR experiment, this led to our data having a lot of error to it.

Another source of error in our data was the error that came with measuring the resonance. As we were moving the vertical line by hand, human error came in when we were trying to find an amplitude of zero, halfway through our pulse. This uncertainty can be seen in the residuals of our data, where the error reflected the offset of the amplitude from zero.

Finally, we learned that the proton and electron g-factors are different due to the proton not being a composite particle like the electron. The proton is made of 2 "up" quarks and 1 "down" quark, resulting in 3 total elementary particles. Meanwhile, the electron is itself an elementary particle, this differences explains the drastic shift from the electron g-factor value of ≈ 2 to the proton g-factor value of ≈ 5.5, as the proton is made of more elementary particles.