# Electron Spin Resonance

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## Objective

The objective of this experiment was to measure the ratio of the magnetic moment of an electron to its angular momentum. In the process, certain resonance curves and the width (measured at half maximum) of these curves gives the frequency (and therefore energy) range for resonance.

## Theory

Electrons have a property called *spin* which can be thought of as a spinning around a certain axis. This property produces a angular momentum which introduces a magnetic moment which experiences a magnetic torque until it aligns itself with the surrounding magnetic field. If there are two electrons in an orbital, they must have opposing directions of spin (this is necessitated by conservation of momentum) resulting in a net spin of 0. Paramagnetic substances are substances that have atoms with unpaired electrons which results in a "net" spin. These atoms have a net magnetic moment and if these magnetic moments do not interact strongly enough to produce a magnetic domain, (i.e. do not create a surrounding magnetic field) the magnetic moments orient themselves randomly.

Since the spin has only two possible configuration, the magnetic moment associated with this is either positive or negative (represented by the magnetic spin quantum number: $m_s$ which is a vector and can have value $\frac{1}{2}$ or $-\frac{1}{2}$)

The spin number of an electron is given by $s = n/2$ where $n$ is the orbital number or the principal quantum number. The Spin angular momentum, S, is then given by $S = \hbar\sqrt{s(s+1)}$. This angular momentum can be used to find the magnetic moment of the electron:

$$\mu_S = \frac{g\mu_B}{\hbar}S = g\mu_B\sqrt{s(s+1)}$$

Where $\mu_B$ is the Bohr magneton.

We observe the absorption and emission of photons as the electrons change energy levels. As is expected, the change is energy is quantized and this change in energy can be calculated using:

$$\Delta E = h\nu = g\mu_B B$$

Where, $\nu$ is the frequency of the photon released when the electron returns to its ground state and $h$ is the Planck's constant. From here, we can see that the g-factor is:

$$g = \frac{h}{\mu_B}\frac{\nu}{B}$$

For this experiment, we use DPPH and bombard it with varying radio-frequencies (varied by plugging in different plug-in coils in the RF circuit and changing the Voltage applied across it). The Magnetic field in the coils is given by the relationship:

$$B = \frac{\mu_0 N}{2R}\left(\frac{4}{5}\right)^{3/2}(2I_0) = 2.115(2I_0) \qquad [mT]$$

$$\delta B = 2.115(\delta 2I_0) \qquad [mT]$$

Where $\delta 2I_0$ is the full width at half maximum read from the oscilloscope.

## Setup and Procedure

The experimental setup consisted of two large wire coils connected in parallel and placed facing each other so as to create an environmental magnetic field that can be modulated with the input voltage. The smaller coil was placed in the center of the magnetic field (between the two coils and on the axis between their centers).
A magnetic field is generated by applying a current through the copper coils. The oscilloscope plots the RF unit data against the power input.
The coils are separated by a distance equal to their average radius, with the RF coil placed between them and in the center. The circuit was connected and the $U_0$ knob is kept at zero. The medium coil was inserted into the apparatus and the frequency was set to 35MHz. The value of $U_0$ was increased until the plot on the oscilloscope resembled the expected resonance curve. The Frequency was incremented in 5MHz steps until a frequency of 75 MHz was reached.

The resonance curves on the oscilloscope are obtained by setting the resonant frequency to a fixed value and then sweeping the magnetic field (through the current) so that the energy differences correspond to the resonant frequency. Knowing proportionality of magnetic field and current gives you the two sides to the equation.

## Data Analysis

The data collected for the smallest and largest coils was found to have too much noise to allow us to draw any significant conclusions from it. For this reason, we restricted our analysis to the data found using the medium coil. For these measurements, the FWHM ($\delta W$) was found to be $2.0 \pm 0.1$cm.
The current ($I_{mod,rms}$) was measured to be $0.370 \pm 0.005$A. This value was multiplied by $\sqrt{2}$ to give the amplitude of the current and then by 2 to give the point-to-point value, $I_{p-p} = 2\sqrt{2} \times 0.370 \pm 0.005 \approx 1.05 \pm 0.02$
From here we gather that:

$$\delta I_0 = I_{p-p} \times \frac{\delta W}{10} = 1.05 \pm 0.02 \times \frac{2.0 \pm 0.1}{10} = 0.21 \pm 0.03\text{A}$$

Which gives us:

$$\delta B = 2.115(2\delta I_0) \approx 0.89 \pm 0.13 \quad [mT]$$

| **Frequency (in MHz)** | $2I_0$ **(in A)** | **Magnetic Field (in mT)** | **g** |
|---|---|---|---|
| 35 | 0.654 | 1.3832 | 1.8086 |
| 40 | 0.740 | 1.5651 | 1.8268 |
| 45 | 0.839 | 1.7745 | 1.8126 |
| 50 | 0.920 | 1.9458 | 1.8367 |
| 55 | 1.020 | 2.1573 | 1.8223 |
| 60 | 1.133 | 2.3963 | 1.7897 |
| 65 | 1.209 | 2.5570 | 1.8170 |
| 70 | 1.321 | 2.7939 | 1.7908 |

Here, $B$ was calculated using the equation:

$$B = 2.115(2I_0) \quad [mT]$$

This relation tells us the magnetic field through the center of the coils halfway between them (uncertainty in this position of the DPPH sample would add to uncertainty). and using this, we can find $g$ using:

$$g = \frac{h}{\mu_B}\frac{\nu}{B}$$

with all the variables converted to SI units.
The mean of all the calculated values of $g$ was $1.8131 \pm 0.0165$ where the uncertainty was calculated using the standard deviation of our measurements.

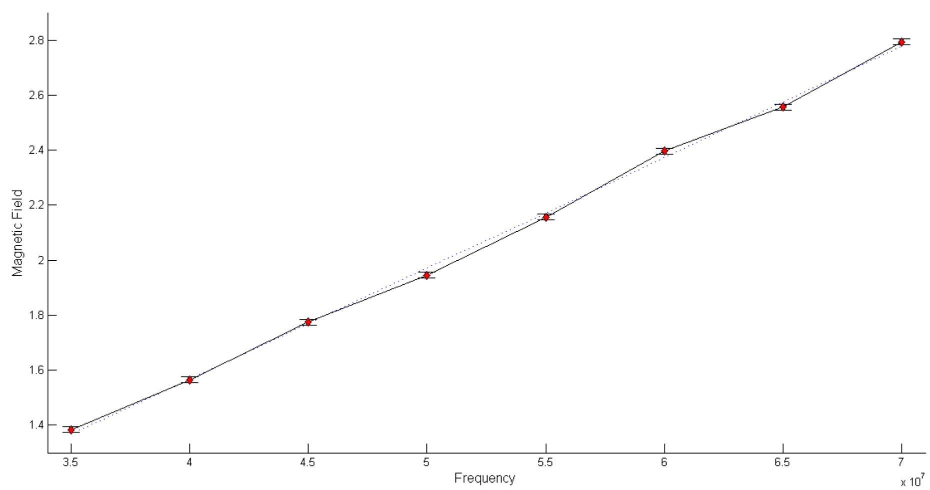


Figure 1: Magnetic Field vs Current

## Uncertainty Analysis

The data collected using the small and large coils contained far too much noise for us to be able to draw any significant conclusions from it and this data was discarded to begin with. For the medium coil, we used uncertainty propagation where necessary, and again to verify our error bars from standard deviation measurements.
The uncertainty in the value of g was found using the standard deviation in all the values obtained from different data points. As can be seen in the plot above, our data is self-consistent and most of the values determined lie in a very small region of uncertainty.
The uncertainty was verified by propagating the uncertainties in our values of current (and therefore magnetic field), but these calculations gave us values of $\sim 0.2 \times 10^{-4}$ which would be negligible. The accepted value of $g$ is $\approx 2.002$ which lies more than 10 standard deviations outside of our average value and suggests a systematic error in our measurements. This could easily arise from misalignment of the apparatus which the experiment was very sensitive to.
For the Uncertainties in $\delta I_0$ and $\delta B$, where uncertainty propagation was required, this was done according to the uncertainty propagation equation:

$$\delta_y = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i}\right)^2 \delta_{x_i}^2}$$

## Questions

**The manufacturer designed this experiment with the coils connected in parallel. A series connection would be better. Why?**
A series connection might be better for this particular experiment because a series connection ensures that the current through both coils is the same and therefore ensures a uniform magnetic field.
**The p-p modulation current $\delta 2I_0$ for the half-width $\delta B$ is obtained from:**

$$\delta 2I_0 = I_{mod,p-p} \frac{\delta W}{10}$$

**where does the factor of 10 come from?**
THe factor of $\frac{1}{10}$ comes from the fact that the resolution of the oscilloscope is 10cm
**In the method given for measuring $\delta B$, the scope controls are not used in a calibrated mode. Why is this OK?**
Using the oscilloscope without calibration is ok because all quantities that would require calibration are measured only as ratios of one-another instead of as numerical values.
**Why is the multimeter set for DC amperes for measuring g and for AC amperes for measuring the line width?**
The multimeter is set to DC amperes when measuring g because DC measures the amplitude of the current which is what relates current to g. To measure line-width, one requires the root-mean-squared value of the current which is given by AC