Union College Winter 2001

Physics 19
Lab #5: Electron Spin Resonance

In this experiment you will detect the "spin" of the electron, and obtain a measure of the electron's magnetic moment, by measuring the energy of interaction of electrons with an external magnetic field. In electron spin resonance, electrons embedded in an external magnetic field change spin states by absorbing energy from an applied oscillating electromagnetic field.

This lab is instructive also because the spin of particles and the resultant interaction with magnetic fields is a commonly used tool for studying assorted aspects of atoms and molecules. Electron spin resonance, also known as electron paramagnetic resonance, uses the spin of electrons. In chemistry and medicine the interaction of the spin of the protons with applied magnetic fields is used in an experimental method known both as nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI).

BACKGROUND

Spin is an intrinsic quantum-mechanical characteristic of fundamental particles. The spin of an electron becomes evident when it is placed in a magnetic field. There is a magnetic dipole moment associated with the electron's spin, and so when embedded in an external magnetic field the energy state of the electron will depend on the orientation of its spin relative to the magnetic field. This is analogous to that of a current loop (discussed in Physics 18).

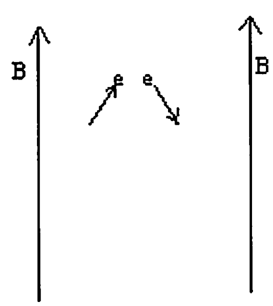

Figure 1: Two spin states of an electron in a magnetic field

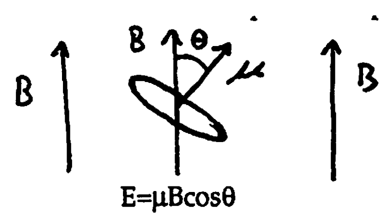

Figure 2: Energy of current loop in B field

The energy states associated with the spin are given by the normal energy of interaction between a magnetic dipole of moment μ and a magnetic field B, that is E=-μ·B=-μBcosθ, where θ is the angle between the magnetic moment and the field lines. However, since an electron's spin energy states are quantized, θ is only allowed two values. The two allowed spin energy states are $\frac{1}{\sqrt{3}}\mu B$ and $-\frac{1}{\sqrt{3}}\mu B$.

The energy difference between the two allowed states, and therefore the energy that can be absorbed by the electrons is $\frac{2}{\sqrt{3}}\mu B$. The requirement for electrons to absorb a photon and flip its spin, then, is that

$L_z = \frac{1}{2}\hbar$, $L = \frac{\sqrt{3}}{2}\hbar$ → $L = \sqrt{3} L_z$, $\mu \propto L$, $\vec{\mu}\cdot\vec{B} = \mu_z B = (\frac{1}{\sqrt{3}}\mu B)$

$$hf = \frac{2}{\sqrt{3}}\mu_e B,$$

where μ_e is the fundamental electron magnetic moment. Since the natural response frequency of the system (the frequency that the electrons absorb) equals the applied frequency (of the oscillating EM field) this is considered a resonance situation (and hence the reason for the name "electron spin resonance").

In this experiment, instead of shining light into the electrons, you will create an oscillating electromagnetic field by applying an oscillating current in a coil. The oscillating electromagnetic field is essentially identical to light waves, and in fact can be called a "photon field". A quantum of energy of the field equals hf, where f is the frequency of oscillation (just as with a photon). The electrons will be inside this coil and inside a larger-scale external magnetic field, created by a set of Helmholtz coils. What you should see in this experiment, is that when $hf = \frac{2}{\sqrt{3}}\mu_e B$ the electrons will absorb energy from the oscillating EM field.

Magnetic Moment and Angular Momentum

If you imagine the electron as a spinning charge you should be able to derive an equation relating its magnetic moment to its spin angular momentum. You should be careful, however, to recognize that the magnetic moment of the electron differs from the classical analogy of a current in a loop in that electron is a really point charge and does not have a finite size to speak of. So, it is not entirely correct to conceptualize the electron's dipole field as due to a spinning charge. This approach, though, leads to a reasonable equation with the right dimensions. One simply puts in a fudge factor at the end, and the quantum mechanic's goal then is to figure out the reason for the exact value of the fudge factor.

<u>Prelab exercise</u>: The magnetic moment of a current in a loop is given by μ=IA where A is the area of the loop. Show that the in this case $\mu=(q/2m)L$. where q is the charge, m the mass of the charges, and L the angular momentum associated with the circling charges.

It might be tempting to assume that the electron's angular momentum and magnetic moment are related identically--i.e. that $\mu_e=(q_e/2m_e)L_e$. However the angular momentum associated with the electron's spin is $\frac{\sqrt{3}}{2}\hbar$ which yields a classical magnetic moment of $\mu_e=\frac{q}{2m}\frac{\sqrt{3}}{2}\hbar$. You should find in this experiment that this value is off by a factor of two. A correction factor, known as the g-factor, must be included in the above equation so that $\mu_e= g_e \frac{q}{2m}\frac{\sqrt{3}}{2}\hbar$. The g-factor for the electron is now known to high accuracy through both experiment and theory to be 2.002319134.

THE EXPERIMENT

EQUIPMENT: (see figure 3)

(a) rf probes: 3 small plug-in coils (inductors), labelled E,F, and G in figure 3

(b) rf oscillator (white box on stand)

(c) Frequency adapter

(d) LC circuit (coil and white box with adjustable capacitor)

(e) Helmholtz coils: 2 coils of diameter 13.6 cm

(f) DPPH sample (in small test tube)

You'll also need two 12-V DC power supplies, frequency meter, oscilloscope, 120-to-25 V AC transformer, and DMM.

The DPPH contains the electrons whose spin will produce the desired resonance. DPPH is a molecule, called diphenylpeirylhydrazil (in case you like big terms), that contains an electron that is unpaired and has 0 orbital angular momentum and therefore behaves like an isolated electron.

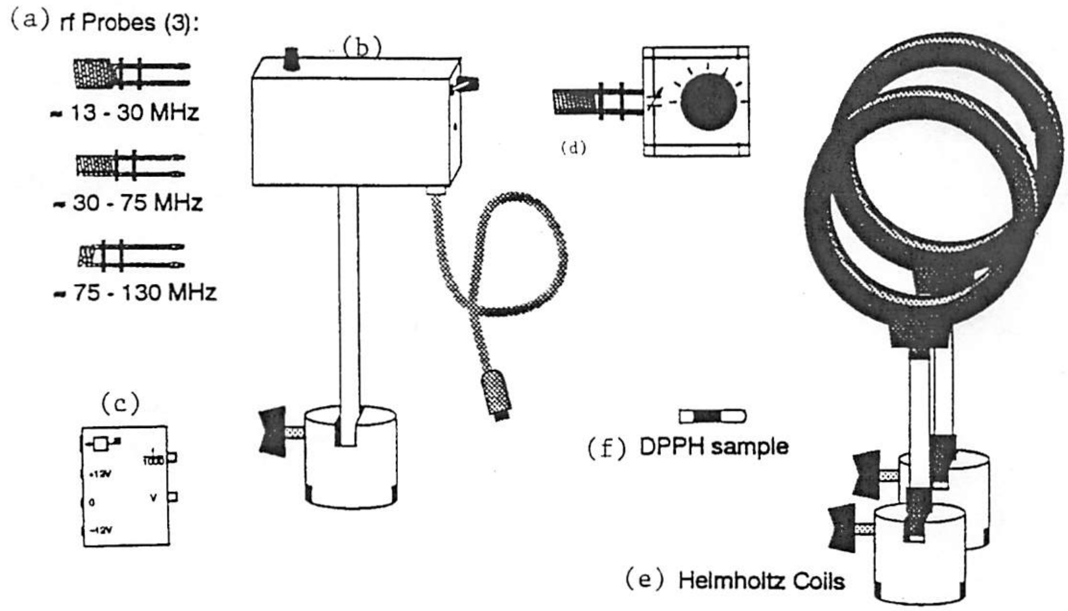

Figure 3: ESR equipment

SET-UP and PROCEDURE:

To measure the magnetic moment of the electron, μ_e, you are to find the resonance condition given by $2\mu_e B=hf$. You will do this by (a) creating a known B field with a set of Helmholtz coils and (b) creating an oscillating EM field of known frequency by sending an oscillating current through some smaller coils. Then, by placing the electrons inside the small coils and the small coils inside the Helmholtz coils, you will provide the electrons with the necessary conditions. You'll find the resonance condition by varying the Helmholtz coils current at 60 Hz and monitoring the voltage across the small coils. When resonance occurs a dip in the small coils voltage will be seen. The dip results because the electrons absorb the energy of the electromagnetic field created by the current, thereby altering the impedance of the coil. To facilitate the reading, a DC offset is applied to the oscillating current of the small coil. Then, you'll only need to read a drop in the DC offset.

Creating the oscillating electromagnetic field and detector of EM absorption:

The three small plug-in coils are capable of producing EM fields of the following frequencies: E (the biggest coil): $\nu \sim 13 - 30$ MHz; F: $\nu \sim 30 - 75$ MHz; G (the smallest): $\nu \sim 75 - 130$ MHz.
To start, insert coil F into the oscillator and set up the circuit shown in figure 4. (Do not insert the DPPH sample yet.) The adapter ports are labelled and should be connected as follows:

"f/1000" attaches to the frequency meter;

"Y" attaches to channel 1 of the oscilloscope;

"+12 V", "0", and "-12 V" attach to the DC supplies as shown.

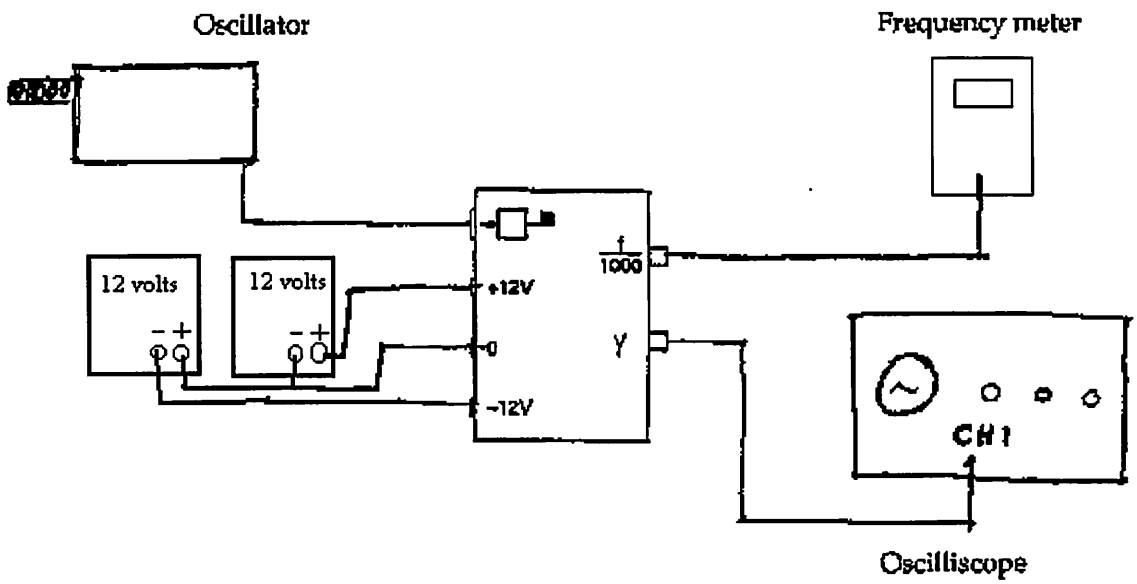

Figure 4: Oscillator set-up

Note that the frequency adapter mixes down the frequency by a factor of 1000, as indicated by the "f/1000" on the port connecting to the frequency meter. This is needed because, as indicated in the chart above, you're going to need to attain frequencies of 10's of MHz, which is not readable with an inexpensive frequency meter.

To avoid damaging the oscillator, please adhere to the following operating rules:

1. DO NOT ALLOW THE APPLIED VOLTAGE TO EXCEED 12 V,
2. BE SURE THAT THE VOLTAGE IS AT 0 BEFORE TURNING THE OSCILLATOR SWITCH ON OR OFF, and
3. DO NOT UNPLUG A COIL WITH THE OSCILLATOR ON.

Steps:

1. Plug in and turn on the DC supply, the oscilloscope, and the frequency meter.
2. Turn on the oscillator, and bring the voltage up to 12 V.

3. Watch the frequency meter and turn up the gain on the oscillator (knob on the back with curved wedge label indicating strength) until a reasonable frequency reading appears on the meter. The meter should see frequencies from 30 to 75 kHz (remember that the frequency is reduced by a factor of 1000).
4. Set the oscilloscope to trigger off of channel 1 and to sweep at high enough frequencies to display the 30 to 75 kHz sine wave of the oscillator. Watch the oscilloscope and play with the gain on the oscillator. Note the clarity of the sine wave signal versus the noise as you play with the gain. Set the gain for optimal clarity of the signal. Check that the frequency reading on the meter agrees with the oscilloscope display. Change the frequency setting by playing with the knob on top of the oscillator labelled f/MHz.

The signal you have on the oscilloscope now is a display of the voltage across the oscillator versus time. When you achieve resonance, it is this signal that will show an absorption. However, this is not the time scale you'll need. The magnetic field will be varied at 60 Hz and you want to know at what value of the magnetic field this signal will be absorbed. So, adjust the oscilloscope so that it sweeps at 60 Hz. Since the scope is sweeping too slow for this signal, the display should appear as a straight line, whose width depends on the gain. When you get electron spin resonance later this straight line will show a dip because the DC offset voltage will be absorbed.

Creating the external magnetic field (Helmholtz coils):

Use the two larger coils to make a set of Helmholtz coils--the requirement for Helmholtz coils is that the coils be placed along the same axis with a separation equal to 1/2 their diameter. The diameter of these coils is 13.6 cm. Connect the coils in series and to the transformer and variac as shown in Figure 5. Since you need the current to go in the same direction in the coils, make sure that the coils face the same way (use the writing on the coils for orientation).

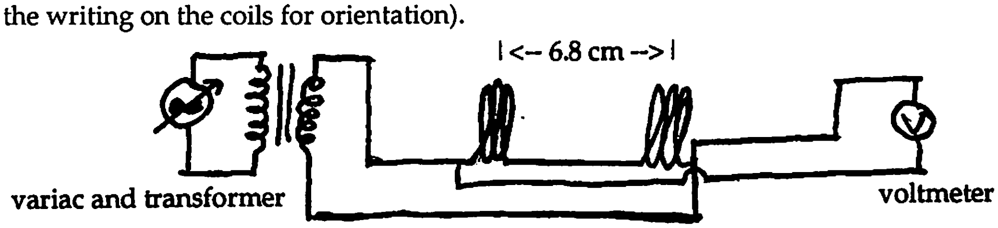

Figure 5: Helmholtz Coils Set-up

The magnetic field inside a set of Helmholtz coils is given by

$$B=\frac{\mu_0 NI}{R}(4/5)^{3/2}$$

where R is the radius = 6.8 cm, I the current, and N the number of turns in each coil = 320. Note that to calculate the magnetic field, you'll need to know the current through the coils. Since the oscilloscope tells you the voltage, you need to measure the resistance. So, use the DMM to measure and record the resistance across the coils. Then change the DMM setting to read volts and attach channel 2 of the oscilloscope to the leads going into the DMM. The DMM provides an additional and quicker way to watch the voltage as you turn up the variac. However, since it is an AC current, the voltmeter (which must be set on AC) will read the r.m.s. voltage, not the amplitude. So, keep in mind that the amplitude voltage is about 1.4 times greater. The amplitude can also be read from the oscilloscope display.

Prelab exercise: What is the magnetic field between the coils if the resistance across the coils is 20 ohms and the applied voltage is 5 volts,?

The coils are reported to be safe for currents up to 2 Amps. Since you will read voltage instead of current, calculate and record the maximum voltage allowed and remember to stay below this limit during the experiment. You should find that you won't need such high voltages. You also should be careful about leaving smaller voltages on the coils for long periods of time. The coils get quite hot and will slowly degrade over time. So, as a general rule of thumb, do not leave the coils with more than 10 V or so for periods of longer than five minutes.

With the variac set at 0, turn on the power. Turn the variac up until the voltmeter shows some reasonable voltage--e.g. 5 volts. Set the oscilloscope to trigger off of and display channel 2 and play with it until you see the AC signal of frequency 60 Hz and amplitude 1.4 times the reading on the voltmeter. You now, effectively, have a display of magnetic field versus time.

Electron Spin Resonance:

1. Making sure, first, that the DC power supply is off and the variac is turned to 0, place the DPPH sample inside coil F (which should still be plugged into the oscillator) and place the coil, with DPPH, inside the Helmholtz coils set-up, as shown in Figure 6.
2. Turn on the DC power supply and the oscillator switch, bring the voltage up to 12 V, and turn up the gain on the oscillator, as before.
3. Set the frequency to around 40 MHz (40 kHz on meter).
4. Set the oscilloscope to trigger off of channel 2 and display both channels. Be sure that you see two signals before continuing.
5. Watch the voltage on the voltmeter and slowly turn up the variac. Be sure that you see the AC signal through the coils appearing on channel 2.
6. Continue raising the voltage until you see strong dips in the channel 1 signal appear. When they do *you have found electron spin resonance*! Raise the voltage a little higher and note that you see four dips per cycle of the magnetic field. You get four dips per cycle at a high voltage because the absolute value of the magnetic field reaches the appropriate value for resonance four times per cycle. You get two dips when the appropriate value of the magnetic field occurs at the extrema of the sine wave, which occurs twice per cycle.

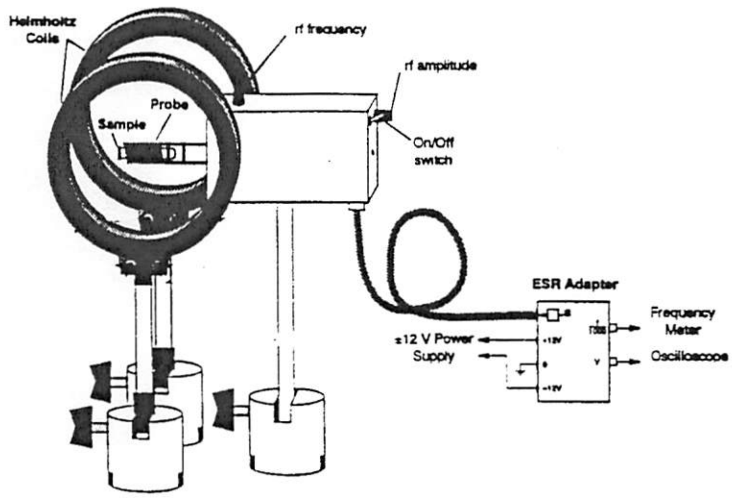

Figure 6: DPPH sample and oscillator inside Helmholtz coils

7. Record the voltage across the Helmholtz coils and the oscillator frequency for the resonance that you have found. However, note that there is a phase shift between the two signals, so you can't simply read the voltage that appears to be in line with the dips. You need to use your knowledge of a sine wave. For example, you can adjust the voltage until you see exactly two dips, in which case the resonance occurs at the extrema of the sine wave. Since there is a range over which two dips occur, a more precise method would be to set the voltage so that you have four equally spaced dips. At what points in the sine wave must these dips occur now? When you go to higher oscillator frequencies, you'll probably find that you can't go to high enough voltages to get four equally spaced dips. In these cases, the two dips approach will have to do.

8. Find electron spin resonance for about 9 to 10 different frequencies, using about 3 frequency setting per plug-in coil, and measure the voltage and frequency of each resonance. **Take care when changing the small coils--remember to turn off the oscillator first.**

ANALYSIS

Calculate the magnetic field for each ESR case you observe and make a plot of B vs f. From the slope of the best fit line, determine the magnetic moment of the electron. Show that the classical relation between angular momentum and magnetic moment of a dipole disagrees with your results for the electron. Calculate the g factor of the electron.