Birla Institute of Technology & Science, Pilani

Pilani Campus

PHY F244 : Modern Physics Laboratory

Electron Spin Resonance

1. **Aim and Objectives** : To determine the Landé g-factor using Electron Spin Resonance.

2. **Keywords** : Magnetic dipole moment, electron Spin, Landé g-factor

3. **Theory** :

   (a) **Basic Principle:** Paramagnetic substances have atoms with unpaired electrons. These atoms have magnetic moments, and if these magnetic moments do not interact strongly enough to produce feromagnetism, the magnetic moments are randomly oriented if no external magnetic field present. The magentic moment of the electron is a result of the adding orbital and spin magnetic moment of the electron.

   The idea of electron spin and its associated magnetic moment was first introduced by George Uhlenbeck and Samuel Goudsmit to explain fine structure in optical spectra. A proper relativistic quantum mechanical treatment of the hydrogen atom leads naturally to the electron possessing, in addition to its mass m and charge e, an intrinsic or spin angular momentum with quantum number $s = 1/2$. The spin vector **S** has magnitude,

   $$S = \sqrt{s(s+1)}\hbar = \frac{\sqrt{3}}{2}\hbar \tag{1}$$

   In the presence of a magnetic field, the component of spin parallel to the field (z direction) is quantised. It has two possible values,

   $$S_z = m_s\hbar = \pm\frac{1}{2}\hbar \tag{2}$$

   Since an electron has both charge and angular momentum, it also has a magnetic moment, μ_s, proportional to the angular momentum, given by
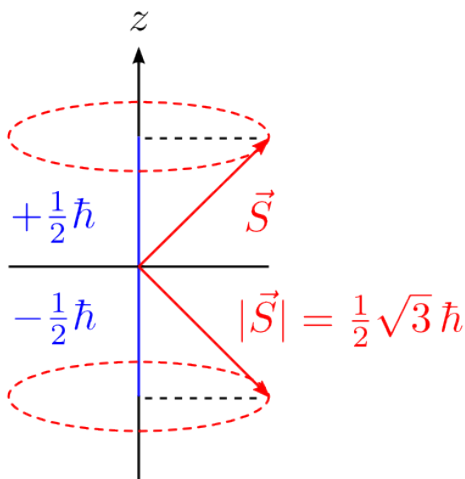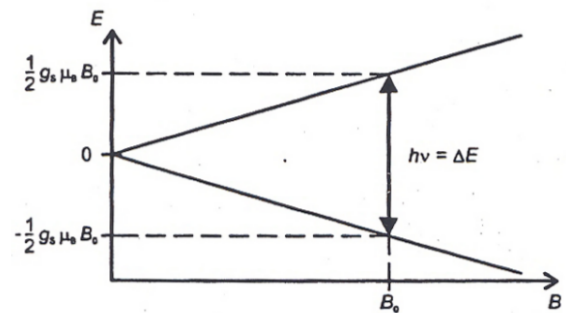

Figure 1: Vector model for electron spin.

Figure 2: Energy splitting of a free electron in a magnetic field and resonance condition for electron spin resonance.
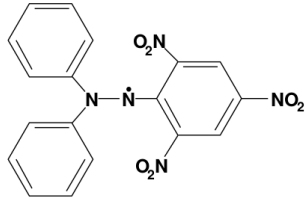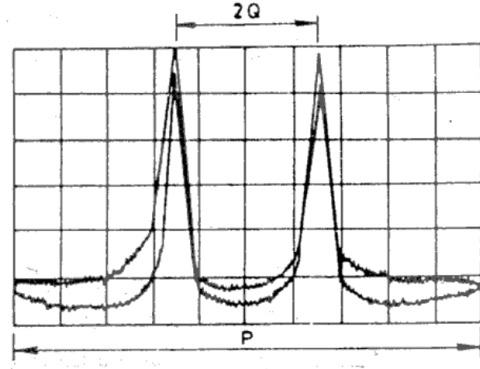
Figure 3: Chemical structure of DPPH.

Figure 4: Resonance peaks as seen on CRO.

$$\mu_s = -g\frac{e}{2m_e}\mathbf{S} \tag{3}$$

where g is the electron spin (Landé) g-factor or, e is the electron charge and m_e is the electron mass. The value of the g-factor as obtaind by Quantum Mechanical calculations is given by,

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \tag{4}$$

where, $J = L + S$ is the total angular momentum, L is orbital angular momentum and S is the spin angular momentum. For our case, $L = 0$ for the free electron in the DPPH sample, and hence $J = S = \pm 1/2\hbar$ and hence we get $g = 2$ when $L = 0$, this is the reason why this particular sample is used.

Quantisation of spin leads to quantisation of the corresponding magnetic moment. The component values for magnetic moment are,

$$\mu_{sz} = -g\frac{e}{2m_e}m_s\hbar = \mp\frac{1}{2}g\mu_B \tag{5}$$

where $\mu_B = e\hbar/2m_e$ is the Bohr Magneton.

In the presence of a magnetic field B, there is potential energy U associated with the orientation of the magnetic moment relative to the magnetic field, given by

$$U = -\mu_s \cdot \mathbf{B} = -\mu_{sz}B = \pm\frac{1}{2}g\mu_B B \tag{6}$$

The energy difference between two electron states is then given by

$$\Delta U = h\nu = g\mu_B B \tag{7}$$

Where, ν is the frequency of the radiation to induce the transition.

(b) **Basic Circuit:** We have 50 Hz magnetic field generated by the Helmholtz coils. The sample is placed inside the tank circuit of critically adjusted RF oscillator (10 - 18 MHz). At resonance the oscillator amplitude registers a dip due to the absorption of the power by the sample. This occurs 4 times periodically in each complete cycle of the Helmholtz coil, which is detected using diode detector and amplified by the low noise, high gain amplifiers.

(c) **Sample:** The sample used in our ESR setup is diphenyl-picryl-hydrazyl (DPPH). It is a widely used standard in ESR experiments. The structure of this organic molecule, shown in the figure, contains three benzene rings. Its important feature is that it contains a single unpaired electron, whose orbital angular momentum is zero. So, the electron has only the spin angular momentum, and the material
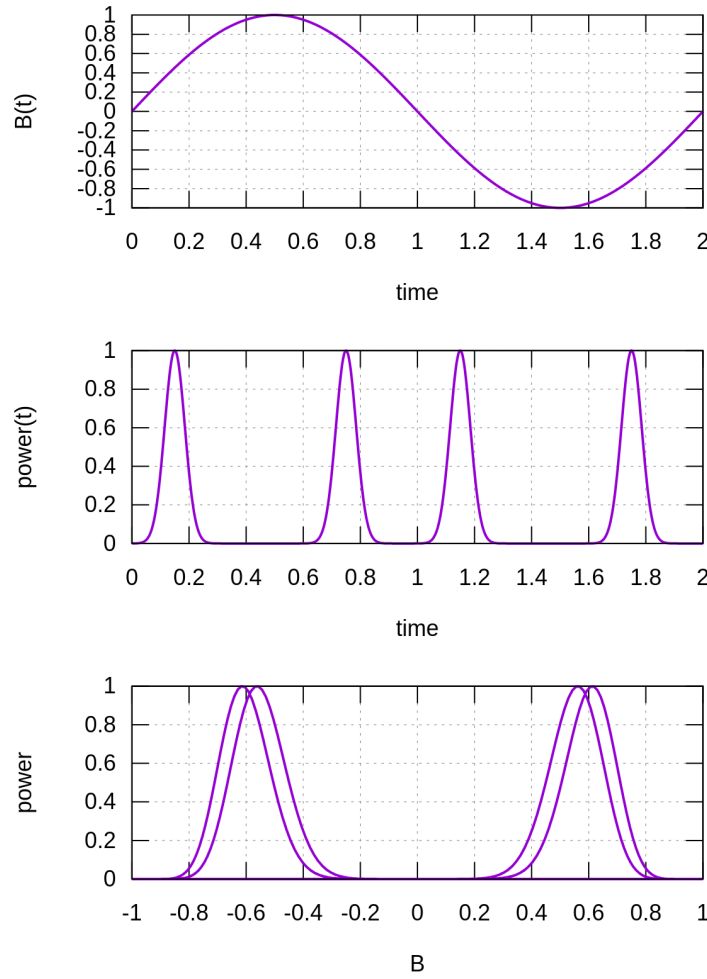
Figure 5: Let us say the magnetic field is oscillating with some frequency (AC current) as shown in the top panel. Let the frequency of the RF oscillator is such that its energy is equal to the seperation between the energy levels for $B = 0.6$, as a result there will be a change only for that say $B = 0.6$ and this would happen 4 times in a cycle as shown in the middle panel. Now if we plot $B(t)$ along x and $power(t)$ along y then we will see the graph as shown in the bottom panel (this is called parametric plot where t is elliminated, similarly in the CRO too we have xy mode which precisely do this thing). Now it is clear the end to end scale of the bottom panel is from is B_{max} (RMS value) and the seperation between 2 peaks is 1.2 i.e 2×0.6. Now this information is used in later calculations.

gives a g-factor which is close to 2.0038 (QED Calculations). One thus has to deal with the simple situation where $j = 1/2$, and only two sublevels are involved.

(d) **Phase Shifter:** This can compensate the undermined phase difference which may be introduced in the amplification stages of the spectrometer and oscilloscope. This can be adjusted/compensated such that we see only 2 peaks corresponding to the resonance conditions.

(e) **Calculations:**

We have the control over the current that is passing through the Helmholtz coils, and this can also be measured. But what we actually need for our calculation is, the magnetic field B_0 applied to the sample at which the resonance is registered.

The magnetic field through the Helmholtz coils is given by the *Biot-Savart* law, and detailed account of this expression is given in the manual on experiment on "Specific charge of the electron e/m_e "

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 N I}{r} \quad \text{Tesla} \tag{8}$$

where, $N = 500$ is number of turns in each coils, $r = 7.7$ cm is the radius of each coil (which is equal

to their separation in Helmholtz setup), and I is current passing through the coils.

As the current is measured by an AC ammeter, the value of the current, and thus the field, is the r.m.s. value. The peak to peak value of the field will be given by wih $N = 500$ and $r = 7.7$ cm (convert in SI units),

$$B_{max} = 2\sqrt{2}B = 2\sqrt{2}\left(\frac{4}{5}\right)^{3/2}\frac{\mu_0 N\,I}{r} = \left[2\sqrt{2}\left(\frac{4}{5}\right)^{3/2}\frac{\mu_0 N}{r}\right] \times I \quad \text{Tesla.} \tag{9}$$

The term in the big rectangular bracket is just the constant, say ξ i.e.

$$\xi = 2\sqrt{2}\left(\frac{4}{5}\right)^{3/2}\frac{\mu_0 N}{r} \implies \boxed{B_{max} = \xi \times I} \tag{10}$$

The CRO is in X channel with the current powering the Helmhotz coil, and Y channel is connected to the output of the RF oscillator which registers the power loss because of the resonance. In the CRO we plot the two signals in the *xy* mode (parametric plot) as shown in Figure 4. How we get these peaks is explained in Figure 6, please refer Figure 6 and its caption for better understanding.

If say P divisions of the CRO corresponds to B_{max}, the magnetic field per division of the X-deflection will be B_{max}/P. The separation between peaks on the CRO is actually $2Q$ (as also discussed in Figure 6), and hence the magnitude of the magnetic field for either resonance is then given by:

$$B_0 = B_{max}\frac{Q}{P} = \frac{\xi}{P} \times I \times Q \tag{11}$$

$$B_0 = \frac{\xi}{2P} \times \text{slope of the graph between } 2Q \ \& \ 1/I \tag{12}$$

From Eq. 7,

$$h\nu = g\mu_B B_0 \implies \boxed{g = \frac{h\nu}{\mu_B B_0}} \tag{13}$$

here, ν is the frequency of the RF oscillator which we are varying, $\mu_B = e\hbar/2m_e$ is the Bohr Magneton.
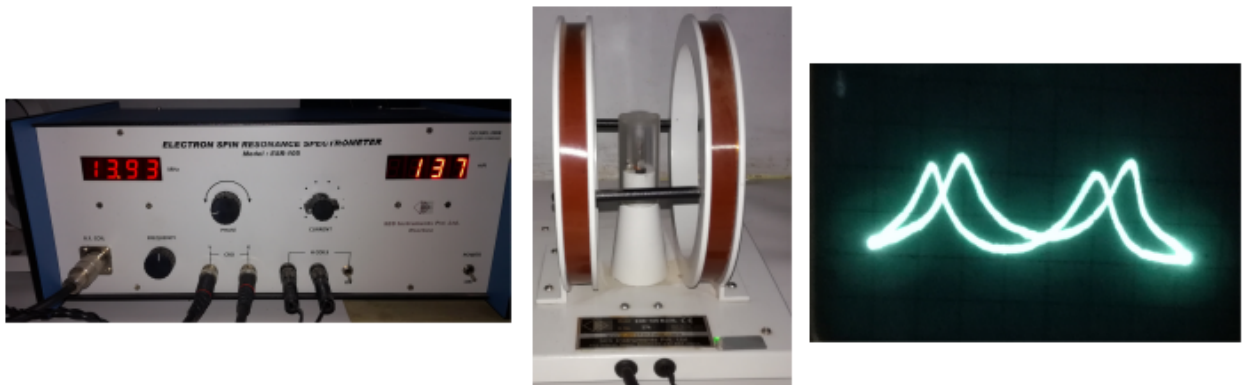

Figure 6: Typical experimental setup.

4. **Tasks**

   (a) Create appropriate observation table.

   (b) Set the frequency of the RF oscillator.

   (c) Set the current in the Helmhotz coil.

   (d) Adjust the phase such that only four peaks overlap to two peaks.

   (e) Measure the value of P (refer Figure 4).

   (f) Measure the separation between these two peaks $2Q$ as shown in Figure 4.

   (g) Repeat the (c)-(f) for different value of the current.

   (h) Vary frequency (4 values) of RF oscillator and again repeat (c)-(f).

   (i) For a fixed frequency plot the graph between $2Q$ and I and obtain the slope of the same.

   (j) Use Eq. 12 and 13 to obtain the value of the g for that frequency.

   (k) On the same graph, plots the results for all the 4 frequencies, and ogtain the g for respective frequencies.

   (l) Obtain the average value of measured g and do the error estimates from the theoretical value of $g = 2$.

5. **Observations and Results** :

S.N.	I (A)	$1/I$	$2Q$ (v_1)	$2Q$ (v_2)	$2Q$ (v_3)	$2Q$ (v_4)
1						
2						
3						
4						
5						
6						
7						

The instruction manual for the experimental setup is also appended.

(iv) RELAXATION AND SATURATION

In the preceding para, we see the mechanism through which the electron return from an excited state to the ground state or relax back to the ground state. This process in the field of magnetic resonance's (ESR, NMR, NQR ETC.) is know as relaxation and the time taken by the process is called the relaxation time. This complete process may be considered as two state process (provided the spin-spin interactions are much stronger than the spin-lattice interaction). First, the energy is absorbed from the radio frequency magnetic field and the equilibrium is established inside the 'spin system'. The time taken by this process is known as the spin-spin relaxation time and is a measure of the rate at which magnetic energy can be distributed within the spin system though total energy is conserved. Secondly, an exchange of energy occurs between the spin system and the lattice. The time taken is known as the **spin lattice relaxation time** and is a measure of the rate of transfer of energy from the spin system to the lattice.

In optical spectroscopy of the relaxation time is usually very short ($\sim 10^{-8}$sec) so that the relaxation time does not impede the absorption rate. In radio frequency, on the other hand, typical relaxation times are in milliseconds or longer and the spin do not have time to relax if the energy is supplied at a faster rate. This situation is called the 'Saturation State'. In other words, no additional energy is absorbed, if the radio- frequency field power is increased beyond certain level.

(v) LINE WIDTH AND THE SPIN-SPIN AND SPIN-LATTICE INTERACTIONS

The effect of the spin-spin interaction is to slightly shift the exact position of energy level of any individual spin in the external field. This energy shift clearly depend on the relative orientation and distance of the spin and thus is different for each spin, resulting in apparent broadening of the energy level. Another way of thinking of the spin-spin interaction is that one electron spin produce a local magnetic field at the position of another spin. Thus, the width of absorption line due to spin-spin interaction may be estimated as $\dfrac{1}{T'}$, where T' is spin-spin relaxation time.

If the spin-lattice interactions are not weak the spin lattice relaxation time T will also be introduced. Let us consider the probability of a transition of an individual paramagnetic particle from one magnetic level to another under the influence of thermal motion. If the probability per second equal A , $T \sim \dfrac{1}{A}$ and the absorption line width would be of the order of $\dfrac{1}{T}$. In general case, however, the absorption line width may be estimated as $\dfrac{1}{T} + \dfrac{1}{T'}$.
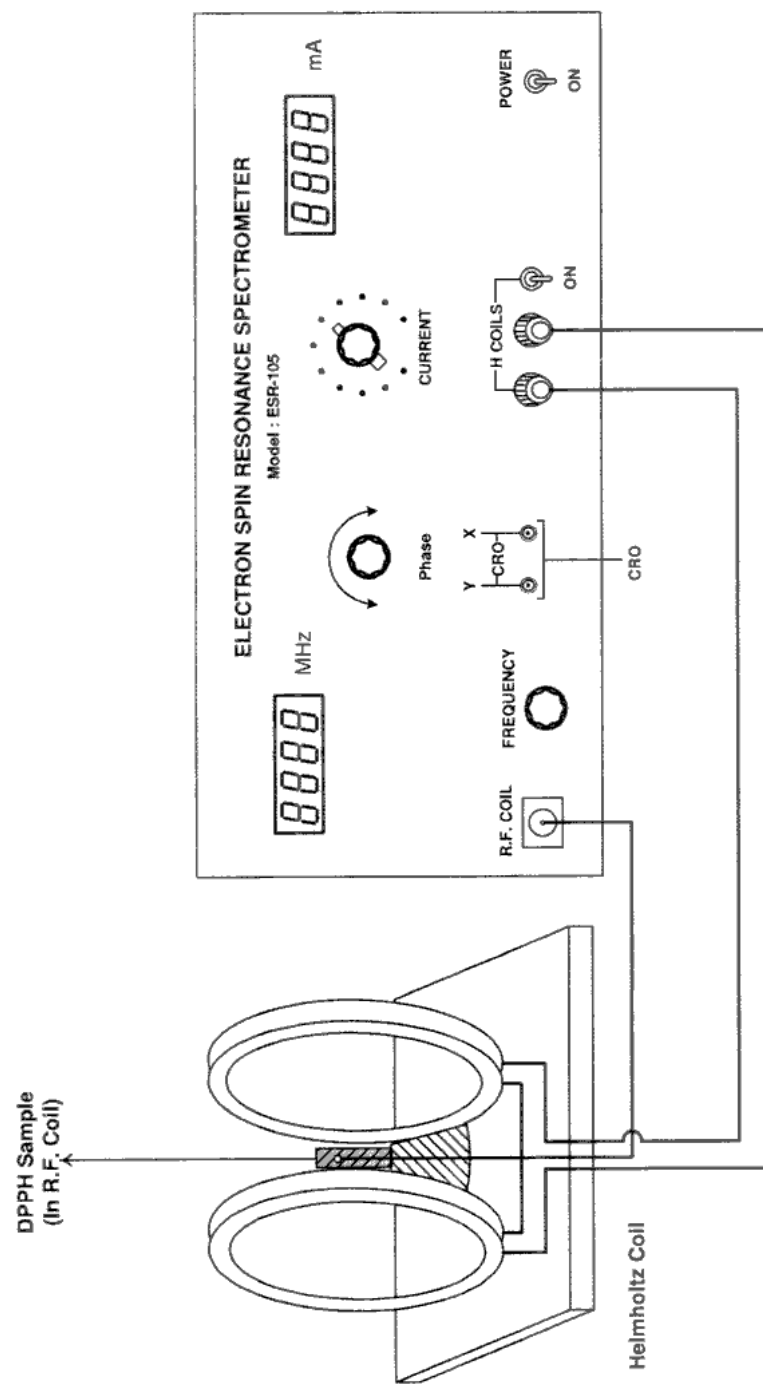
Thus, we see that from the width of absorption line it is possible to measure the relaxation time. In fact most of the research in this field involve the study of relaxation phenomena which in turn provide information about internal interactions in solids and liquids.

The position and number of lines of paramagnetic resonance absorption also depend on the internal interactions.

(vi) ELECTRON PARAMAGNETIC RESONANCE AND SPECTROSCOPY

Paramagnetic resonance is an integral part of spectroscopy, as it provides a means for determining the position of the energy levels of magnetic particles. It is interesting to consider the peculiar features of Paramagnetic resonance in comparison with optical spectroscopy.

1. Let us first note that the frequencies used in magnetic resonance experiments range from 10^9 to 10^{11} cps. These frequencies situated below the limits of the infrared part of the spectrum, allow highly accurate investigation of energy level splitting so small that they are inaccessible or almost inaccessible by optical methods.

2. The probability of spontaneous transition in the radio-frequency region is very small, since this probability is proportional to v^3. Therefore, in paramagnetic resonance studies one is forced to deal only with induced absorption and emission.

3. While in the great majority of cases optical spectra arise from electric dipole transitions between energy levels, the lines of paramagnetic resonance absorption arise exclusively from magnetic dipole transitions. Consequently, the Einstein coefficients for induced absorption and emission will, in the case of paramagnetic resonance, be smaller by roughly four orders of magnitude.

4. As a result, the paramagnetic resonance effect is exceedingly small; if it can be observed at all is due to the high sensitivity of electronic methods of detection and the enormous number of photons coming into play (1mW corresponds to $n \cong 10^{20}$ photons per sec at a frequency of 10^{10} cps).

5. In the optical frequency region the line width is always very small in comparison with the fundamental frequency. In paramagnetic resonance the relation between these quantities becomes quite different, since the interactions causing a broadening of the lines can be of the same order of magnitude as the energy splitting which determines the resonance frequency. Because of this the width of paramagnetic resonance lines is often comparable to the fundamental frequency and can be measured with great accuracy. This opens up wide possibilities for investigation of different types of interactions in paramagnetic substances by means of analysis of the shape and width of a paramagnetic resonance line and of the character of its dependence upon various factors.

6. The most important factors determining the line width are magnetic dipole interactions, exchange forces, local electrical fields created by neighbouring magnetic particles, and finally, thermal motion; the natural line widths of radio- frequency spectra are completely negligible.

7. In contrast with optical experiments, in radio-frequency spectroscopy it is customary to use radiation which is so monochromatic that the generated band of frequencies is incomparably narrower than the absorption line width.

8. Paramagnetic resonance spectra are not studied by varying the frequency of the incident radiation, but by varying the characteristic frequencies of the absorbing systems. This is achieved by varying the static magnetic field.

ELECTRON SPIN RESONANCE SPECTROMETER

Model : ESR-105

MHz

mA

CURRENT

Phase

FREQUENCY

R.F. COIL

X
Y CRO
CRO

CRO

H COILS

ON

POWER

ON

DPPH Sample
(In R.F. Coil)

Helmholtz Coil

Panel Diagram of Electron Spin Resonance Spectrometer, ESR-105

(vii) GENERAL CONSIDERATIONS

For a free electron, by substituting the proper values of constants : $g=2.00$, $\mu_0=0.927 \times 10^{-20}$ erg / Gauss and $h=6.625 \times 10^{-27}$ erg.sec. in equation (2), we get,

$$\frac{\nu_0}{H_0} = 2.8 \text{ MHz/Gauss}$$

That is ESR can be observed at radio frequencies in a magnetic field of few gauss or otherwise in the microwave region in a magnetic field of a few kilogauss. The latter alternate has many distinct advantages :

(a) For each transition the absorbed energy is much larger, and thus the signal-to-noise ratio is much improved.

(b) A high magnetic field is used, thus providing separation between levels that are intrinsically wide and would remain partially overlapped at low fields.

Because of these advantages, ESR in microwave region is preferred for research purpose, though, it is very sophisticated and expensive.

The former is preferable, where simplicity, easy operation and cost factor are the main considerations and no high resolution is required **ideal for postgraduate level experiments**.

(viii) EXPERIMENTAL TECHNIQUES

In the radio frequency region, two types of methods are chiefly used:

1. The method of reaction on the generator

2. The method based on a determination of the change in a load factor of the oscillatory circuit due to paramagnetic loss.

The latter method has been used here. The sample under investigation is placed in an induction coil, which is the component of the tank circuit of the oscillator (generator). This is the Zavoisky's technique. It is based on the fact that under certain conditions such as absorption of power from generator, the watt load (Δw) on the generator changes. This change of Δw is proportional to the change in base current ΔI_b or collector current ΔI_c of the generator. The proportionality, however, holds only the power dissipated by the sample due to paramagnetic absorption is small in comparison to the total losses in the circuit. This change in ΔI_c is detected with the conventional circuits. To make the detection simple and more sensitive, the magnetic field and hence the Larmer frequency of the sample is modulated with a low frequency field 50Hz in the present set-up.
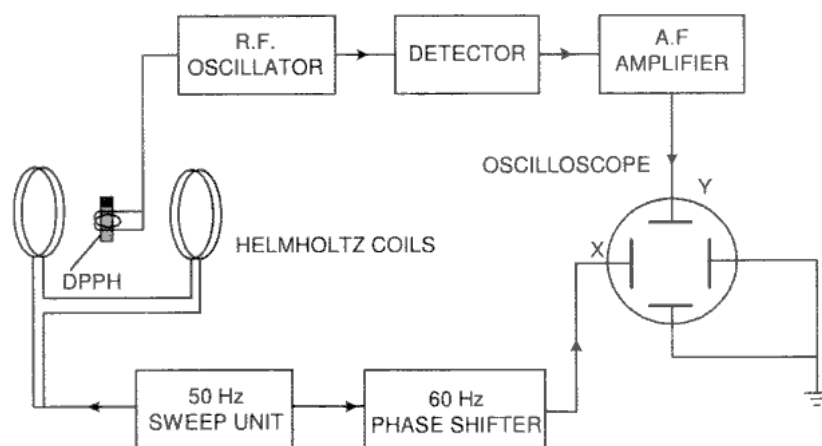
Fig. 3 : Block Diagram of the ESR Set

(ix) DESCRIPTION OF THE ESR SPECTROMETER

A block diagram of the ESR Spectrometer is given in Fig. 3 and panel diagram on the previous page.

1. **Basic Circuit**: The first stage of the ESR circuit consists of a critically adjusted (marginal) radio frequency oscillator having a frequency range of approximately 10–17MHz. A marginal oscillator is required here so that the slightest increase in its load decreases the amplitude of oscillation to an appreciable extent. The sample is kept inside the tank coil of this oscillator, which in turn, is placed in the 50Hz magnetic field, generated by the Helmholtz coils. At resonance, i.e. when the frequency of oscillation equal to the Larmer's frequency of the sample, the oscillator amplitude registers a dip due to the absorption of power by the sample. This obviously, occurs periodically - four times in each complete cycle of the Helmholtz coils supply voltage. The result is in amplitude modulated carrier (Fig. 4A) which is then detected using a diode detector and amplified by a chain of three low noise, high gain audio - frequency amplifiers of excellent stability. A sensitivity control is provided in the amplifier to suit the input requirement of any oscilloscope.

2. **Phase Shifter**: In order to make it possible to use an ordinary displaying type oscilloscope, instead of a measuring oscilloscope which preserve the phase between X and Y plates signals, a phase shifter is provided. This can compensate the phase difference which is introduced in the amplification stage of the ordinary oscilloscope.

    The circuit diagram of the phase shifter is shown in Fig. 4B. The primary of the transformer is fed from the 220V, 50Hz (or 110V, 60Hz) mains and the secondary is centre tapped developing V_1-0-V_1 (say). The operation of the circuit may be explained with the help of the vector diagram shown in Fig. (4B). The vectors OA and BO represent the voltage developed in the secondary, in phase and magnitude. The current flowing in the circuit ADB leads the voltage vector BA due to the presence of capacitor C and is shown in the diagram as I. Voltage developed across resistance R, i.e. V_R is in phase with the current I, and the voltage across across capacitor V_c is 90° (lag) out of phase with the current. The vector sum of V_c and V_R is equal to $2V_1$. These are also plotted in the diagram. It is clear from the diagram that as R is varied, V_R will change and the point D will trace a semicircle, shown dotted. The vector OD, or the voltage across points 0 and D, will, therefore, have a constant magnitude equal to V_1 and its phase, variable from 0 to 180°. This is the voltage which is fed to the X-amplifier of the oscilloscope to correct for any phase change which might have taken place in the rest of the circuit.

3. **50 Hz Sweep Unit** : For modulation with a low frequency magnetic field, a 50 Hz current flows through the helmholtz coils. As the resonance in this frequency range occurs at low magnetic fields, no static D.C. magnetic field is required.

4. **Power Supplies :**
    a) D.C. Power Supply : The ESR circuit requires a highly stabilised almost ripple free voltage. These are obtained using integrated circuit regulator.

    b) Helmholtz Coils Power Supply : The Helmholtz coils power supply consists of a step down transformer (220 to 35 V AC). Variable coil current is provided in 10 steps using a band switch, while the current is displayed on a 3 ½ digit panel meter. The output is taken from the two terminals provided on the panel.
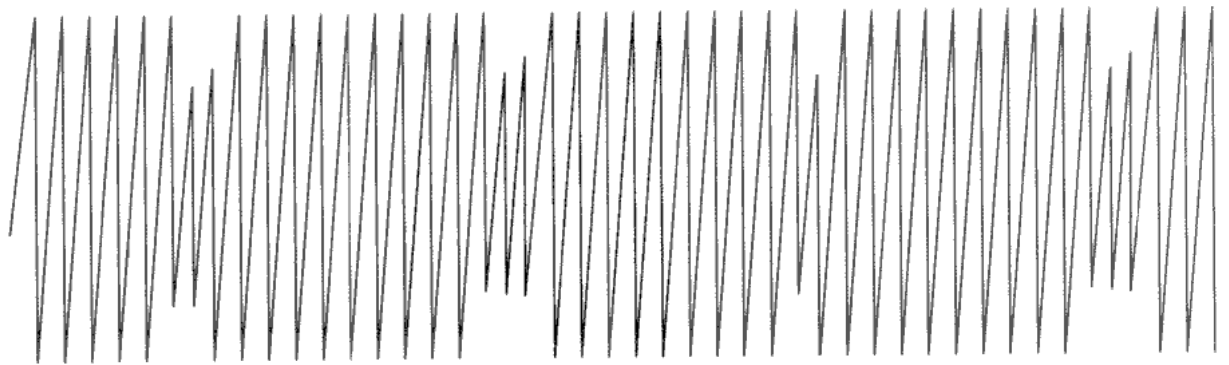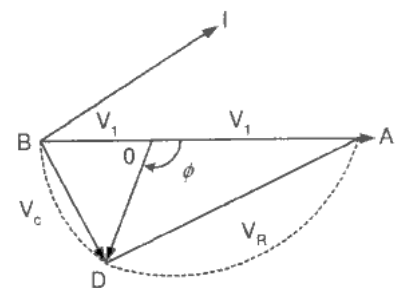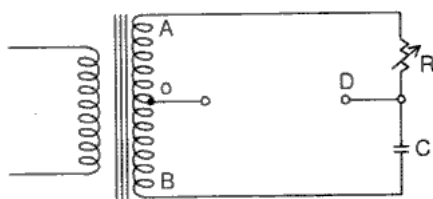
At A

At B

Fig. 4 (A)

Fig. 4 (B)

5.   **Helmholtz Coils** : There are two coils exactly alike and parallel to each other, so connected that current passes through them in the same direction. The two coils increase the uniformity of the field near the centre.

Number of turns	:	500 in each coil
Diameter of the Windings	:	15.4 cm
Separation of the coil	:	7.7 cm

In the centre of the coils, an attachment is provided to keep the sample in place and to minimise shocks and vibrations.

6.   **Test Sample:** A test sample, Diphenyl Picryl Hydrazyl (DPPH) (Fig. 5) is placed in a plastic tube, which itself is in the induction coils. This increases the filling factor to the maximum. DPPH is a free radical and widely used as a standard for ESR measurements.

8.   **Controls & Terminals** :   (Please refer to Panel Diagram)
- (1) Mains   : To switch 'ON' or 'OFF' the ESR Spectrometer.
- (2) Phase   : To adjust the phase between X and Y plates signals.
- (3) Current   : To control current in Helmholtz coils.
- (4) 'H' Coils   : Terminals and switch for Helmholtz coils.
- (5) Frequency   : To adjust the frequency of the Oscillator.
- (6) X,Y,E   : For X, Y and Earth terminals of the Oscilloscope.

9.   **Oscilloscope**: As the Oscilloscope is not supplies with the spectrometer, it is presumed that the worker is already familiar with the control knobs and functioning of the Oscilloscope in question.

Any Oscilloscope, normally available in the laboratory of the following specifications or better, will be quite suitable for the observation of ESR resonance :

Screen diameter   : 12.5 cm
Vertical amplifier sensitivity   : 50 mV/cm

PACKING LIST

- i.   ESR Spectrometer, ESR-104: One
- ii. Helmholtz coils fitted with R.F. Coil: One
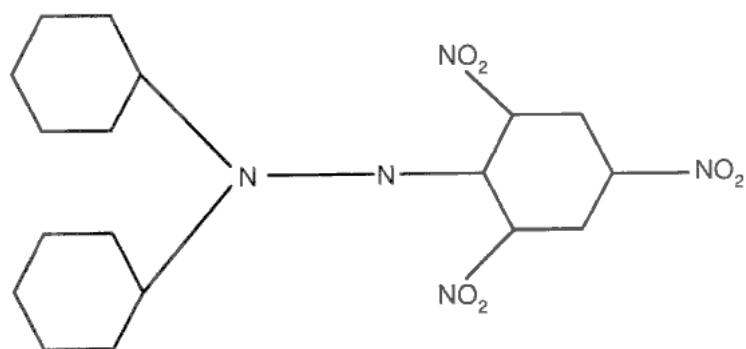- iii. Sample - DPPH (inside R.F. Coil)

Fig 5.: Chemical structure of DPPH (2,2-Diphenyl-1-
picrylhydrazyl, (free radical, 95%))

INSTALLATION

Now for installation proceed as follows :

1) Connect the Coaxial cable of the induction coil to the Oscillator through the socket.
2) Connect the Helmholtz coils to the terminal marked 'H' coil.
3) Connect the terminal marked X,Y, and E on the ESR Spectrometer to the X plate, Y plate input and earth of the Oscilloscope respectively and switch the Oscilloscope.
4) Connect the spectrometer with the AC mains 220 ±10% Volts, 50 Hz and switch - on the power. Ensure that the equipment is properly earthed.

OPERATING INSTRUCTIONS

(i) OPERATION

(1) Switch on 'H. COIL' power and adjust the current at 150 mA.

(2) Set the front panel controls of ESR Spectrometer as follows

Frequency : Centred

Phase : Centred

(3) Observe four peaks on the Screen of CRO. Now adjust the FREQUENCY of the Spectrometer and SENSITIVITY of the CRO to obtain the best results (i.e. sharp peaks and good signal to noise ratio).

(4) Adjust the PHASE knob to coincide the two peaks with the other two as far as possible.

(5) Adjust the orientation of Helmoltz coils with respect to the main unit for best overlap of base lines.

(ii) ORIGIN OF FOUR PEAKS

The observed peaks are in fact absorption dips, because the sample absorb power from the induction coil, reasons explained in Chapter 1. The reason for getting peaks is due to odd number of amplifying stages in the circuitry.

The spin precesses with Larmor's frequency $(\omega_0 = \dfrac{eH_0}{2mc})$ and hence varies in magnitude and direction due to variation of magnetic field $\overline{H_0}$ which is due to an alternating current in the Helmholtz coils. Now if the radio frequency field, ω_1 falls in the range of ω_0 the resonance occurs. The positions of the four peaks can be understood with Fig. (3).

If the X plate signal (50Hz) and Y plate signal (ESR output) are in phase the I and II peaks and III and IV peaks will coincide. The coincidence of peaks on the x-scale needs to be calibrated for magnetic field measurements. The coincidence ensures that the magnetic field is zero at the centre and has the peak values at the two ends. Complete merger of the peaks on y- scale may not occur due to many reasons such as 50Hz pick-ups, ripples in the power supply etc. Though, every effort has been made to minimise these factors but the large amplification ($\cong 4000$) in the circuitry make them substantial. However, any non- coincidence on the y-scale is immaterial as neither any measurement of the y-scale is involved in the calculation of g- factor nor any measurement is made on it.

APPENDIX

(i) SAMPLE CALCULATIONS

Magnetic field at the centre of a Helmholtz coil is :

$$H_0 = \frac{32 \pi n}{10 \sqrt{125} \cdot a} \cdot I = KI \text{ gauss}$$

Where I is the current in amperes and other symbols have their usual meaning. Since the current measured is rms the magnetic field is also rms. The peak to peak magnetic field will be :

$$H_{PP} = 2\sqrt{2}\, H$$

The H_{PP} corresponds to the total X-deflection on the oscilloscope with zero field at the centre. Substituting the values a=7.7cm; n=500, we obtain

H_{PP}=165.25 gauss/amp

Let us take a typical observation (Fig. 8). The measured values are :

v_0=14.00 MHz; I=200 mA; P=100 mm and 2Q=30 mm

Since P corresponds to H_{PP}, the magnetic field per mm of the X-deflection will be H_{PP}/P and hence the magnetic field for either resonance is

$$H_0 = \frac{H_{PP}}{P} \cdot Q = \frac{165.25 \times 0.2 \times 15}{100} = 4.96 \text{ gauss}$$

Substituting the values in the relation

$h v_0 = g \mu_0 H$

$$g = \frac{h\, v_0}{\mu_0\, H_0} = \frac{6.625 \times 10^{-27}}{0.927 \times 10^{-20}} \times \frac{14.00 \times 10^6}{4.96} = 2.04$$

(ii) EXPERIMENTAL PROCEDURE

1. Increase the horizontal sensitivity of the Oscilloscope to the maximum **within the linear range**.

2. Obtain the best possible resonance peaks by varying the frequency, detection level and vertical sensitivity of the oscilloscope, keeping the current at 150 mA (say).

3. Keep the frequency fixed but vary the current flowing through the coils and measure the corresponding horizontal separation between the two peaks (2Q) after adjusting the phase. Take five to six sets of observations.

4. Draw a graph in 1/I Vs Q which should be a straight line. Calculate the g-factor using the QI value from the graph.

5. Repeat the experiment with different frequency.

    The reason for drawing graph between 1/I and Q with fixed is that the measurements of I and Q are likely to contain some random errors.