

Experiment 7: Electron Spin Resonance Proton Spin Resonance Nuclear Magnetic Resonance*

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Abstract

In this experiment you will observe the resonant transition of an electron between two quantum states of the free radical diphenyl-picri-hydrazyl (DPPH) that differ in magnetic energy and determine the Landè g-factor for DPPH. A similar transition will be observed for the protons in glycerine and polystyrene and the fluorine nuclei in polytetrafluoroethene (PTFE). You will also determine the nuclear g-factors for these materials from the study of their resonance peaks.

1 Introduction

One of early quantum theory's fantastic successes was its ability to predict the atomic spectrum of hydrogen. However, it initially was still unable to describe the spectrum of an atom subjected to a magnetic field. Under these circumstances, it was found that the spectral lines split into multiplets – that is, single lines were split into doublets (two lines), triplets (three lines), or more. It was soon realized that some of these multiplet states could be described by the magnetic moment caused by the orbital motion of the electron around the nucleus.

1.1 Zeeman Effect

An electron of mass m orbiting at radius r is analogous to a current i traversing the circumference of a loop of area A whose magnetic moment is given by

$$\mu = iA = -ef\pi r^2 \quad (1)$$

where $-e$ is the charge of the electron, and f is the frequency of revolution. This can be related to the angular momentum of the electron,

$$L = mvr = m2\pi r^2 f \quad (2)$$

*Adapted from the manual for the TELTRON Spin Resonance apparatus, *Student Enquiry Series B: The Production, Properties, and Uses of Electron and Proton Spin Resonance*, 1997 TELTRON Ltd., London, England.

so

$$\vec{\mu} = \left(\frac{-e}{2m}\right) \vec{L}. \quad (3)$$

Note that $\vec{\mu}$ and \vec{L} are in opposite directions.

States of different angular momentum, thus have different magnetic moments, so placing such atoms in a magnetic field changes their potential energy by an amount

$$U_M = -\vec{\mu} \cdot \vec{B} = \left(\frac{e}{2m}\right) \vec{L} \cdot \vec{B} = \left(\frac{e}{2m}\right) LB \cos \theta. \quad (4)$$

Here, B effectively defines the z -axis, so that θ is the angle between the direction of the angular momentum vector and the z -axis and $\cos \theta = L_z/L$. Recalling that the z -component of orbital angular momentum is quantized by the “magnetic quantum number”, so that $L_z = m_\ell \hbar$, we find

$$U_M = B \left(\frac{e\hbar}{2m}\right) m_\ell. \quad (5)$$

Given that $\ell = 0, 1, \dots, n-1$ and $m_\ell = -\ell, -\ell+1, \dots, \ell-1, \ell$, we see that a p state (where $\ell = 1$) will have three slightly different energies due to the different possible m_ℓ ($-1, 0$, or 1). Thus, an atom with nonzero orbital angular momentum will exhibit spectral line multiplets due to the slightly different energies of the m_ℓ states (this is the Zeeman effect). The quantity $(e\hbar)/(2m)$ is called the Bohr magneton and has the value

$$\mu_B = \frac{e\hbar}{2m} = 5.788 \times 10^{-5} \text{eV/T}. \quad (6)$$

This effectively explains the observed odd multiplets; however, since the number of possible m_ℓ 's is always odd, it does not explain the observed *even* multiplets (this is the *anomalous* Zeeman effect, also known as *fine structure*).

1.2 Spin

In 1925, George Uhlenbeck and Samuel Goldsmit postulated the addition of “electron spin” angular momentum to the magnetic moment as a way of explaining the anomalous Zeeman effect. It is now believed that the electron is in fact a point particle so its “spin” is in fact intrinsic angular momentum (rather than due to any actual rotation of the particle around an axis). The angular momentum associated with the electron was postulated to be $S_z = \hbar/2$ (half that of the orbital angular momentum) and after a study of the spectral evidence it was recognized that it could be $+\hbar/2$ or $-\hbar/2$. The positive sign represents the case where the spin rotation is parallel to that of the orbital rotation, being in the same plane and in the same direction and anti-parallel when the two rotations are in opposite directions as in Figure 1. Electrons, then, have spin angular momenta S of magnitude

$$S = \sqrt{s(s+1)}\hbar = \frac{\sqrt{3}}{2}\hbar, \quad (7)$$

(clearly, $s = 1/2$) and the component S_z of S along a magnetic field in the z -direction is

$$S_z = m_s \hbar = \pm \frac{\hbar}{2}. \quad (8)$$

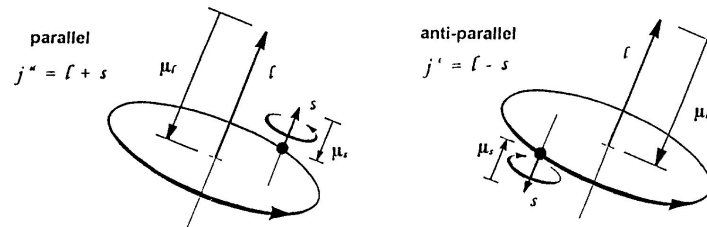


Figure 1: Pictorial representation of parallel and anti-parallel spin.

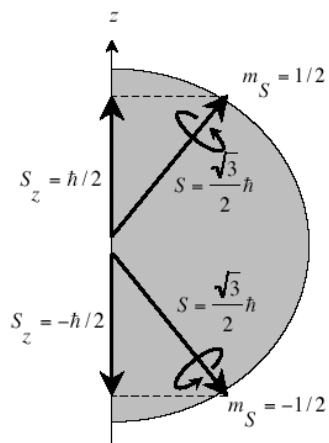
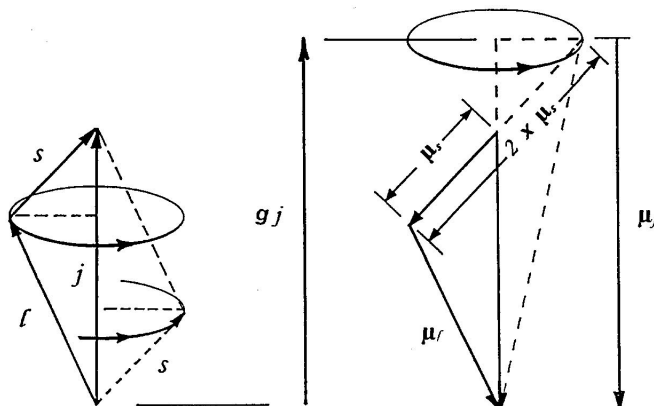


Figure 2: The two possible orientations of S_z .

Figure 3: Vector representation of j and μ_j .

where $m_s = \pm 1/2$ (see Figure 2). Since there are only two possible spin states, the addition of this spin angular momentum explains even numbered multiplets.

An electron orbiting and spinning in a magnetic field has a total magnetic moment, defined by an inner quantum number, j , which combines that due to ℓ (the azimuthal quantum number) and that due to the spin quantum number, s , where

$$j = \ell + s \quad (9)$$

and from vector analysis

$$m_j = j \cos \theta \quad (10)$$

where m_j is the inner magnetic quantum number. The resultant combined magnetic moment is μ_j (see Figure 3). By convention, in the absence of an external magnetic field, the positive direction for both m_j and m_s is that of the ℓ vector. In the magnetic field generated by the orbit of the electron, the energy of the anti-parallel (U_+) state is higher than that of the parallel state (U_-); a majority of electrons occupy the lower, less excited state.

1.3 Electron Spin Resonance

In parallel with the preceding discussion of the Zeeman effect, one would expect the net magnetic moment to be

$$\mu_j = m_j \mu_B \quad (11)$$

and the energy absorbed in stimulating a spin transition from the lower to the higher state to be

$$U_+ - U_- = m_j B \mu_B. \quad (12)$$

However, a non-point electron spinning about its own axis is not analogous to the rotation of a point electron in orbital rotation and so μ_j , cannot be defined in the same manner as for μ_ℓ ; furthermore, practical evidence reveals many more than the few component lines which are predicted from a

theoretical study such as that of Figure 3. This indicates that the magnitude of the splitting is not identical in the higher and lower states and seems dependent on the values of j and ℓ ; in some cases such as the alkalis, the splitting between the ground states is observed as being as much as twice what might be expected.

The earlier simple relationship of Equation 11 is therefore varied to

$$\mu_j = -gj\mu_B \quad (13)$$

where g , is the Landè splitting factor – a rational number which depends upon the values of j and ℓ and has a value of 1 when $s = 0$ and 2 when $\ell = 0$. This effectively assumes that the magnetic moment of the electron due to its spin, μ_s is one whole Bohr magneton, which accords with practical observations and not $1/2$ as might be expected. So we get

$$U_+ - U_- = m_j g B \mu_B \quad (14)$$

and there are m_j energy levels separated by the quantized energy value $gB\mu_B$.

If energy is injected into the system in an attempt to excite a spin transition, it will be preferentially absorbed if its frequency ν satisfies the relationship

$$h\nu = gB\mu_B \quad (15)$$

This is a process where one vibration is produced in response to another of equal frequency and, as in other physical phenomena it is called resonance.

The energy state of any individual electron can now be defined using the quantum numbers n , ℓ , m_ℓ , and m_s . However, any electron in an elevated state can be expected to influence and be influenced by the behavior of neighboring electrons, both within their parent atoms and those attached to nearby atoms and molecules.

The vector treatment of the coupling of the angular momentum of more than one electron in the same atom involved the use of both electronic and atomic quantum numbers. If the value of ℓ for each of the interacting electrons is ℓ_1, \dots, ℓ_n , then the resultant quantum number is L (which is always an integer), where

$$L_{\text{tot}} = \ell_1 + \ell_2 + \dots + \ell_n. \quad (16)$$

The spin quantum numbers s_1, \dots, s_n for n electrons also combine to give a resultant S where

$$S_{\text{tot}} = s_1 + s_2 + \dots + s_n \quad (17)$$

and since s_n can be either $+1/2$ or $-1/2$, the value of S is zero or integral when n is even and half-integral when n is odd; thus with 2 electrons, S is 0 or 1 and with 3 electrons S is $1/2$ or $3/2$.

The vector J representing the total angular momentum of the atom is then given by the vector sum

$$J = L_{\text{tot}} + S_{\text{tot}} \quad (18)$$

The result of excitation of an atom with J zero or integral is singlets, triplets, etc. (odd multiplicities) or with J half-integral is doublets, quartets etc. (even multiplicities). If the atom is to remain in a state of energy equilibrium, then this total angular momentum of the atom due to the constituent electrons must be expected to be reflected in some manner in another neighboring system, that of the nucleus and in particular in the proton population which accounts for its mass and electronic charge.

1.4 Proton Spin Resonance/Nuclear Magnetic Resonance

The nucleus has mass and charge but does not orbit about any focal point, therefore it does not have any orbital angular momentum. But, like the electron, it has intrinsic angular momentum – i.e. spin due to the protons and neutrons that make it up (protons and neutrons are both spin-1/2 particles like electrons). The nuclear spin quantum number, I , combines with the total angular momentum J to give

$$F = I + J \quad (19)$$

where F is the hyperfine quantum number.

While small, hyperfine spectral shifts can be seen when comparing the spectra of different isotopes, where there are an equal number of electrons, but differing atomic masses. To parallel the explanation of the electronic fine structure, the nuclear magnetic moment is defined as

$$\mu_I = g_I I \mu_N \quad (20)$$

where μ_N is the nuclear magneton

$$\mu_N = \frac{e\hbar}{2m_p} = 5.051 \times 10^{-27} \text{ J/T} \quad (21)$$

(here, m_p is the proton mass). The nuclear magneton is smaller than the Bohr magneton by the ratio of the proton mass to the electron mass ($m_p/m_e = 1836$). The hyperfine energy splitting of states for an atom in a magnetic field B is then

$$U_N = g_I I \mu_N B. \quad (22)$$

The nuclear g -factor is dependent in a complex manner on the binding of the neutrons and protons within the nucleus and it is not as mathematically predictable as the Landè splitting factor. There exist tables which provide values for both μ_I and g_I , but none of these can be considered absolute until the structure of the nucleus is fully defined.

Excitation of the nucleus should display $2I+1$ levels in accordance with the restrictions of space quantization, all separated by the extremely small energy of Equation 22. As for an electron, if energy is injected into the system in an attempt to excite a nuclear transition, it will be preferentially absorbed if its frequency ν satisfies the relationship

$$h\nu = g_I B \mu_N. \quad (23)$$

2 Equipment

Teltron Spin Resonance Apparatus	Teltron Spin Resonance Accessories Kit
– Spin Cell Mount	– Electron Probe
– Spin Resonance Console	– Pole Face Rings
– Zeeman Magnet	– Proton Probe
– Scan Coils (2)	– Pole Face Disks
– Power Supplies (2)	– Sample and Reference Phials
Frequency Counter	Digital Oscilloscope with Dual Trace Capability
2-channel Minijack to Banana Connector	BNC to Banana Connector (3)

3 Procedure

Thoroughly read and understand the provided equipment manual *Student Enquiry Series B: The Production, Properties, and Uses of Electron and Proton Spin Resonance* (hereafter referred to as the *Manual*) before beginning this experiment.

3.1 Electron Spin Resonance

1. Assemble the Spin Cell Mount.
 - (a) Insert the two Pole Face Rings into the vertical slots located at the front of and on each side of the Spin Cell Mount.
 - (b) Hold one of the Scan Coils such that the arrow points in the same direction as that on the surface panel of the Spin Cell Mount; insert one of the tubular steel cores into the bore of the coil. The open end of each core must interface with a pole face ring. Repeat the procedure with the second Scan Coil and the other core. Plug the Scan Coil leads into the 2 mm sockets on the surface panel in accordance with the color coding.
 - (c) Lock the core assembly onto the central cell column using the knobs at the top of each end plate. Gently turn both knobs simultaneously to avoid distorting the central cell column; the compression should feel “finger tight”.

The current in the coils is ramped from 0 to 250 mA at a frequency of 20 Hz from within the spin resonance console. The very high frequency radiation is also sourced in the spin resonance console and is imposed on the electron “target sample” by a miniature coil protruding from the electron probe; this probe is mounted on the front of the cell column and so creates a coil axis at right angles to that of the magnetic flux B .

The sensitivity control marked SENS on the top of the probe controls the level of oscillations in the probe electronic circuit; increasing the sensitivity from the minimum reduces the oscillator level. Rotation of the control in a clockwise direction reduces the level to the point where the red LED level indicator of channel 2 on the console begins to become dim but is not extinguished, indicating that oscillation is marginal and only just being maintained. In this condition the circuit is at its most sensitive to external influences allowing the temporary state of resonance to exhibit a maximized peak. Oscillation ceases completely with any further increase of this sensitivity adjustment. Conversely, the amplitude of the resonance peak may be reduced by decreasing this sensitivity.

The electron target is a small sample of a free radical sealed within a narrow glass phial which can be inserted into the probe coil from the back of the cell column; push in the phial until it stops. The preferential absorption of VHF radiation during a sweep of B , displayed at channel 1, extracts energy from the tuned circuit supplying it; the loss of this energy is not compensated and so the system exhibits a reduction in amplitude of oscillation during the period of resonance. The circuitry of the spin resonance console inverts this at channel 2 to output a positive peak on an oscilloscope display.

2. Connect Channels 1 and 2 on the Digital Oscilloscope to the Channel 1 and Channel 2 output banana sockets on the Spin Resonance Console; ground both oscilloscope channels to

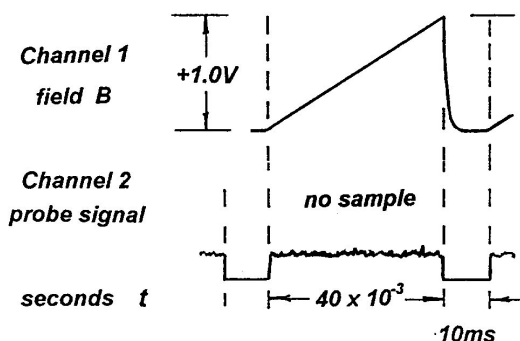


Figure 4: The two initial traces.

the ground socket on the Spin Resonance Console. Turn on the oscilloscope and set both channels to 200 mV/division with DC coupling, a timebase of 5 ms/division, triggering to channel 1 normal mode with DC coupling and negative slope. Press the “Display” button on the oscilloscope and put it into dual trace mode.

3. Connect the Frequency Meter using the 3 mm minijack socket (note that this jack outputs the probe frequency/1000). Turn on the Frequency Meter and set it to read a frequency of at least 70 kHz (with a gate time 0.1 s).
4. With the cable facing downward, carefully insert the coil tube protruding from the Electron Probe housing into the cavity at the front of the cell column and secure the assembly by pressing home the fixed pair of 4 mm plugs; connect the coaxial cable to the BNC socket marked “Probe” at Channel 2 on the Spin Resonance Console.
5. Turn on the power to the Spin Cell Mount and the Spin Resonance Console.
6. On the Spin Resonance Console, check that the signal level indicator LED of Channel 2 is illuminated, and using the sliding switch, set the coarse frequency control to MID.
7. On the Spin Cell Mount, check that the stop/run LED is illuminated.
8. On the Proton Probe, check that the power on LED is lit. Use a small screwdriver to reduce the sensitivity control, SENS, to the minimum setting (fully counterclockwise).
9. Check that the Frequency Meter reads approximately 60 kHz.
10. On the oscilloscope, adjust the trigger level control to obtain a stable trace as shown in Figure 4.
11. Obtaining a resonance peak
 - (a) Carefully insert the orange sample phial into the cavity at the back of the cell column. This electron target is a small sample of the free radical diphenyl-picri-hydrazyl (DPPH).

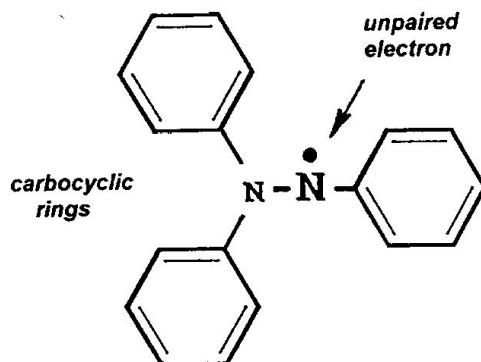


Figure 5: The free radical DPPH.

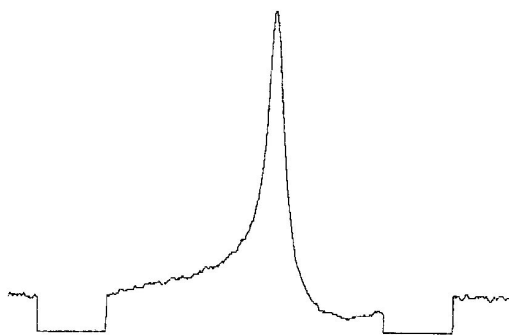


Figure 6: A DPPH resonance peak

This paramagnetic compound has a loosely bound unpaired electron on a nitrogen atom which can be excited more easily than a material with a more complete electron shell structure (see Figure 5).

- (b) Increase the SENS control on the top of the probe housing until the Channel 2 red signal LED on the console begins to dim. The Channel 2 on the oscilloscope should now display a resonance peak as in Figure 6.
- (c) Remove the sample phial and replace it with the black reference phial. Observe the absence of a peak. Remove the reference tube and replace it with the DPPH sample.
- (d) Once you have a good resonance peak, push the "Stop" button then the "Cursor/Measure" button on the oscilloscope. Use the reference and difference cursors to determine the sweep time, t_R , and the Scan Coil voltage, V_R , at which resonance occurs (see Figure 7). Record these values along with the frequency at which resonance occurred and the material of the sample. Print out your resonance peak for inclusion with your report.

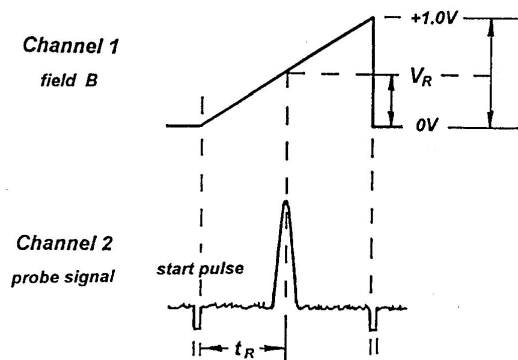


Figure 7: The values V_R and t_R at the instant of resonance.

12. Repeat step 11 for both the HI and LOW frequency settings.

3.2 Proton Spin Resonance/Nuclear Magnetic Resonance

In comparison to the electron spin workstation, the magnetic flux density B must be greatly augmented to compensate for the much increased mass of the proton. This is achieved by replacing the hollow cores with a very strong Zeeman magnet. The flux density is boosted one hundredfold by the Zeeman magnet to the order of 0.3 Tesla, with a small sweep still being provided by the scan coils. A flux of this magnitude is still only sufficient to influence those materials where there is a relatively large population of atoms with a low atomic weight such as hydrogen and fluorine. The VHF radiation frequency, ν , is reduced to about 13 MHz.

1. Mount the Zeeman Magnet and Scan Coils to the Spin Cell Mount.
 - (a) Insert the two Pole Face Disks into the vertical slots located at the front of and on each side of the Spin Cell Mount.
 - (b) Spring the pivot posts at each end of the yoke of the Zeeman Magnet firmly into the clips set into the back of the Spin Cell Mount, with the keeper post resting on the bench top.
 - (c) Firmly force the keeper out of the jaws of the magnet by pushing down with both thumbs on the top of the keeper while using your fingers to pull the magnet assembly upwards and clear of the keeper. **Be careful with your fingers, this is a very strong magnet!**
 - (d) Hold one of the Scan Coils such that the arrow points in the same direction as that on the surface panel of the Spin Cell Mount; insert it into the gap between the jaws of the magnet and slide it sideways onto one of the cores; repeat the procedure with the second Scan Coil and the other magnet core. Plug the Scan Coil leads into the 2 mm sockets on the surface panel in accordance with the color coding.

- (e) Press down firmly on the laminations protruding from the outside of each coil to relocate the keeper back into the jaws of the magnet.
 - (f) Rotate the Zeeman Magnet with the coils mounted until the keeper rests on the back surface of the cell column housing.
 - (g) Now the magnet assembly must be transferred from the keeper to the Pole Face Disks. Press firmly with both thumbs on the open edge of the disks in the front of the cell while using your fingers to pull the assembly forward until the cores become axially seated on the molded portion of the cell column plastic housing.
 - (h) Lock the magnet assembly onto the central cell column using the knobs at the top of each end plate. Gently turn both knobs simultaneously to avoid distorting the central cell column; the compression should feel “finger tight”.
 - (i) Rotate the keeper until the keeper post rests on the bench top.
2. Connect Channels 1 and 2 on the Digital Oscilloscope to the Channel 1 and Channel 2 output banana sockets on the Spin Resonance Console; ground both oscilloscope channels to the ground socket on the Spin Resonance Console. Turn on the oscilloscope and set both channels to 200 mV/division with DC coupling, a timebase of 5 ms/division, triggering to channel 1 normal mode with DC coupling and negative slope. Press the “Display” button on the oscilloscope and put it into dual trace mode.
 3. Connect the Frequency Meter using the 3 mm minijack socket (note that this jack outputs the probe frequency/1000). Turn on the Frequency Meter and set it to read a frequency of at least 14 kHz (with a gate time 0.1 s).
 4. With the cable facing downward, carefully insert the coil tube protruding from the Proton Probe housing into the cavity at the front of the cell column and secure the assembly by pressing home the fixed pair of 4 mm plugs; connect the coaxial cable to the BNC socket marked “Probe” at Channel 2 on the Spin Resonance Console.
 5. Turn on the power to the Spin Cell Mount and the Spin Resonance Console.
 6. On the Spin Resonance Console, check that the signal level indicator LED of Channel 2 is illuminated, and using the sliding switch, set the coarse frequency control to MID.
 7. On the Spin Cell Mount, check that the stop/run LED is illuminated.
 8. On the Proton Probe, check that the power on LED is lit. Use a small screwdriver to reduce the sensitivity control, SENS, to the minimum setting (fully counterclockwise).
 9. Check that the Frequency Meter reads approximately 13.2 kHz.
 10. On the oscilloscope, adjust the trigger level control to obtain a stable trace as shown in Figure 4.
 11. Obtaining a resonance peak

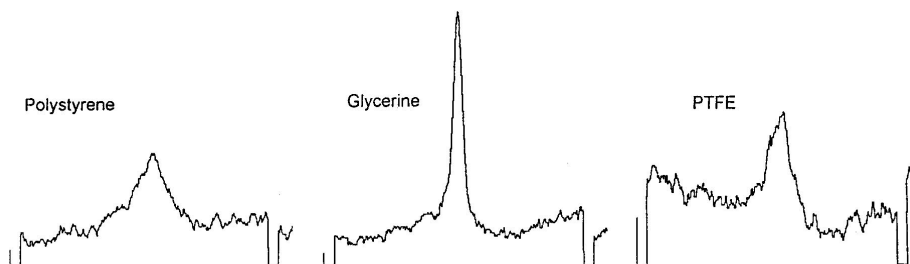


Figure 8: A comparison of three NMR resonance peaks

- (a) The range over which the magnetic field is scanned by the coils, 3 mT, is only about 1% of the total field 300 mT. In order to produce a resonance signal, the frequency of the probe must be tuned to match a corresponding 1% range.
 - (b) Carefully insert the Glycerine Sample Phial (yellow) into the cavity at the back of the cell column. Increase the SENS control on the top of the probe housing until the Channel 2 red signal LED on the console begins to dim. The Channel 2 on the oscilloscope should now display a resonance peak as in Figure 8.
 - (c) If no resonance peak is visible, it is necessary to retune the probe frequency. Remove the Sample Phial. Withdraw the Proton Probe from the from the cell column and reinsert it with the cable facing upwards, thus gaining access to the frequency control labeled FREQ. Replace the Sample Phial and adjust the frequency until a resonance peak is observed. The required frequency will be in the range 12.7 to 13.5 MHz. Ensure that the red signal LED on Channel 2 on the console remains illuminated; if necessary, adjust the sensitivity control now on the underside of the probe housing by carefully tilting the entire assembly backwards.
 - (d) Remove the sample phial, withdraw and replace the proton probe with the SENS control facing upwards, if necessary repeat step 11b.
 - (e) Loosen the end plate knobs locking the system and observe the effect on the oscilloscope signal intensity. Retighten for maximum intensity.
 - (f) Once you have a good resonance peak, push the “Stop” button then the “Cursor/Measure” button on the oscilloscope. Use the reference and difference cursors to determine the the sweep time, t_R , and the Scan Coil voltage, V_R , at which resonance occurs (see Figure 7). Record these values along with the frequency at which resonance occurred and the material of the sample (the glycerine molecule has eight hydrogen nuclei). Print out your resonance peak for inclusion with your report.
12. Replace the glycerine sample with the empty Reference Phial (black) and observe the absence of the resonance peak. There may be a small peak due to resonance of hydrogen nuclei in the plastic material from which the probe is made.
 13. Replace the black Reference Phial with the Polystyrene Sample Phial (green) and repeat the procedure of Step 11. The subsequent resonance peak is wider and of reduced amplitude as in Figure 8 (the styrene molecule also contains eight hydrogen nuclei).

14. Replace the Polystyrene Sample Phial with the blue PFTE¹ Sample Phial and repeat the procedure of Step 11. Resonance of the fluorine protons occurs at a lower frequency than that of the previous two samples, so the probe frequency will have to be retuned (in extreme cases, the coarse frequency control will have to be set to LO). The resonance peak is smaller in amplitude to that of glycerine (the normal PFTE molecule contains 8 fluorine nuclei).

4 Analysis

4.1 Calculation of g

The current supplied to the Scan Coils is a linear ramp current from 0 to 250 mA over a time interval of 40 ms. This generates a magnetic field contribution, B_{SC} with a linear sweep from 0 to 3.67×10^{-3} T. A signal of 0 to 1 V that is directly proportional to this field is output to Channel 1 of the oscilloscope. The value of B at the instant of resonance can be calculated from the measurements of V_R or t_R :

$$B = \frac{V_R}{1 \text{ V}} \cdot 3.67 \times 10^{-3} \text{T}, \quad (24)$$

or

$$B = \frac{t_R}{40 \text{ms}} \cdot 3.67 \times 10^{-3} \text{T}. \quad (25)$$

1. Calculate the Scan Coil field for each of your frequencies. For each frequency, calculate two values for B , one from V_R and one from t_R .
2. Plot the magnetic field at resonance versus frequency. From Equation 15 it is clear that the plot should be approximately linear with a slope of $h/(g\mu_B)$.
3. Fit a least-squares line to your data and calculate the DPPH g -factor. Compare it to the accepted value of 2.0036.

4.2 Calculation of g_I

The flux density to which the sample is subjected is comprised of two components: the field of the Scan Coils and the field of the Zeeman Magnet.

The current supplied to the Scan Coils is a linear ramp current from 0 to 250 mA over a time interval of 40 ms. This generates a magnetic field contribution, B_{SC} with a linear sweep from 0 to 3.2×10^{-3} T. A signal of 0 to 1 V that is directly proportional to this field is output to Channel 1 of the oscilloscope. The value of B_{SC} at the instant of resonance can be calculated from the measurements of V_R or t_R :

$$B_{SC} = \frac{V_R}{1 \text{ V}} \cdot 3.2 \times 10^{-3} \text{T}, \quad (26)$$

or

$$B_{SC} = \frac{t_R}{40 \text{ms}} \cdot 3.2 \times 10^{-3} \text{T}. \quad (27)$$

(This is slightly different than that of the ESR experiment due to the different core configuration.)

¹Polytetrafluoroethylene (PFTE) is commonly known by its trade name, Teflon[©].

The flux density, B_{ZM} , due to the Zeeman Magnet is marked on the shroud of the magnet and is approximately 300×10^{-3} T.

The total field at resonance is then

$$B_{tot} = B_{SC} + B_{ZM}. \quad (28)$$

1. Calculate the Scan Coil field for each of your samples. For each sample, calculate two values for B_{SC} , one from V_R and one from t_R , then average them together.
2. Calculate the total field, B_{tot} for each of your samples using Equation 28 .
3. Use your average values for B_{tot} in Equation 23 to determine the nuclear g -factor for each of your samples.