Study of Electron Spin Resonance using DPPH and Magnetic Resonance Magnetic Compass

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We report two laboratory demonstrations of magnetic resonance: a field-sweep electron spin resonance (ESR) measurement on a DPPH sample and a classical resonance test using a compass needle driven by an AC field. The ESR study produced a measured Landé g-factor of $g = (2.196 \pm 0.013)$ while the compass experiment confirmed the expected $f_{\rm res} \propto \sqrt{B}$ dependence of the mechanical resonance frequency. The ESR result is of the correct order but exhibits a systematic offset attributed chiefly to magnetic-field calibration and sample positioning. Together the experiments concisely illustrate the same underlying resonance physics in both quantum and classical regimes.

I. OBJECTIVE

1. Observing Resonance Peaks of DPPH.

2. Calculating Landau's g-factor from v_1 and v_0 (using Electron Spin Resonance)

3. Observing the Magnetic Resonance and plotting appropriate graphs.

II. THEORY

Resonance as a general phenomenon

Resonance is a universal response of a physical system when it is driven at a frequency that matches a natural frequency of the system. In both the macroscopic compass demonstration and the microscopic electron spin resonance (ESR) experiment the same basic idea appears: a magnetic moment in a static magnetic field has a characteristic precession (or oscillation) frequency, and an oscillating magnetic field that matches that frequency produces a large response. The compass experiment is a classical, mechanical realization of magnetic resonance, while ESR probes quantum spin transitions; both are therefore natural companions in a laboratory study of magnetic resonance.

A. Classical magnetic-resonance demonstration with a compass [1]

Consider a thin magnetic needle (compass) with magnetic moment $\boldsymbol{m}$ and moment of inertia J placed in the horizontal plane. Let a strong static field from a permanent magnet be $\mathbf{B}_{\rm PM}$ (taken as the dominant static field) and let a weak oscillatory drive field from a coil be $\mathbf{B}_{\rm drive}(t)$. The net torque on the needle equals the time derivative of its angular momentum:

$$\boldsymbol{\tau} = \boldsymbol{m} \times (\mathbf{B}_{\rm PM} + \mathbf{B}_{\rm drive}(t)) = J\ddot{\theta}\,\hat{\mathbf{z}}, \tag{1}$$

where θ is the small deflection angle of the needle in the plane of the compass. The z- component of the previous equation becomes:

$$mB_{\rm PM}\,\sin(-\theta) + mB_{\rm drive}\sin\left(\frac{\pi}{2} - \theta\right) = J\ddot{\theta} \tag{2}$$

Using small angle approximation, $\sin(-\theta) \approx$ -θ and $\sin\left(\frac{\pi}{2} - \theta\right) = 1$. This simplifies the equantion as:

$$\ddot{\theta} + \omega_0^2\theta = \omega^2$$

where,

$$\omega_0 = \sqrt{\frac{mB_{\rm PM}}{J}}, \omega = \sqrt{\frac{mB_{\rm drive}}{J}} \tag{3}$$

Resonance condition: Resonance occurs when the driving angular frequency ω matches the natural angular frequency ω_0 of the system ($\omega = \omega_0$), which results in an increase in the oscillation amplitude. The resonance frequency (in Hz) is given as:

$$f_{\rm res} = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{mB_{\rm PM}}{J}}. \tag{4}$$

In the dipole approximation the static field of the permanent magnet at distance d from its centre scales as

$$B_{\rm PM}(d) \approx \frac{\mu_0}{4\pi}\,\frac{2\,m_{\rm PM}}{d^3}, \tag{5}$$

where $m_{\rm PM}$ is the dipole moment of the permanent magnet. Combining Eqs. (4) and (5) yields the expected distance dependence of the resonance frequency:

$$f_{\rm res}(d) = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{2\pi}\frac{m_{PM}}{d^3}\frac{m}{J}} \tag{6}$$

This relation is the basis for the simple table-top experiment: by moving the magnet and recording the frequency at which the compass needle oscillates strongly, one maps out the $d^{-3/2}$ behaviour predicted by the dipole model.

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B. Quantum magnetic resonance: electron spin resonance (ESR) [2]

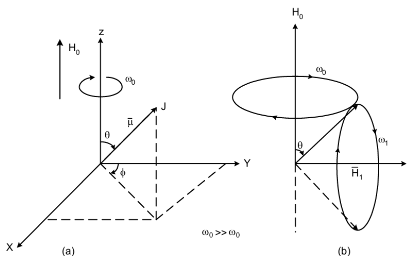

FIG. 1. Precession of a magnetic moment $\bar{\mu}$ when placed in a magnetic field H_0.
(a) The spin precesses with angular frequency $\omega_0 = \gamma H_0$; the angle θ is a constant of the motion.
(b). In addition to H_0 a week magnetic field H_1 is now also applied. H_1 is rotating about the z axis with angular frequency ω_0 and therefore $\bar{\mu}$ precesses about H_1 with angular frequency $\omega_1 = \gamma H_1$; θ is not any more conserved.

In ESR an unpaired electron with magnetic moment $\hat{\boldsymbol{\mu}} = -g\mu_B\hat{\mathbf{S}}/\hbar$ (where μ_B is the Bohr magneton, g the spectroscopic g-factor and $\hat{\mathbf{S}}$ the spin operator) is placed in a static magnetic field $\mathbf{B}_0 = B_0\hat{\mathbf{z}}$. The Zeeman interaction gives the Hamiltonian

$$\hat{H}_Z = -\hat{\boldsymbol{\mu}} \cdot \mathbf{B}_0 = g\,\mu_B\,B_0\,\frac{\hat{S}_z}{\hbar}, \tag{7}$$

and the energy separation between adjacent spin sublevels is

$$\Delta E = g\,\mu_B\,B_0. \tag{8}$$

Resonance absorption of photons of frequency ν occurs when

$$h\nu_1 = g\,\mu_B\,B_0, \tag{9}$$

which provides a direct route to determine g if ν and B_0 are known. In laboratory practice ν is often fixed and one sweeps B_0 (or vice versa) to locate the resonance. THe fine structure of splitting and allowed transitions are shown in fig. 2.

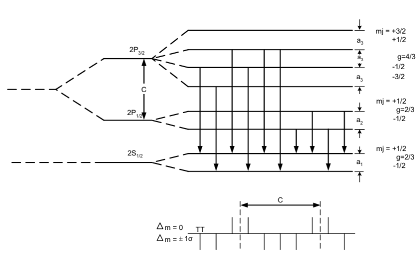

FIG. 2. Diagram showing allowed transitions and splitted energy levels under the influence of external magnetic field.

C. ESR in solids [2]

In a paramagnetic solid placed in a static magnetic field H_0, electron spins occupy Zeeman levels.

1. **Spin–Spin Interaction** – Neighboring spins interact with each other, redistributing energy within the spin system but keeping the total spin energy constant.

2. **Spin–Lattice Interaction** – Spins exchange energy with the lattice (the solid acting as a thermal reservoir). This process allows the absorbed RF energy at resonance to be transferred into heat, making ESR absorption observable.

D. Relaxation, Saturation and Line Width

- **Relaxation:** In ESR, relaxation refers to the return of spins to equilibrium. Spin–spin relaxation time (T_2) describes energy redistribution within the spin system, while spin–lattice relaxation time (T_1) measures energy transfer from spins to the lattice.

- **Saturation:** If the RF power is too high, spins cannot relax quickly enough, leading to saturation, where no further energy absorption occurs despite increased RF power.

- **Line Width:** Spin–spin interactions broaden the absorption line by causing local energy shifts, giving a linewidth of order $1/T_2$. Spin–lattice relaxation also contributes, and the general linewidth is of order $1/T_2 + 1/T_1$. Thus, linewidth analysis provides information on internal interactions in solids and liquids.

E. Origin of the Four Peaks

The observed features are fundamentally *absorption dips* (the sample absorbs RF power), but the detector/amplifier chain—having an odd number of inverting stages—renders them as peaks on the display. Resonance occurs when the RF frequency matches the Larmor frequency, $\omega_0 = \gamma H_0$ (with γ the gyromagnetic ratio). Field modulation (50 Hz) together with X–Y phasing of the oscilloscope produces two pairs of responses (I&II and III&IV); when the X (modulation) and Y (ESR) signals are in phase the paired peaks coincide on the X-scale, which is used to calibrate the magnetic field so that the center corresponds to zero field (as shown in fig. 3). Small non-coincidences on the Y-scale arise from 50 Hz pickup, power–supply ripple and high amplifier gain, but these do not affect the determination of the g-factor.

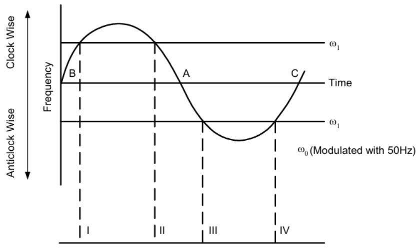

FIG. 3. The radio frequency is linear by polarised, which can be regarded as two circularly polarised fields of opposite direction (say clockwise and anti-clockwise). Further magnetic field H_0 also changes direction. Thus resonance occurs when the two frequencies (ω_1 and ω_0) becomes equal in magnitude as well as direction i.e. four times in one full cycle of H_0.

III. OBSERVATION AND DATA ANALYSIS

In the DPPH ESR experiment we observed absorption dips on the oscilloscope that shifted with coil current and frequency; their separation gave the resonance field used to compute the Landé g-factor.
In the compass setup, the needle's oscillations were small at extreme magnet distances but became pronounced at intermediate distances when the drive frequency equaled the needle's natural precession frequency, indicating resonance.
All plots were generated with the Python code available at [3].

TABLE I. Data table of ESR with DPPH sample at freq. =12.80 MHz and P = 16 V

I(mA)	Q(V)	H(mT)	H_{pp} (G)	H_0 (G)	g
144	4.8	0.49	13.86	4.16	2.199
182	3.6	0.65	18.38	4.13	2.210
220	3.0	0.77	21.78	4.08	2.242
258	2.5	0.93	26.30	4.11	2.226
294	2.1	1.07	30.26	3.97	2.304
331	1.9	1.19	33.66	4.00	2.287
366	1.8	1.33	37.62	4.23	2.163
403	1.7	1.46	41.29	4.39	2.084
435	1.6	1.58	44.69	4.47	2.046
				Average g	**2.196**

TABLE II. Data table of ESR with DPPH sample at freq. =14.83 MHz and P = 16 V

I(mA)	Q(V)	H(mT)	H_{pp} (G)	H_0 (G)	g
143	5.6	0.49	13.86	4.85	2.185
181	4.4	0.65	18.38	5.05	2.099
218	3.5	0.77	21.78	4.76	2.227
258	3.0	0.93	26.30	4.93	2.150
293	2.7	1.07	30.26	5.11	2.074
330	2.3	1.19	33.66	4.84	2.190
365	2.0	1.33	37.62	4.70	2.255
400	1.8	1.46	41.29	4.65	2.279
435	1.7	1.58	44.69	4.75	2.231
				Average g	**2.188**

TABLE III. Data table of ESR with DPPH sample at freq. =15.81 MHz and P = 16 V

I(mA)	Q(V)	H(mT)	H_{pp} (G)	H_0 (G)	g
143	5.8	0.49	13.86	5.02	2.251
182	4.7	0.65	18.38	5.40	2.092
219	3.8	0.77	21.78	5.17	2.185
258	3.2	0.93	26.30	5.26	2.148
293	2.7	1.07	30.26	5.11	2.211
330	2.4	1.19	33.66	5.05	2.237
365	2.1	1.33	37.62	4.96	2.287
400	2.0	1.46	41.29	5.16	2.190
434	1.8	1.58	44.69	5.03	2.246
				Average g	**2.205**

TABLE IV. Data table of magnetic resonance with compass

f_R(in Hz)	distance d (in cm)	Magnetic field B(in mT)
2.798	5.4	0.18
2.613	5.9	0.17
2.466	6.4	0.16
2.380	6.9	0.15
2.332	7.9	0.13
2.108	8.9	0.11
1.824	11.9	0.09
1.767	12.9	0.08
1.559	16.9	0.06

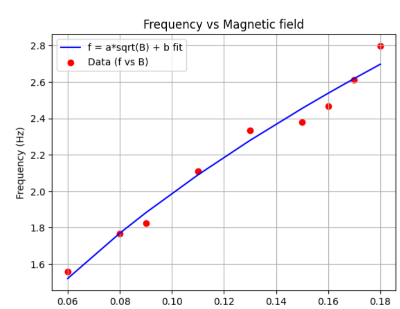

FIG. 4. Plot of Resonant frequency as a function of magnetic field

A. Calculation of Landé g-factor

Landé g-factor is calculated by resonance condition equation, which is

$$h\nu_1 = g\mu_B H_0 \implies g = \frac{h\,\nu_1}{\mu_B\,H_0} \tag{10}$$

where,

$$h = 6.625\times10^{-27}\ \mathrm{erg\,s}, \qquad \mu_B = 0.927\times10^{-20}\ \mathrm{erg\,G^{-1}}.$$

Using the above formula, the value of g is calculated for each measurement and average g is calculated for each set of data-table.

IV. ERROR ANALYSIS

The overall average Landé g-factor(g) is $\left(\frac{2.196+2.188+2.205}{3}\right) = 2.196$. The standard error in the mean value of g is,

$$\Delta g_{mean} = \frac{\sigma_g}{\sqrt{N}}$$

where

$$\sigma_g = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(g_i - g_{mean})^2}$$

The value of σ_g comes out as 0.070 and so, $\Delta g_{mean} = \frac{0.070}{\sqrt{27}} \approx 0.013$. Also, the percentage deviation from the literature value of g (i.e., $g_{lit.} = 2.0036$)) is calculated as: % deviation (in mean g) $= \frac{|2.1960-2.0036|}{2.0036} \times 100\% = 9.6$ %

V. RESULTS AND DISCUSSION

In the magnetic resonance experiment with a compass, the measured resonance frequency f_{res} rises with the applied permanent-magnet field B_{PM} and follows the expected square-root dependence

$$f_{\mathrm{res}} = \frac{1}{2\pi}\sqrt{\frac{m\,B_{\mathrm{PM}}}{J}} \propto \sqrt{B_{\mathrm{PM}}},$$

where m is the needle's magnetic moment and J its moment of inertia. A fit of f_{res} versus B_{PM} is consistent with this relation (see Fig. 4); small deviations from the ideal curve are attributable to damping at the pivot, slight misalignment of magnet and coil, and non-uniformity of the magnet field.

From the ESR experiment with DPPH, the mean g-factor Landé, which was determined experimentally, is as follows:

$$\boxed{g_{mean} = (2.196 \pm 0.013)} \tag{11}$$

On comparing with the literature value of g (i.e., $g_{lit.} = 2.0036$), a deviation of 9.6 % observed.

VI. PRECAUTIONS

1. Ensure the setup is isolated from mechanical and electrical disturbances to avoid signal noise.
2. Keep the magnetic fields from the permanent magnet and Helmholtz coils mutually perpendicular and uniform.
3. Avoid prolonged high currents through the coils to prevent overheating and damage.

VII. CONCLUSION

Both the classical (compass) and quantum (ESR with DPPH) demonstrations reproducibly exhibited magnetic resonance: the compass showed the expected $f_{\mathrm{res}} \propto \sqrt{B}$ behaviour, and the ESR signal satisfied the resonance condition. From the ESR with DPPH measurements, we obtain $g_{mean} = (2.196 \pm 0.013)$.
Overall, the experiment succinctly confirms the universality of resonance and the utility of these methods for measuring magnetic properties.

[1] School of Physical Sciences, NISER Bhubaneswar, Magnetic resonance with compass: Laboratory manual, `https://www.niser.ac.in/sps/assets/files/msc/Magnetic_resonance_with_compass2025.pdf` (2025), accessed: 2025-10-04.

[2] School of Physical Sciences, NISER Bhubaneswar, Electron spin resonance: Laboratory manual, `https://www.niser.ac.in/sps/assets/files/msc/Electron_spin_resonance_manual2024.pdf` (2024), accessed: 2025-10-04.

[3] A. Arya, Codify, `https://github.com/Anuj-Arya1/Codify.git` (2025).