Electron Spin Resonance: An Experiment for Perceiving Quantum Physics Intuition

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MOTIVATION & BACKGROUND

Quantum physics applies to enormous number of physical phenomena starting from elementary-particles through the events in atomic scale to all the way to the origin of the early universe. Many modern technologies would be impossible to understand without invoking quantum physics. Almost all the electronic, magnetic, and optoelectronic devices (transistor, laser, LED, MRI, NMR, sensors, *etc.*) are based on a quantum understanding of the atomic phenomena in solids. However, there is a major problem in the realization of quantum physics as it implies counterintuitive concepts and thoughts. This has led, for example, Niels Bohr (1952) to comment "*For those who are not shocked when they first come across quantum theory cannot possibly have understood it*" and Richard Feynman (1965) to remark "*I think I can safely say that nobody understands quantum mechanics*" or Roger Penrose to comment that "*theory makes no sense*". Electron spin resonance (ESR) is a purely quantum mechanical effect. It relates the interaction of an applied magnetic field to an electron's magnetic moment, which is the manifestation of intrinsic spin. Since the spin of an electron may either be up or down, so may its magnetic moment. The ESR experiment uses a diphenylpicrylhydrazyl (DPPH) sample which has an unpaired electron and its orbital contribution to the magnetic moment is negligible because the molecule moves on a highly delocalized orbit. Since the electron is free, only its spin contributing to the magnetic moment. Thus the Landé g-factor for DPPH is very close to that for a free electron. In this experiment the magnetic field is produced by a pair of Helmholtz coils is series connection with as and dc power supply and photon frequency of 10-50 MHz was used to produce the resonance. This advanced lab experiment allows students to realize the quantum physics concept learned in theory.

THEORY

The electron spin magnetic moment is important in the spin-orbit interaction which splits atomic energy levels and gives rise to fine structure in the spectra of atoms. The electron spin magnetic moment is also a factor in the interaction of atoms with external magnetic fields (Zeeman effect). When an atom or a molecule/compound with an unpaired electron is placed in a strong magnetic field, the spin of the unpaired electron can align in two different ways creating two spin states, ms = ± ½. If a particle with magnetic moment μ placed in a uniform magnetic field of H_o, then the moment μ will precess around H_o with an angular Larmor frequency, ω_o (**Fig. 1a**),

$$\omega_o = g\left(\frac{e}{2mc}\right) H_o$$

Where g is Lande' g-factor (g = 1 for pure orbital momentum and g = 2 for free electron spin. When an additional weak magnetic field is applied perpendicular to z-axis (Larmor precessioning) with angular frequency ω_1 and if the $\omega_1 \neq \omega_o$ then the angle between the H_1 and magnetic moment μ will continuously change so that their interaction will average out to zero. If $\omega_1 = \omega_o$, then the angle between H_1 and magnetic moment is maintained and the net interaction is effective and therefore μ precess around H_1 with angular frequency ω_1 (**Fig. 1b**) .

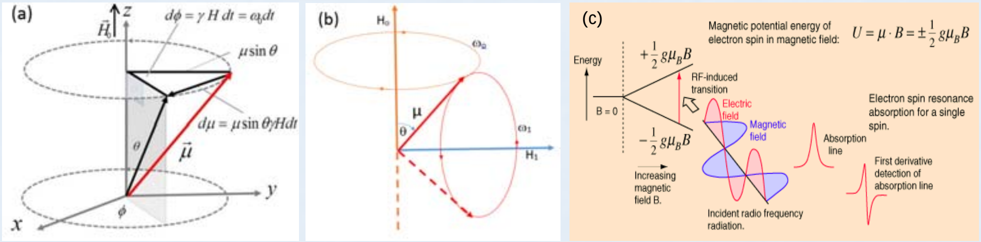


Fig. 1: Schematic representation of precession of a single moment μ in an external magnetic field along z-axis (a) and field perpendicular to the Larmor precession (b) and spilling of energy levels in magnetic field (Zeeman Effect).

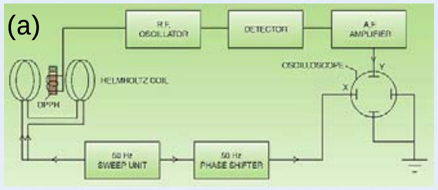
If a particle having a magnetic moment μ is placed in a uniform magnetic field of intensity B, then the energy can be written as:

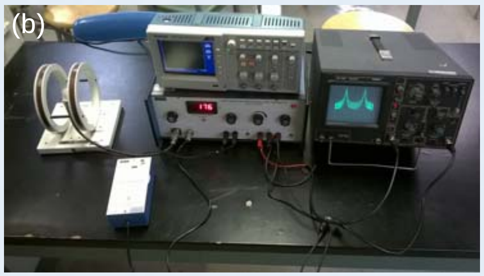
$$\Delta E = h\upsilon = g\mu_B \mathbf{B}$$

$$\text{Lande' g-factor } g = \frac{h\upsilon P}{\mu_o\, QI\, H_a}$$

h = 6.626 x 10^{-34} J/s
υ = Radio frequency
μ_B = 9.274 x 10^{-24} J/T
QI = 2.556
Ha = 168 Gauss

EXPERIMENTAL DETAILS





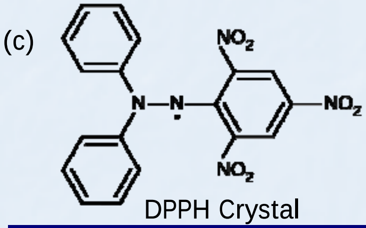


*Fig. 2: Block diagram (a) and experimental setup (b) of electron spin resonance (**SVS Labs Inc. CA, USA**). (c) Chemical structure of DDPH (2, 2-Diphenyl-1-Picrylhydrazyl (free radical 95%) that used for studying electron spin resonance.*

RESULTS & DISCUSSION

A DPPH sample was placed between the Helmholtz coils. The compound has free electron (Fig. 2) due to unpaired electron in nitrogen atom. The signal from the AC source, which supplies current for the magnetic field, is fed to the X-plate of the oscilloscope, and the absorption signal is fed to the Y-plate. Without Y- plate, as can be seen, the field strength becomes B_o four times in a single sweep cycle (**Fig. 3a**). Now if the absorption signal is fed to the Y-plate, whenever field strength becomes Bo, the Y-axis will show a peak. So, one should see four peaks (**Fig. 3b**) corresponding to the points 1, 2, 3, and 4 (**Fig. 3a**). But one can see that on the X-axis the CRO screen, points 2 and 3 are the same because they correspond to the same value of field Bo. So the **four peaks should be overlap such that only two are visible** (Fig. 3c) by changing phase. After changing phase, the frequency of RF Oscillator was varied and resonance is observed at **17.6 MHz.**

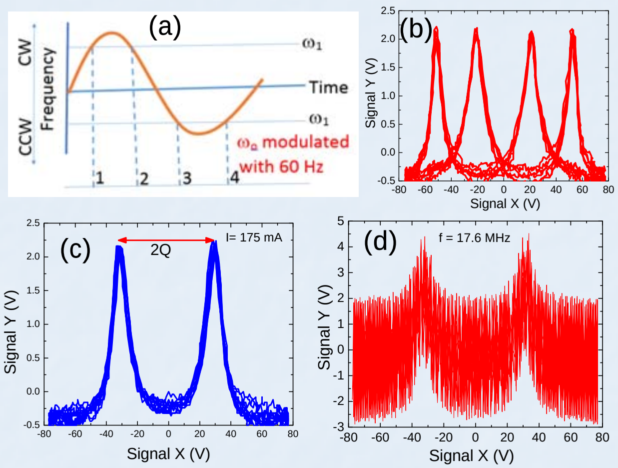


Fig. 3: (a) Schematic representation on one swip cycle; (b) Four absorption peaks observed in DPPH and overlapped to two (c) by changing phase, (d) resonance observed as 17.6 MHz.

The g value was calculated for resonance frequency of 17.6 MHz and found to be 2.002, which is very close to theoretical value (2.0047).

CONCLUSION

The electron spin resonance is a very sensitive technique and can be applied in solid state physics and chemistry to investigate the paramagnetic ions in crystals, unpaired electron in semiconductors and organic free radicals, color centers and radiation damage center, ferromagnetic and antiferromagnetic materials. This is excellent experiment for demonstration of quantum mechanical phenomena in solids.