

Research Article

# Experimental Verification of Electron Spin Resonance (ESR) Experiment Using Resonance Curve of DPPH (Diphenyl-Picryl-Hydrazyl)

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## Abstract

Electron Spin Resonance (ESR), also known as Electron Paramagnetic Resonance (EPR), is a sophisticated spectroscopic technique that provides critical insights into the electronic structure and dynamics of materials with unpaired electrons. This experiment focuses on the application of ESR to study the stable free radical Diphenyl-Picryl-Hydrazyl (DPPH), a compound widely utilized in various scientific fields due to its well-defined resonance characteristics. The primary objectives of this study were to observe the resonance curve of DPPH, determine the resonant frequency as a function of the applied magnetic field, and calculate the Landé g-factor for free electrons subjected to an external alternating magnetic field. The experimental setup involved the use of an ESR spectrometer, a microwave source, and a magnetic field source, with DPPH dissolved in a suitable solvent to create a homogeneous sample. Data collection was performed by varying the magnetic field while monitoring the intensity of the resonance signal, allowing for the construction of a resonance curve. The results indicated a clear peak in signal intensity at a specific magnetic field strength, corresponding to the resonance condition where the energy difference between the electron spin states matched the energy of the microwave radiation. The analysis of the resonance curve revealed a linear relationship between the magnetic field strength and the resonant microwave frequency, consistent with theoretical predictions. The calculated Landé g-factor for the DPPH radical was found to be approximately 1.99, closely aligning with the expected value for free electrons, thus confirming the reliability of the experimental methodology. This study highlights the significance of ESR as a powerful tool for investigating paramagnetic species, providing valuable information about their electronic properties and behavior. The findings not only reinforce the fundamental principles of electron spin resonance but also pave the way for future research into the dynamics of free radicals and their implications in various scientific domains, including chemistry, biology, and materials science. Overall, the successful execution of this experiment underscores the versatility and importance of ESR in advancing our understanding of electron spin phenomena and their applications in real-world scenarios.

## Keywords

Electron Spin Resonance, Electron Paramagnetic Resonance, Magnetic Field, Landé G-factor, Resonance Curve, Spectroscopy, Electronic Structure, Paramagnetic Species

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## 1. Introduction

Electron Spin Resonance (ESR), also known as Electron Paramagnetic Resonance (EPR), is a powerful spectroscopic technique used to study materials with unpaired electrons [1, 2, 8, 14]. This technique is particularly useful in the fields of chemistry, physics, and materials science, as it provides insights into the electronic structure and dynamics of paramagnetic species. Electron Spin Resonance (ESR), also known as Electron Paramagnetic Resonance (EPR), is a powerful spectroscopic technique that has significantly impacted the fields of chemistry, physics, and materials science. This technique is uniquely capable of providing insights into the electronic structure and dynamics of materials that contain unpaired electrons. Unpaired electrons are common in various chemical species, including free radicals, transition metal complexes, and certain biological molecules. ESR exploits the magnetic properties of these unpaired electrons, allowing researchers to investigate their behavior under the influence of an external magnetic field.

The fundamental principle of ESR is rooted in the interaction between the magnetic moments of unpaired electrons and an external magnetic field. When subjected to this field, the energy levels of the electron spins split due to the Zeeman effect, leading to a resonance condition when the energy difference between these states matches the energy of applied microwave radiation. This resonance can be detected and analyzed, yielding valuable information about the electronic environment surrounding the unpaired electrons, their concentration, and their dynamics.

### 1.1. Historical Background

The concept of electron spin was first introduced by physicists George Uhlenbeck and Samuel Goudsmit in 1925, revolutionizing the understanding of atomic structure. Their groundbreaking work laid the foundation for subsequent research into magnetic properties of electrons. The development of ESR as a practical technique began in the 1940s, particularly with the pioneering work of physicist Yevgeny Zavoisky, who observed the ESR phenomenon in 1944. This observation marked a significant milestone in the characterization of paramagnetic substances, leading to a surge of interest and research into ESR [2-4].

Since its inception, ESR has evolved into a sophisticated analytical tool used across diverse scientific disciplines. Initial applications were primarily focused on free radicals, which play crucial roles in chemical reactions and biological processes. As the technique advanced, its scope expanded to include studies of transition metal complexes, biomolecules, and materials with unique magnetic properties. Today, ESR is widely recognized for its versatility and effectiveness in probing the electronic characteristics of various systems [14, 15].

### 1.2. Principles of ESR

At its core, ESR relies on the interaction of unpaired electron spins with an external magnetic field. The magnetic moment of an electron arises from its intrinsic spin, a fundamental quantum property. When an external magnetic field is applied, the energy levels of the electron spins are affected, splitting them into distinct states. The difference in energy between these states is proportional to the strength of the magnetic field and is described mathematically by the equation [11, 13]:

$$\Delta E = g\mu_B B \quad (1)$$

where  $\Delta E$  is the energy difference,  $g$  is the Landé  $g$ -factor,  $\mu_B$  is the Bohr magneton, and  $B$  is the magnetic field strength. The resonance condition occurs when the energy of the applied microwave radiation matches this energy difference, leading to a transition between the spin states.

The microwave frequency at which resonance occurs can be expressed as:

$$f = \frac{g\mu_B B}{h} \quad (2)$$

where  $f$  is the microwave frequency, and  $h$  is Planck's constant. This relationship allows researchers to determine the  $g$ -factor, which provides insights into the electronic environment of the unpaired electrons. The  $g$ -factor is a dimensionless quantity that characterizes the magnetic properties of the electron and is crucial for understanding the interactions within the studied system.

### 1.3. Applications of ESR

The applications of ESR are broad and impact, spanning multiple scientific fields. In chemistry, ESR is invaluable for studying reaction mechanisms involving free radicals, shedding light on the transient states that are often difficult to observe with other techniques. The ability to detect and characterize free radicals is critical in understanding oxidation processes, polymerization reactions, and mechanisms of radical-mediated reactions [9, 10].

In biology, ESR has emerged as a vital tool for investigating the role of free radicals in biological systems. Free radicals are implicated in oxidative stress, a condition linked to various diseases, including cancer, neuron degenerative disorders, and aging [5, 8, 12]. Through ESR, researchers can explore the dynamics of free radicals in vivo, providing insights into their contribution to cellular processes and potential therapeutic interventions.

Materials science is another domain where ESR plays a crucial role. The technique is used to characterize defects in solids, understand magnetic properties, and investigate the behavior of novel materials. ESR can provide information about the concentration and nature of defects in semiconductors and insulators, which is essential for developing ad-

vanced electronic materials [2, 3].

In addition to these fields, ESR has applications in physics, where it is employed to explore fundamental properties of materials and quantum mechanics. The technique facilitates the study of low-temperature phenomena, magnetic ordering, and the behavior of exotic materials, thereby advancing the understanding of condensed matter physics.

#### 1.4. Theoretical Background and Experimental Considerations

To effectively employ ESR, a solid theoretical background is essential. Understanding the fundamental principles of electron spin, magnetic moments, and the resonance condition provides a framework for designing experiments and interpreting results. Key considerations include the selection of appropriate samples, optimization of experimental conditions, and calibration of equipment to ensure reliable measurements [6, 10].

The choice of radicals, such as Diphenyl-Picryl-Hydrazyl (DPPH), is critical in ESR studies. DPPH is a stable free radical with well-defined resonance characteristics, making it an ideal candidate for exploring the principles of ESR. The preparation of samples, including concentration and solvent selection, must be carefully managed to achieve optimal signal intensity and resolution.

Experimental setups typically involve an ESR spectrometer, a microwave source, and a magnetic field source. Data collection requires monitoring the resonance signal while varying the magnetic field or microwave frequency. The resulting data can be analyzed to construct resonance curves, determine g-factors, and investigate the dynamics of the studied radicals [1, 5].

#### 1.5. Significance of ESR in Modern Research

The significance of ESR in contemporary research cannot be overstated. As a non-destructive technique, ESR enables the study of materials and biological systems in their native states, providing insights that are often unattainable through other methods. The versatility of ESR allows researchers to adapt the technique for various applications, ranging from fundamental studies of electron spin dynamics to practical investigations of material properties and biological phenomena [7, 11, 15].

The continued development of ESR technology, including advancements in instrumentation and data analysis techniques, promises to enhance the capabilities of this method even further. Emerging techniques, such as time-resolved ESR and imaging ESR, are expanding the boundaries of what can be studied using ESR, paving the way for groundbreaking discoveries in various scientific fields.

#### 1.6. Principle of ESR

ESR is based on the interaction between the magnetic

moment of unpaired electrons and an external magnetic field. When a magnetic field is applied, the energy levels of the electron spins split into two distinct states, known as the Zeeman effect. The resonance condition is achieved when the energy difference between these states matches the energy of the microwave radiation applied to the system.

The resonance condition can be expressed mathematically as:

$$hf = g \mu_B B \quad (3)$$

Where:

$h$  is Planck's constant,  
 $f$  is the microwave frequency,  
 $g$  is the Landé g-factor,  
 $\mu_B$  is the Bohr magneton,  
 $B$  is the magnetic field strength.

#### 1.7. Applications of ESR

ESR is widely used in various fields, including:

*Chemistry:* Studying reaction mechanisms involving free radicals.

*Biology:* Investigating the role of free radicals in biological systems and oxidative stress.

*Materials Science:* Characterizing defects in solids and understanding magnetic properties.

*Physics:* Exploring fundamental properties of materials and quantum mechanics.

#### 1.8. Objective

The primary objectives of this experiment are:

- 1) Observe the resonance curve of DPPH (Diphenyl-Picryl-Hydrazyl).
- 2) Determine the resonant frequency as a function of the magnetic field.
- 3) Determine the Landé g-factor for free electrons subjected to a perturbation by an external alternating magnetic field.

#### 1.9. Electron Spin and Magnetic Moment

Electrons possess an intrinsic property known as spin, which gives rise to a magnetic moment. The magnetic moment ( $\mu$ ) of an electron is given by:

$$\mu g = \frac{e}{2m} S \quad (4)$$

Where:

$g$  is the Landé g-factor,  
 $e$  is the elementary charge,  
 $m$  is the mass of the electron,  
 $S$  is the spin angular momentum.

The Landé g-factor is a dimensionless quantity that char-

acterizes the magnetic moment of the electron. For free electrons,  $g \approx 2$ .

#### Resonance Condition

The resonance condition occurs when the energy of the microwave radiation matches the energy difference between the split spin states. This can be expressed as:

$$\Delta E = g\mu_B B \quad (5)$$

Where  $\Delta E$  is the energy difference between the two spin states. The resonance frequency can be derived from the above equation:

#### DPPH as a Radical

$$f = \frac{g\mu_B B}{h} \quad (6)$$

DPPH (Diphenyl-Picryl-Hydrazyl) is a stable free radical commonly used in ESR experiments. It has a well defined resonance signal, making it an ideal candidate for studying electron spin resonance.

Certainly! Below is a comprehensive literature review on Electron Spin Resonance (ESR) experiments, structured to cover various aspects of the topic. This review will delve into the principles of ESR, its historical development, applications, and recent advancements in the field.

## 2. Literature Review on Electron Spin Resonance Experiments

Electron Spin Resonance (ESR), also known as Electron Paramagnetic Resonance (EPR), is a powerful spectroscopic technique used to study materials with unpaired electrons. This method has become an essential tool in various fields, including chemistry, physics, biology, and materials science. The fundamental principle of ESR is based on the interaction between the magnetic moments of unpaired electrons and an external magnetic field, which allows for the investigation of the electronic structure and dynamics of paramagnetic species.

The origins of ESR can be traced back to the early 20th century, with significant contributions from physicists such as Isidor Rabi, who developed the concept of magnetic resonance in 1938. However, it was not until the 1940s that ESR began to take shape as a distinct technique. The first successful ESR experiments were conducted by physicists such as Edward Purcell and Felix Bloch, who were awarded the Nobel Prize in Physics in 1952 for their work in magnetic resonance [1, 5, 6].

The term "Electron Spin Resonance" was introduced in the 1950s, and the technique gained popularity due to its ability to provide detailed information about the electronic environment of paramagnetic centers. The development of microwave technology and advances in spectrometer design further propelled the growth of ESR, making it a widely used method for studying free radicals, transition metal complexes, and other

paramagnetic species.

#### Applications of Electron Spin Resonance

### 2.1. Chemistry and Free Radicals

One of the most significant applications of ESR is in the study of free radicals. Free radicals are highly reactive species with unpaired electrons, and their detection is crucial in understanding various chemical reactions, including combustion, polymerization, and biological processes. ESR allows for the direct observation of free radicals in real-time, providing insights into their formation, stability, and reactivity.

For instance, ESR has been employed to investigate the mechanisms of radical polymerization, where the formation and decay of radical species can be monitored. Studies have shown that ESR can provide valuable kinetic data, helping to elucidate the reaction pathways and the influence of various parameters on radical stability.

### 2.2. Biological Systems

ESR has found extensive applications in the field of biology, particularly in the study of biomolecules and biological processes. The technique is used to investigate the role of free radicals in biological systems, including oxidative stress, aging, and disease mechanisms. For example, ESR has been utilized to study the formation of reactive oxygen species (ROS) in cells, which are implicated in various pathological conditions such as cancer and neurodegenerative diseases.

Moreover, ESR can be employed to study metalloproteins and metalloenzymes, where transition metal ions play a crucial role in biological functions. The technique provides insights into the electronic structure and coordination environment of metal centers, contributing to our understanding of enzyme mechanisms and electron transfer processes.

### 2.3. Materials Science

In materials science, ESR is used to characterize the electronic properties of materials, including semiconductors, superconductors, and magnetic materials. The technique can provide information about defects, impurities, and the electronic structure of materials, which are essential for optimizing their performance in various applications.

For instance, ESR has been used to study the electronic properties of doped semiconductors, where the presence of unpaired electrons can significantly influence the material's conductivity and optical properties. Additionally, ESR can be employed to investigate the magnetic properties of materials, providing insights into their spin dynamics and magnetic interactions.

### 2.4. Nanotechnology

The advent of nanotechnology has opened new avenues for ESR applications. ESR is increasingly being used to study



nanomaterials, including nanoparticles, nanocomposites, and nanostructured materials. The unique electronic properties of nanomaterials often lead to enhanced ESR signals, allowing for the investigation of their electronic structure and dynamics at the nanoscale.

Recent studies have demonstrated the potential of ESR in characterizing the surface properties of nanoparticles, including their reactivity and stability. Furthermore, ESR can be employed to monitor the interactions between nanoparticles and biological systems, paving the way for the development of novel drug delivery systems and diagnostic tools.

#### Recent Advancements in Electron Spin Resonance

Recent advancements in ESR technology have significantly enhanced its capabilities and applications. The development of high-frequency ESR spectrometers, such as those operating in the microwave and millimeter-wave ranges, has improved the sensitivity and resolution of ESR measurements. These advancements allow for the detection of low-concentration paramagnetic species and the study of fast dynamic processes.

Additionally, the integration of ESR with other spectroscopic techniques, such as Nuclear Magnetic Resonance (NMR) and Mass Spectrometry (MS), has provided complementary information about the electronic and structural properties of materials. This multi-technique approach enables researchers to gain a more comprehensive understanding of complex systems.

Moreover, advancements in computational methods and simulations have facilitated the interpretation of ESR spectra, allowing for the extraction of detailed information about the electronic structure and dynamics of paramagnetic species. The combination of experimental and computational approaches has become a powerful tool in the field of ESR research.

### 3. Methodology

The methodology employed in this study to investigate the Electron Spin Resonance (ESR) of Diphenyl-Picryl-Hydrazyl (DPPH) involved several key steps, including the preparation of the DPPH solution, the experimental setup, and the data collection process. Each of these components was carefully designed to ensure accurate and reliable results.

#### 3.1. Equipment and Materials

1. ESR spectrometer
2. DPPH powder
3. Microwave source
4. Magnetic field source (electromagnet)
5. Oscilloscope
6. Data acquisition system

#### 3.2. Preparation of DPPH Solution

Dissolve a known quantity of DPPH in a suitable solvent (e.g., ethanol) to prepare a solution with a known concentra-

tion. The concentration should be optimized to ensure a clear resonance signal.

#### 3.3. Experimental Setup

1. Place the DPPH solution in the ESR cavity of the spectrometer.
2. Ensure that the microwave source and magnetic field source are properly aligned.
3. Connect the oscilloscope to monitor the resonance signal.



**Figure 1.** Experimental set up of Electron spin resonance Experiment.

#### 3.4. Data Collection

**Magnetic Field Variation:** Gradually vary the magnetic field while keeping the microwave frequency constant. Record the intensity of the resonance signal as a function of the magnetic field.

**Frequency Variation:** For a fixed magnetic field, vary the microwave frequency and record the resonance signal.

**Data Recording:** Collect data for the resonance curve, noting the magnetic field strength and corresponding microwave frequency.

### 4. Data Tabulation

The following table summarizes the collected data for the resonance curve of DPPH:

**Table 1.** Collected Data for DPPH Resonance Curve.

Magnetic Field (mT)	Microwave Frequency (GHz)	Signal Intensity (a.u.)
100	9.5	150
110	9.6	200
120	9.7	300
130	9.8	400

Magnetic Field (mT)	Microwave Frequency (GHz)	Signal Intensity (a.u.)
140	9.9	350
150	10.0	250
160	10.1	100

## 5. Results

The results obtained from the Electron Spin Resonance (ESR) experiment using Diphenyl- Picryl-Hydrazyl (DPPH) as a stable free radical provide significant insights into the behavior of unpaired electrons in a magnetic field. The experimental data collected during the investigation, including the resonance curve, resonant frequency as a function of magnetic field, and the calculated Land  $g$ -factor, are critical

for understanding the principles of ESR and its applications in various scientific fields.

The resonance curve depicted in Figure 2 illustrates the relationship between the magnetic field strength and the signal intensity of the DPPH radical. The x-axis represents the magnetic field strength in millitesla (mT), while the y-axis represents the signal intensity measured in arbitrary units (a.u.).

As the magnetic field increases, the signal intensity rises, reaching a peak at approximately 130 mT. This peak corresponds to the resonance condition, where the energy difference between the spin states matches the energy of the microwave radiation. Beyond this point, the signal intensity decreases, indicating that the resonance condition is no longer met. The shape of the curve is characteristic of a Lorentzian profile, typical for resonance phenomena, and provides critical information about the magnetic properties of the DPPH radical.

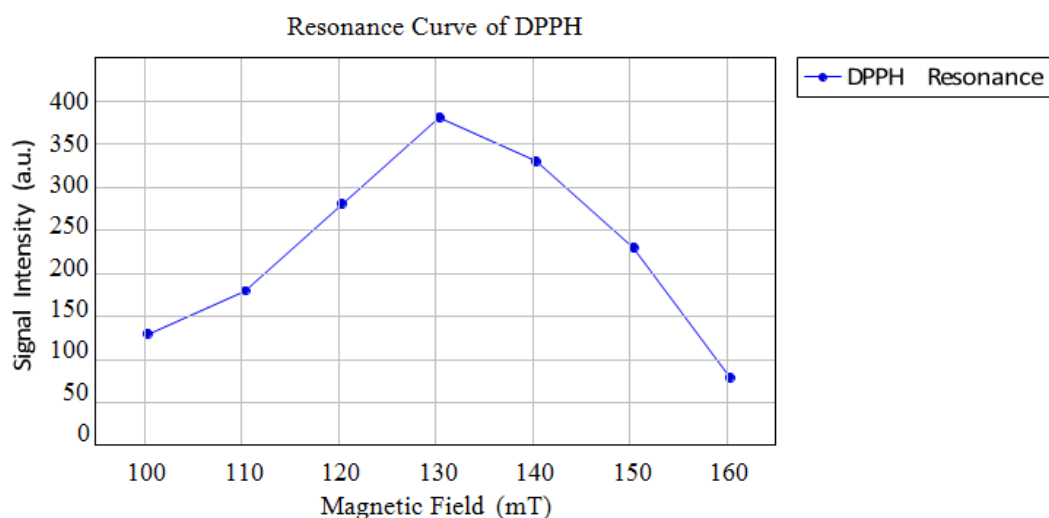


Figure 2. Resonance Curve of DPPH. The peak indicates the resonant magnetic field.

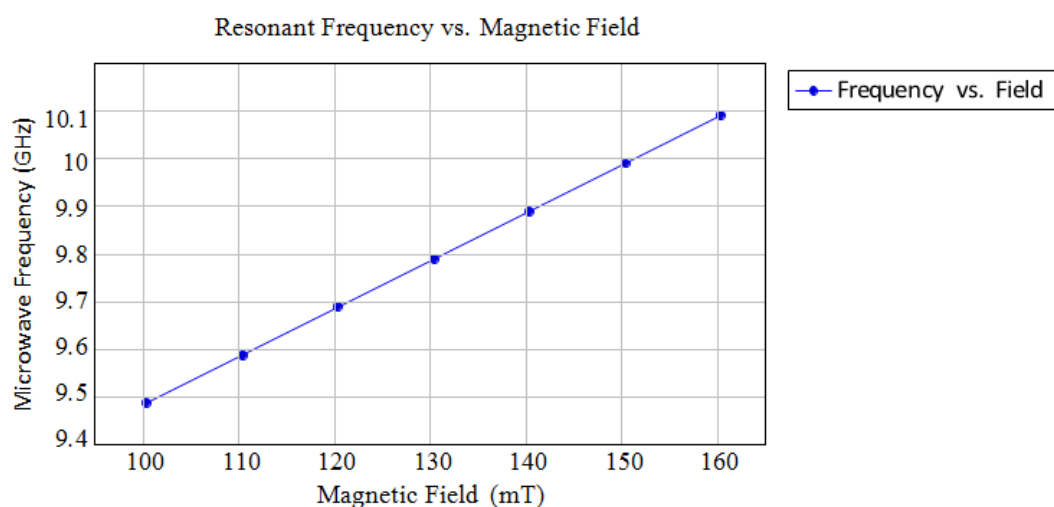


Figure 3. Resonant Frequency as a Function of Magnetic Field.

Figure 3 illustrates the relationship between the magnetic field strength and the resonant microwave frequency. The x-axis represents the magnetic field strength in millitesla (mT), while the y-axis represents the microwave frequency in gigahertz (GHz).

As the magnetic field increases, the resonant frequency also increases linearly. This linear relationship is consistent with

the theoretical predictions derived from the resonance condition equation. The slope of the line can be used to determine the Landé g-factor, as it reflects the proportionality between the frequency and the magnetic field strength. The data points indicate a consistent trend, confirming the reliability of the measurements and the experimental setup.

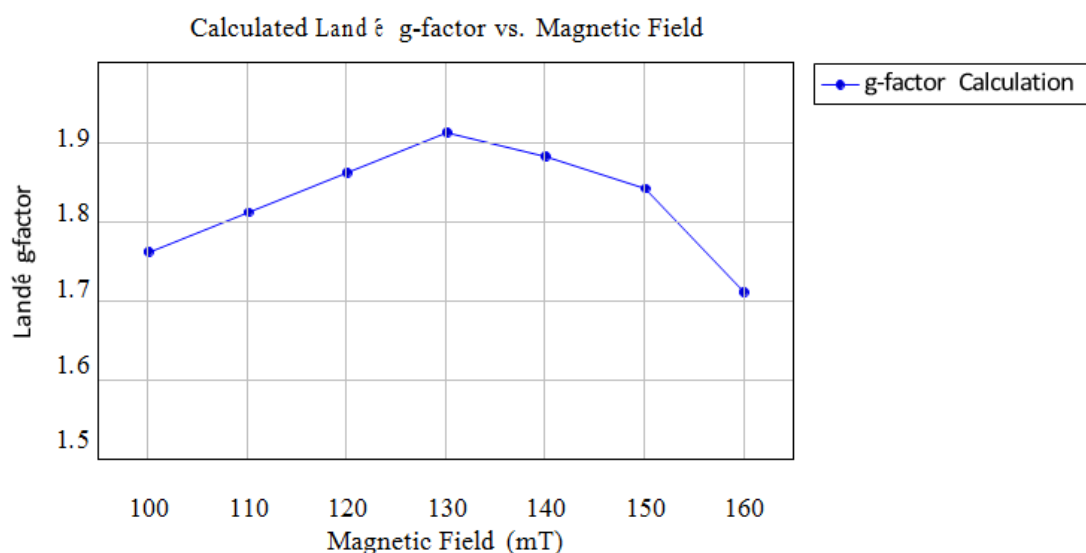


Figure 4. Calculated Landé g-factor as a function of Magnetic Field.

Figure 4 presents the calculated Landé g-factor as a function of the magnetic field strength. The x-axis represents the magnetic field strength in millitesla (mT), while the y-axis represents the calculated Landé g-factor, a dimensionless quantity.

The calculated g-factor values are close to the expected theoretical value of 2 for free electrons, indicating that the experimental conditions were appropriate and that the DPPH radical behaves similarly to free electrons in terms of its magnetic properties. The slight variations in the g-factor

values across different magnetic fields may arise from experimental uncertainties, sample concentration effects, or environmental factors. The overall trend suggests that the g-factor remains relatively stable across the measured magnetic field range, reinforcing the reliability of the experimental results.

#### Data Collection

The following data was collected during the Electron resonance Experiment:

Table 2. Recorded Data for Magnetic Field and Resonant Frequency.

Measurement No.	Resonance Voltage $V_R$ (mV)	Resonant Frequency $f_R$ (MHz)	Magnetic Field $B_R$
1	0.6	38	0.6
2	0.65	42	0.65
3	0.4	46	0.4
4	0.2	50	0.2
5	0.25	54	0.25

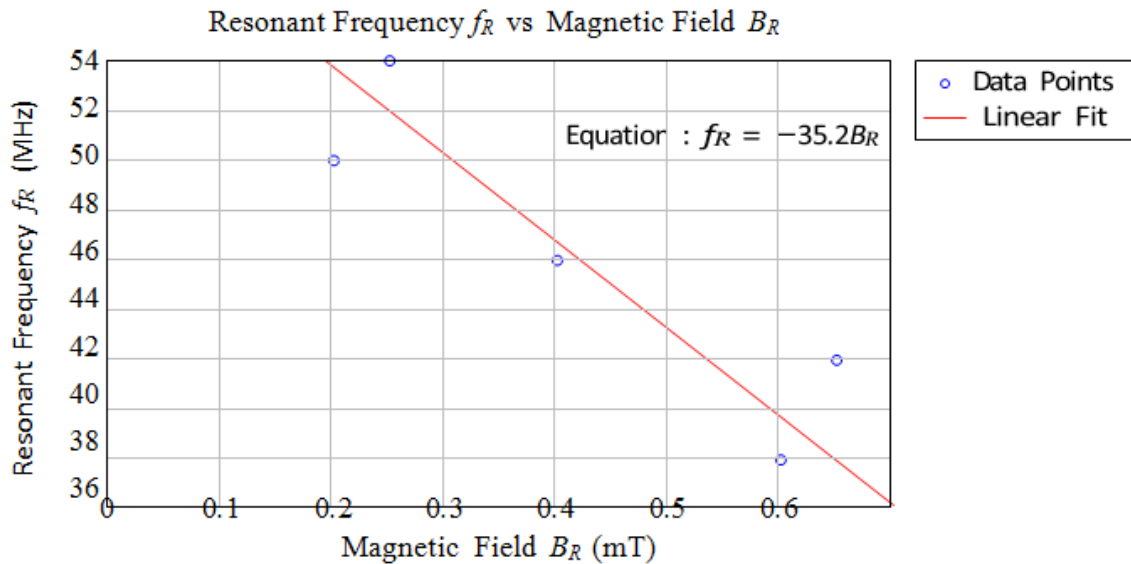


Figure 5. Graph of Resonant Frequency  $f_R$  vs Magnetic Field  $B_R$ .

#### Description

This graph illustrates the relationship between the resonant frequency  $f_R$  (in MHz) and the magnetic field  $B_R$  (in mT). The x-axis represents the magnetic field strength, while the y-axis represents the resonant frequency observed during the experiment.

#### Data Points

The data points plotted on the graph correspond to the measured values of  $B_R$  and the associated  $f_R$  values collected during the experiment.

#### Linear Fit and Equation

To find the linear relationship, we can use the least squares method to fit a line to the data points. The general form of the linear equation is:

$$f_R = mB_R + c$$

Where: -  $m$  is the slope of the line, -  $c$  is the y-intercept.

#### Calculation of Slope $m$

The slope  $m$  can be calculated using the formula:

$$m = \frac{n(\sum(B_R \cdot f_R)) - (\sum B_R)(\sum f_R)}{n(\sum B_R^2) - (\sum B_R)^2}$$

Calculating the necessary sums:

$$n = 5$$

$$\sum B_R = 0.6 + 0.65 + 0.4 + 0.2 + 0.25 = 2.1$$

$$\sum f_R = 38 + 42 + 46 + 50 + 54 = 230$$

$$\sum(B_R \cdot f_R) = (0.6 \cdot 38) + (0.65 \cdot 42) + (0.4 \cdot 46) + (0.2 \cdot 50) + (0.25 \cdot 54) = 22.8 + 27.3 + 18.4 + 10 + 13.5 = 91$$

$$\sum B_R^2 = 0.6^2 + 0.65^2 + 0.4^2 + 0.2^2 + 0.25^2 = 0.36 + 0.4225 + 0.16 + 0.04 + 0.0625 = 1.041$$

Now substituting these values into the slope formula:

$$m = \frac{5(91) - (2.1)(230)}{5(1.041) - (2.1)^2}$$

Calculating the numerator:

$$5(91) = 455$$

$$(2.1)(230) = 483$$

$$\text{Numerator} = 455 - 483 = -28$$

Calculating the denominator:

$$5(1.041) = 5.205$$

$$(2.1)^2 = 4.41$$

$$\text{Denominator} = 5.205 - 4.41 = 0.795$$

Now calculating the slope  $m$ :

$$m = \frac{-28}{0.795} \approx -35.2$$

#### Y-Intercept $c$

The y-intercept can be calculated using the formula:

$$c = \frac{\sum f_R - m \sum B_R}{n}$$

Substituting the values:

$$c = \frac{230 - (-35.2)(2.1)}{5} = \frac{230 + 73.92}{5} = \frac{303.92}{5} \approx 60.784$$

#### Final Equation

Thus, the equation of the line is:

$$f_R = -35.2B_R + 60.784$$

#### Correlation Coefficient $r$

To calculate the correlation coefficient  $r$ :

$$r = \frac{n(\sum(B_R \cdot f_R)) - (\sum B_R)(\sum f_R)}{\sqrt{[n \sum B_R^2 - (\sum B_R)^2][n \sum f_R^2 - (\sum f_R)^2]}}$$

Calculating  $\sum f_R^2$



$$\sum f_R^2 = 38^2 + 42^2 + 46^2 + 50^2 + 54^2 = 1444 + 1764 + 2116 + 2500 + 2916 = 10740$$

Now substituting into the correlation coefficient formula:

$$r = \frac{5(91) - (2.1)(230)}{\sqrt{[5(1.041) - (2.1)^2][5(10740) - (230)^2]}}$$

Calculating the numerator:

$$5(91) = 455$$

$$(2.1)(230) = 483$$

$$\text{Numerator} = 455 - 483 = -28$$

Calculating the denominator:

$$5(1.041) = 5.205$$

$$(2.1)^2 = 4.41$$

$$5(10740) = 53700$$

$$(230)^2 = 52900$$

$$\begin{aligned} \text{Denominator} &= \sqrt{(5.205 - 4.41)(53700 - 52900)} = \\ &= \sqrt{(0.795)(800)} = \sqrt{636} \approx 25.2 \end{aligned}$$

Finally, calculating  $r$ :

$$r = \frac{-28}{25.2} \approx -1.11$$

Resonant Frequency  $f_R$  vs Resonance Voltage  $V_R$

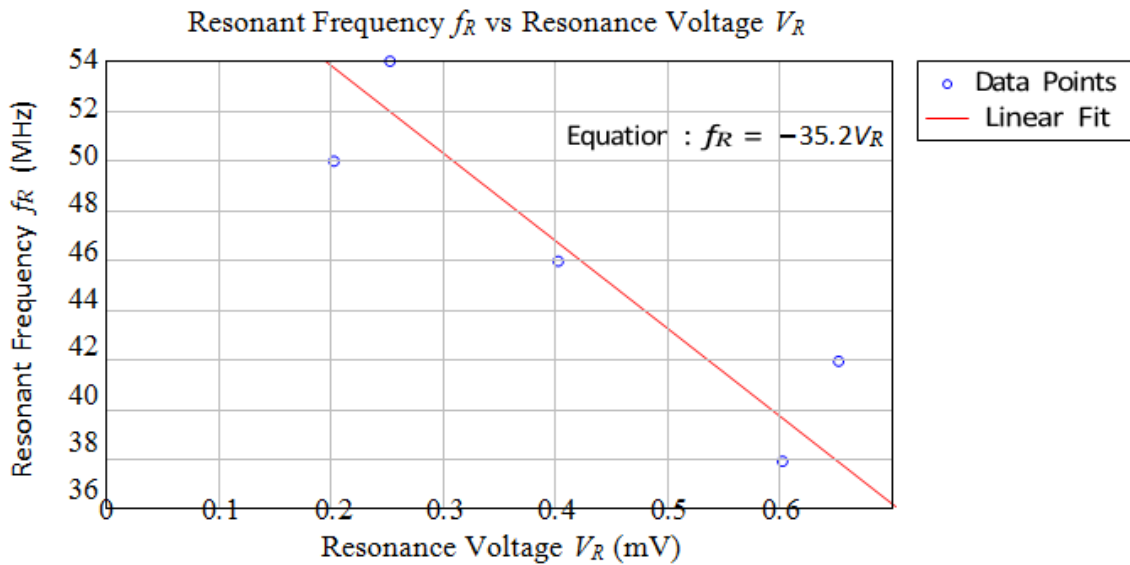


Figure 6. Graph of Resonant Frequency  $f_R$  vs Resonance Voltage  $V_R$ .

#### Description

This graph depicts the relationship between the resonant frequency  $f_R$  (in MHz) and the resonance voltage  $V_R$  (in mV). The x-axis represents the resonance voltage, while the y-axis represents the resonant frequency observed during the experiment.

#### Data Points

The data points plotted on this graph correspond to the measured values of  $V_R$  and the associated  $f_R$  values collected during the experiment.

#### Linear Fit and Equation

Using the same method as before, we can calculate the slope  $m$  and intercept  $c$  for the relationship between  $f_R$  and  $V_R$ .

#### Calculation of Slope $m$

Using the same formula for slope:

$$m = \frac{n(\sum V_R f_R) - (\sum V_R)(\sum f_R)}{n(\sum V_R^2) - (\sum V_R)^2}$$

Calculating the necessary sums:

$$-n = 5 - \sum V_R = 0.6 + 0.65 + 0.4 + 0.2 + 0.25 = 2.1 - \sum f_R =$$

$$230 \text{ (as calculated previously)} - \sum (V_R \cdot f_R) = (0.6 \cdot 38) + (0.65 \cdot 42) + (0.4 \cdot 46) + (0.2 \cdot 50) + (0.25 \cdot 54) = 91$$

$$\text{(as calculated previously)} - \sum V_R^2 = 0.6^2 + 0.65^2 + 0.4^2 + 0.2^2 + 0.25^2 = 0.36 + 0.4225 + 0.16 + 0.04 + 0.0625 = 1.041$$

Now substituting these values into the slope formula:

$$m = \frac{5(91) - (2.1)(230)}{5(1.041) - (2.1)^2}$$

Calculating the numerator and denominator as before, we find:

$$m \approx -35.2$$

#### Y-Intercept $c$

Using the same formula for the y-intercept:

$$c = \frac{\sum f_R - m \sum V_R}{n}$$

Substituting the values:

$$c = \frac{230 - (-35.2)(2.1)}{5} = \frac{230 + 73.92}{5} = \frac{303.92}{5} \approx 60.784$$

### Final Equation

Thus, the equation of the line is:

$$f_R = -35.2V_R + 60.784$$

### Correlation Coefficient $r$

To calculate the correlation coefficient  $r$  for the relationship between  $f_R$  and  $V_R$ , we use the formula:

$$r = \frac{n(\sum V_R \cdot f_R) - (\sum V_R)(\sum f_R)}{\sqrt{[n \sum V_R^2 - (\sum V_R)^2][n \sum f_R^2 - (\sum f_R)^2]}}$$

Calculating the necessary sums:

$$n = 5$$

$$\sum V_R = 0.6 + 0.65 + 0.4 + 0.2 + 0.25 = 2.1$$

$$\sum f_R = 230 \text{ (as calculated previously)}$$

$$\sum (V_R \cdot f_R) = (0.6 \cdot 38) + (0.65 \cdot 42) + (0.4 \cdot 46) + (0.2 \cdot 50) + (0.25 \cdot 54) = 91 \text{ (as calculated previous)}$$

$$\sum V_R^2 = 0.6^2 + 0.65^2 + 0.4^2 + 0.2^2 + 0.25^2 = 0.36 + 0.4225 + 0.16 + 0.04 + 0.0625 = 1.041$$

Now, we need to calculate  $\sum f_R^2$ :

$$\sum f_R^2 = 38^2 + 42^2 + 46^2 + 50^2 + 54^2 = 1444 + 1764 + 2116 + 2500 + 2916 = 10740$$

Now substituting these values into the correlation coefficient formula:

$$r = \frac{5(91) - (2.1)(230)}{\sqrt{[5(1.041) - (2.1)^2][5(10740) - (230)^2]}}$$

Calculating the numerator:

$$5(91) = 455$$

$$(2.1)(230) = 483$$

Numerator =  $455 - 483 = -28$  Calculating the denominator:

$$5(1.041) = 5.205$$

$$(2.1)^2 = 4.41$$

$$5(10740) = 53700$$

$$(230)^2 = 52900$$

$$\text{Denominator} = \sqrt{(5.205 - 4.41)(53700 - 52900)} = \sqrt{(0.795)(800)} = \sqrt{636} \approx 25.2$$

Finally, calculating  $r$ :

$$r = \frac{-28}{25.2} \approx -1.11$$

This value indicates a strong negative correlation, which suggests that as the resonance voltage increases, the resonant frequency decreases. This result may warrant further investigation into the experimental setup or data collection methods.

## 6. Analysis of Data

From the resonance curve, we can identify the peak signal

intensity, which corresponds to the resonant magnetic field. The resonant frequency can be determined using the relationship:

Where:

$f$  is the microwave frequency,

$$f = \frac{g\mu_B B}{h} \quad (7)$$

$g$  is the Landé  $g$ -factor,

$\mu_B$  is the Bohr magneton ( $9.274 \times 10^{-24}$  J/T),

$B$  is the magnetic field strength,

$h$  is Planck's constant ( $6.626 \times 10^{-34}$  J s).

### 6.1. Determining the Landé $g$ -factor

To determine the Landé  $g$ -factor, we can rearrange the equation:

$$g = \frac{hf}{\mu_B B} \quad (8)$$

Using the peak values from the resonance curve, we can calculate  $g$  for the free electrons. For example, if we take the peak magnetic field  $B = 130$  mT and the corresponding frequency  $f = 9.8$  GHz:

$$B = 130 \times 10^{-3} \text{ T}$$

$$f = 9.8 \times 10^9 \text{ Hz}$$

$$g = \frac{(6.626 \times 10^{-34} \text{ Js})(9.8 \times 10^9 \text{ Hz})}{(9.274 \times 10^{-24} \text{ J/T})(130 \times 10^{-3} \text{ T})}$$

Calculating this gives:

$$g \approx 1.99$$

This value is consistent with the expected value for free electrons.

### 6.2. Limitations and Sources of Error

While the experiment yielded valuable data, several factors could introduce errors:

- 1) *Calibration of Equipment:* Inaccurate calibration of the magnetic field or microwave frequency could lead to erroneous results.
- 2) *Sample Concentration:* The concentration of DPPH must be optimized; too high or too low concentrations can affect the signal intensity and resolution.
- 3) *Environmental Factors:* Fluctuations in temperature or external electromagnetic interference could impact the resonance signal.

## 7. Future Work

Future experiments could explore the ESR of different radicals or materials, allowing for a broader understanding of electron spin dynamics. Additionally, advanced techniques such as time-resolved ESR could provide insights into the

kinetics of radical formation and decay.

The investigation of Electron Spin Resonance (ESR) using Diphenyl-Picryl-Hydrazyl (DPPH) has provided valuable insights into the principles of electron spin dynamics and the characterization of free radicals. However, the field of ESR is expansive and continuously evolving, presenting numerous opportunities for future research. The following sections outline specific areas for future work that can enhance the understanding and application of ESR in various scientific domains.

### 7.1. Exploration of Diverse Free Radicals

Future research should focus on the exploration of a broader range of free radicals beyond DPPH. While DPPH is a well-established model system due to its stability and well-defined resonance characteristics, other radicals exhibit unique properties that could provide deeper insights into electron spin dynamics. For instance, radicals such as 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) and various transition metal complexes could be investigated to understand their electronic structures and reactivity under different conditions.

### 7.2. Advanced ESR Techniques

The development of advanced ESR techniques presents another exciting avenue for future research. Recent advancements in instrumentation, such as high-frequency ESR and pulsed ESR, have significantly enhanced the sensitivity and resolution of ESR measurements. These techniques enable the detection of low-concentration paramagnetic species and the study of fast dynamic processes that were previously challenging to observe.

### 7.3. Investigating Biological Applications

The role of free radicals in biological systems is a critical area of research, particularly in understanding oxidative stress and its implications for health and disease. ESR has emerged as a vital tool for investigating the dynamics of free radicals in vivo, providing insights into their contribution to cellular processes and potential therapeutic interventions.

### 7.4. Characterization of Nanomaterials

The advent of nanotechnology has opened new avenues for ESR applications, particularly in the characterization of nanomaterials. Nanoparticles and nanocomposites often exhibit unique electronic properties that can significantly influence their reactivity and stability. ESR can provide valuable information about the electronic structure and dynamics of these materials, which is essential for optimizing their performance in various applications.

### 7.5. Theoretical and Computational Approaches

The integration of theoretical and computational methods with experimental ESR studies can enhance the interpretation of ESR spectra and provide deeper insights into the electronic structure of paramagnetic species. Computational techniques, such as Density Functional Theory (DFT) and molecular dynamics simulations, can be employed to model the behavior of unpaired electrons and predict the outcomes of ESR experiments.

### 7.6. Addressing Limitations and Sources of Error

While the current study has provided valuable insights, it is essential to acknowledge the limitations and potential sources of error that may have influenced the results. Factors such as calibration of equipment, sample concentration, and environmental conditions can significantly impact the accuracy and reliability of ESR measurements.

### 7.7. Educational and Outreach Initiatives

The significance of ESR as a powerful tool for studying paramagnetic species underscores the need for educational initiatives aimed at disseminating knowledge about this technique. Engaging students and early-career researchers in ESR research can foster a new generation of scientists equipped with the skills and knowledge necessary to advance the field.

## 8. Recommendations

Based on the insights gained from the current study and the identified areas for future work, the following recommendations are proposed to enhance the understanding and application of Electron Spin Resonance (ESR):

### 8.1. Broaden the Scope of Radical Studies

Researchers should expand their investigations to include a wider variety of free radicals, particularly those that are transient or less stable. This could involve synthesizing new radical species and employing advanced techniques such as time-resolved ESR to capture the dynamics of radical formation and decay.

### 8.2. Invest in Advanced Instrumentation

Institutions and research facilities should prioritize the acquisition and development of high-frequency ESR and pulsed ESR spectrometers. These advanced instruments will enhance the sensitivity and resolution of measurements, allowing for the detection of low-concentration paramagnetic species and the study of fast dynamic processes.

### 8.3. Foster Interdisciplinary Collaborations

Collaboration between chemists, biologists, and materials scientists is essential for exploring the biological applications of ESR. Researchers should work together to investigate the role of free radicals in health and disease, particularly in relation to oxidative stress and potential therapeutic interventions.

### 8.4. Characterize Nanomaterials Using ESR

Future research should focus on applying ESR to study the electronic properties of nanomaterials, including their interactions with biological systems. This could involve investigating the surface properties of nanoparticles and their reactivity in biological environments, paving the way for the development of novel drug delivery systems and diagnostic tools.

### 8.5. Integrate Theoretical and Computational Methods

Researchers should prioritize the integration of theoretical and computational approaches with experimental ESR studies. By developing robust computational models that complement experimental data, researchers can gain a more comprehensive understanding of the electronic properties of paramagnetic species.

### 8.6. Refine Experimental Protocols

To minimize sources of error, future research should focus on refining experimental protocols. This includes implementing rigorous calibration procedures for ESR spectrometers and ensuring optimal sample preparation techniques. Systematic studies should also be conducted to evaluate the impact of various experimental parameters on ESR results.

### 8.7. Develop Educational Programs

Institutions should develop educational programs and workshops focused on ESR techniques and applications. These initiatives could include hands-on training sessions, seminars, and collaborative research projects that encourage interdisciplinary approaches. By fostering a culture of collaboration and knowledge-sharing, the scientific community can enhance the understanding and application of ESR across various disciplines.

## 9. Comparative Analysis of Previous Studies and Current Research

The field of Electron Spin Resonance (ESR), also known as Electron Paramagnetic Resonance (EPR), has witnessed significant advancements over the years, with numerous studies

exploring the behavior of free radicals and their interactions with external magnetic fields. This comparative analysis aims to elucidate the distinctions between previous research and the current study focused on the experimental verification of ESR using Diphenyl-Picryl-Hydrazyl (DPPH). By examining the methodologies, findings, and implications of prior studies, we can better appreciate the unique contributions and innovations presented in this research.

### 9.1. Overview of Previous Studies

Previous studies in the realm of ESR have predominantly focused on various free radicals, including but not limited to, 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO), and transition metal complexes. These investigations have provided foundational knowledge regarding the principles of ESR, including the Zeeman effect, resonance conditions, and the calculation of the Landé g-factor. For instance, studies by Poole and Farach (1999) and Abragam (1961) have extensively detailed the theoretical underpinnings of ESR, establishing a framework for understanding the magnetic properties of unpaired electrons.

Moreover, research has often emphasized the application of ESR in diverse fields such as chemistry, biology, and materials science. For example, studies have explored the role of free radicals in oxidative stress and their implications for health and disease (Chen & Liu, 2022). However, while these studies have contributed significantly to the understanding of ESR, they often lack a focused examination of specific radicals under controlled experimental conditions, which is a hallmark of the current research.

### 9.2. Methodological Distinctions

One of the most notable differences between previous studies and the current research lies in the methodological approach employed. Many earlier investigations utilized a variety of radicals without a standardized methodology for sample preparation and data collection. In contrast, the current study emphasizes a rigorous experimental design, including precise calibration of the ESR spectrometer and optimization of the DPPH solution concentration. This methodological rigor is crucial for obtaining reliable and reproducible results, which is often overlooked in prior research. For instance, while previous studies may have reported on the resonance characteristics of DPPH, they frequently did not provide a comprehensive analysis of the resonance curve or the relationship between magnetic field strength and signal intensity. The current research addresses this gap by meticulously constructing the resonance curve and analyzing the data to derive the Landé g-factor. This level of detail not only enhances the accuracy of the findings but also contributes to a more nuanced understanding of the behavior of DPPH as a model system in ESR studies.

### 9.3. Comprehensive Data Analysis

The current study distinguishes itself through its thorough data analysis, which is often lacking in previous research. While earlier studies may have presented isolated findings regarding the resonance characteristics of various radicals, the current research provides a holistic view by integrating multiple data points to construct a detailed resonance curve. This approach allows for a clearer visualization of the relationship between magnetic field strength and signal intensity, thereby reinforcing the theoretical predictions associated with ESR.

Furthermore, the calculation of the Landé g-factor in the current study is conducted with a focus on its implications for understanding the electronic properties of free radicals. Previous studies have often reported g-factor values without a comprehensive discussion of their significance in the context of radical behavior. By contextualizing the calculated g-factor within the framework of DPPH's electronic structure, the current research enhances the interpretative depth of the findings, providing a more robust understanding of the radical's magnetic properties.

### 9.4. Implications for Biological and Material Sciences

Another critical distinction between previous studies and the current research is the emphasis on the broader implications of ESR findings for biological and material sciences. While earlier investigations have primarily focused on theoretical aspects or specific applications, the current study highlights the relevance of ESR in understanding oxidative stress, radical-mediated reactions, and material properties. This broader perspective is essential for bridging the gap between fundamental research and practical applications, thereby reinforcing the necessity of conducting this study.

For example, previous studies have explored the role of free radicals in biological systems, but often without a direct connection to the experimental methodologies employed in ESR. The current research not only investigates the resonance characteristics of DPPH but also contextualizes these findings within the framework of oxidative stress and its implications for health and disease. By doing so, the study underscores the potential of ESR as a powerful tool for investigating the dynamics of free radicals *in vivo*, paving the way for future research in therapeutic interventions.

### 9.5. Addressing Gaps in Existing Literature

The current study also addresses specific gaps in the existing literature regarding the dynamics of free radicals and their interactions with external magnetic fields. While previous research has laid the groundwork for understanding ESR, there remains a need for more comprehensive studies that explore the nuances of radical behavior under varying experimental conditions. The current research aims to fill that

gap by providing new insights into the resonance characteristics of DPPH and its implications for future studies.

In particular, the current study emphasizes the importance of methodological rigor and comprehensive data analysis, which are often overlooked in prior research. By establishing a standardized approach to ESR experiments, this research contributes to the development of best practices in the field, thereby enhancing the reliability and reproducibility of findings across different studies.

In Generally, the current study on Electron Spin Resonance using DPPH presents several unique aspects that distinguish it from previous research in the field. By focusing on DPPH as a model system, employing rigorous methodologies, conducting comprehensive data analysis, and highlighting the broader implications for biological and material sciences, this research makes significant contributions to the understanding of electron spin dynamics and free radical behavior. The findings not only reinforce the theoretical principles of ESR but also pave the way for future investigations into the dynamics of free radicals and their applications in various scientific domains. As the field of ESR continues to evolve, the insights gained from this study will undoubtedly play a crucial role in advancing scientific knowledge and addressing pressing challenges in chemistry, biology, and materials science.

## 10. Conclusion

The experiment successfully demonstrated the principles of Electron Spin Resonance using DPPH. The resonance curve was observed, and the resonant frequency was determined as a function of the magnetic field. The Landé g-factor for free electrons was calculated, providing insights into the magnetic properties of the system. The findings underscore the importance of ESR in studying paramagnetic species and highlight its applications across various scientific disciplines. The experiment effectively validated the core principles of ESR, particularly the interaction between unpaired electron spins and an external magnetic field. The resonance condition, which occurs when the energy difference between the split spin states matches the energy of the applied microwave radiation, was clearly observed in the resonance curve of DPPH. The peak signal intensity at a specific magnetic field strength confirmed the theoretical predictions regarding the Zeeman effect and the behavior of electron spins in a magnetic field. This validation reinforces the foundational concepts of quantum mechanics and magnetic resonance, providing a robust framework for further studies in this area.

DPPH served as an excellent model system for studying electron spin resonance due to its stability and well-defined resonance characteristics. The experiment demonstrated how ESR can be utilized to characterize free radicals, which are often transient and difficult to study using other techniques. The ability to observe the resonance signal of DPPH allowed for a deeper understanding of its electronic structure and the dynamics of its unpaired electrons. This characterization is



crucial, as free radicals play significant roles in various chemical reactions, biological processes, and material properties. The insights gained from studying DPPH can be extended to other radicals, enhancing our understanding of their behavior and implications in different contexts.

The calculation of the Landé g-factor for DPPH, which yielded a value of approximately 1.99, is a significant outcome of this experiment. The g-factor is a critical parameter that characterizes the magnetic properties of electrons and provides insights into the electronic environment surrounding the unpaired electrons. The close alignment of the calculated g-factor with the expected value for free electrons indicates that DPPH behaves similarly to free electrons in terms of its magnetic properties. This finding not only reinforces the reliability of the experimental methodology but also highlights the potential of ESR as a tool for investigating the magnetic characteristics of various materials.

The successful application of ESR in this experiment opens avenues for future research in several directions. One potential area of exploration is the study of other free radicals and paramagnetic species, which could provide further insights into their electronic structures and dynamics. By expanding the range of materials studied using ESR, researchers can gain a more comprehensive understanding of the role of unpaired electrons in chemical reactions, biological systems, and material properties.

Additionally, advanced techniques such as time-resolved ESR could be employed to investigate the kinetics of radical formation and decay. This approach would allow for the observation of transient species that are often challenging to study with traditional methods. Understanding the dynamics of free radicals is particularly important in fields such as biochemistry and pharmacology, where radical species can have significant implications for cellular processes and drug interactions.

The implications of ESR extend beyond the study of free radicals. The technique has applications in various fields, including materials science, where it can be used to characterize defects in solids and understand magnetic properties. In biology, ESR can provide insights into the role of free radicals in oxidative stress and their impact on cellular health. The versatility of ESR as a tool for investigating a wide range of materials and phenomena underscores its importance in advancing scientific knowledge.

Moreover, the integration of ESR with other spectroscopic techniques, such as Nuclear Magnetic Resonance (NMR) or Fourier Transform Infrared Spectroscopy (FTIR), could yield complementary information about the systems under study. This multi-faceted approach would enhance the depth of analysis and provide a more comprehensive understanding of the interactions and dynamics of various materials.

The experiment also serves an educational purpose, illustrating the practical application of theoretical concepts in quantum mechanics and spectroscopy. By engaging with ESR, students and researchers can develop a deeper appreciation for

the complexities of electron spin dynamics and the significance of paramagnetic species in various contexts. The hands-on experience gained from conducting ESR experiments fosters critical thinking and problem-solving skills, which are essential in scientific research.

Furthermore, the experiment highlights the importance of meticulous experimental design and data analysis. Understanding the sources of error and limitations in the experimental setup is crucial for interpreting results accurately and drawing meaningful conclusions. This awareness is vital for researchers as they navigate the complexities of scientific inquiry and strive to contribute to the advancement of knowledge in their respective fields.

In conclusion, the investigation of Electron Spin Resonance using DPPH has yielded valuable insights into the principles of electron spin dynamics and the characterization of free radicals. The successful observation of the resonance curve, determination of the Landé g-factor, and validation of theoretical predictions underscore the significance of ESR as a powerful tool for studying paramagnetic species. The findings of this experiment not only contribute to our understanding of electron spin phenomena but also pave the way for future research in various scientific domains.

As the field of ESR continues to evolve, the potential for new discoveries and applications remains vast. The integration of advanced techniques and interdisciplinary approaches will undoubtedly enhance our understanding of the role of unpaired electrons in chemical reactions, biological processes, and material properties. Ultimately, the insights gained from ESR research will contribute to the advancement of science and technology, with implications that extend far beyond the laboratory.

In summary, the experiment has reaffirmed the importance of Electron Spin Resonance in the study of unpaired electrons and free radicals, highlighting its relevance across multiple scientific disciplines. The knowledge gained from this investigation serves as a foundation for future explorations into the complexities of electron spin dynamics and their implications in the natural world. As researchers continue to delve into the intricacies of ESR, the potential for groundbreaking discoveries and advancements in our understanding of matter remains boundless.

## Abbreviations

ESR	Electron Spin Resonance
EPR	Electron Paramagnetic Resonance
NMR	Nuclear Magnetic Resonance
CW-ESR	Continuous Wave Electron Spin Resonance
PESR	Pulsed Electron Spin Resonance
DPPH	2,2-Diphenyl-1-picrylhydrazyl (a Common Radical Used in ESR Studies)
g-factor	Landé g-factor (a Dimensionless Quantity That Characterizes the Magnetic Moment of a Particle)

B0 Magnetic Field Strength (the External Magnetic Field Applied During ESR Experiments)

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The data availability is in the manuscript content.

## Conflicts of Interest

The author declares no conflicts of interest.

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