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# Electron paramagnetic resonance

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# 1 Motivation

The motivation of this experiment is to determine the magnetic moment caused by the spin of a free electron and their gyromagnetic ratio. Diphenylpikrylhydracyl is a sample which offers free electrons. Methods of high frequency spectroscopy are used for this purpose: The experimental conditions are varied until a resonance absorption of the electrons occurs. With the resonance condition it is possible to determine the magnetic moment.

# 2 Theory

Electrons without orbital angular momentum still have a magnetic moment. This is not compatible with classical physics and can only be explained by quantum physics. According to quantum physics electrons have a kind of inner orbital angular momentum, called spin.

## 2.1 Realtionship between magnetic moment and orbital angular momentum

First of all, based on the consideration that the wave function for an atom in the one-electron approximation can be represented as

$$\psi_{n,l,m}(r,\vartheta,\varphi) = R_{n,l}(r)\theta_{l,m}(\vartheta)\phi(\varphi) = \frac{R_{n,l}(r)\theta_{l,m}\mathrm{e}^{im\varphi}}{\sqrt{2\pi}}, \tag{1}$$

a relationship between the orbital angular momentum and the magnetic moment can be found.

$$\mu_B = -\frac{e_0\hbar m}{2m_0} \tag{2}$$

$m\hbar$ is the orbital angular momentum and $\mu_B$ is the product of the natural constants, called Bohr Magneton.

## 2.2 Splitting of the energy levels in an external magnetic field

If an external magnetic field is applied, the energy levels of an eletron are split (Zeeman Effect). The spin quantum number is calculated as then according to

$$2s + 1 = 2 \tag{3}$$

This is due to the fact that the components of a vector are at most equal to their amount, the Orientation quantum number $m$ only assume the following values:

$$m = 0, \pm 1, \pm 2, ..., \pm l \tag{4}$$

So there are only $2l + 1$ settings for the Orientation quantum number $m$, where $l$ is the orbital angular momentum. Therefore, the following relationship applies to the Z-component of the spin:

$$S_Z = m_s\hbar = \pm\frac{\hbar}{2}. \tag{5}$$

The magnetic moment $\mu$ of the spin is then

$$\mu_{S_Z} = -\frac{g \cdot \mu_B}{2}. \tag{6}$$

$g$ is referred to as the gyromagnetic ratio and may assume a value other than 1.

### 2.3 Electron Paramagnetic Resonance

The Electron Paramagnetic Resonance method is used to determine the gyromagnetic ratio $g$. This ratio describes how the spin-caused magnetic moment differs from the magnetic moment caused by the orbital angular momentum. With an external magnetic field, the energy of a free electron is converted into two sub-levels, where the energy difference between the two levels is

$$\Delta E = g\mu_B B. \tag{7}$$

If now energy, which corresponds to the energy difference $\Delta E$, is supplied to the system in form of light quanta, then 7 results to

$$h\nu = g\mu_B B. \tag{8}$$

The electrons on the lower energy level are now able to absorb the energy, switch their spin and therefore reach the higher energy level. This is called Electron Paramagnetic Resonance. The excited electrons do not remain on that higher level, but dispense the additional energy in complicated ways to their surroundings. It is possible to measure

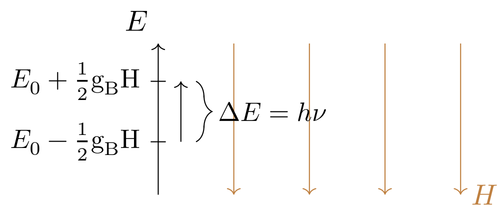


**Figure 1:** Energy level of free electrons split into two by an external magnetic field $H$. $\Delta E$ can be modified by varying $H$.

this effect by placing a sample into a coil of a bridge circuit and inducing a homogeneous magnetic field by a Helmholtz coil. If now a high frequency voltage produces a high frequency magnetic field in the sample-coil, the transition shown in figure 1 is induced which causes a change of the magnetism of the sample. As a consequence this change of magnetism becomes visible as a change of the bridge voltage, that has been balanced without the homogenous magnetic beforehand.

The magnetic field of a Helmholtz coil can be determined with

$$B(I) = \frac{8\mu_0 n I}{\sqrt{125} \cdot r} \tag{9}$$

where $\mu_0$ is the vacuum permeability. A high-frequency voltage is applied to the bridge circuit. When the bridge voltage is measured as a function of a changing current (the one inducing the homogenous magnetic field in the Helmholtz coil) one of two possible graphs shown in figure 2 can be seen on a connected oscilloscope.

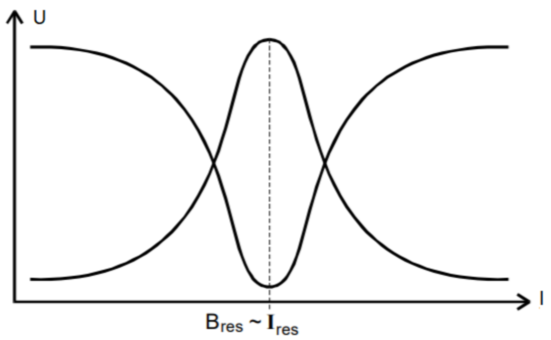


**Figure 2:** Possible Measurements of the Electron Paramagnetic Resonance. [1]

# 3 Execution

The first step is to set up the apparatus according to Figure 3. The frequency of the supply voltage for the bridge circuit should meet the condition

$$\nu_{OSC} + \nu_{ZF} = \nu_e. \tag{10}$$

where $\nu_{OSC}$ is produced by a separate oscillator and $\nu_e$ is the beat frequency. It is necessary to regulate the initiate frequency down to make it measurable. In addition the selective amplifier is adjusted precisely to $\nu_e$ and therefore takes the biggest part in amplification and suppressing other frequencies. Furthermore a demodulator rectifies and smoothes the voltage to make it measurable. While $\nu_{ZF} = 552\,\mathrm{Hz}$, $\nu_{OSC}$ can be set to fixed values and $\nu_e$ can be adjusted accordingly.

The superheterodyne receiver is now adjusted by slowly increasing the ZF-amplifier until a voltage is visible. The preamplifier is then set up so that the output voltage becomes maximum. Then the bridge is adjusted. Then this process is repeated until the maximum ZF-gain is reached. Then the ramp generator is switched on. A resonance curve should now be visible, which is recorded by the XY recorder. The required current for the resonance can be read from the drawing and thus the gyromagnetic ratio of

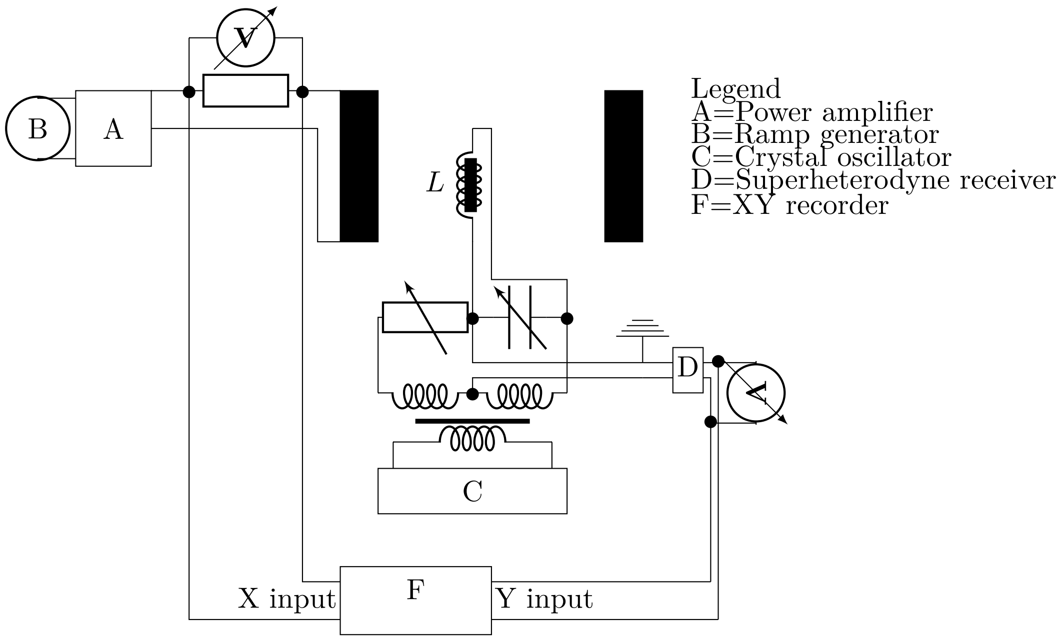


**Figure 3:** Measurement setup of the electron spin resonance method. The Helmholtz coil generates an external field proportional to the fed-in ramp voltage. The change of the complex resistance of the coil with the sample leads to a change of the bridge voltage, which is fed with a high frequency voltage.

the sample can be determined according to the formula 8. The magnetic field can be determined with formula 9.

# 4 Evaluation

Formula 8 can be converted to g:

$$g = \frac{h\nu}{B\mu_B} \tag{11}$$

with $h = 6.626070040 \cdot 10^{-34}\,\mathrm{J\,s}$ [3] and $\mu_B = 927.4009994 \cdot 10^{-26}\,\mathrm{J/T}$ [2]. The values can be taken from Table 1. The error is determined by the Gaussian distribution, since both $h$ and $\mu_B$ have errors:

$$\Delta g = \sqrt{\frac{\partial g}{\partial h} + \frac{\partial g}{\partial \mu_B}} \tag{12}$$

However, the error is $10^{-7}$ smaller than the value and can therefore be ignored. The

**Table 1:** Gyromagnetic ratio determined for different frequencies $\nu_e$ according to the electron spin resonance method. $x$ is the position of the resonance current on the XY recorder, $B$ is the magnetic field of the Helmholtz coil and the gyromagnetic ratio $g$ and the error $\Delta g$.

| $\nu_e$ / MHz | $x$ / cm | $B$ / mT | $g$ | $\Delta g$ |
|---|---|---|---|---|
| 29,448 | 15,5 | 1,09 | 1,94 | 0,00 |
| 29,448 | 14,0 | 0,98 | 2,14 | 0,00 |
| 23,888 | 11,4 | 0,80 | 2,13 | 0,00 |
| 23,888 | 12,8 | 0,90 | 1,90 | 0,00 |
| 14,798 | 7,4 | 0,52 | 2,04 | 0,00 |
| 14,798 | 8,4 | 0,59 | 1,79 | 0,00 |
| 19,448 | 10,4 | 0,73 | 1,90 | 0,00 |
| 19,448 | 9,0 | 0,63 | 2,20 | 0,00 |

average value is $(2,01 \pm 0,13)$. Compared with the literature value $2,00$ , there is a deviation from $0,5\%$.

# 5 Discussion

The discrepancy of the individual values for the gyromagnetic ratio can be explained by the interference voltage. The earth's magnetic field has already been taken into account by the use of two frequencies. The apparatus was carried out both in and against the direction of the earth's magnetic field. In view of the low voltages used, the precision of the measurement, which shows a deviation of 14%, is in order.

# References

[1] TU Dortmund. *Experiment instructions for the experiment 28.* [Online; as at 20.10.2018]. 2018. URL: `http://129.217.224.2/HOMEPAGE/Anleitung_FPMP.html`.

[2] National Institute of Standards and Technology. *Bohr magneton*. [Online; Stand 20.10.2018]. URL: `https://physics.nist.gov/cgi-bin/cuu/Value?mub`.

[3] National Institute of Standards and Technology. *Planck constant*. [Online; Stand 20.10.2018]. URL: `https://physics.nist.gov/cgi-bin/cuu/Value?h`.