V28

Elektronenspin-Resonanz

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Durchführung: 23.01.19 Abgabe: 31.01.19

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1 Objective

In this experiment the method of the electron spin resonance (ESR) is utilized to find out how the electron spin and the associated magnetic momentum are related. Furthermore, the Earth's magnetic field can be calculated.

2 Theory

The wave function of an atom approximately has the form

$$\Psi_{n,l,m}(r,\vartheta,\varphi) = \mathrm{R}_{n,l}(r)\Theta_{l,m}(\vartheta)\phi(\varphi).$$

The radial component R depends on the principal quantum number n and the quantum number l that describes the orbital angular momentum. The polar angle Θ is determined by l and the quantum number m for the magnetic orientation. The azimuth angle only denpends on m.

The current density

$$\vec{S} = \frac{\hbar}{2i\mathrm{m}_0}\left(\Psi^*\nabla\Psi - \Psi\nabla\Psi^*\right)$$

causes a magnetic momentum which is influenced by the magnetic orientation and the Bohr magneton:

$$\mu_z = \mu_B \cdot m.$$

The Bohr magneton is a constant with the value $-\frac{1}{2}\frac{\mathrm{e}_0}{\mathrm{m}_0}\hbar$.

If an elctron with an angular momentum enters a homogenous outer magnetic field it can take the energy values

$$E = E_0 + \mu_z B = E_0 + m\mu_B B.$$

Since m can take the values $m = 0, \pm 1, \pm 2, ..., \pm l$ and l is a non-negative integer the energy level can be split into $2l+1$ levels (shown in figure 1) which is called Zeeman effect.

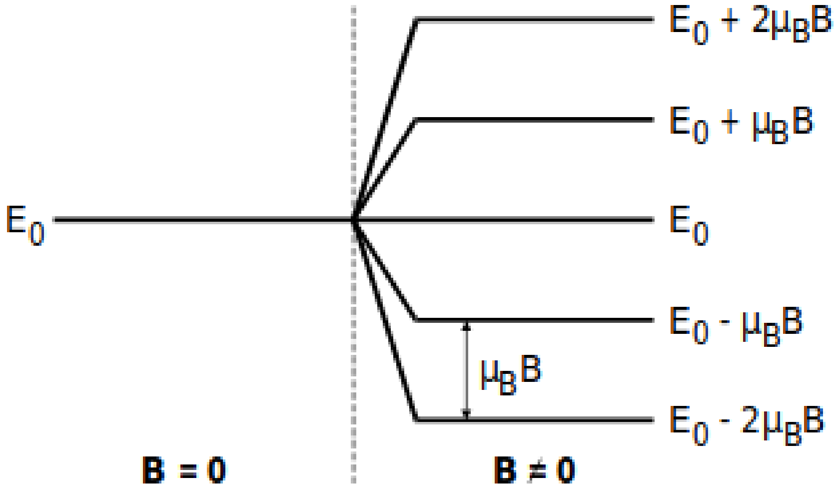

Abbildung 1: Split of the energy level of an electron due to the Zeeman effect [1].

The Stern Gerlach experiment shows the split of an electron beam in an inhomogenous magnetic field although the electrons do not have an orbital angular momentum. Thus, the quantum number $m_s = \pm\frac{1}{2}$ is introduced. It characterizes the spin which is the angular momentum of the electrones themselves and can take the values $\pm\frac{1}{2}\hbar$ in its z-component.
The spin also causes a magnetic moment similar to the orbital angular momentum:

$$\mu_{Sz} = -gm_s\mu_B.$$

The Lande-factor g is a constant that shows how the product of spin quantum number and Bohr magneton is connected to the magnetic moment.
If an electron with a spin enters an outer homogenous magnetic field the energy splits into to levels (spin-up and spin-down):

$$E = E_0 \pm \frac{1}{2}g\mu_B B.$$

The distance of these two levels is $\Delta E = g\mu_B B$.
Due to the Maxwell Boltzmann statistics there are more electrons in the spin-down state than in the spin-up state when there is an equilibrium. This fact can be used to measure the g factor. When a photon with the energy $h\nu = g\mu_B B$ meets a spin-down electron it can be absorbed and thus the spin is flipped from down to up. If this happens to several electrons this effect can be measured on a macroscopic scale. When there is a source of photons that all have the same frequency and the power of the magnetic field is known g can be easily calculated if the resonance frequency at which the electrons flip is found.

3 Setup

The needed free elctrons come from a substance called diphenylpicrylhydracyl. Most of its electrons are connected in pairs of electrons which compensate each others' spins. However, there is one free electron in each molecule which has a spin that is not neutralized and an angular momentum that can be neglected since it is not there if it is averaged over time. Thus, the electrons of the substance can be assumed as free electrons with spin and no l. The sample is in a Helmholtz coil that can create a homogenous magnetic field (figure 2).

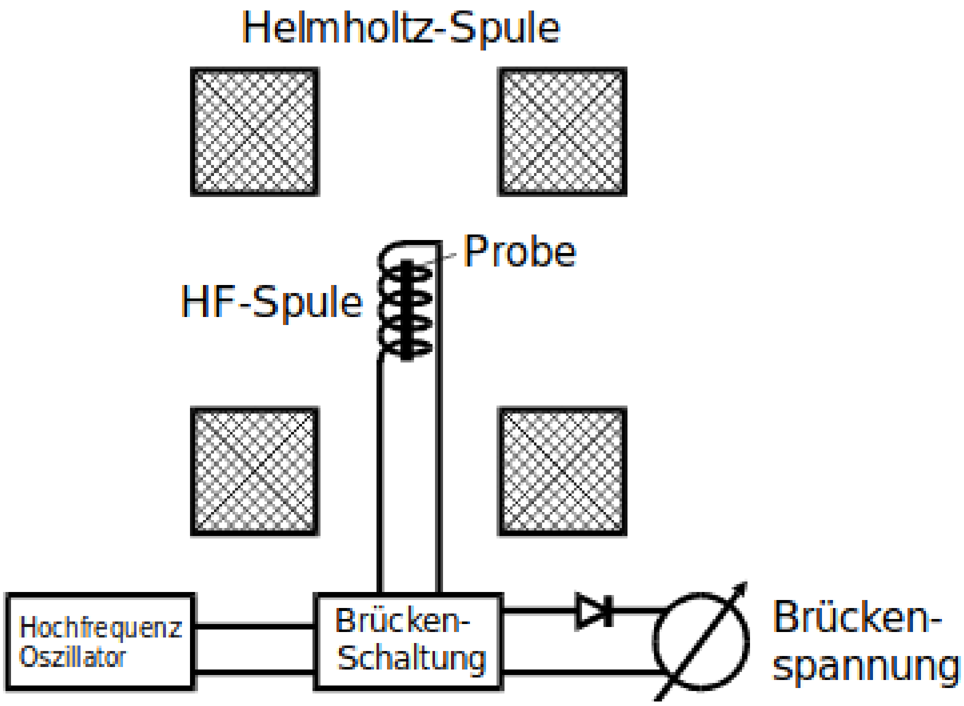

Abbildung 2: Sample within bridge circuit [1].

When the field is changed the magnetization of the sample changes as well. The sample is wrapped with a high frequency coil that is part of a bridge circuit and gets its power from a high frequency oscillator. The bridge circuit can be adjusted with the elements C_{grob}, C_{fein} and R. A change in magnetization of the sample leads to a change in the resistance of the high frequency coil and thus causes the bridge voltage to change what can be measured by a voltmeter.
There are some more elements needed in order to amplify the current and suppress unwanted side effects. The full circuit can be seen in figure 3.

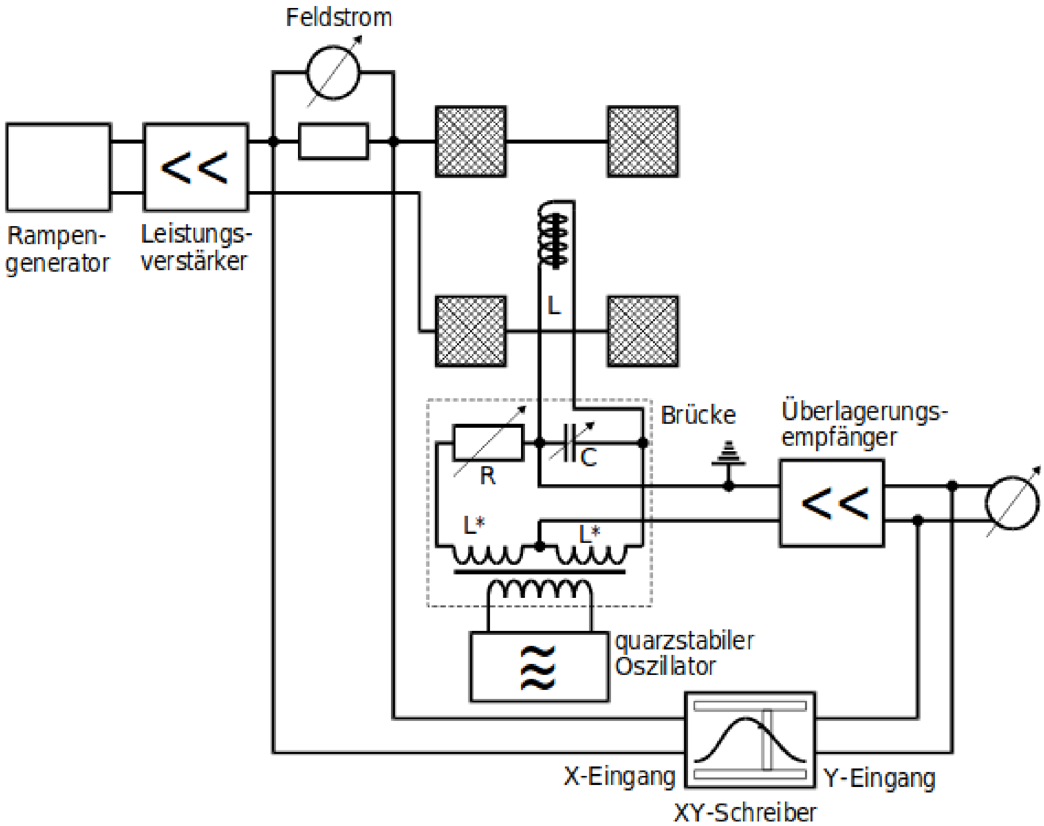

Abbildung 3: Complete curcuit to measure the electron spin resonance [1].

The voltage of the bridge is enhanced by the amplifier which also cuts off some of the interference voltages. Most of the remaining interference voltages are suppressed by an overlap receiver that brings the signal and a voltage from an oscillograph together. Just the frequencies that are close to the amplified frequency cannot be suppressed. Because the signal was transformed to alternating voltage it has to be flattened and transformed to direct voltage by the demodulator. An oscilloscope shows the voltage so it can be checked whether the resonance point is found. Then the X-Y-writer is able to draw the resonance curve .

4 Implementation

At first the Helmholtz coil has to be adjusted so that its axis is parallel to the Earth's magnetic field. After that the signal frequency is set. The oscillator frequency has to be set to the difference of the signal frequency and the frequency of the ZF-amplifier. The preamplifier has to be at its maximum when the bridge is adjusted with the help of C_{grob}, C_{fein} and R until there is almost no voltage. After that the magnetic field has to be changed until a resonance point is found. This can be printed by the X-Y-writer.

Resonance points have to be found for four frequencies. For each frequency there has to be one measurment with the Helmholtz coil parallel and one with the Helmholtz coil antiparallel to the Earth's magnetic field to perceive its influence.

5 Analysis

In order to calculate the magnetic field of the earth and the g-factor of the electron, the drawn resonance curves will be analysed. The distance between the zero and the resonance point on the X-axis equals the applied current because a centimeter translates to 50 mA. Furthermore results the corresponding magnetic field B through equation **??**. Finally the results for the parallel and anti-parallel field direction are displayed in table 1 and 2.

Tabelle 1: Frequence ν, distance Δx, current I and the magnetic field B for the parallel orientation.

ν/MHz	Δx/cm	I/mA	B/µT
14,798	8,40	420,0	589,14
19,488	10,60	530,0	743,44
23,888	12,85	642,5	901,24
29,488	15,35	767,5	1076,58

Tabelle 2: Frequence ν, distance Δx, current I and the magnetic field B for the anti-parallel orientation.

ν/MHz	Δx/cm	I/mA	B/µT
14,798	7,10	355,0	497,96
19,488	9,85	492,5	690,84
23,888	12,05	602,5	845,13
29,488	13,90	695,0	974,89

The earths magnetic field will be calculated through the difference of the magnetic fields for the different orientation divided by two:

$$B_{\text{Earth}} = \frac{B_{\text{p}} - B_{\text{ap}}}{2} \tag{1}$$

The Values are displayed in table 3.

The following step will be the calculation of the mean value and the corresponding standard deviation. For that the package *Numpy* from *Python 3.6.6* will be used:

$$\bar{B}_{\text{Earth}} = (37 \pm 10)\,\mu\text{T} \tag{2}$$

Tabelle 3: The calculated values for the magnetic field of the earth

ν/MHz	B_{Earth}/µT
14,798	45,588
19,488	26,301
23,888	28,054
29,488	50,848

Considering the larger difference between the B_{Earth}-values in table 3, the mean $\bar{B}^*_{\text{Earth}}$ between only the first and last value will also be calculated:

$$\bar{B}^*_{\text{Earth}} = (48 \pm 2)\mu\text{T} \tag{3}$$

Next will be the estimation of the g-factor, which is calculated with

$$g = \frac{h\nu}{B\mu_{\text{B}}}. \tag{4}$$

The mean value results through the g-factors for different frequencies and field orientation as listed in table 4.

$$\bar{g} = 1{,}978 \pm 0{,}117 \tag{5}$$

Tabelle 4: The calculated values for the g-factor. The second column stands for the parallel orientation and the third column for the anti-parallel orientation.

ν/MHz	g_p	g_{ap}
14,798	1,795	2,123
19,488	1,869	2,011
23,888	1,894	2,019
29,488	1,954	2,158

6 Discussion

The final results and their theoretical value as well as a comparison between them are listed in table 5. Although the deviance of B_{Earth} is rather high, the theoretical value is still within the error. Comparatively, the theoretical value is not located within the error of B^*_{Earth}. Even though the deviation of the calculated g-factor is rather small, the theoretical value does also not lie within the error. In the first place could the adjustment of the bridge be a possible error source. The reason for that lies within the difficulty to find the resonance curves for the frequency 23,888 MHz. Additionaly does the wide drawing of the XY-Writer lead to imprecize locating of the resonance points.

Tabelle 5: The calculated values, the theoretical values and the deviation between them in percent.

	Calculations	Theorie	Deviation (percent)
B_{Earth}	$(37 \pm 10)\mu T$	$44\,\mu T$[2]	$14,32\%$
B^*_{Earth}	$(48 \pm 2)\mu T$	$44\,\mu T$[2]	$9,59\%$
g	$1{,}978 \pm 0{,}117$	$1,761$[3]	$12,32\%$

Literatur

[1] TU Dortmund. *Versuchsanleitung V28*. URL: `http://129.217.224.2/HOMEPAGE/PHYSIKER/BACHELOR/FP/SKRIPT/ESR.pdf` (besucht am 31. 01. 2019).

[2] *earth magnetic field*. URL: `http://www.biosensor-physik.de/biosensor/erdmagnetfeld.htm` (besucht am 31. 01. 2019).

[3] *gyromagnetic moment*. URL: `https://physics.nist.gov/cgi-bin/cuu/Value?gammae` (besucht am 31. 01. 2019).