



# F44 Zeeman Spectroscopy

## Short Report

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**Abstract** *The Zeeman effect is an atomic physics phenomenon that describes how spectral lines of an element are split when the magnetic moment of the atom is coupled to an external magnetic field. The aim of this experiment was to observe the normal Zeeman effect in cadmium and then to investigate the splitting of the spectral lines as a function of the magnetic field strength. In a second part of the experiment we determine the wavelength of the red cadmium line by using a Czerny Turner spectrometer. We also had to determine the spectral line of an unknown element, which unfortunately was not possible because we could not resolve it. In our measurement we determined only the wavelength  $\lambda_{\text{Cd}} = (643.8 \pm 2.9) \text{ nm}$ . In addition, the Bohr magneton  $\mu_B$  could be calculated from both test parts, for which we obtained the value  $\mu_B = (10.3 \pm 0.5) \times 10^{-24} \text{ J/T}$ .*

## 1. Introduction

The Zeeman effect was studied first in 1896 by the Dutch physicist Peter Zeeman when he observed the widening of the yellow D-lines of burning sodium between strong magnets. Later he found out that the widening of the lines was actually a division in up to 15 components.

The spectral lines of an element arise when an electron emits a photon at the transition between different energy levels, which wavelength depends on the energy difference of the energy levels. If a strong external magnetic field is applied, individual energy levels are changed by coupling the magnetic moment of the electron with the external magnetic field, which leads to a splitting of the spectral lines. A distinction is made between the normal Zeeman effect observed in the experiment and the anomalous Zeeman effect. These differ in the total spin  $S$  of the electron, which is  $S = 0$  at the normal Zeeman effect and  $S \neq 0$  at the anomalous Zeeman effect.

## 2. Theoretical Basics

### Normal Zeeman effect

To understand the basics of the Zeeman effect, we first assume that the magnetic moment of an electron  $I$  can be sufficiently described by Bohr's atomic model.

According to this model, the electron orbits the atomic nucleus as point mass  $m_e$  with velocity  $v$  and charge  $e$  at a distance  $r_B$ , the Bohr radius. Using this approximation, the orbital magnetic mo-

ment

$$\boldsymbol{\mu}_l = \frac{evr}{2} \cdot \mathbf{n} \quad (1)$$

is obtained.

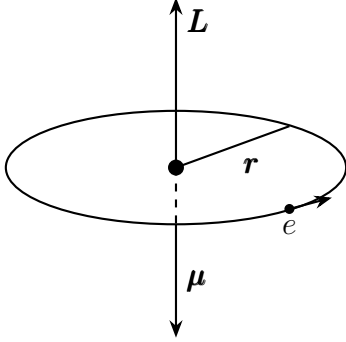


Figure 1: Bohr model of an electron with the angular momentum  $\mathbf{L}$  and the magnetic moment  $\boldsymbol{\mu}$

Thus  $\mathbf{n}$  is the normal vector, perpendicular to the disk on which the electron moves (see Fig. 1).

You can easily see that the magnetic moment resembles the angular momentum of the electron

$$\mathbf{l} = \mathbf{r} \times \mathbf{p} = m_e r v \cdot \mathbf{n}. \quad (2)$$

If an external magnetic field  $\mathbf{B}$  is applied, it interacts with the magnetic moment of the electron so that the energy level

$$\Delta E_{\text{pot}} = -\boldsymbol{\mu}_l \cdot \mathbf{B} = \frac{e}{2m_e} \cdot \mathbf{l} \cdot \mathbf{B} \quad (3)$$

changes.

Now the angular momentum of the electron along the magnetic field vector  $\mathbf{B}$  is quantized in the form

$$|\mathbf{l}| = \sqrt{l(l+1)}\hbar \quad (4)$$

with the quantum number  $l = 0, 1, \dots, n-1$  and the  $z$ -component

$$l_z = m_l \hbar, \quad (5)$$

which runs in the range  $-l \leq m_l \leq l$ .

This allows you to simplify the energy difference to

$$\Delta E_{\text{pot}} = \frac{e\hbar}{2m_e} m_l B = \mu_B m_l B, \quad (6)$$

where  $\mu_B$  describes the Bohr magneton we are looking for.

(1) Changing the energy level by  $\Delta E_{\text{pot}}$  causes the original energy level with angular momentum  $l$  to split into  $2l+1$  lower levels with the same angular momentum  $l$  but different  $m_l$  (see Fig. 2).

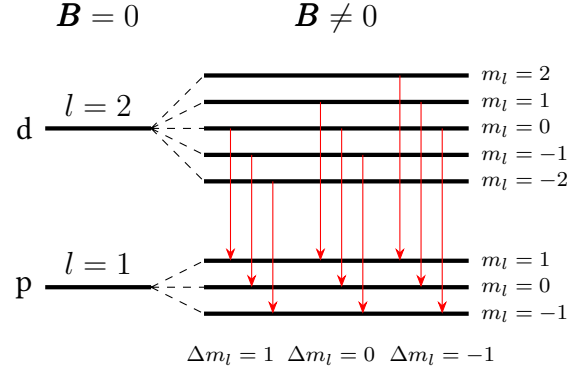


Figure 2: Schematic of the energy levels through the normal Zeeman effect

Alternatively, this equation can also be derived quantum mechanically. All spins and torques of the electrons of an atom are considered as individual sums, as well as the total spin  $\mathbf{J}$  required for the Hamilton operator in the external magnetic field.

This gives the equation

$$\Delta E_{\text{pot}} = \mu_B \cdot M_J \cdot B \cdot g_j \quad (7)$$

with the Landé factor  $g_j$ , which is one for the normal Zeeman effect we needed. The matrix element  $M_J$  that appears in the equation is explained again in the following section.

### Selection Rules and polarization of light

When an electron “jumps” between two electron shells  $E_i$  and  $E_k$ , it emits a photon with a wavelength  $\lambda$ , which depends on the energy difference of the electron shells

$$\frac{hc}{\lambda} = E_{\text{photon}} = \Delta E = E_i - E_k. \quad (8)$$

However, there are restrictions on which transitions are possible. Important for this is the dipole

matrix element

$$M_{ik} = e \int \psi_i^* \mathbf{r} \psi_k dV, \quad (9)$$

which describes the transition probability between the electron shells  $k$  to  $i$ . It must also have at least one component other than zero for a transition from  $k$  to  $i$  to be possible.

If we evaluate the integral in three spatial directions, we get the conditions

$$\Delta M_J = M_{J,i} - M_{J,k} = 0, \pm 1, \quad (10)$$

$$\Delta L = L_i - L_k = \pm 1, \quad (11)$$

$$\Delta S = 0. \quad (12)$$

Assuming the magnetic field vector  $\mathbf{B}$  points in the  $z$ -direction, only the matrix element  $(M_{ik})_z$  cannot become zero for  $\Delta M_J = 0$ . These transitions are called  $\pi$  transitions. These are equivalent to a dipole oscillating along the  $z$ -axis, which means that no radiation is emitted along the  $z$ -direction. In the other two directions, this oscillation of the dipole can be observed as linearly polarized light.

If  $\Delta M_J = \pm 1$ , we get  $\sigma$  transitions, for which the  $z$ -component of the dipole matrix becomes zero and the  $x$ - and  $y$ -components are not equal to zero, but phase shifted to each other by  $\pi/2$ . This causes us to observe circularly polarized light along the  $z$ -axis and linearly polarized light along the  $x$ - and  $y$ -axis.

The direction of observation along the  $z$ -axis is called longitudinal and for  $\Delta M_J = +1$  and  $\Delta M_J = -1$  circular polarized  $\sigma$ -lines should be visible. In contrast, linearly polarized  $\pi$ -lines should be observed in the transverse direction (perpendicular to the  $z$ -axis).

### 3. Measurements Log and Evaluation

#### First Part: Spectroscopy of the Zeeman effect

In the first part of the experiment, the Zeeman effect was investigated using the red cadmium line,

which is formed at the transition from  $^1D_2 \rightarrow ^1P_1$ .

To this end, it should first be examined whether a hysteresis effect occurs with the magnets used. For this purpose, three measurements were performed with a Hall probe each with increasing and decreasing field strength in the relevant range and the results for  $B_{inc}$  and  $B_{dec}$  were averaged. In Figure 3 you see the results of this measurement. You can see that there is a small difference

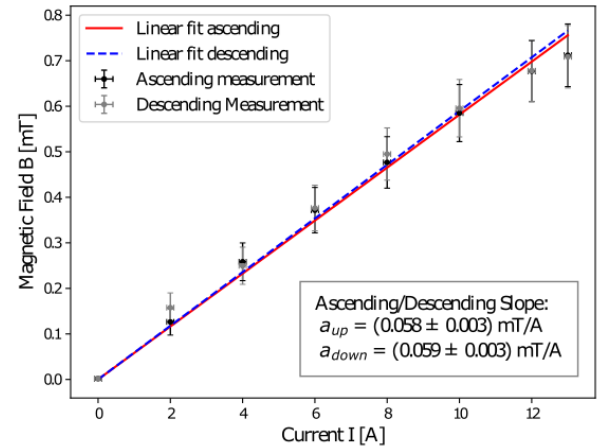


Figure 3: Comparison of the magnetic field strength with increasing and decreasing current strength

between the measurements, but the fit reveals that this difference is within the error, which is why in our case there is no significant effect.

Next, the Zeeman effect should be qualitatively investigated in longitudinal and transverse direction. For this purpose, we used the structure shown in figure 4. The most important element of this construction is the Lummer-Gehrcke plate with almost plane-parallel surfaces. If light enters the plate through a prism with an angle of incidence of  $\beta$ , it is reflected inside the plate. After each reflection some light is refracted at the surface, which is focused with the help of a lens and brought to interference.

If the path difference meets the conditions

$$\Delta = 2d\sqrt{n^2 - 1} = k\lambda \quad (13)$$

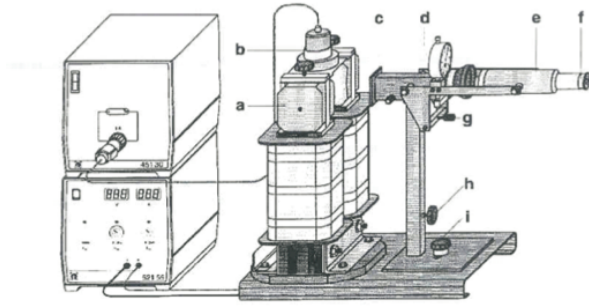


Figure 4: Experimental set-up: a) Pole pieces of the magnet, b) Cd lamp, c) Red light filter, d) Lummer-Gehrcke Plate, e) Telescope, f) Eyepiece, g) Height adjustment for the telescope, h) Locking screw for the telescope holder, i) Locking screw for the base plate. [2]

constructive interference with the gear difference  $\Delta = \Delta_1 - \Delta_2$ , the refractive index  $n = n_2$  and  $n_1 \approx 1$ , the thickness of the plate  $d$  and the interference order  $k$  is obtained. The reflection angle  $\alpha$  within the plate is assumed to be approximately  $90^\circ$ , resulting in near total reflection within the plate.

Our interference pattern of the Lummer-Gehrcke plate for a transversal image can be seen in Figure 5.

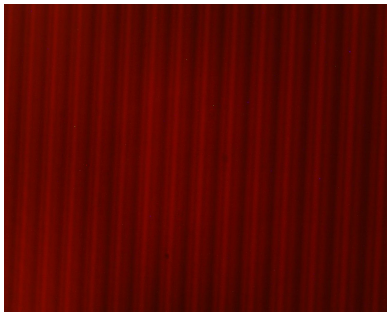


Figure 5: Zeeman effect in transverse direction at  $I = 13A$

## Second Part: Precision spectroscopy

### 4. Critical Comment

#### References

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