F44 Zeeman Spectroscopy

Short Report

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Abstract *The Zeeman effect is an atomic physics phenomen 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* $\lambda_{Cd} = (643.8 \pm 2.9)\,\mathrm{nm}$. *In addition, the Bohr magneton* μ_B *could be calculated from both test parts, for which we obtained the value* $\mu_B = (10.3 \pm 0.5) \times 10^{-24}\,\mathrm{J/T}$.

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 moment

$$\boldsymbol{\mu}_l = \frac{evr}{2} \cdot \boldsymbol{n} \tag{1}$$

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

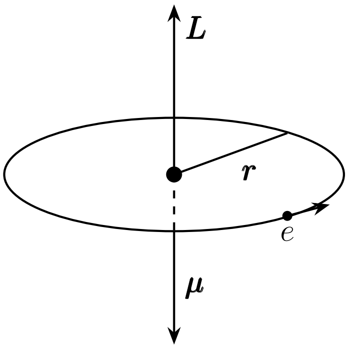

Figure 1: Bohr model of an electron with the angular momentum $\boldsymbol{L}$ and the magnetic moment $\boldsymbol{\mu}$

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

$$\boldsymbol{l} = \boldsymbol{r} \times \boldsymbol{p} = m_e r v \cdot \boldsymbol{n}. \tag{2}$$

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

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

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

$$|\boldsymbol{l}| = \sqrt{l(l+1)}\hbar \tag{4}$$

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

$$l_z = m_l \hbar, \tag{5}$$

which runs in the range $-l \le m_l \le l$.
This allows you to simplify the energy difference to

$$\Delta E_{\text{pot}} = \frac{e\hbar}{2m_e} m_l B = \mu_{\text{B}} m_l B, \tag{6}$$

where μ_B describes the Bohr magneton we are looking for.
Changing the energy level by ΔE_{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).

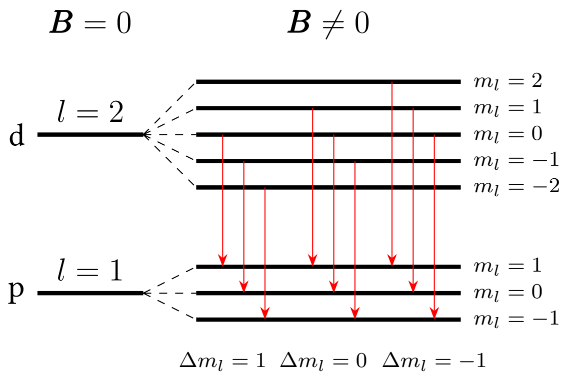

Figure 2: Schematic of the energy levels trough the normal Zeeman effect

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 $\boldsymbol{J}$ required for the Hamilton operator in the external magnetic field.
This gives the equation

$$\Delta E_{\text{pot}} = \mu_{\text{B}} \cdot M_J \cdot B \cdot g_j \tag{7}$$

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 λ, which depends on the energy difference of the electron shells

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

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

$$M_{ik} = e \int \psi_i^* \boldsymbol{r}\, \psi_k \, \mathrm{d}V \,, \tag{9}$$

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

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

$$\Delta L = L_i - L_k = \pm 1, \tag{11}$$

$$\Delta S = 0. \tag{12}$$

Assuming the magnetic field vector $\boldsymbol{B}$ points in the z-direction, only the matrix element $(M_{ik})_z$ cannot become zero for $\Delta M_J = 0$. These transitions are called π 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 σ 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 σ-lines should be visible.
In contrast, linearly polarized π-lines should be observed in the transverse direction (perpendicular to the z-axis).

3. Measurements Log and Evaluation

4. Critical Comment

References

[1] Wolfgang Demtröder. *Experimentalphysik 3. Atome, Moleküle und Festkörper.* ger. 5. Aufl. 2016. Springer-Lehrbuch. Berlin, Heidelberg: Springer Spektrum, 2016, Online–Ressource (XXI, 588 S. 740 Abb. in Farbe, online resource). ISBN: 978-3-662-49094-5. DOI: 10.1007/978-3-662-49094-5. URL: http://dx.doi.org/10.1007/978-3-662-49094-5.