Observing the normal Zeeman effect in transverse and longitudinal configuration

Spectroscopy with a Fabry-Perot etalon

Objects of the experiment
- Observing the line triplet for the normal transverse Zeeman effect.
- Determining the polarization state of the triplet components.
- Observing the line doublet for the normal longitudinal Zeeman effect.
- Determining the polarization state of the doublet components.

Principles
Normal Zeeman effect:

The Zeeman effect is the name for the splitting of atomic energy levels or spectral lines due to the action of an external magnetic field. The effect was first predicted by H. A. Lorenz in 1895 as part of his classic theory of the electron, and experimentally confirmed some years later by P. Zeeman. Zeeman observed a line triplet instead of a single spectral line at right angles to a magnetic field, and a line doublet parallel to the magnetic field. Later, more complex splittings of spectral lines were observed, which became known as the anomalous Zeeman effect. To explain this phenomenon, Goudsmit and Uhlenbeck first introduced the hypothesis of electron spin in 1925. Ultimately, it became apparent that the anomalous Zeeman effect was actually the rule and the “normal” Zeeman effect the exception.

The normal Zeeman effect only occurs at the transitions between atomic states with the total spin \( S = 0 \). The total angular momentum \( J = L + S \) of a state is then a pure orbital angular momentum \( J = L \). For the corresponding magnetic moment, we can simply say that:

\[
\mu = \frac{\mu_B J}{\hbar}
\]

(II)

where

\[
\mu_B = \frac{\hbar e}{-2 m_e}
\]

(III)

\( (m_B = \text{Bohr's magneton}, \ m_e = \text{mass of electron}, \ e = \text{elementary charge}, \ \hbar = \hbar/2\pi, \ h = \text{Planck's constant}). \)

In an external magnetic field \( B \), the magnetic moment has the energy

\[
E = -\mu \cdot B
\]

(III)

The angular-momentum component in the direction of the magnetic field can have the values

\[
J_z = M_J \cdot \hbar \quad \text{with} \quad M_J = J, J-1, ..., -J
\]

(IV)

Therefore, the term with the angular momentum \( J \) is split into \( 2J + 1 \) equidistant Zeeman components which differ by the value of \( M_J \). The energy interval of the adjacent components \( M_J, M_J+1 \) is

\[
\Delta E = \mu_B \cdot B
\]

(V)

We can observe the normal Zeeman effect e.g. in the red spectral line of cadmium \( \lambda_0 = 644 \text{ nm}, \ \omega_0 = 646 \text{ THz} \). It corresponds to the transition \( ^1D_2 (J = 2, S = 0) \rightarrow ^1P_1 (J = 1, S = 0) \) of an electron of the fifth shell (see Fig. 1). In the magnetic field, the \(^1D_2 \) level splits into five Zeeman components, and the level \(^1P_1 \) splits into three Zeeman components having the spacing calculated using equation (V).
Optical transitions between these levels are only possible in the form of electrical dipole radiation. The following selection rules apply for the magnetic quantum numbers $M_J$ of the states involved:

$$\Delta M_J = \begin{cases} 
\pm 1 & \text{for } \sigma \text{ components} \\
0 & \text{for } \pi \text{ components}
\end{cases} \quad \text{(VI)}$$

Thus, we observe a total of three spectral lines (see Fig. 1); the $\pi$ component is not shifted and the two $\sigma$ components are shifted by

$$\Delta f = \pm \frac{\Delta E}{\hbar} \quad \text{(VII)}$$

with respect to the original frequency. In this equation, $\Delta E$ is the equidistant energy split calculated in (V).

Angular distribution and polarization

Depending on the angular momentum component $\Delta M_J$ in the direction of the magnetic field, the emitted photons exhibit different angular distributions. Fig. 2 shows the angular distributions in the form of two-dimensional polar diagrams. They can be observed experimentally, as the magnetic field is characterized by a common axis for all cadmium atoms.

In classical terms, the case $\Delta M_J = 0$ corresponds to an infinitesimal dipole oscillating parallel to the magnetic field. No quanta are emitted in the direction of the magnetic field, i.e. the $\pi$ component cannot be observed parallel to the magnetic field. The light emitted perpendicular to the magnetic field is linearly polarized, whereby the $E$-vector oscillates in the direction of the dipole and parallel to the magnetic field (see Fig. 3).

Conversely, in the case $\Delta M_J = \pm 1$ most of the quanta travel in the direction of the magnetic field. In classical terms, this case corresponds to two parallel dipoles oscillating with a phase difference of 90°. The superposition of the two dipoles produces a circulating current. Thus, in the direction of the magnetic field, circularly polarized light is emitted; in the positive direction, it is clockwise-circular for $\Delta M_J = +1$ and anticlockwise-circular for $\Delta M_J = -1$ (see Fig. 3).

Spectroscopy of the Zeeman components

The Zeeman effect enables spectroscopic separation of the differently polarized components. To demonstrate the shift, however, we require a spectral apparatus with extremely high resolution, as the two $\sigma$ components of the red cadmium line are shifted e.g. at a magnetic flux density $B = 1 \, \text{T}$ by only $\Delta f = 14 \, \text{GHz}$, respectively $\Delta \lambda = 0.02 \, \text{nm}$. 

Connecting leads with conductor cross-section 2.5 mm²
In the experiment a Fabry-Perot etalon is used. This is a glass plate which is plane parallel to a very high precision with both sides being aluminized. The slightly divergent light enters the etalon, which is aligned perpendicularly to the optical axis, and is reflected back and forth several times, whereby part of it emerges each time (see Fig. 4). Due to the aluminizing this emerging part is small, i.e., many emerging rays can interfere. Behind the etalon the emerging rays are focused by a lens on to the focal plane of the lens. There a concentric circular fringe pattern associated with a particular wavelength $\lambda$ can be observed with an ocular. The aperture angle of a ring is identical with the angle of emergence $\alpha$ of the partial rays from the Fabry-Perot etalon.

The rays emerging at an angle of $\alpha_k$ interfere constructively with each other when two adjacent rays fulfil the condition for “curves of equal inclination” (see Fig. 4):

$$\Delta = 2d \cdot \sqrt{n^2 - \sin^2 \alpha_k} = k \cdot \lambda$$

(VIII)

($\Delta$ = optical path difference, $d$ = thickness of the etalon, $n$ = refractive index of the glass, $k$ = order of interference).

A change in the wavelength by $\delta \lambda$ is seen as a change in the aperture angle by $\delta \alpha$. Depending on the focal length of the lens, the aperture angle $\alpha$ corresponds to a radius $r$ and the change in the angle $\delta \alpha$ to a change in the radius $\delta r$. If a spectral line contains several components with the distance $\delta \lambda$, each circular interference fringe is split into as many components with the radial distance $\delta r$. So a spectral line doublet is recognized by a doublet structure and a spectral line triplet by a triplet structure in the circular fringe pattern.

**Setup**

The complete experimental setup in transverse configuration is illustrated in Fig. 5.

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**Fig. 4** Fabry-Perot etalon as an interference spectrometer. The ray path is drawn for an angle $\alpha > 0$ relative to the optical axis. The optical path difference between two adjacent emerging rays is $\Delta = n \cdot \Delta_1 - \Delta_2$.

**Fig. 5** Experimental setup for observing the Zeeman effect in transverse configuration. The position of the left edge of the optics riders is given in cm.

- **a** Cadmium lamp with holding plate
- **b** Clamps
- **c** Pole pieces
- **d** Positive lens, $f = 150$ mm (condenser lens)
- **e** Fabry-Perot etalon
- **f** Positive lens, $f = 150$ mm (imaging lens)
- **g** Colour filter (red) in holder
- **h** Ocular with line graduation
**Mechanical and optical setup:**

- Screw the threaded rod into the base of the rider.
- Put the U-yoke over the threaded rod on the base of the rider so that it is freely rotatable and put on the coils.
- Mount the pole pieces and the holding plate of the cadmium lamp using the clamps so that a distance of approx. 10 mm is left between the pole pieces and that the opening of the holding plate points to the back. Do not yet fasten the screws of the clamps.
- Cautiously insert the cadmium lamp between the pole pieces.
  
  See to it that the cadmium lamp is exactly in the middle of the pole pieces, that the point where the bulb is sealed off points to the back and that the supply leads are swivelled out of the ray path as far as possible.
- If necessary, reduce the distance between the pole pieces in order that later on a stronger magnetic field is available.
- Fix the pole pieces and the holding plate with the screws of the clamps.
- Mount the optical components according to Fig. 5.

**Electrical connection:**

- Connect the cadmium lamp to the universal choke; after switching on wait 5 min until the light emission is sufficiently strong.
- Connect the coils of the electromagnet in series and then to the high current power supply.

**Adjusting the observing optics:**

Remark: the optimum setup is achieved when the red circular fringe pattern is bright and contrasty with its centre on the line graduation. While adjusting do not yet insert the polarization filter and the quarter-wave plate in order that the observed image is as bright as possible.

- Focus the ocular at the line graduation.
- Move the imaging lens until you observe a sharply defined image of the circular fringe pattern.
- Move the condenser lens until the observed image is illuminated as uniformly as possible.
- Shift the centre of the circular fringe pattern to the middle of the line graduation by slightly tipping the Fabry-Perot etalon with the adjusting screws.

If the adjustment range does not suffice:

- Rotate the Fabry-Perot etalon with its frame or adjust the height of the imaging lens and the ocular to each other.
Carrying out the experiment

a) Observing in transverse configuration:
- First observe the circular fringe pattern without magnetic field ($I = 0$ A).
- Slowly enhance the magnet current up to about $I = 3$ A until the split fringes are clearly separated.

For the distinction between $\pi$ and $\sigma$ components:
- Introduce the polarization filter into the ray path (see Fig. 6), and set it to 90° until the two outer components of the triplet structure disappear.
- Set the polarization filter to 0° until the (unshifted) component in the middle disappears.

b) Observing in longitudinal configuration:
- Rotate the entire setup of the cadmium lamp with the pole pieces on the rider base with thread by 90°.
- First observe the circular fringe pattern without magnetic field ($I = 0$ A).
- Slowly enhance the magnet current up to about $I = 3$ A until the split fringes are clearly separated.

For the distinction between $\sigma^+$ and $\sigma^-$ components:
- Introduce a quarter-wavelength plate into the ray path between the cadmium lamp and the polarization filter (see Fig. 6), and set it to 0°.
- Set the polarization filter to $+45^\circ$ and $-45^\circ$. In each case one of the two doublet components disappears.

Measuring example and evaluation

a) Observing in transverse configuration: see Fig. 7

b) Observing in longitudinal configuration: see Fig. 8

Additional information
The total intensity of all Zeeman components is the same in all spatial directions. In transverse observation, the intensity of the $\pi$ component is equal to the total intensity of the two $\sigma$ components.