

## Observing the normal Zeeman effect in transverse and longitudinal configuration

### 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. Lorentz* 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:

$$\mu = \frac{\mu_B}{\hbar} J \quad (I)$$

where

$$\mu_B = \frac{\hbar e}{2m_e} \quad (II)$$

$\mu_B$  = Bohr's magneton,  $m_e$  = mass of electron,  $e$  elementary charge,  $\hbar$  = Planck's constant)

In an external magnetic field  $B$ , the magnetic moment has the energy

$$E = -\mu \cdot B \quad (III)$$

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

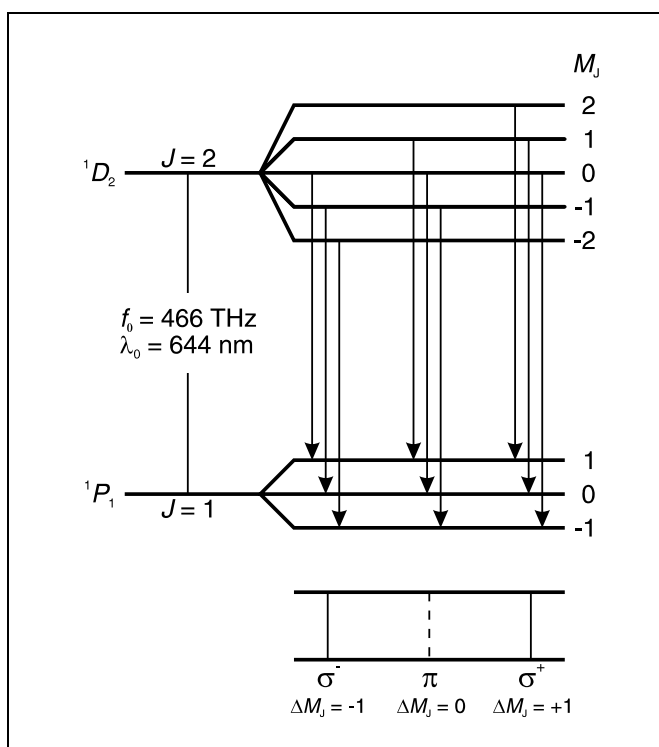
$$J_z = M_J \cdot \hbar \quad \text{mit } M_J = J, J-1, \dots, -J \quad (IV)$$

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

$$\Delta E = \mu_B \cdot B \quad (V)$$

We can observe the normal Zeeman effect e.g. in the red spectral line of cadmium ( $\lambda_0 = 643.8 \text{ nm}$ ,  $f_0 = 465.7 \text{ THz}$ ). 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).

Fig. 1: Level splitting and transitions of the normal Zeeman effect in cadmium



**Apparatus**

|   |        |
|---|--------|
| 1 Cadmium lamp for Zeeman effect . . . . .                    | 451 12 |
| 1 Optical system for observing<br>the Zeeman effect . . . . . | 471 20 |
| 1 Lummer-Gehrcke plate . . . . .                              | 471 21 |
| 1 Electromagnet for Zeeman effect . . . . .                   | 514 50 |

|  |        |
|--|--------|
| 1 Universal choke for 451 12 . . . . . | 451 30 |
| 1 High current power supply . . . . .  | 521 55 |

Connecting leads with conductor cross-section 2.5 mm<sup>2</sup>

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:

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

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

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

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

**Safety notes**

The electrical leads on the cadmium lamp and the resistors of the starting electrodes are open and easily accessible:

- Do not touch any current-carrying (live!) parts.

The *Lummer-Gehrcke* plate has been manufactured with great precision with regard to the parallelism and flatness of its surfaces.

- Do not mechanically stress the Lummer-Gehrcke plate by bending or in any other manner.
- Pick up the Lummer-Gehrcke plate only by the edges.
- When mounting the Lummer-Gehrcke plate, make sure that the plate is supported evenly in its holder over its entire length.
- Before transporting the apparatus, remove the Lummer-Gehrcke plate from its holder and store it in a safe place.

Loose ferromagnetic objects can be strongly attracted by the electromagnet and can damage the quartz bulb of the cadmium lamp.

- Check to make sure that the pole pieces are screwed tight before switching on the magnet current.
- When the magnet current is switched on, do not handle ferromagnetic objects in the vicinity of the cadmium lamp.

Deposits of skin secretions can destroy the quartz bulb of the cadmium lamp when it becomes hot.

- Never handle the quartz bulb of the cadmium lamp with your bare hands.

**Angular distribution and polarization**

Depending on the angular momentum component  $\Delta M_J$  in the direction of the magnetic field, the emitted photons demonstrate 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 counterclockwise-circular for  $\Delta M_J = -1$  (see Fig. 3).

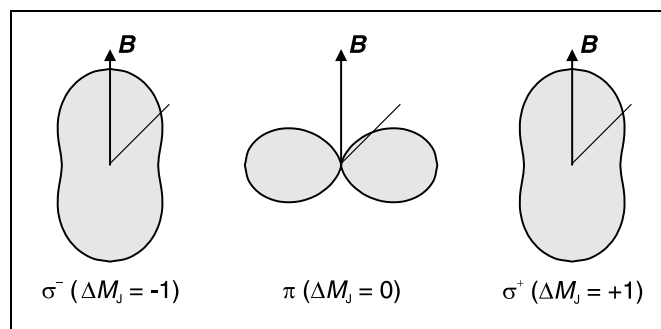


Fig. 2: Angular distributions of the electrical dipole radiation ( $\Delta M_J$ : angular-momentum components of the emitted photons in the direction of the magnetic field)

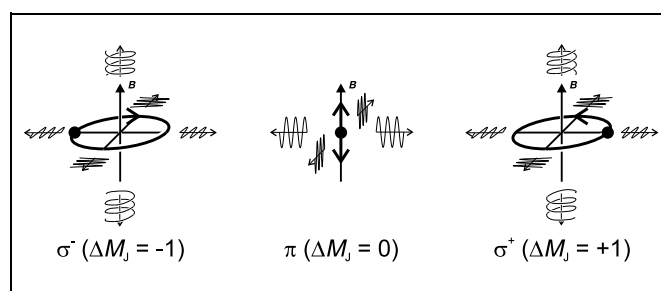
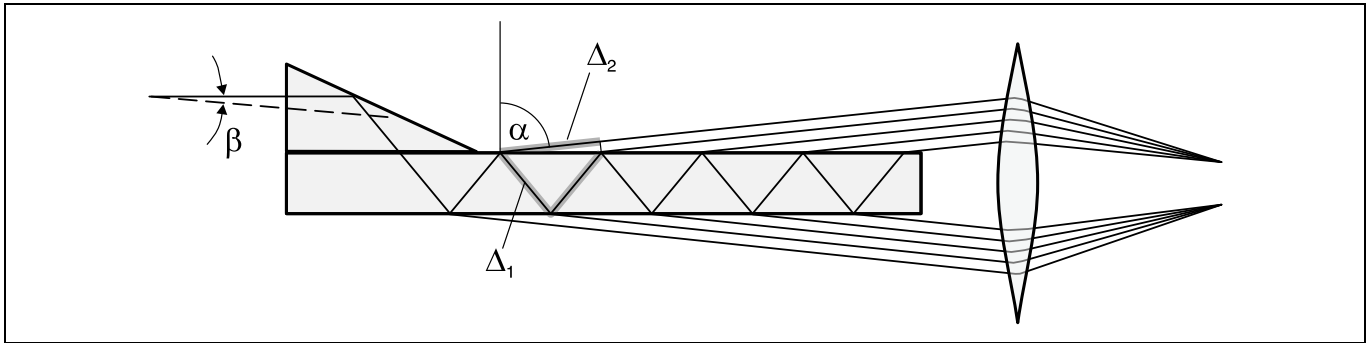


Fig. 3: Schematic representation of the polarization of the Zeeman components

**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  $B = 1$  T by only  $\Delta f = 14$  GHz, respectively  $\Delta \lambda = 0.02$  nm.

A *Lummer-Gehrcke* plate is used for this experiment. This component has been manufactured with great precision with respect to the parallelism and flatness of its surfaces. The light, which is divergent in the vertical direction, passes through a



horizontal slit via an attached prism into a long, plane-parallel glass plate (see Fig. 4). Inside this plate, the light is reflected back and forth repeatedly, with some part of it emerging each time. When observed at an angle of  $\alpha \approx 90^\circ$ , the reflection within the plate occurs almost completely within the limit angle of total reflection. The result is a high reflection coefficient, i.e. many of the rays can interfere with each other when the plate is long enough. The emerging waves are observed from behind the plate using a telescope focused on infinity. For a given wavelength  $\lambda$ , two mirror-image identical systems of horizontal lines can be observed above and below the plate. Each interference line can be assigned to one emerging angle  $\alpha$  of the component rays from the Lummer-Gehrcke plate and an angle of incidence  $\beta$  at the prism.

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

$$\Delta = 2d \cdot \sqrt{n^2 - \sin^2 \alpha_k} = k \cdot \lambda \quad \text{mit } k = 1, 2, 3, \dots \quad (\text{VIII})$$

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

A change in the wavelength by  $\delta\lambda$  appears as a shift in the interference lines by the angle  $\delta\alpha$ . If a spectral line contains multiple components with a distance  $\delta\lambda$ , each interference line is split into a corresponding number of components with the spacing  $\delta\alpha$ . It thus becomes possible to recognize a spectral-line doublet in a doublet structure and a spectral-line triplet in a triplet structure in the interference lines.

Fig. 4: Lummer-Gehrcke plate as an interference spectrometer (the beam path for the angle of incidence  $\beta = 0^\circ$  is drawn as a series of unbroken lines). The optical path difference between two adjacent emerging rays is  $\Delta = n\Delta_1 - \Delta_2$

## Setup

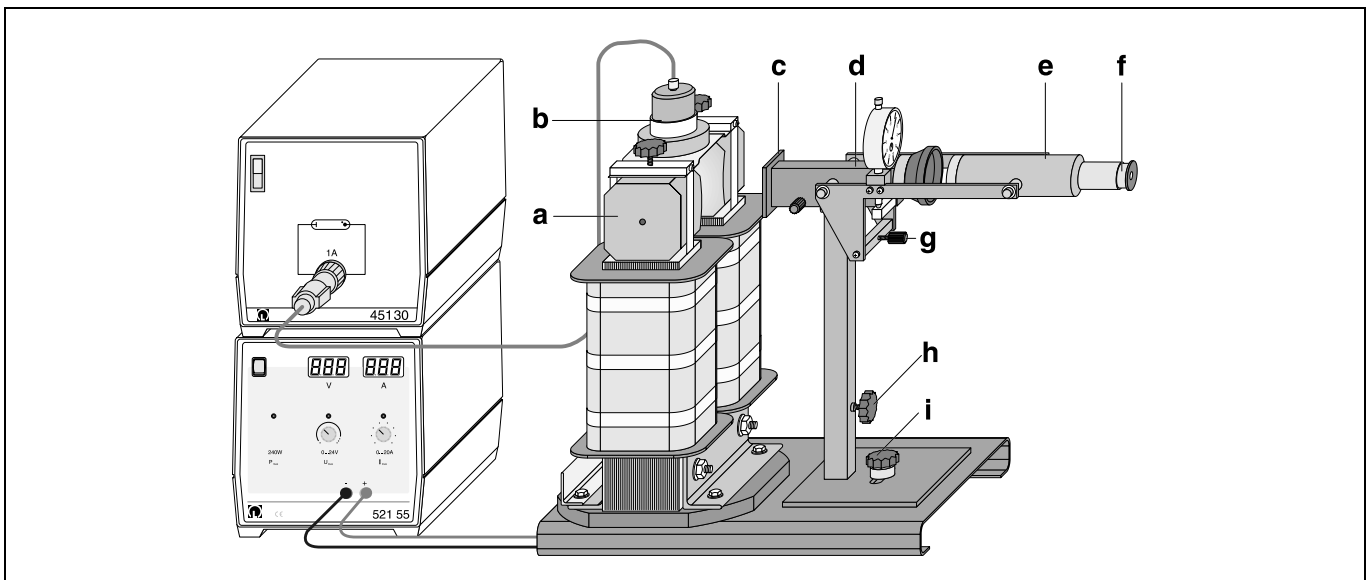
### First-time setup:

Fig. 5 shows the complete setup in the transverse configuration.

- Mount the electromagnet for the Zeeman effect on the base plate of the optical system. When tightening the hex screw (size 27) beneath the base plate, make sure that you can still turn the electromagnet on the base plate when you really try.
- Mount the pole pieces of the electromagnet (**a**) at a spacing of 10 mm.

Fig. 5: Experiment setup for the Zeeman effect in the transverse configuration

- (a) pole pieces
- (b) cadmium lamp with holder
- (c) plug-in holder for red filter
- (d) cover
- (e) telescope
- (f) ocular
- (g) height adjustment for telescope
- (h) arresting screw for column
- (i) arresting screw for column base



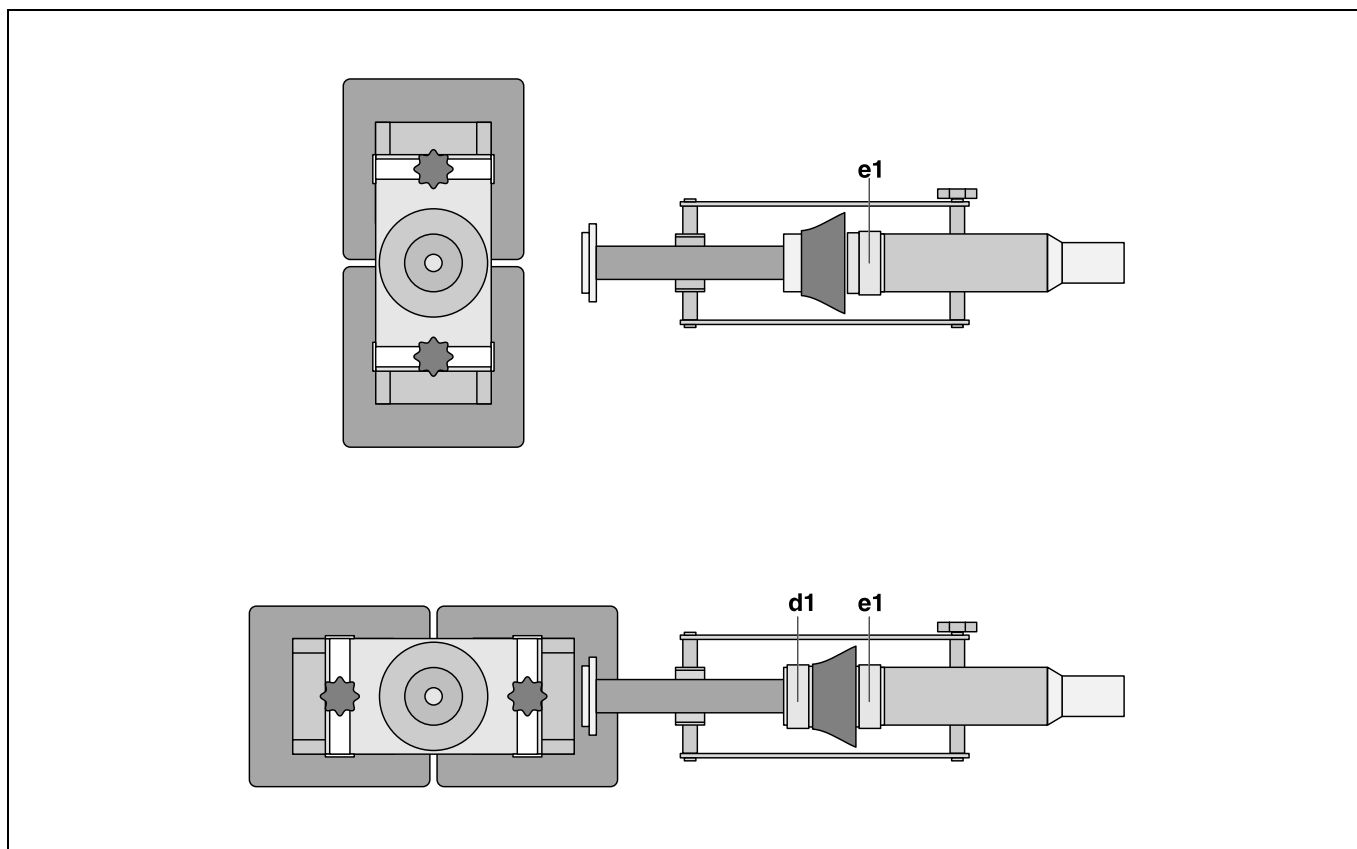


Fig. 6: Top view of setup in the transverse configuration (top) and the longitudinal configuration (bottom)  
**(d1)** holder with quarter-wavelength foil  
**(e1)** holder with polarization filter

- Screw in the holder for the cadmium lamp **(b)** with the opening facing the electrical connections of the electromagnet.
- Secure the pole pieces and the holder of the cadmium lamp using arresting screws and retaining straps.
- Turn the fused point on spectral lamp toward the side with the electrical connections so that the electrical leads do not obstruct the beam path.
- Screw in the column of the optical system so that the column base is as far as possible from the electromagnet.
- Remove the cover **(d)** and carefully place the Lummer-Gehrcke plate on the velour-lined base. Make sure the plate is aligned horizontally and is evenly supported over its entire length. Slide the prism as close as possible to the illuminated side.
- Turn the cover together with the cylindrical attachment toward the telescope **(e)** and rest it carefully against the telescope without disturbing the Lummer-Gehrcke plate. Then tighten the arresting screws.
- Slide the red filter with collecting lens into the plug-in holder **(c)**.
- To prevent interference from ambient light, slide the flexible light screen onto the cylindrical attachment of the cover, and slide the foam rubber ring over the telescope.

#### Switching from transverse to longitudinal observation:

- Loosen arresting screw **(i)** on the column base and move the column of the optical system as far as possible from the electromagnet.
- Remove the red filter with collecting lens from the plug-in holder.
- Swivel the electromagnet with cadmium lamp into the desired position (see Fig. 6) and align it so that the edge of the base plate of the electromagnet is parallel to the rear edge of the base plate of the optical system.
- Slide the red filter with collecting lens into the plug-in holder.
- Bring the column of the optical system and the electromagnet as close together as possible.

#### Electrical connection:

- Connect the cadmium lamp to the universal choke. After switching on, wait five minutes until a sufficiently strong light intensity is obtained.
- Connect the coils of the electromagnet in parallel (connect socket 1 to socket 3 and socket 2 to socket 4) and connect this assembly to the high current power supply.

#### Adjusting the optical system for observing the Zeeman effect:

*Adjust the height of the optical system in the longitudinal configuration, and do not change it when swiveling to the transverse configuration.*

*The optical system is optimally adjusted when the red horizontal interference patterns above and below the Lummer-Gehrcke plate show maximum brightness and contrast.*

- Remove the ocular of the telescope **(f)**; to optimize brightness and contrast, alternately

- a) shift and swivel the entire optical system left and right on the base plate (fix with arresting screw **(i)**);
- b) set the height of the complete optical system in relation to the cadmium lamp and the hole in the pole pieces (fix with arresting screw **(h)**).
- To improve brightness and contrast of the lines, you may need to raise the entire cover or the red filter with collecting lens in the plug-in holder.

#### Fine adjustment:

When the telescope is aimed precisely at the rear of the Lummer-Gehrcke plate, the interference lines appear symmetrically distributed between the top and the bottom. The bright inner lines are best suited for observation.

- Hold the ocular up to the light and focus the cross-hairs.
- Replace the ocular in the tube of the telescope and focus the interference lines by shifting the ocular.

### Carrying out the experiment

Note: the polarization filter is somewhat darker than the quarter-wavelength foil.

#### a) Observing in the transverse configuration:

- First observe the pattern of interference lines without the magnetic field ( $I = 0$  A) and align the telescope so that the cross-hairs of the ocular rest on an interference line.
- Slowly increase the magnet current to about  $I = 10$  A, until the split lines are clearly separated from each other.

To distinguish between the  $\pi$  and the  $\sigma$ -components:

- Slide the foam rubber ring over the holder of the polarization filter.
- Place the holder with polarization filter **(e1)** over the telescope (see Fig. 6) and turn it around the axis of observation until the middle component of the line triplet disappears.
- Turn the holder with polarization filter  $90^\circ$  further until the outer components of the line triplet disappear.

#### b) Observing in the longitudinal configuration:

- First observe the pattern of interference lines without the magnetic field ( $I = 0$  A) and align the telescope so that the cross-hairs of the ocular rest on an interference line.
- Slowly increase the magnet current to about  $I = 10$  A, until the split lines are clearly separated from each other.

To distinguish between the  $\sigma^+$  and the  $\sigma^-$  components:

- Slide the flexible light screen onto the holder for the quarter-wavelength foil.
- Mount the holder with quarter-wavelength foil **(d1)** on the cylindrical attachment of the cover, and the holder with polarization filter **(e1)** on the telescope (see Fig. 6).
- Turn the holder with polarization filter around the axis of observation until one of the two doublet components disappears, and turn it  $90^\circ$  further until the other component disappears.

### Measuring example and evaluation

#### a) Observing in the transverse configuration:

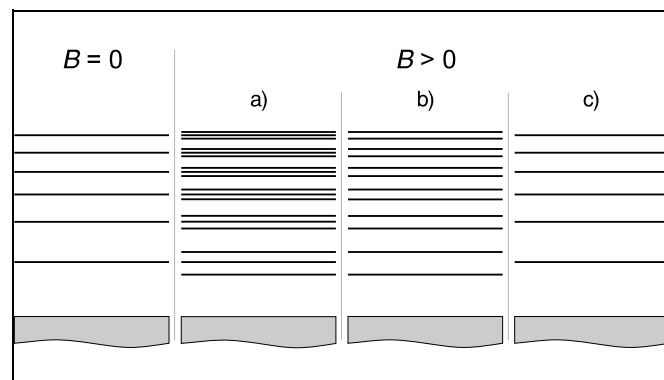


Fig. 7: Interference pattern for the Zeeman effect in the transverse configuration

- a) observed without polarization filter
- b) observed with polarization direction of the filter perpendicular to the magnetic field
- c) observed with polarization direction of the filter parallel to the magnetic field

#### b) Observing in the longitudinal configuration:

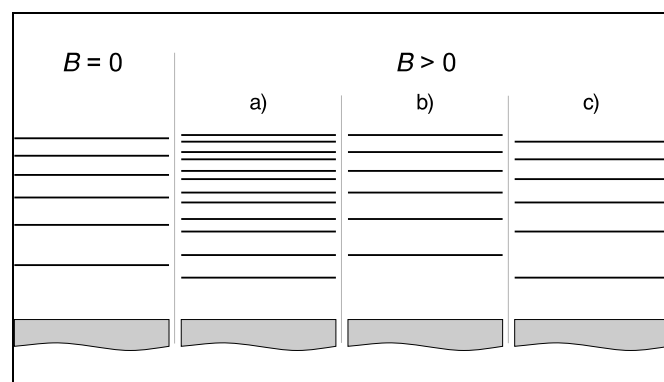


Fig. 8: Interference pattern for the Zeeman effect in the longitudinal configuration

- a) observed without quarter-wavelength foil and polarization filter
- b), c) observed with quarter-wavelength foil and polarization filter to demonstrate counterclockwise and clockwise-circular polarization

### 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.

