Atomic and nuclear physics

Atomic shell
Normal Zeeman effect

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:

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

where

$$\mu_B = \frac{\hbar e}{-2 \, m_e} \qquad (II)$$

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

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

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

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

$$J_z = M_J \cdot \hbar \text{ with } M_J = J, J - 1, \ldots, -J \qquad (IV)$$

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

$$\Delta E = \mu_B \cdot B \qquad (V).$$

We can observe the normal *Zeeman* effect e.g. in the red spectral line of cadmium (λ_0 = 643,8 nm, f_0 = 465,7 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).

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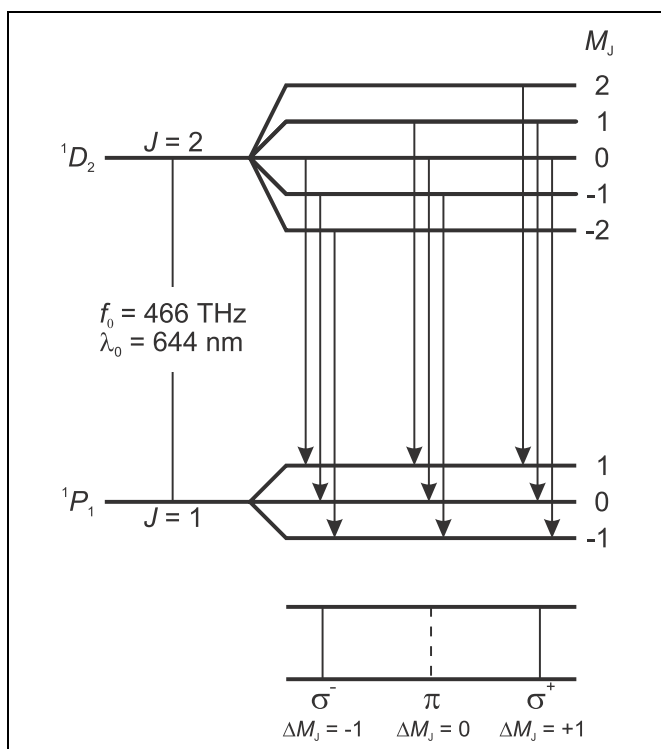
Apparatus

1 cadmium lamp for Zeeman effect	451 12
1 U-core with yoke	562 11
2 coils, 10 A, 480 turns	562 131
1 pair of pole pieces with large bores . . .	560 315
1 Fabry-Perot etalon	471 221
2 positive lenses with barrel, 150 mm . . .	460 08
1 quarter-wave plate	472 601
1 polarization filter	472 401
1 holder with spring clips	460 22
1 filter set, primary	467 95
or	
1 holder for interference filter	468 41
1 interference filter, 644 nm	468 400
1 ocular with line graduation	460 135
1 precision optical bench, standardized	
cross section, 1 m	460 32
1 rider base with thread	460 358
7 optics rider 60/50	460 351
1 universal choke for 451 12	451 30
1 high current power supply	521 55

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:

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

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

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

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

Connecting leads with conductor cross-section 2.5 mm^2

Angular distribution and polarization

Depending on the angular momentum component ΔM_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 π- 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).
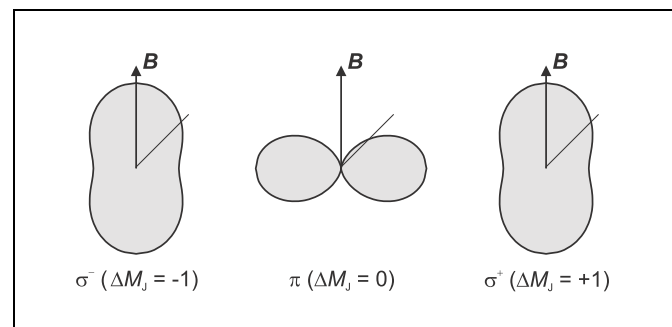

Fig. 2   Angular distributions of the electrical dipole radiation (ΔM_J: angular-momentum components of the emitted photons in the direction of the magnetic field)

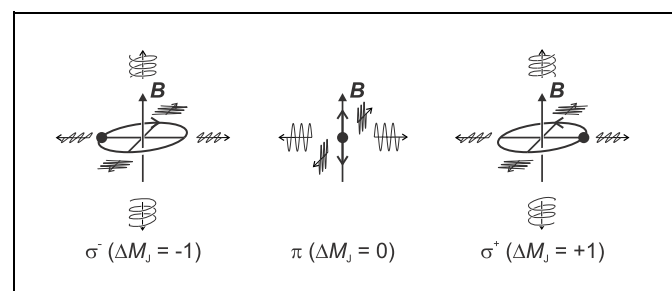Fig. 3   Schematic representation of the polarization of the Zeeman components (ΔM_J: angular-momentum components of the emitted photons in the direction of the magnetic field)

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 σ 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.
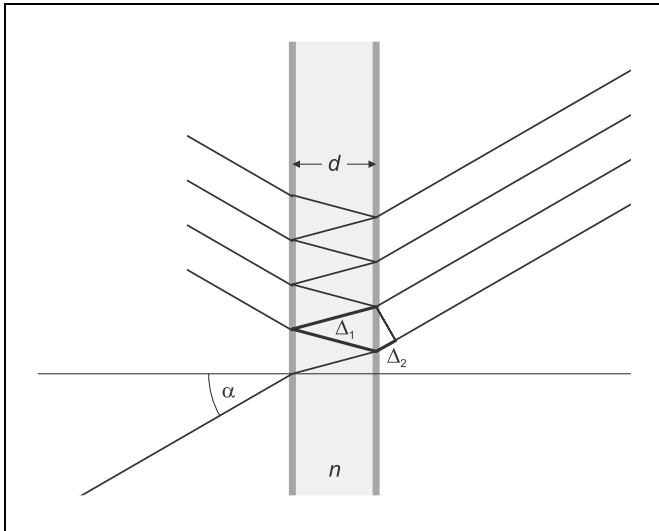
$$\Delta = 2\,d \cdot \sqrt{n^2 - \sin^2 \alpha_k} = k \cdot \lambda \qquad \text{(VIII)}$$

(Δ = 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 α corresponds to a radius r and the change in the angle $\delta\alpha$ to a change in the radius δr. 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 δr. 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.

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 $\Delta = n \cdot \Delta_1 - \Delta_2$.

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 λ can be observed with an ocular. The aperture angle of a ring is identical with the angle of emergence α of the partial rays from the Fabry-Perot etalon.

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

Setup

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

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
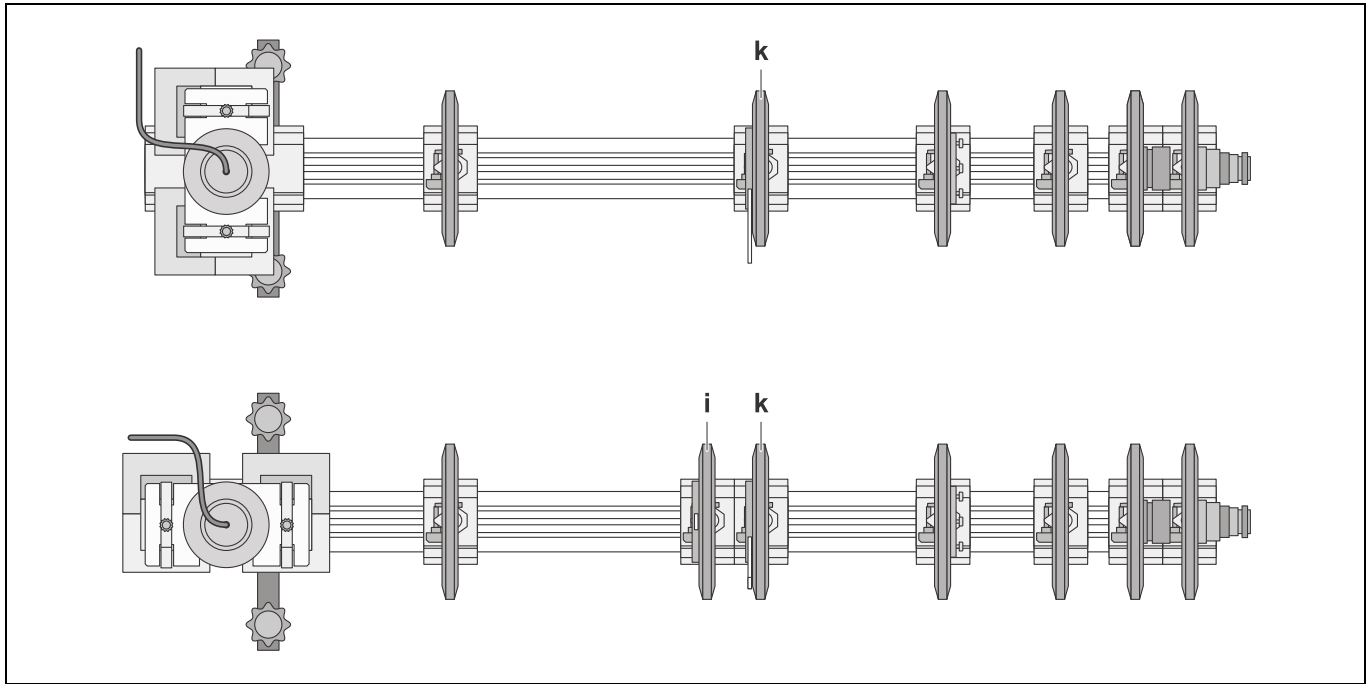**h** Ocular with line graduation
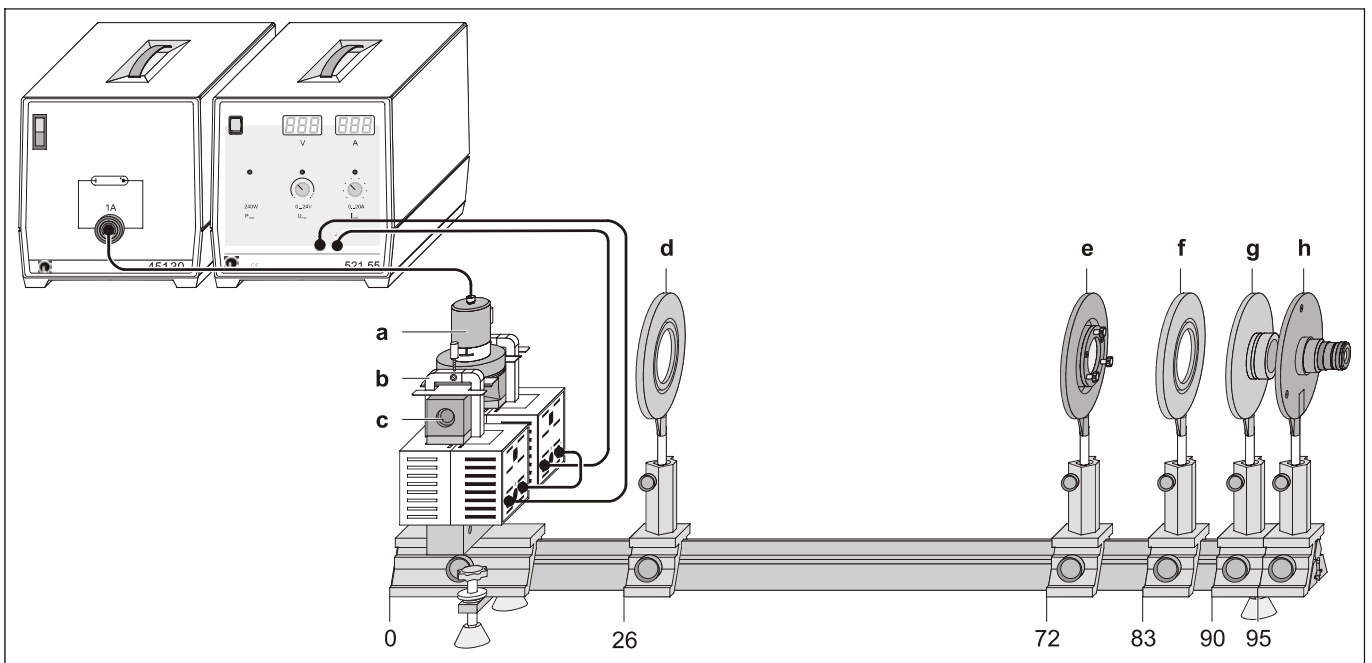
Fig. 6   Setup in transverse configuration (above) and in longitudinal configuration (below), as seen from above.
   i Quarter-wavelength plate
   k Polarization filter

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 π and σ 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 σ+ and σ- 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° and −45°. In each case one of the two doublet components disappears.

Fig. 7 top: Circular fringe pattern associated with the Zeeman effect in transverse configuration
    a) without polarization filter
    b) direction of polarization perpendicular to the magnetic field
    c) direction of polarization parallel to the magnetic field

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 π component is equal to the total intensity of the two σ components.

Fig. 8 bottom: Circular fringe pattern associated with the Zeeman effect in longitudinal configuration
    a) without quarter-wavelength plate
    b), c) with quarter-wavelength plate and polarization filter for detecting circular polarization