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Instruction Sheet

Cadmium Lamp with Holder for Zeeman-Effect — Cat. No. 451 12
Optical Device for Lummer-Gehrcke-Plate — Cat. No. 471 20
Lummer-Gehrcke-Plate — Cat. No. 471 21
Electromagnet for Zeeman Effect — Cat. No. 514 50

1. Zeeman Effect
2. Description of the Apparatus
3. Operating Instructions

1. Zeeman Effect, Principles, Examples of Calculation

A magnetic field changes the spectrum lines of a light source. The splitting up of the spectrum lines in several sharply separated components is called "Zeeman Effect". i. e. the splitting up in three components (Lorentz triplet) "**normal** Zeeman effect" and the splitting up in more than three components "**anomalous** Zeeman effect".

Elements the luminous electrons of which have paired antiparallel spin angular momentums exhibit the normal Zeeman effect, e. g. cadmium. The resultant spin quantum S is then $S = 0$ and the total angular momentum only consists of the orbital angular momentum. An externally applied magnetic field induces the spinning electrons to carry out precessional motions having the frequency

$$\nu = \frac{1}{4\pi}\frac{e}{m}B$$

ν = Larmor frequency

The precessional motion in the magnetic field causes the splitting up of the spectrum lines, which can be rather clearly demonstrated in the case of cadmium.

For a long time the splitting up of the red cadmium lines was taken as a simple example of the normal Zeeman effect. It was assumed that only the transition $^1P_1 - {}^1D_2$ emits the red line, whereas today it is known that the red line also contains other transitions of nearly the same energy difference. The calculation of the specific electron mass derived from the displacement of the spectrum lines remains unchanged.

Fig. 2 shows in a simplified manner the term diagram and polarization diagram of the red cadmium line (λ = 643.8 nm).

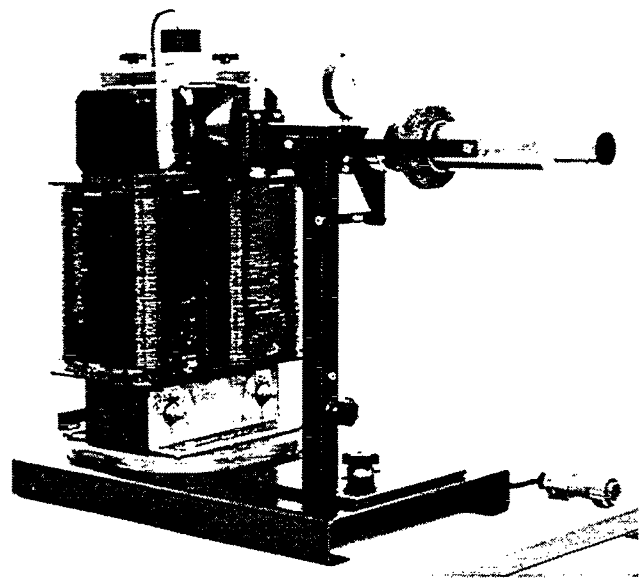
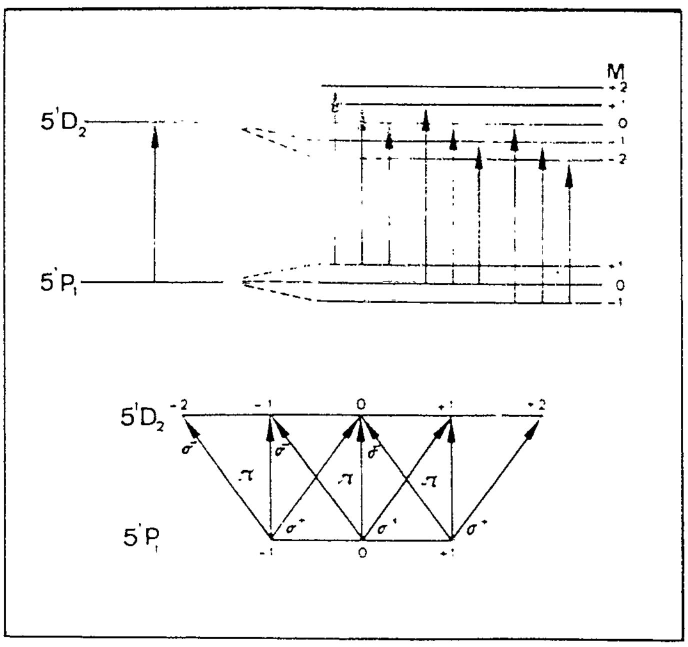


Fig. 1 Experimental assembly for observing the Zeeman effect

Fig. 2 Term diagram and polarization diagram



The red cadmium line is split up in the magnetic field in two outer σ-components and one inner π-component. This applies to transversal viewing, i. e. observation perpendicular to the direction of the magnetic field. All three visible lines of this Lorentz-triplet are linearly polarized, i. e. the central line, which corresponds to the spectrum line of the light source without external magnetic field, in direction of the magnetic field, and the two outer lines perpendicular to the direction of the magnetic field.

When viewing in longitudinal direction, i. e. in direction of the external magnetic field, a doublet is recognized. No central line is visible here. The two split-up lines are circularly polarized against each other.

To observe the splitting up of spectrum lines in the magnetic field, a spectroscope of high resolving power is required. In the described experimental assembly a Lummer-Gehrcke plate is used having a resolving power of

approx. $\frac{\lambda}{\Delta\lambda} = 500\,000.$

From the visible displacement of the spectrum lines results a measurable change of the wave length or frequency. The two σ-components or outer secondaries of the triplet or the two lines of the doublet are shifted, for example, to a frequency $\nu + \Delta\nu$ or $\nu - \Delta\nu$. For the displacement $\Delta\nu$ it applies, however:

$$\Delta\nu \pm \frac{1}{4\pi} \times \frac{e}{m} \times B.$$

from which e/m can be calculated:

$$\frac{e}{m} = \frac{4\pi}{B} \times \Delta\nu \qquad (1)$$

B = flux density in tesla $(\frac{Vs}{m^2})$
$\Delta\nu$ = frequency shift

$\Delta\nu$ must be derived from the resolution of the Lummer-Gehrcke-plate and from the wave-length displacement determined at a certain B.

According to Kohlrausch (Praktische Physik, volume III, page 385) for the differences of wavelength observable at a Lummer-Gehrcke-plate it applies

$$\Delta\lambda = \frac{\delta a}{\Delta a} \times \frac{\lambda^2 \sqrt{n^2 - 1}}{2d\,(n^2 - 1 - n \times \lambda \frac{\delta n}{\delta\lambda}} \qquad (2)$$

In the calculation the term $\frac{n^{\lambda}\,\delta n}{\delta\lambda}$ can be neglected.

It follows $\Delta\lambda = \frac{\delta a}{\Delta a} \times \frac{\lambda^2 \sqrt{n^2 - 1}}{2d\,(n^2 - 1)}$

δa = distance of one of the split-off lines from the original position of the interference lines (without magnetic field)

Δa = distance between two interference lines (without magnetic field)

Using a suitable method, the proportion $\frac{\delta a}{\Delta a}$ can be adjusted so that a simple fraction, e. g. 1/4, is obtained.

λ = wavelength of the red cadmium line = 643.8 nm

n = refractive index for the quartz glass of the Lummer-Gehrcke-plate = 1.4567

d = Thickness of the Lummer-Gehrcke-plate = 4.04 mm

c = velocity of light

To determine the specific charge of the luminous electron, the frequency shift must be calculated from the wavelength displacement. Calculation is made via the relationship between wavelength, frequency and velocity of light.

$$c = \lambda\,\nu$$

When forming the total differential

$$\frac{\delta\, c^2}{\delta\lambda \times \delta\nu} = \lambda d\nu + \nu d\lambda$$

it follows for c const.

$$0 = \lambda d\nu + \nu d\lambda.$$

The transition $d \rightarrow \Delta$ and entering $\nu = \frac{c}{\lambda}$ results in

$$\Delta\nu = -\frac{c\Delta\lambda}{\lambda^2}$$

$$\Delta\nu = -\frac{c}{\lambda^2} \text{ corresponds to } \Delta\nu = \frac{c}{\lambda^2}\Delta\lambda \quad (3)$$

The frequency shift may be negative or positive.

Using the equipment for observing the Zeemann effect, the following values were measured with longitudinal viewing:

d = 4.04 mm

$\frac{\delta a}{\Delta a} = \frac{1}{4}$ at a field strength of 0.7 tesla.

When observing the doublet the field strength of the magnet was increased until from the system of interference lines (prior to switching on the magnetic field) a new system was formed having double the number of uniformly distributed lines. Δa is the spacing of the interference lines prior to switching on the magnetic field, and δa is the deviation of one of the two lines of the doublet from the initial position.

It can be read from Fig. 3 that $\frac{\delta a}{\Delta a} = \frac{1}{2}$ when the lines of the doublet are adjusted so that their spacing from each other is uniform.

Entering $\lambda = 6.438 \times 10^{-5}$ cm, d = 0.404 cm and n = 1.4567 in formula (2) gives

$$\Delta\lambda = \frac{1}{4}\sqrt{\frac{1.4567^2 - 1}{2 \times 0.404\,(1.4567^2 - 1)}} \times \lambda^2$$

$$\Delta\lambda = 0.31\,\lambda^2$$

$$\Delta\lambda = 12.8 \times 10^{-8} \text{ cm}$$

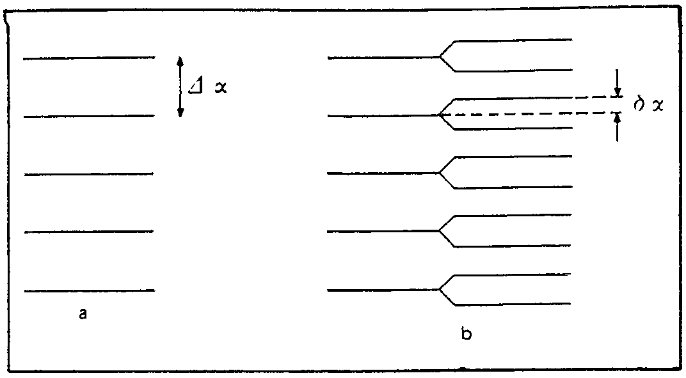


Fig. 3 Splitting up while observing the doublet, $\delta\alpha = \frac{1}{4}\Delta\alpha$
a) before switching on the magnetic field
b) after switching on the magnetic field

When entering the term $\Delta\lambda = 0.31\ \lambda^2$ in equation (3) it follows

$$\Delta\nu = c \times 0.31 \frac{\text{cm}}{\text{cm}^2}$$

and with the velocity of light

$c = 3 \times 10^{10} \frac{\text{cm}}{\text{s}}$ there results

$$\Delta\nu = 0.31 \times 3 \times 10^{10} \frac{\text{l}}{\text{s}'} \cdot \frac{\text{cm cm}}{\text{s cm}^2} = \frac{1}{\text{s}} = \text{Hz}$$

$\Delta\nu = 9.3 \times 10^9$ Hz.

With $B = 0.7$ Tesla it follows according to equation (1):

$$\frac{e}{m} = \frac{4\pi}{0.7} \times 9.3 \times 10^9$$

$$\frac{e}{m} = 1.67 \times 10^{11} \frac{m^2}{V s^2} =$$

$$1.67 \times 10^{11} \frac{A\ s}{\text{kg}} .$$

In the literature the value for $\frac{e}{m}$ is indicated from observation of the Zeeman effect with

$$\frac{e}{m} = 1.76 \times 10^{11} \frac{As}{\text{kg}}$$

2. Description of the Apparatus

2.1. A spectrum lamp without outer protective bulb is to be used. The diameter of the quartz burner of the spectrum lamp without protective bulb is approx. 8 mm so that the distance of the pole pieces may be approx. 10 mm. The current-carrying lines of the burner are insulated with glass fibre tubing. The supply leads at the burner ends and the resistors of the ignition electrodes are freely exposed and must not be touched during operation. Furthermore, it should be avoided to touch the quartz bulb by hand. The spectrum lamp has a nine-pin base matching the socket. When inserting the lamp into the socket, only touch the metal base of the spectrum lamp and exert a pressure on the rim of the metal base by means of a screw driver.

The metal base has a catch fitting into the slit of the socket. Also when extracting the lamp from the socket place screw driver into the slit below the base to push the lamp out of the socket.

The socket of the spectrum lamp is rotatable and adjustable in height. In this way the spectrum lamp can be shifted until the burner is positioned in the middle between the pole pieces.

The socket is slipped into a bridge which is pressed against the pole pieces of the magnet by two tommy screws.

Caution! Make sure before switching on the magnet current that the two tommy screws are tightened. When the magnetic field builds up loosely fitted pole pieces may attract each other and destroy the spectrum lamp.

Two ball clamps and one guide pin are used to fix the socket of the spectrum lamp. The guide pin fits into a cutout of the bridge.

The lamp socket is equipped with a supply lead with special plug fitting into the coupler socket of the new-type universal choke (451 30). If the spectrum lamp is to be connected to the older-type universal choke (451 22), the special plug must be replaced by plugs of connecting leads. The green-yellow conductor is for safety earthing for which there is no connection on the older-type universal choke. A connection can be provided on the older-type universal choke using special coupling or adapter (451 20) and connecting cables and plugs.

Insert the spectrum lamp with bridge into the pole pieces in such a way that the opening of the bridge shows in direction of the electrical connections of the magnet. At the same time the lamp itself must be turned so that the seal-off tip of the quartz burner shows in the same direction.

2.2. Optical Viewing Device for the Zeeman Effect (Fig. 4)

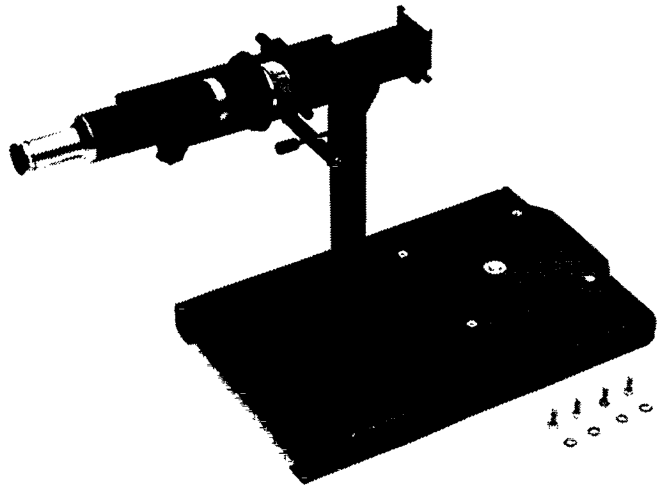


Fig. 4

Base plate for the electromagnet, column and holder for the Lummer-Gehrcke-plate and the telescope form one unit. The column base of the optical device is fixed to the base plate by one single tommy screw. The movable counterpart of this tommy screw is fitted in a slit below the base plate. Also the opening in the column base has the shape of a slit so that with loosened tommy screw the column base can be moved in all directions.

The column is adjustable in height for correct positioning of the inlet window of the Lummer-Gehrcke-plate.

The column carries the holder for the Lummer-Gehrcke-plate and the holding bracket for the observation telescope. The holder (a milled part) has an inside lining of velour foil for the Lummer-Gehrcke-plate and is closed on top by a cover. The cover, fixed to the holder by three small screws, is equipped at the light inlet with inlet diaphragm and a frame to insert a coloured filter and at its rear end with a cylindrical attachment onto which a rotatable holder with polarization foil can be fitted.

The two swivel arms for the telescope are inserted into pegs of the holding brackets. The telescope itself is held at the end of the two swivel arms. It can be turned on two pegs and locked by a tommy screw. The tommy screw in the bridge of the holding bracket supports the swivel arms against the column and is used to adjust inclination and height of the telescope.

A holder with polarization foil or retardation foil can be fitted on the light-admission side of the telescope.

There is furthermore a funnel-shaped light shield which can be attached either to the round filter holder of the polarization foil or to the filter holder of the retardation foil.

The observation telescope has a movable eyepiece for focusing the lines under observation.

2.3. Lummer-Gehrcke-Plate

The Lummer-Gehrcke-plate made of quartz fits into the velour-lined milled holder. The high-grade plane-parallel surface-ground plate has the dimensions 120 mm x 15 mm x 12 mm. A light-inlet prism is glued to one end of the plate.

The Lummer-Gehrcke-plate should be handled with great care. It should always be positioned so that it is uniformly supported over its whole length.

To observe the Zeeman effect, the front end of the plate and part of the light-inlet surface of the prism is covered.

When transporting the optical device, the Lummer-Gehrcke-plate should be removed from the holder and stored in a safe plate.

2.4. Electromagnet for the Zeeman Effect (Fig. 5)

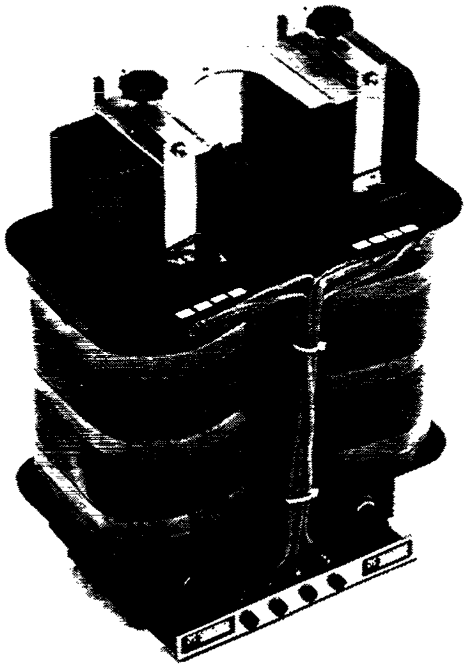


Fig. 5

The electromagnet for the Zeeman effect, consisting of U-core and coils, is mounted on a solid PVC plate. Pole pieces of special alloy are fitted to the ground ends of the U-core and secured by clamp straps and tommy screws.

Each of the two coils of the magnet has two windings the supply leads of which are connected to a socket terminal board.

These windings can be switched in series by connecting the supply leads to sockets 1 and 4, and socket 2 to socket 3.
The windings are switched in parallel by connecting the supply leads to sockets 1 and 2 or 3 and 4, socket 1 to socket 3 and socket 2 to socket 4.

For voltage, current and field strength between the pole pieces (spacing 10 mm) the following guide values can be assumed:

For connection in series

$\frac{U}{V}$	$\frac{I}{A}$	$\frac{B}{\text{Tesla}}$
17.5	15	0.87
12.0	10	0.70
6.0	5	0.4

For connection in parallel

$\frac{U}{V}$	$\frac{I}{A}$	$\frac{B}{\text{Tesla}}$
7	20	0.8
5	15	0.6
3.5	10	0.4
1.7	5	0.2

In the center of the PVC base plate a screw socket is inserted by means of which the electromagnet can be screwed to the base plate of the optical device. The fastening screw is introduced through the base plate from below and tightened.

Weights and dimensions:

1. Spectrum lamp with holder for Zeeman Effect:
   0.6 kg, 150 mm x 80 mm x 160 mm
2. Optical device for Zeeman Effect:
   2.7 kg, 160 mm x 410 mm x 360 mm
3. Base plate:
   3.7 kg, 270 mm x 410 mm x 35 mm
4. Lummer-Gehrcke plate:
   0.1 kg, 120 mm x 15 mm x 12 mm
5. Electromagnet for Zeeman Effect:
   42 kg, 260 mm x 220 mm x 420 mm.

3. Operating Instructions

3.1. Mounting the experimental assembly

Screw the electromagnet onto the base plate of the optical device (see Figs. 1 and 5). The magnet should be rotatable on the base plate by applying some force.

Screw the optical device onto the base plate. With the tommy screw not tightened the column of the optical device should be movable on the base plate.

Insert pole pieces and holder of the spectrum lamp. The pole pieces should be placed with their flat ends outwards so that they are approximately flush with the outer sides of the U-core in the coils, the blunted cones of the pole pieces showing inward. Spacing of the small inside surface of the pole pieces approx. 10 mm. The pole pieces should be aligned so as to give a straight view through the boreholes of the two pole pieces. The opening of the holder of the spectrum lamp when the spectrum lamp is inserted should show towards the side of the supply leads of the electromagnet.

Firmly tighten the tommy screws on lamp holder and pole pieces.

Introduce spectrum lamp, turning the lamp in its rotatable clamp fixture so that the sealed-off tip of the lamp bulb shows towards the side of the electrical connections of the magnet. Adjust seal-off tip and the two insulated connecting wires so that they are in angular position to the field direction. The insulated connecting wires may nearly touch the pole pieces. Adjust the spectrum lamp in height so that the lamp bulb is centered in the magnetic field. In transverse viewing direction (perpendicular to the magnetic field) the observation is only little disturbed by the visible connecting wire, and in longitudinal viewing direction (in direction of the magnetic field) the other connecting wire should not disturb the view at all.

Turn the magnet on the base plate so that the electrical connections are on the side opposite to the optical viewing device. The magnet is then so positioned that the longer axis of its base crosses the longer axis of the base plate.

Connect the spectrum lamp to the choke and start operation. If choke with five-pin plug is available, correct tapping is assured. If the lamp plug has to be connected via an adapter and banana plug to a choke with selectable connection, connection should be made in position Hg-Cd.

Cover both ends of the Lummer-Gehrcke-plate with adhesive tape, particularly on the side for light inlet, place the plate into the holder of the optical viewing device. Grip the Lummer-Gehrcke-plate only by its long sides. In no case should it be bent or exposed to any other form of mechanical strain. The Lummer-Gehrcke-plate should be placed with its prism towards the light inlet slit and the flat end side towards the observation telescope. The distance of the Lummer-Gehrcke-plate from the holder ends should be equal on both sides. The plate can be shifted a little to either side to bring the lines in focus.

Place holder with cover and inlet slit so that the cylindrical attachment shows toward the observation telescope. For fixation and height adjustment see "Directions to improve optical viewing".

Caution! Do not tilt the optical device after having inserted the Lummer-Gehrcke-plate which lies loosely on the holder. Therefore, the Lummer-Gehrcke-plate should not be inserted before the optical device has been connected to the base plate.

Place the diaphragm onto the cylindrical attachment of the cover. Align telescope. The telescope should allow glancing observation of the Lummer-Gehrcke-plate. Direct the optical viewing device towards the light source and carefully shift it in height until green-blue and red streaks become clearly visible in the telescope. At the same time the streaks of the intense green-blue mercury line, the blue mercury line and the red mercury line become visible.

Insert red filter and adjust position of Lummer-Gehrcke-plate and observation telescope until the system of red interference lines becomes clearly visible. Adjust eyepiece sharply. Precise focusing is only possible each time for a limited area of the band spectrum. When directing the telescope towards the rear end of the Lummer-Gehrcke-plate, the streaks appear symmetrically distributed upward and downward, over the surface of the plate. Observation can also be made from below as shown in Fig. 6.

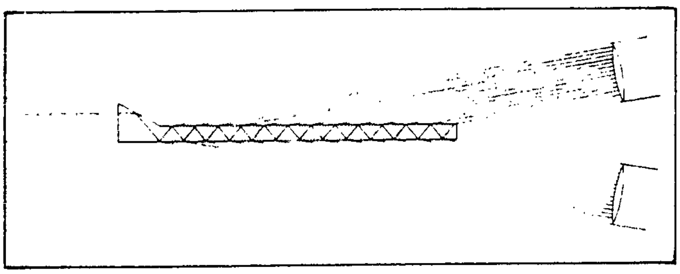


Fig. 6 Interference fringes issued in grazing beams from a Lummer-Gehrcke-plate

3.2. Observation of the fringe pattern of the red cadmium line

Insert polarization filter (the polarization-filter foil is slightly darker than the retardation foil). Turn the polarization filter (covered by diaphragm). The observed fringes do not change, they are not polarized.

Connect the magnet to a d.c. supply and slowly increase the current. Depending on the voltage source it may be preferable to switch the windings of the magnet either in series or in parallel. When viewed through the telescope, the splitting-up of the red interference lines starting at about 4 A becomes clearly visible. Make observation first without polarization filter only with the diaphragm. The splitting-up of the lines increases with increasing current. At approx. 9 A to 10 A the splitting-up of each interference line in three components is so far advanced (with transverse direction of view) that now again a pattern is resulting where the interference lines are uniformly distributed over the field of view (Fig. 7).

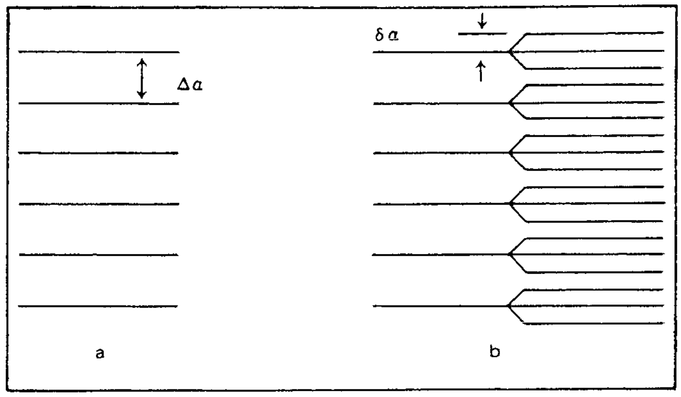


Fig. 7 Splitting-up while observing the triplet, $\delta a = \frac{1}{3}\Delta a$
a) before switching on the magnetic field
b) after switching on the magnetic field

As the human eye is well capable of recognizing small irregularities in a line pattern it is possible to adjust very accurately the current or field strength respectively to a value at which a new line pattern with uniform spacing is formed.

3.3. Polarization of the lines of the triplet

Insert polarization filter and observe the line splitting (triplet viewed in transverse direction) when turning the polarization filter. In one position the central line disappears while in the other position the two side lines are eliminated. Central line and secondary lines are well distinguished by reducing the magnetic field (3 to 5 A) so that the split-up interference lines are no longer uniformly distributed over the field of view. The central line and the two secondary lines are polarized perpendicular to each other.

The direction of polarization of the filter foil is checked by observing the light reflected at a glass plate. When light is incident on a glass plate at the Brewster angle (57°), the reflected light is polarized perpendicular to the plane of incidence. If the angle is not exactly maintained, e. g. due to stray light, the intensity change is still sufficient to determine the direction of polarization by turning the filter foil.

Observation of the fringe pattern using a polarization filter shows that the central line appears polarized in direction of the magnetic field while the secondary lines appear polarized perpendicular to the magnetic field. Observation in transverse direction shows the lines of the Lorentz triplet where the central line is called the π-line and the two other ones the σ-lines.

3.4. Observation of the doublet and determination of its direction of polarization

To observe the doublet, the magnet must be turned on the base plate after having moved back the optical device to the extreme outer position. Align the magnet so as to allow proper adjustment of the optical device in direction of the borehole in the pole piece of the magnet.

Switch on the Hg-Cd lamp and adjust the optical device vertically, horizontally and in viewing direction. The line pattern should appear as bright as possible. Due to their geometry and spacing, the interference fringes are weaker in longitudinal direction of view than in transverse direction of view.

Switch on the magnetic field and observe splitting-up of each line into a doublet without using a filter. Insert polarization filter and observe the splitting-up. When turning the polarization filter, the intensity of the two lines should not change. There is, however, a rather distinct change of intensity as the polarization filter foil used has polarizing as well as retarding properties (properties of a $\frac{\lambda}{4}$-plate.

Place holder with retardation foil on the telescope and repeat observation of the lines of the doublet. A polarization filter adjustment can be found at which the one or the other line can be eliminated by turning the retardation foil left or right. When the deflecting direction of the retardation foil is shifted by 45° to the left against the direction of polarization of the polarization-filter foil, one of the two circularly polarized σ-lines of the doublet is passed. When the retardation foil is turned by 45° to the right the oppositely directed polarized σ-line is passed (σ^+-line and σ^--line) (Fig. 8).

Bibliography: Physics Experiments, Volume 3 (599 942)
New Physics Leaflets for Colleges and Universities, Volume 1 (599 952)

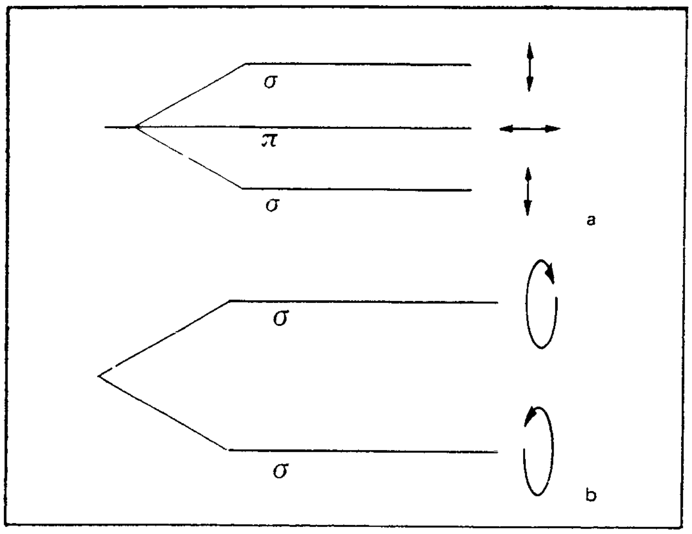


Fig. 8 Polarization of the triplet a and the doublet b

Directions to improve optical viewing

By vertical shifting of the cover the inlet opening as well as the outlet opening are displaced upward or downward. This allows to influence the brightness of the lines and the stray light. After adjustment of the cover the clamping screws must be tightened again. Disturbing stray light can be reduced by glueing foils onto the inlet prism. Then one specific line of the light inlet surface of the prism remains free. The most favourable light inlet opening is not the same for every Lummer-Gehrcke-plate and must, therefore, be determined by experiment.