Normal Zeeman Effect

INVESTIGATION OF THE NORMAL ZEEMAN EFFECT IN LONGITUDINAL UND TRANSVERSAL CONFIGURATION

- **Observation of doublet and triplet splitting of the red cadmium line in an external magnetic field.**
- **Investigation of the polarization of the doublet and triplet components.**

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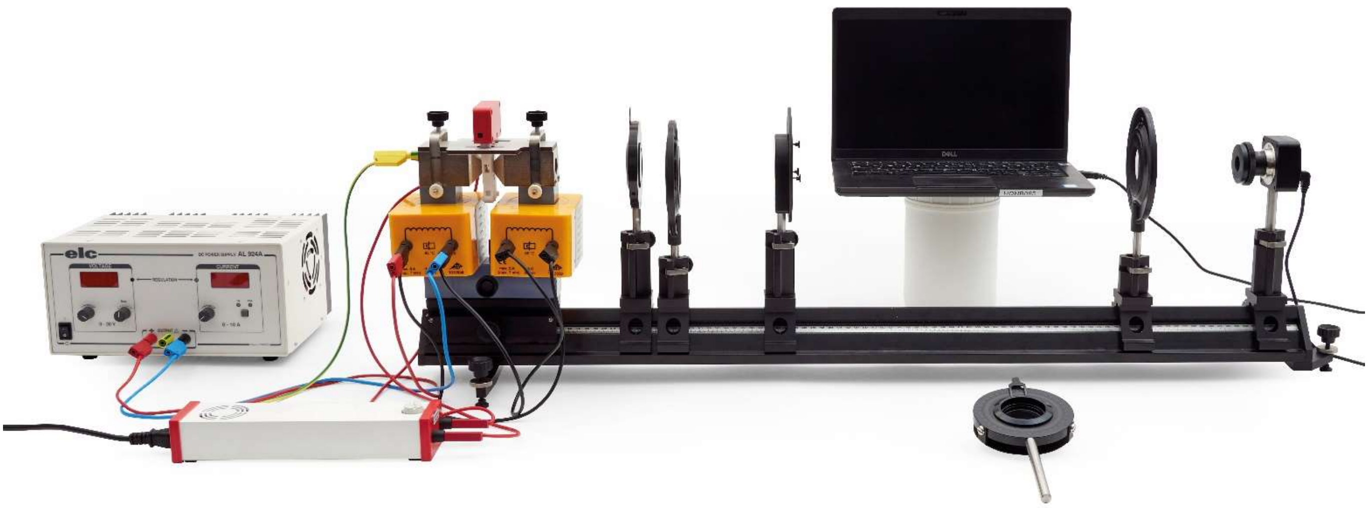

Fig. 1: Experimental setup for the normal Zeeman effect in longitudinal configuration

GENERAL PRINCIPLES

The Zeeman effect refers to the splitting of atomic energy levels or spectral lines under the influence of an external magnetic field. It was discovered in 1896 by its namesake Pieter Zeeman as a broadening of the sodium D lines and classically explained by Hendrik Antoon Lorentz with the help of the Lorentz force, which the magnetic field exerts on the electrons in the atomic shell. In this so-called normal Zeeman effect, as is the case for the red cadmium line (λ = 643.8 nm), for example, a double splitting into a line doublet is observed parallel to the magnetic field (longitudinal) and a triple splitting into a line triplet is observed perpendicular to the magnetic field (transversal). More complex splittings are referred to as the anomalous Zeeman effect, which could only be explained with the help of the existence of the electron spin postulated by Goudsmit and Uhlenbeck in 1925. Quantum mechanically, the anomalous Zeeman effect is based on the interaction of the magnetic field with the magnetic moment of the electron shell generated by the orbital angular momentum and spin of the electrons. In this respect, the anomalous Zeeman effect represents the normal case, the normal Zeeman effect a special case.

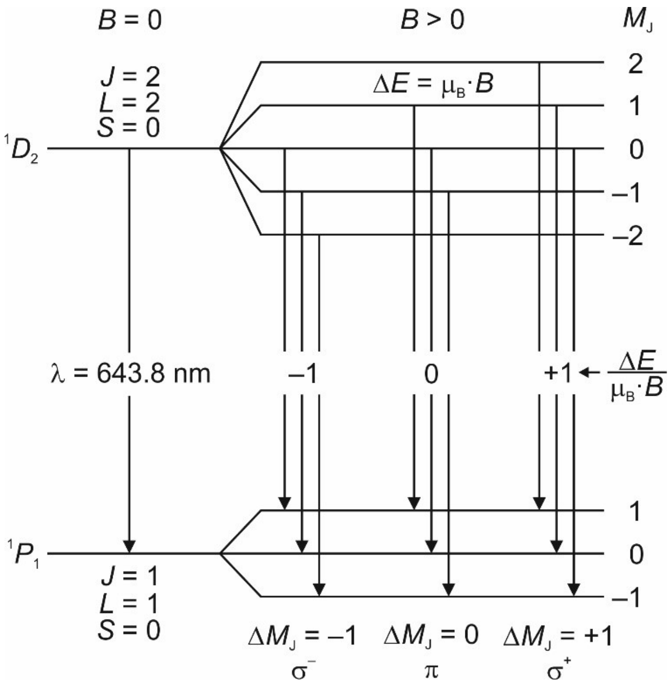

Fig. 2: Normal Zeeman effect at the red cadmium spectral line. Splitting of the energy levels and transitions permitted according to the selection rules for electric dipole radiation

The normal Zeeman effect only occurs for transitions between atomic states whose total spin adds up to $\boldsymbol{S} = \mathbf{0}$. The red Cd line corresponds to the transition $^1D_2 \rightarrow {}^1P_1$ with the wavelength λ = 643.8 nm (Fig. 2). Since both levels have a total spin with the quantum number $S = 0$, the normal Zeeman effect can be observed here, and the total angular momentum $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$ corresponds to the total orbital angular momentum, i.e. $\boldsymbol{J} = \boldsymbol{L}$. It generates a magnetic moment

$$(1)\quad \boldsymbol{\mu} = \frac{\mu_B}{\hbar} \cdot \boldsymbol{J}$$

with the Bohr magneton

$$(2)\quad \mu_B = \frac{e}{2 \cdot m_e} \cdot \hbar = 9.274 \cdot 10^{-24}\,\frac{\text{J}}{\text{T}}\,.$$

e: elementary charge
m_e: mass of the electron
$\hbar = h/2\pi$: reduced Planck constant

In an external magnetic field

$$(3)\quad \boldsymbol{B} = \begin{pmatrix} 0 \\ 0 \\ B \end{pmatrix}$$

the energy

$$(4)\quad E = \boldsymbol{\mu} \bullet \boldsymbol{B} = \mu_z \cdot B$$

is associated with the magnetic moment. Due to the directional quantization, the component J_z of the total angular momentum parallel to the magnetic field can only have the values

$$(5)\quad J_z = M_J \cdot \hbar \text{ mit } M_J = -J, -(J-1), \ldots, (J-1), J\,.$$

J: Total angular momentum quantum number

The energy level with the total angular momentum quantum number J thus splits into $2J+1$ equidistant components, which differ in the magnetic quantum number M_J (Fig. 2). With Eq. (1) follows

$$(6)\quad \mu_z = \frac{\mu_B}{\hbar} \cdot J_z\,,$$

thus, according to Eq. (4)

$$(7)\quad E = \mu_z \cdot B = \frac{\mu_B}{\hbar} \cdot J_z \cdot B$$

and finally with Eq. (5):

$$(8)\quad E = \mu_B \cdot M_J \cdot B\,.$$

The energy distance between two levels with energies E_1 and E_2 ($E_1 > E_2$) is therefore calculated as follows:

$$(9)\quad \Delta E = E_1 - E_2 = \left(M_{J,1} - M_{J,2}\right) \cdot \mu_B \cdot B = \Delta M_J \cdot \mu_B \cdot B\,.$$

According to Eq. (5), level $^1D_2$ is split into five and level $^1P_1$ into three components, each with the equidistant energy difference given by Eq. (9).

According to the selection rules for electric dipole radiation, transitions between these levels are permitted with

$$(10)\quad \Delta M_J = \begin{cases} +1 & \text{(right circularly polarized light, } \sigma^+\text{)} \\ 0 & \text{(linearly polarized light, } \pi\text{)} \\ -1 & \text{(left circularly polarized light, } \sigma^-\text{)} \end{cases},$$

where the emitted light is polarized as indicated above. Since three of the nine theoretically possible transitions coincide in terms of energy, a total of three spectral lines can be observed (Fig. 2), one unshifted π component and, according to $E = \hbar \cdot \omega$ two σ components shifted by

$$(11)\quad \Delta\lambda = -\frac{\lambda^2}{2 \cdot \pi \cdot \hbar \cdot c} \cdot \Delta E$$

c: vacuum speed of light

with a correspondingly higher or lower wavelength. Eq. (11) results in a shift of $|\Delta\lambda|$ = 0.0065 nm by inserting Eq. (9) and (2) for the flux density B = 334 mT set in the experiment.

The spatial distribution of the emitted light is different for the π and the two σ components. The case $\Delta M_J = 0$ classically corresponds to a Hertzian dipole oscillating parallel to the magnetic field. Accordingly, linearly polarized light is emitted perpendicular to the magnetic field (transversal) and no light is emitted parallel to the magnetic field (longitudinal) (Fig. 3). The cases $\Delta M_J = \pm 1$ correspond to two dipoles oscillating perpendicular to each other with a phase difference of 90°. Accordingly, light that is circularly polarized parallel to the magnetic field is emitted both parallel and perpendicular to the magnetic field, namely left circularly polarized for $\Delta M_J = -1$ and right circularly polarized for $\Delta M_J = +1$.

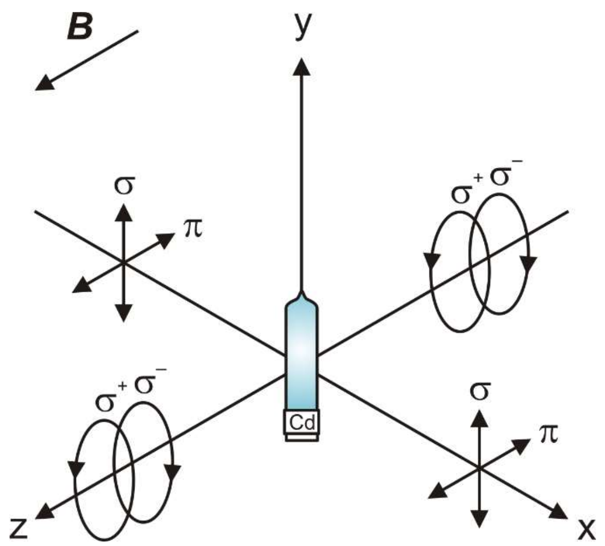

Fig. 3: Polarization of electric dipole radiation depending on the direction of propagation

A quarter-wavelength filter with a downstream polarization filter is therefore required to analyze the polarization of light when observing in the longitudinal direction, as the observation is made perpendicular to the polarization plane of the σ components (Fig. 3). The quarter-wavelength filter converts the circularly polarized light into linearly polarized light, which can then be analyzed using the polarization filter. When the quarter-wavelength filter is set to –45°, the σ^+ component is converted accordingly and can be observed, while the σ^- component disappears. When the quarter-wavelength filter is set to +45°, the opposite is true. Only one polarization filter is required for observation in the transverse direction, as the observation is made parallel to the plane of polarization of the σ components, and these appear therefore linearly polarized (Fig. 3). The π component is always linearly polarized. When the polarization filter is set to 0°, the σ components can be observed accordingly, while the π component disappears. When the polarization filter is set to 90°, the opposite is true.

In the experiment, the splitting is observed with the help of a digital camera preceded by a Fabry-Pérot etalon and imaging optics. The Fabry-Pérot etalon is designed to fulfill the resonance condition for the specific wavelength of 643.8 nm of the red Cd line. When the light from the cadmium lamp passes through the Fabry-Pérot etalon, interference rings are created which, like the spectral line, are split as a function of the external magnetic field and imaged onto the camera sensor by the optics. Observation parallel or perpendicular to the external magnetic field is made possible by a rotating electromagnet. The splitting is observed qualitatively and the polarization of the doublet and triplet components is examined using a quarter-wavelength filter with polarization attachment and a polarization filter.

The spectroscopy with a Fabry-Pérot etalon is subject of the experiment UE5020900, in which the interference rings are measured as a function of the external magnetic field and the Bohr magneton is determined.

EQUIPMENT LIST

1	Cadmium lamp with accessories @230 V	1021366
or		
1	Cadmium lamp with accessories @115 V	1021747
1	Fabry-Pérot etalon 644 nm	1020903
1	DC power supply, linear regulated, 1 – 30V, 0 – 10A @230V	1025380
or		
1	DC power supply, 0 – 20 V, 0 – 5 A @115 V	1003311
1	U Core D	1000979
2	Coil D, 900 turns	1012859
1	Electromagnet accessory for Zeeman effect	1021365
1	Microscope camera BRESSER MikroCam SP 3.1	1024060
1	Lens 12 mm for Bresser microscope camera	1024059
1	Stainless steel rod with ¼ inch thread, 100 mm	1025431
1	Red filter mounted on holder	1025376
2	Convex lens on stem f =+100 mm	1003023
1	Quarter-wavelength filter on stem	1021353
1	Polarising attachment	1021364
1	Polarisation filter on stem	1008668
1	Optical precision bench D, 1000 mm	1002628
1	Support for optical bench D, set	1012399
1	Optical base D	1009733
3	Optical rider D, 90/36	1012401
2	Optical rider D, 60/36	1002639
1	Safety experiment leads, 75 cm, blue, red, (2 pcs)	1017718
1	Safety experiment leads, 75 cm, black, (2 pcs)	1002849

SAFETY INSTRUCTIONS

- Before setting up the experiment, read and observe the operating instructions for the devices and in particular the safety instructions formulated therein.
- Protect the Cd lamp from mechanical shocks. Do not touch the glass bulb of the Cd lamp with bare hands.
- Only operate the Cd lamp with the ballast supplied. Before putting the Cd lamp mounted on the electromagnet in operation, it is essential to establish the protective earthing. To do this, connect the PE sockets on the ballast and the pole piece of the electromagnet accessory for Zeeman effect (1021365) to each other using the yellow-green safety experiment lead (protective earth conductor) supplied.
- Before putting the electromagnet in operation, ensure that the pole pieces are in the correct position as described in the operating instructions for the electromagnet accessory for Zeeman effect (1021365).

The maximum current through the coils D with 900 turns is 5 A (7 minutes). It can be doubled for short periods (30 seconds). The coils have an internal reversible thermal fuse which trips at a winding temperature of 85°C. The reset time is 10-20 minutes, depending on the ambient temperature.

- Carry out the measurement quickly enough to prevent the thermal fuse from tripping due to high currents flowing for too long.
- Do not operate the coils without a transformer core.

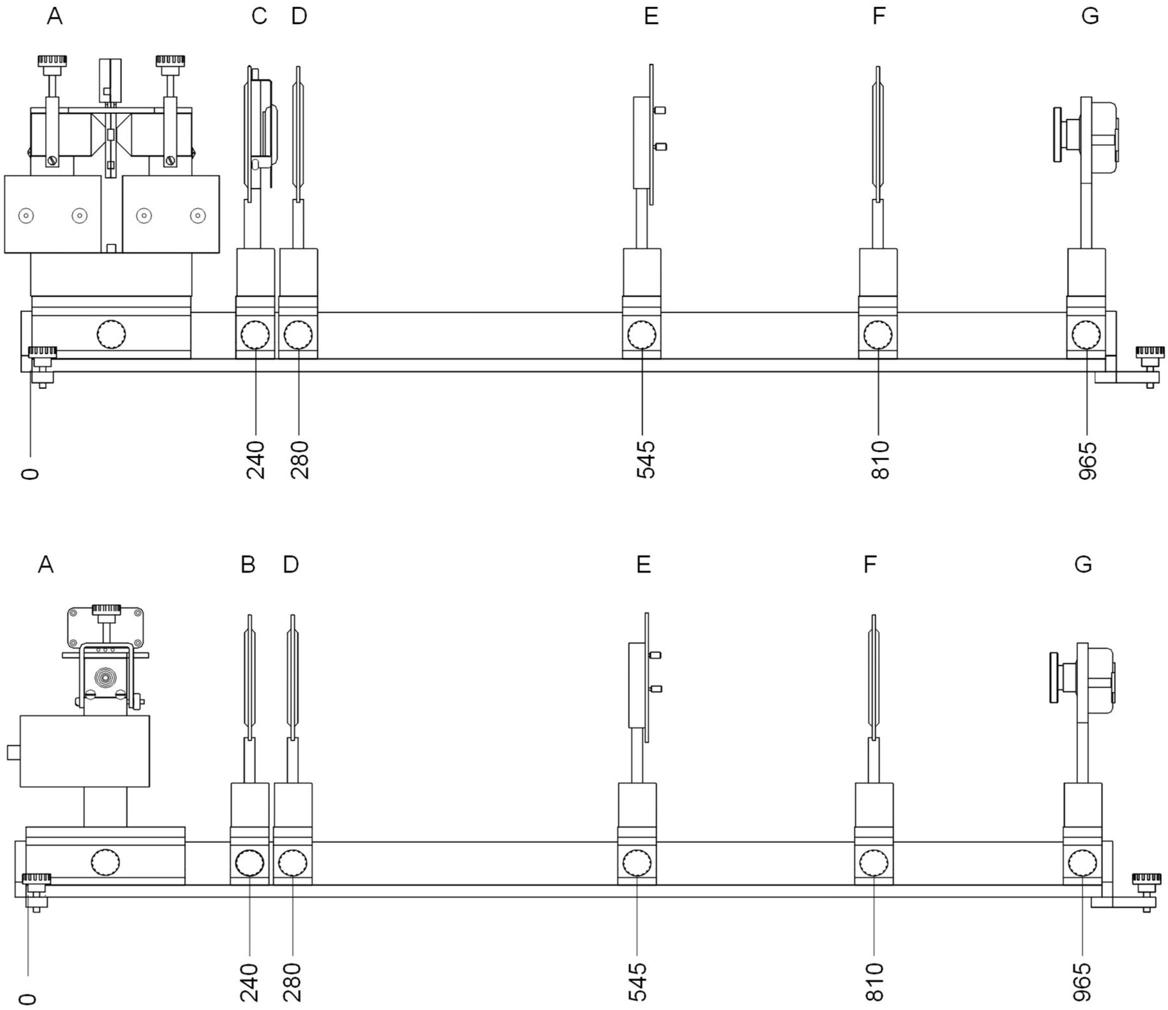

Fig. 4: Experimental setup for the normal Zeeman effect in longitudinal (top) and transversal (bottom) configuration. A: Electromagnet with Cd lamp, B: Polarization filter, C: Quarter wavelength filter with polarizing attachment, D: Convex lens *f* = 100 mm (condenser lens), E: Fabry-Pérot etalon, F: Convex lens *f* = 100 mm (imaging lens), G: Camera with 12 mm lens. See text for exact positioning of components

GENERAL NOTES

The camera software must be installed on the measuring computer.

It is recommended to carry out the experiment in a dark room in order to minimize stray light from the surroundings and to achieve optimum exposure and contrast of the camera's live image.

Due to the temperature sensitivity of Fabry-Pérot etalons, the center of the interference rings may look differently depending on the ambient temperature and may therefore differ from the screenshots in this manual.

SETUP

Mounting the electromagnet and the Cd lamp

- Mount the supports for optical bench (1012399), the long one on the left-hand side of the optical bench, the short one on the right-hand side (scale at the front). Set up the optical bench on a level experimental site.
- Position and fix the optical base (1009733) on the optical bench so that it is flush left with the front plate (Fig. 4).
- Assemble the electromagnet in longitudinal configuration (Fig. 4 top) on the optical base as described in the operating instructions for the electromagnet accessory for Zeeman effect (1021365).
- Mount the cadmium lamp on the electromagnet as described in the operating instructions for the Cd lamp with accessories (1021366 / 1021747).
- Connect the PE sockets on the ballast of the Cd lamp and on the pole piece of the electromagnet using the supplied yellow-green safety experiment lead (protective conductor).
- Connect the Cd lamp to the ballast using the 4 mm safety experiment leads. Connect the ballast to the mains using the mains cable. Do not switch on the ballast yet.

- Connect the “0” tap of the left coil to the “900” tap of the right coil and the “0” tap of the right coil to the “900” tap of the left coil. Then connect the “0” tap of the left coil to the “-“ output of the DC power supply unit and the “900” tap of the left coil to the “+” output of the DC power supply unit (Fig. 1). Connect the DC power supply unit to the mains using the mains cable. Do not switch on the DC power supply unit yet.

Mounting the camera and optics

- Screw the tripod rod (1025431) into the 1/4” tripod thread at the bottom of the camera.
- Screw the 12 mm lens (1024059) into the C-mount thread on the front of the camera.
- Screw the red filter (1025376) onto the 12 mm lens.
- Mount the polarizing attachment (1021364) on the quarter-wavelength filter (1021353) as described in the operating instructions.

The polarization filter on stem (1008668), the two convex lenses on stem, f = 100 mm (1003023) and the Fabry-Pérot etalon (1020903) require no further assembly.

Starting up the experiment and adjustment

- Switch on the ballast of the Cd lamp and wait approx. 5 minutes.

After a warm-up time of approx. 5 minutes, the Cd lamp has reached 90% of its light output.

- Position and fix a long optical rider (1012401) for the camera on the optical bench so that it is flush right with the front plate. Insert the camera into the optical rider as far as it will go, then move it upwards by approx. 2 cm and fix it.
- Center the 12 mm lens so that it has sufficient clearance in both directions of rotation.
- Position and fix a short optical rider (1002639) for the imaging lens (convex lens f = 100 mm, 1003023) at 810 mm. Insert the imaging lens into the optical rider as far as it will go and fix it.
- Start the computer and connect the camera to the computer using the USB cable.
- Start the software. The camera is automatically detected and appears in the camera list. Select the camera and click on it.

The live image is displayed in the window and looks like Fig. 5 after the optimization described below.

- Darken the room if the live image is affected by stray light.

Note:
The screenshots in Fig. 5 - Fig. 7c were taken in a completely darkened room.

- Open the “Power Frequency (anti-flicker)” menu item in the camera window (scroll down if necessary) and click on “AC (50 Hz)” or “AC (60 Hz)”.

This setting minimizes the influence of the mains frequency on the camera's live image.

- Select the optimum exposure time manually. Do not use the white balance, otherwise the effect of the red filter will be compensated.
- If necessary, optimize the sharpness by turning the 12 mm lens.
- If necessary, move the camera slightly up or down in the optical rider so that the image is centered.

Note:
Due to the optical imaging, a real, upside-down image is created. If the camera is moved upwards in the optical rider, the image moves downwards and vice versa.

- Position and fix a short optical rider (1002639) for the condenser lens (convex lens f = 100 mm, 1003023) at 280 mm on the optical bench. Insert the condenser lens into the optical rider as far as it will go and fix it. If necessary, move the imaging lens so that the light spot appears to fill the image and adjust the exposure time (live image as in Fig. 6).
- Position and fix a long optical rider (1012401) for the Fabry-Pérot etalon (1020903) at 545 mm on the optical bench. Insert the Fabry-Pérot etalon into the optical rider as far as it will go and fix it.

Note:
The interference rings may appear blurred and too bright. To optimize sharpness and exposure, the camera position, focus and exposure time have to be adjusted.

- Move the camera to 965 mm, if necessary move it slightly up or down in the optical rider so that the image is centered again, optimize the sharpness by turning the 12 mm lens and adjust the exposure time (live image as in Fig. 7).
- Do not yet place the quarter-wavelength filter with polarizing attachment or the polarization filter in the beam path.

The setup is now configured for the experiment.

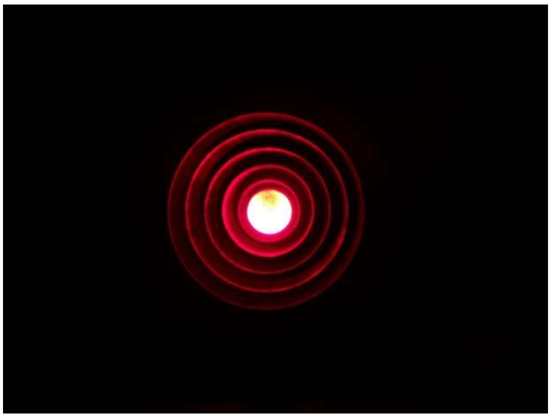

Fig. 5: Live image with camera and imaging lens. Stepped hole of the pole piece and light spot of the Cd lamp appear concentric and centered

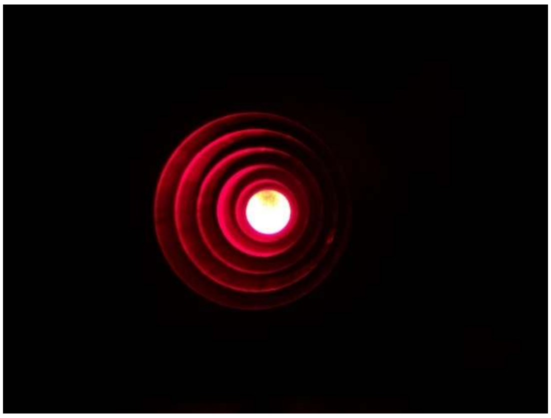

Fig. 5a: Electromagnet twisted. The stepped hole does not appear concentric. Correction: Turn the electromagnet so that it is centered

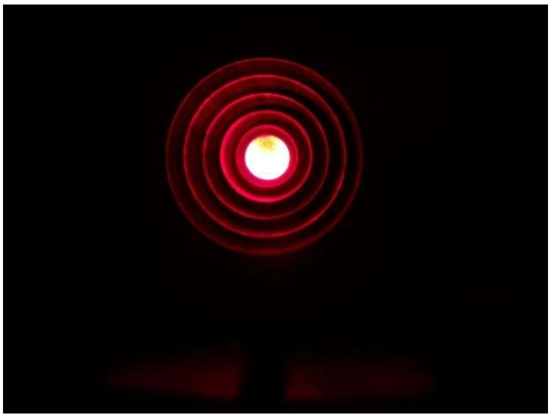

Fig. 5b: Camera too low in the optical rider. Correction: Move the camera up in the optical rider so that it is centered

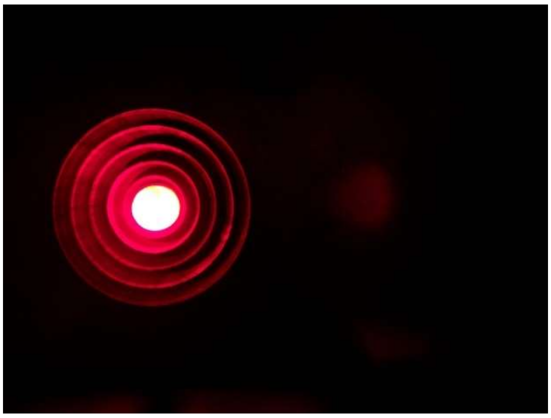

Fig. 5c: Camera twisted in the optical rider. Correction: Rotate the camera in the optical rider so that it is centered

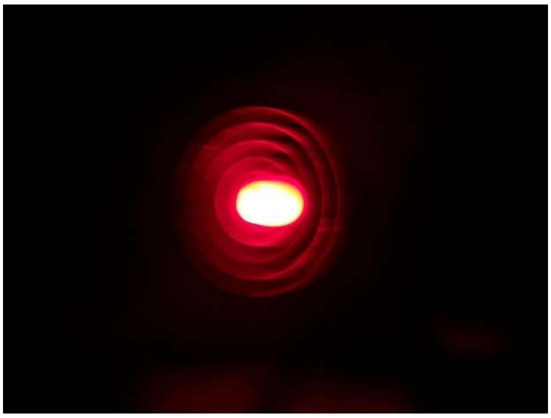

Fig. 5d: Imaging lens twisted in the optical rider. Correction: Rotate the imaging lens in the optical rider so that it is aligned perpendicular to the optical axis

Fig. 6: Live image with condenser lens

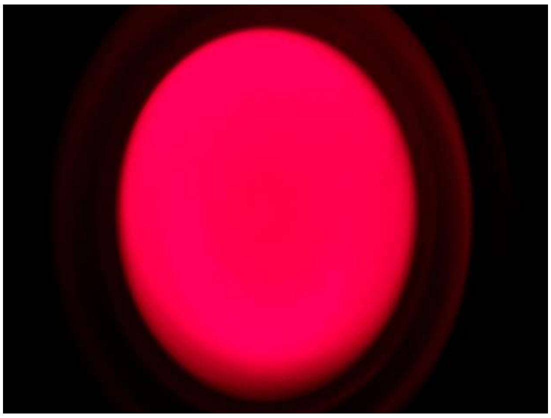

Fig. 6a: Condenser lens twisted in the optical rider. Correction: Rotate the condenser lens in the optical rider so that it is aligned perpendicular to the optical axis

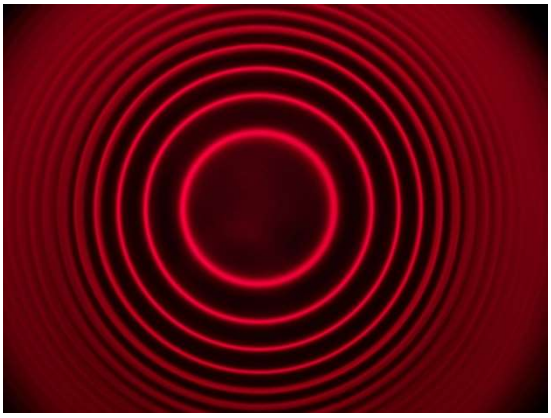

Fig. 7: Live image with Fabry-Pérot etalon

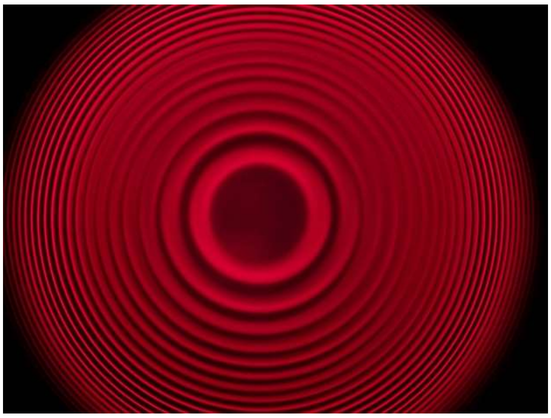

Fig. 7a: Poor focusing. Correction: Turn the 12 mm lens so that the interference rings are clearly visible

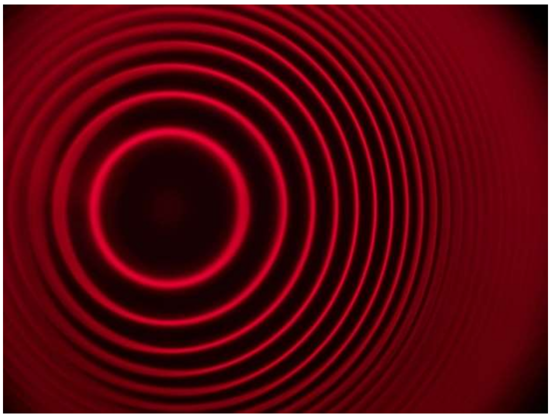

Fig. 7b: Etalon twisted in the optical rider. Correction: Rotate the etalon in the optical rider so that it is aligned perpendicular to the optical axis

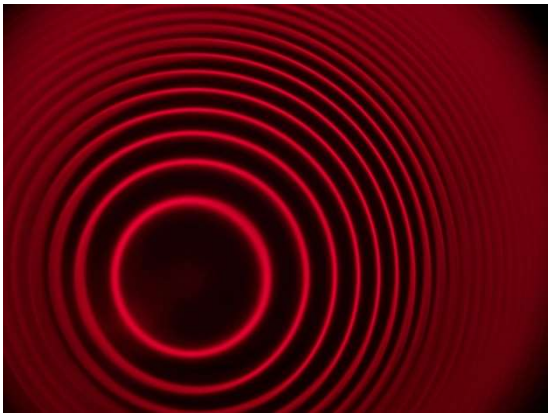

Fig. 7c: Etalon tilted. Correction: Adjust using the three adjusting screws on the housing.

EXPERIMENT PROCEDURE, MEASUREMENT EXAMPLE UND EVALUATION

Observation in longitudinal direction

Carry out the following steps, observe how the interference rings change and take screenshots (Fig. 8).

- Do not apply an external magnetic field.

Only the interference rings generated by the Fabry-Pérot etalon are observed, each of which corresponds to the red Cd spectral line (Fig. 8a).

- Apply an external magnetic field by switching on the DC power supply unit and increasing the current through the coils to 3.5 A (B = 334 mT).

Note:
When a magnetic field is applied, the exposure time should be ≥ 20 ms, as otherwise “flickering lines” may occur due to an interference of the camera's “rolling shutter sensor”.

The splitting into the line doublet with the two shifted components σ^- and σ^+ is observed, the unshifted π component is not observed (Fig. 8b).

- With the magnetic field applied, position the quarter-wavelength filter with polarization attachment between the electromagnet and the convex lens using a long optical rider (1012401) (Fig. 4 C).

Note:
The quarter-wavelength filter must be on the side of the Cd lamp.

- With the magnetic field applied, set the quarter-wavelength filter with polarization attachment to –45°.

The σ^- component disappears (Fig. 8c).

- With the magnetic field applied, set the quarter-wavelength filter with polarization attachment to +45°.

The σ^+ component disappears (Fig. 8d).

- Remove the quarter-wavelength filter with polarization attachment from the beam path.
- Reduce the current to zero and switch off the DC power supply unit.

Observation in transversal direction

- Turn the electromagnet so that the pole pieces are oriented perpendicular to the direction of the optical axis (Fig. 4).
- Do not apply an external magnetic field.

Only the interference rings generated by the Fabry-Pérot etalon are observed, each of which corresponds to the red Cd spectral line (Fig. 8e, Fig. 9).

- Apply an external magnetic field by switching on the DC power supply unit and increasing the current through the coils to 3.5 A (B = 334 mT).

The splitting into the line triplet with the unshifted π component and the two shifted components σ^- and σ^+ is observed (Fig. 8f, Fig. 9).

- With the magnetic field applied, position the polarization filter between the electromagnet and the convex lens (Fig. 4 B) and set it to 0°, i.e. perpendicular to the magnetic field.

The π component disappears (Fig. 8g, Fig. 9).

- With the magnetic field applied, set the polarization filter to 90°, i.e. parallel to the magnetic field.

The two σ components disappear (Fig. 8h, Fig. 9).

- Remove the polarization filter from the beam path.
- Reduce the current to zero and switch off the DC power supply unit.

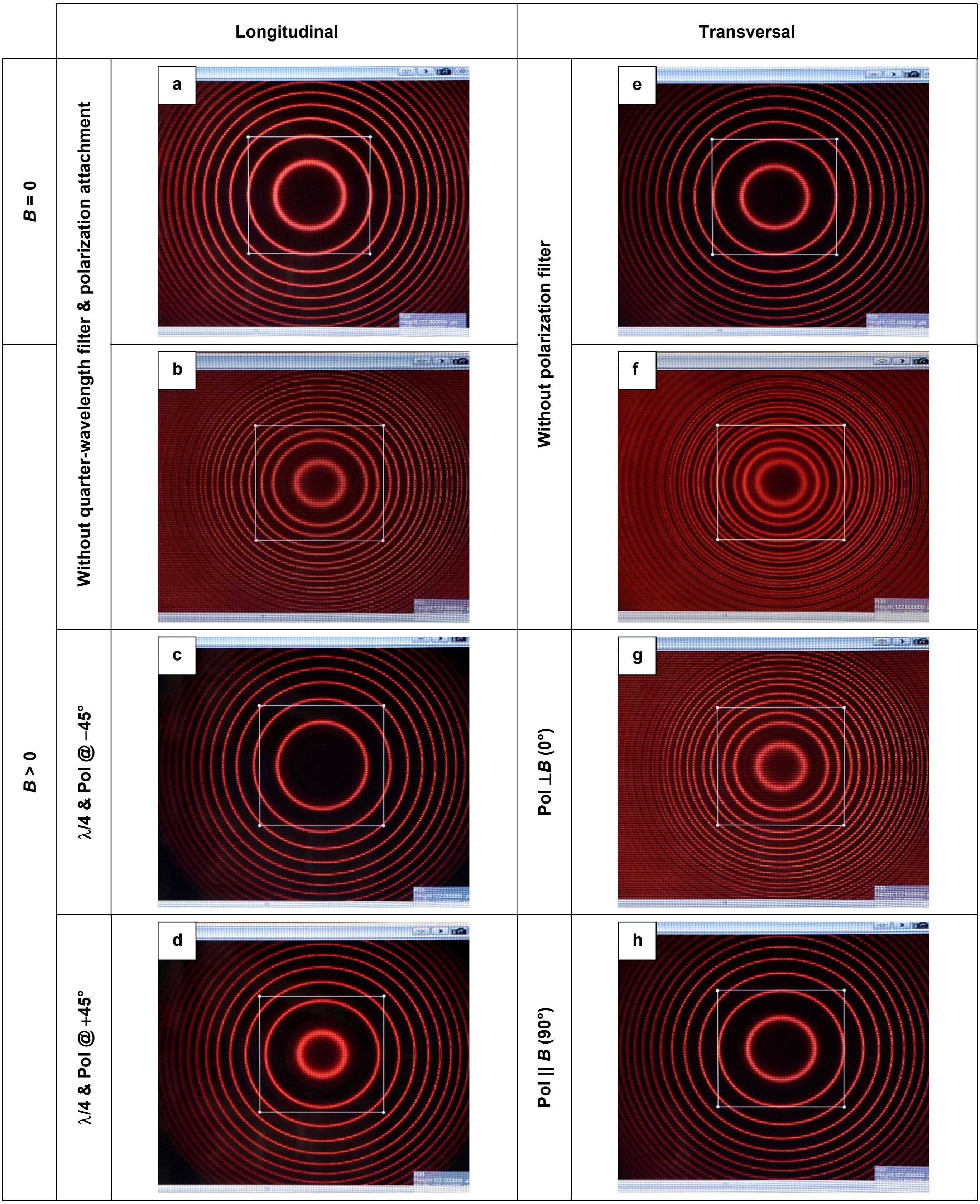

Fig. 8: Observation of the doublet and triplet splitting of the red cadmium line in the external magnetic field and investigation of the polarization. For better orientation, the second interference ring counted from the center is marked with a frame

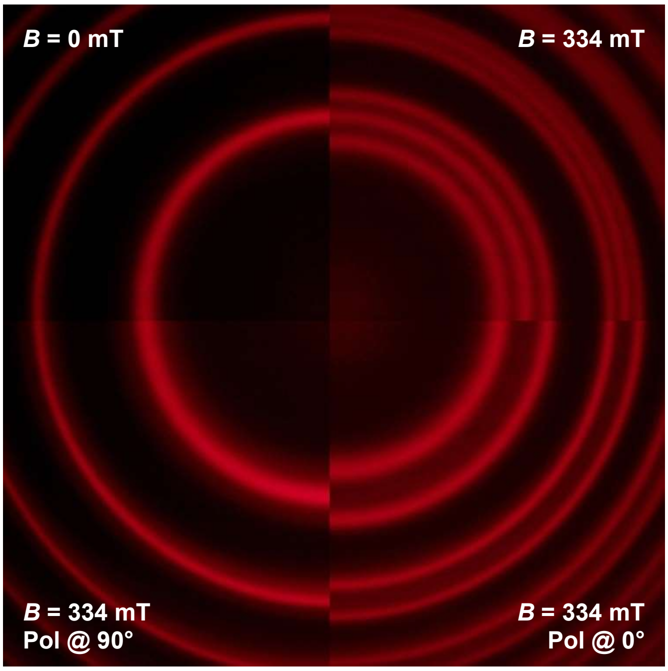

Fig. 9: Normal Zeeman effect when observed in transversal direction. Splitting of the interference rings and polarization states at a glance