Atomic and nuclear physics

Electron shell

Normal Zeeman effect

INVESTIGATION OF THE TRANSVERSAL AND LONGITUDINAL ZEEMAN EFFECT

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

UE5020700–1

07/18 TL/UD

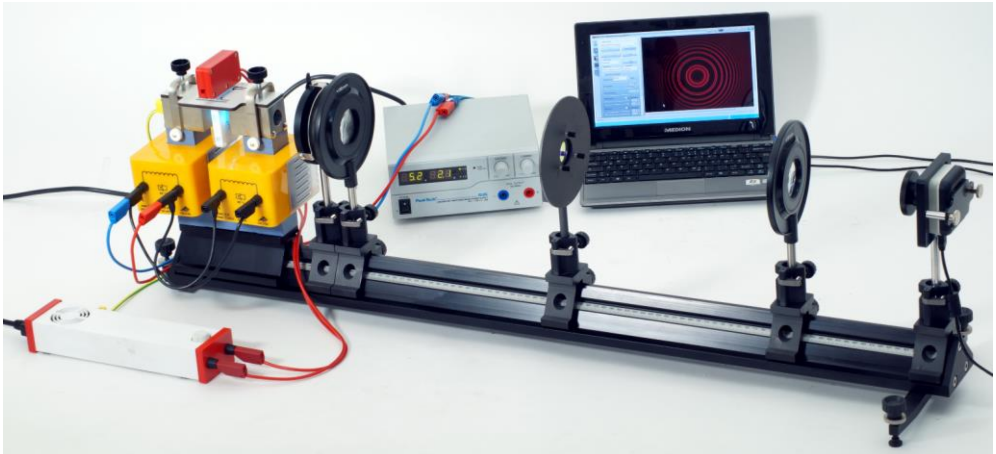

Fig. 1: Measurement arrangement for the longitudinal Zeeman effect

BACKGROUND

The Zeeman effect refers to the splitting of atomic energy levels or spectral lines due to the action of an external magnetic field. Named after P. Zeeman, the scientist who discovered it in 1896, it was classically explained by H. A. Lorentz by means of the Lorentz force that the magnetic field exerts on an electron orbiting the nucleus. In this so-called "normal" Zeeman effect, the spectral line splits into a line doublet (longitudinal Zeeman effect) parallel to the magnetic field and a line triplet (transversal Zeeman effect) perpendicular to the magnetic field. The term "anomalous" Zeeman effect refers to more complex splitting phenomena that remained unexplained till Goudsmit and Uhlenbeck postulated the existence of electron spin in 1925. Quantum mechanically, the anomalous Zeeman effect relates to the interaction of the magnetic field with the electron shell's magnetic moment generated by the orbital angular momentum and spin of the electrons. In this regard, the anomalous Zeeman effect represents the normal case and the normal Zeeman effect represents a special case.

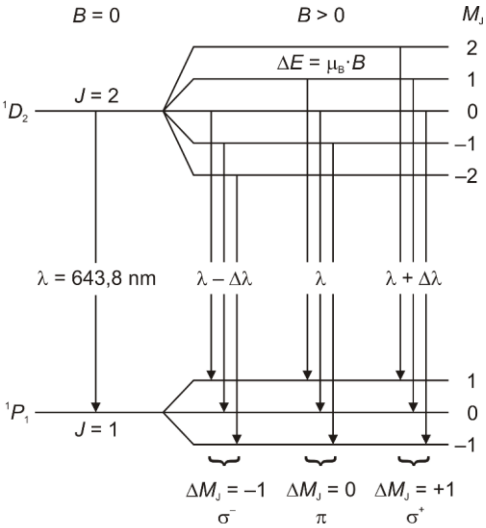

Fig. 2: Normal Zeeman effect in the red spectral line of cadmium. Splitting of energy levels and transitions permitted according to the selection rules for electrical dipole radiation.

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The normal Zeeman effect occurs only at the transitions between atomic states with the total spin ***S* = 0**. The total angular momentum ***J* = *L* + *S*** then corresponds to the orbital angular momentum, i.e. ***J* = *L***. It generates a magnetic moment

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

with Bohr's magneton

(2) $\mu_B = -\frac{1}{2} \cdot \frac{e}{m_e} \cdot \hbar$.

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

In an external magnetic field (Fig. 3)

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

the magnetic moment has the energy

(3) $E = \boldsymbol{\mu} \cdot \boldsymbol{B} = \mu_z \cdot B$

Due to space quantisation, the component J_z of the total angular momentum parallel to the magnetic field can only have the values

(4) $J_z = M_J \cdot \hbar$ with $M_J = -J, -(J-1), \ldots, (J-1), J$
J: total angular momentum quantum number

In this case, the energy level of the total angular momentum quantum number J thus splits into $2J+1$ equidistant components, which differ by the magnetic quantum number M_J (Fig. 2). With eq. (1), it follows that

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

Whereby according to eq. (3)

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

and finally with eq. (4):

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

Therefore the energy interval between adjacent levels is:

(9) $\Delta E = \mu_B \cdot B$.

The normal Zeeman effect can be observed in the red spectral line of cadmium. It corresponds to the transition $^1D_2 \rightarrow {^1P_1}$ with the wavelength λ = 643.8 nm (Fig. 2). According to eq. (4), level $^1D_2$ splits into five components and level $^1P_1$ splits into three components, each with the equidistant energy interval given by eq. (9.

According to the selection rules for electrical dipole radiation, the permissible transitions between these levels are ones with

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

whereby the light emitted is polarised as indicated above. Thus, we observe a total of three spectral lines (Fig. 2): one π component that is not shifted and, according to $E = \hbar \cdot \omega$, two π components shifted by

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

c: speed of light in vacuum

with a corresponding longer or shorter wavelength. In a magnetic field of flux density B = 1 T, applying equations (9) and (2) to equation (11) results in a shift of only $|\Delta\lambda|$ = 0.02 nm.

The spatial distribution of the emitted light is different for the π component and the two σ components. In classical terms, the case $\Delta M_J = 0$ corresponds to a Hertzian dipole oscillating parallel to the magnetic field. Accordingly, linearly polarised light is emitted perpendicular to the magnetic field, and no light is emitted parallel to the magnetic field (Fig. 3). The cases $\Delta M_J = \pm 1$ correspond to two dipoles oscillating perpendicularly to each other with a phase difference of 90°. Accordingly, light is emitted both parallel and perpendicular to the direction of the magnetic field. That light is circularly polarised parallel to the direction of the magnetic field, i.e. anti-clockwise circularly polarised for $\Delta M_J = -1$ and clockwise circularly polarised for $\Delta M_J = +1$.

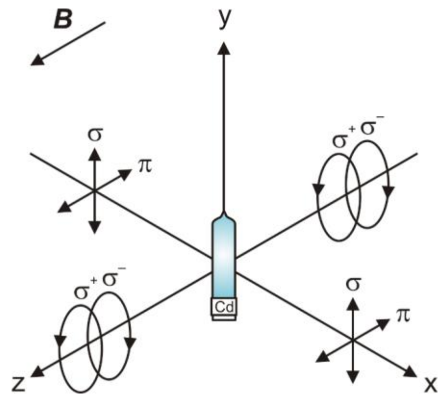

Fig. 3: Polarisation of electrical dipole radiation depending on the direction of travel

In the experiment, the splitting is observed using a digital camera fitted with a Fabry-Pérot etalon and imaging optics. The Fabry-Pérot etalon is designed to meet the resonance condition for the specific wavelength 643.8 nm of the red Cd line. As it passes through the Fabry-Pérot etalon, the light from the cadmium lamp creates interference rings that split like the spectral lines according to the external magnetic field and are recorded by the optics of the camera sensor. The electromagnets can be rotated on their axes to permit observation parallel or perpendicular to the external magnetic field.

In this first part of the experiment, we observe the splitting qualitatively and investigate the polarisation of the doublet and triplet components by means of the quarter-wavelength plate with polarising attachment and the polarisation filter.

Spectroscopy with a Fabry-Pérot interferometer falls within the scope of the second part of the experiment (UE5020700–2), which is described separately.

EQUIPMENT LIST

1	Cd lamp with accessories @230V	1021366 (U8557780-230)
or		
1	Cd lamp with accessories @115V	1021747 (U8557780-115)
1	U-shaped core D	1000979 (U8497215)
2	Coils D 900 taps	1012859 (U8497390)
1	Electromagnet accessory for Zeeman effect	1021365 (U8557770)
1	DC power supply 1 – 32 V, 0 – 20 A @230V	1012857 (U11827-230)

In countries with 110 – 120 V mains, a power supply that corresponds to power supply 1012857 is required

1	Set of 15 experiment leads, 75 cm, 1mm^2	1002840 (U13800)
1	Fabry-Pérot etalon	1020903 (U8557590)
2	Convex lens on rod, f = 100 mm	1003023 (U17102)
1	Quarter-wavelength plate on rod	1021353 (U22023)
1	Polarising attachment	1021364 (U8557760)
1	Polarisation filter on rod	1008668 (U22017)
1	Optical bench D, 100 cm	1002628 (U10300)
1	Set of feet for optical bench D	1012399 (U103041)
1	Optical base D	1009733 (U10319)
5	Optical slider D 90/36	1012401 (U103161)
1	Holder and filter for Moticam	1021367 (U8557790)
1	Digital camera Moticam 1	1021162 (U13160)

SAFETY INSTRUCTIONS

- Before setting up the experiment, read and follow the equipment instruction manuals and specifically the safety instructions therein.
- Protect the Cd lamp against mechanical impacts. Do not touch the glass bulb of the Cd lamp with your bare hands.
- Operate the Cd lamp using only the ballast unit supplied with the lamp. Before putting the Cd lamp mounted on the electromagnet into operation for the first time, be sure to establish the protective earth connection. To do so, use the yellow and green safety experiment lead (protective earth conductor) supplied to connect the PE socket of the ballast unit to the pole piece of the electromagnet accessory for Zeeman effect (1021365).
- Before putting the electromagnet into operation, ensure that the pole piece is correctly positioned as described in the instruction manual of the electromagnet accessory for Zeeman effect (1021365).

The coils are designed to carry a maximum current of 5 A for no more than 7 minutes. The current can be raised to as much as twice that value, 10 A, for up to 10 seconds.

- Set the maximum current to 5 A for no more than 7 minutes and higher currents up to 10 A for no more than 10 seconds.

GENERAL INSTRUCTIONS

The experiment is best conducted in a dark room, in order to minimise stray light from the surroundings and to achieve optimal illumination and optimal contrast of the live image of the digital camera.

“Motic Images Plus” software must be installed on the measurement computer.

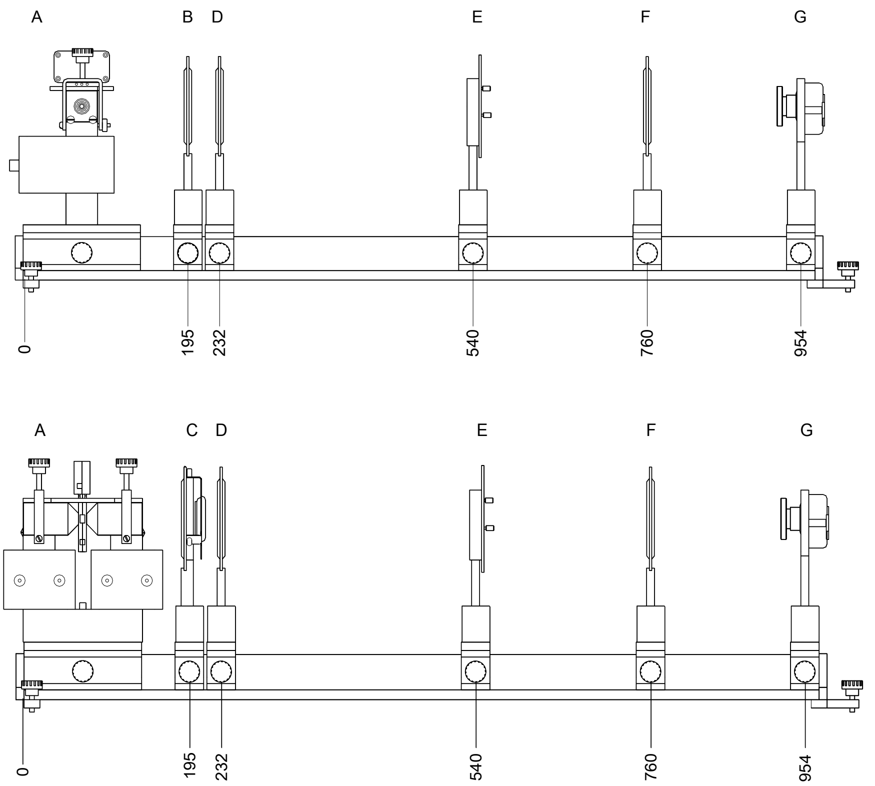

Fig. 4: Equipment set-up for the longitudinal (bottom) and transversal (top) Zeeman effect. A: Electromagnet with Cd lamp, B: Polarisation filter, C: Quarter-wavelength plate with polarising attachment, D: First convex lens *f* = 100 mm, E: Fabry-Pérot etalon, F: Second convex lens *f* = 100 mm, G: Camera module

SET-UP

Installation of the electromagnet and Cd lamp

- Mount the set of feet for optical bench (1012399) and place the optical bench on a level workspace.
- Position and fix the optical base (1009733) on the optical bench flush along the left end at the 0-millimetre mark (Fig. 4).
- Assemble the electromagnet in the longitudinal configuration (Fig. 4, bottom) on the optical base as described in the instruction manual of the electromagnet accessory for Zeeman effect (1021365).
- Mount the cadmium lamp to the electromagnet as described in the instruction manual of the Cd lamp with accessories (1021366 / 1021747).
- Use the supplied yellow and green safety experiment lead (protective earth conductor) to connect the PE socket of the Cd lamp ballast unit to the pole piece of the electromagnet.
- Use the 4-mm safety experiment lead to connect the Cd lamp to the ballast unit. Use the mains cable to connect the ballast unit to the mains power. Do not switch on the ballast unit yet.
- Connect the two coils of the electromagnet to the rear output (0 – 20 A) of DC power supply with opposing polarities (connect the “0” and “900” taps in each case) (Fig. 1). Use the mains cable to connect the DC power supply to the mains power. Do not switch on the DC power supply yet.

Installation of camera module and optics

- Assemble the camera module as described in the instruction manual of the holder and filter for Moticam (1021367).
- Mount the polarising attachment (1021364) to the quarter-wavelength plate (1021353) as described in the instruction manual.

The polarisation filter on rod (1008668), the two convex lenses on rod, *f* = 100 mm (1003023) and the Fabry-Pérot etalon (1020903) need no further assembly.

- Insert the camera module and the optics into the optical slider up to the stop, fix them in place, and position and adjust them on the optical bench one after the other as described below.

Putting the experiment into operation and making adjustments

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

After warming up for about 5 minutes, the Cd lamp reaches 90% of its light output.

- First position the camera module on the optical bench right in front of the electromagnet.
- Start the computer and use the USB cable to connect the camera module to the computer.
- Launch the Motic Images Plus application. Click “File” and select “Capture” in the window that opens.

The live image module opens in an extra window.

- In the basic settings, the system automatically selects the connected Moticam as “Motic MC35N Cam” with a resolution of 1280x720. If necessary, select the camera manually and click the “Open” button.

The live image is displayed.

- Manually select the exposure so no over-exposure occurs. Do not use the white compensation function, because it will compensate for the effect of the red filter.
- To optimise the live image, click on the “Extended settings” button. Enable “Eliminate noise” and set the value to 4. When using a Moticam 2, you can also click on “Extended functions”, select “Select exposure” in the menu that opens up, and enable “Priority image quality” and “50 Hz” in the window that opens up.
- If stray light impairs the live image, heavily darken the room accordingly.

The live image displays the stepped hole with the spot of the Cd lamp at the centre (Fig. 6 a).

- For the remaining adjustments, proceed as shown in Fig. 6 a – f (electromagnet, Cd lamp, camera module), 7 a, b (first convex lens), 8 a, b (second convex lens) and 9 a – e (Fabry-Pérot etalon).

Notes

If you slide the camera module along the optical bench, you might need to adjust its height and orientation along the optical axis by sliding it up or down and turning it in the optical slider. The position of the Moticam in the holder might require adjustment. To do so, loosen the attachment bracket slightly, shift the Moticam to the correct position, and re-tighten the attachment bracket by hand.

In the following section, focus relates to the lens of the Moticam camera module.

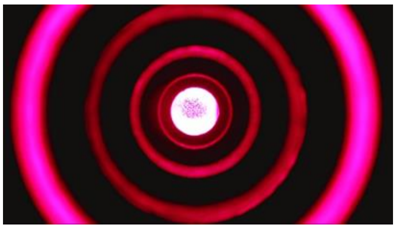

Fig. 6 a: Camera module positioned directly in front of the electromagnet. Stepped hole of the pole piece and Cd lamp spot appear concentric and centred.
Focus on the spot.

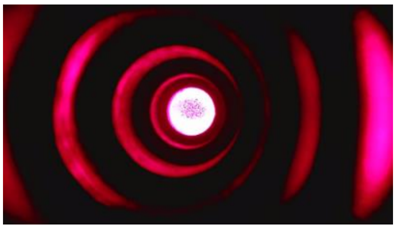

Fig. 6 b: Adjustment error: Electromagnet skewed. The stepped hole does not appear concentrically.

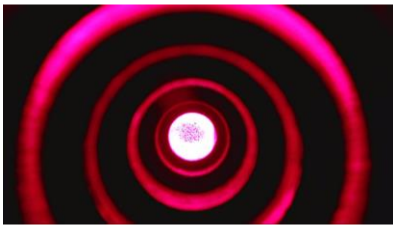

Fig. 6 c: Adjustment error: Camera module set too high in the optical slider

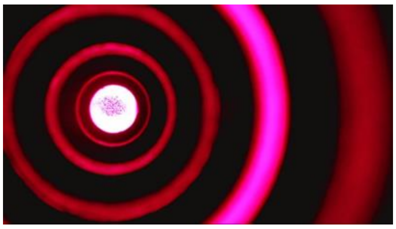

Fig. 6 d: Adjustment error: Camera module skewed in the optical slider

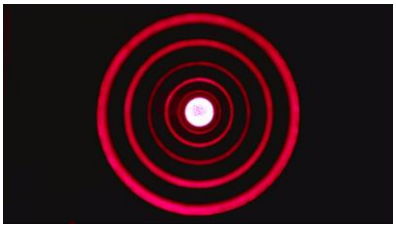

Fig. 6 e: Camera module pushed along the optical bench so far from the electromagnet that the image of the stepped hole fills the screen

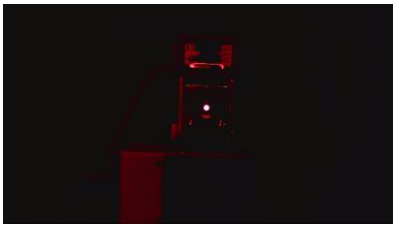

Fig. 6 f: Camera module pushed to the 954-mm position and fixed in place (cf. Fig. 4 g). Focus on the spot, which now appears only as a small point.

Fig. 7 a: First convex lens positioned and fixed in place at 232 mm on the optical bench (cf. Fig. 4 d). Stepped hole and spot appear enlarged, but do not fill the screen.

Fig. 7 b: Adjustment error: Convex lens skewed in the optical slider

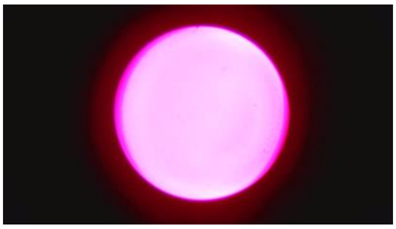

Fig. 8 a: Second convex lens positioned and fixed in place at 760 mm on the optical bench (cf. Fig. 4 f). The spot appears enlarged and nearly fills the screen.

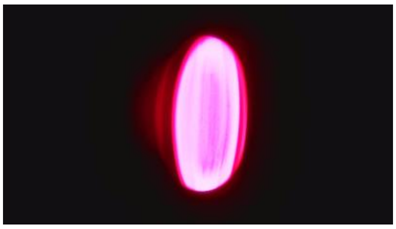

Fig. 8 b: Adjustment error: Convex lens skewed in the optical slider

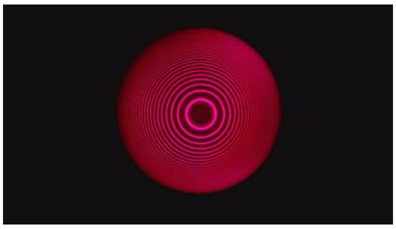

Fig. 9 a: Fabry-Pérot etalon positioned and fixed in place at 540 mm on the optical bench (cf. Fig. 4 e), interference rings appear in sharp focus.

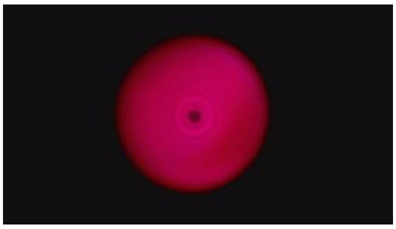

Fig. 9 b: Adjustment error: Poor focus

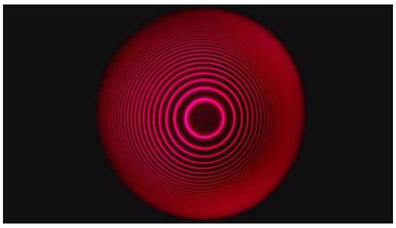

Fig. 9 c: Second convex lens pushed towards the camera module so the interference rings fill the screen. Focus adjusted accordingly.

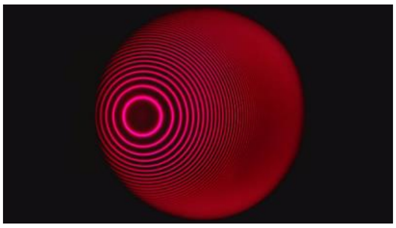

Fig. 9 d: Adjustment error: Etalon skewed in the optical slider.

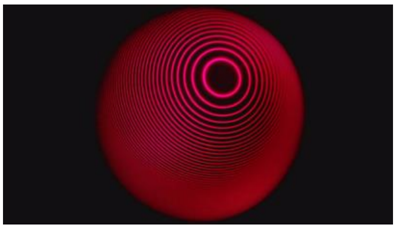

Fig. 9 e: Adjustment error: Etalon tilted. Correction: Reposition using the three adjustment screws in the housing.

PROCEDURE, MEASUREMENT EXAMPLE AND ANALYSIS

Longitudinal Zeeman effect

Carry out the following steps, observe how the interference rings change, and record screenshots (Fig. 10).

- Do not apply an external magnetic field.

The display shows only the interference rings generated by the Fabry-Pérot etalon, which correspond to the red Cd spectral lines (Fig. 10 a).

- Apply the external magnetic field. To do so, switch on the DC power supply and set the current supplied to the coils to 3.5 A.

The pattern splits into the line doublet displaying the two shifted components σ_- and σ_+. The π component that is not shifted does not appear (Fig. 10 b).

- With the magnetic field applied, position the quarter-wavelength plate with polarising attachment between the electromagnet and the convex lens (Fig. 4 c) and set it to –45°.

The σ_- component disappears (Fig. 10 c).

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

The σ_+ component disappears (Fig. 10 d).

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

Transversal Zeeman effect

- Rotate the electromagnet to orient the pole pieces perpendicular to the direction of the optical axis (Fig. 4, top).
- Do not apply an external magnetic field.

The display shows only the interference rings generated by the Fabry-Pérot etalon, which correspond to the red Cd spectral lines (Fig. 10 e).

- Apply the external magnetic field. To do so, switch on the DC power supply and set the current supplied to the coils to 3.5 A.

The pattern splits into the line triplet displaying the π component that is not shifted and the two shifted components σ_- and σ_+ (Fig. 10 f).

- With the magnetic field applied, position the polarisation 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. 10 g).

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

The two σ components disappear (Fig. 10 h).

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

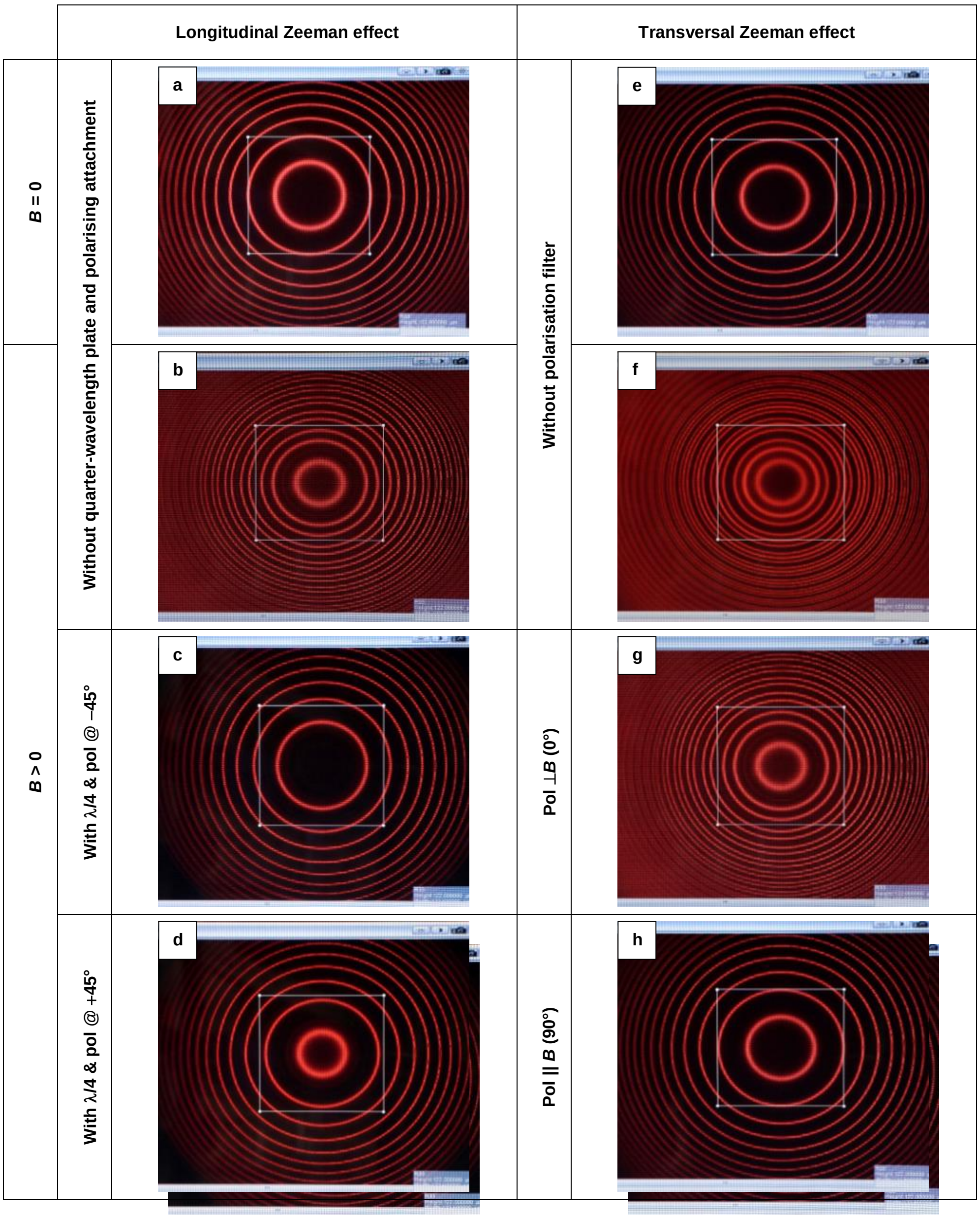

Fig. 10: Observation of the doublet and triplet splitting of the red cadmium line in an external magnetic field and investigation of polarisation, screenshots from the camera software. As an orientation aid, the second interference ring from the centre is indicated with a frame.