

Measuring the Zeeman splitting of the red cadmium line as a function of the magnetic field – spectroscopy using a Fabry-Perot etalon

Objects of the experiment

- Observing the Zeeman splitting with a Fabry-Perot interferometer – using a WebCam
- Determining Bohr's magneton μ_B and the specific electron charge $\frac{e}{m_e}$

Principles

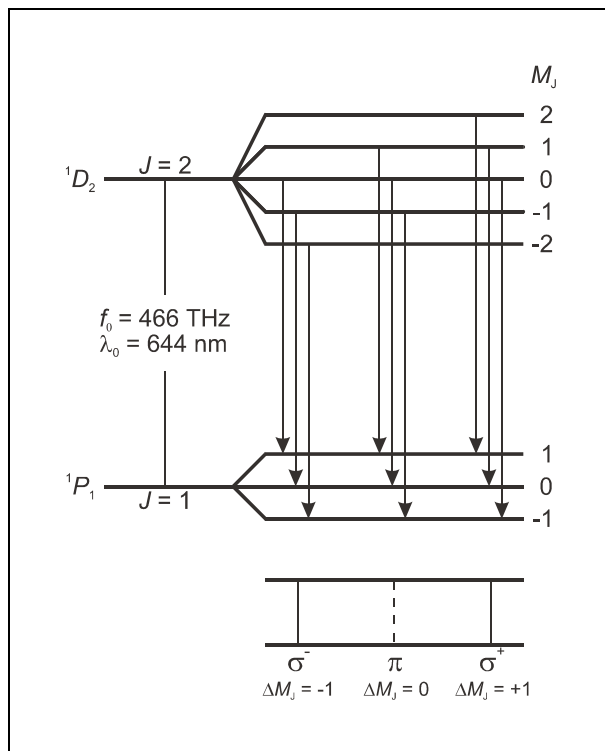


Fig. 1: Level splitting and transitions of the normal Zeeman effect in cadmium

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 $\mathbf{J} = \mathbf{L} + \mathbf{S}$ of a state is then a pure orbital angular momentum ($\mathbf{J} = \mathbf{L}$). For the corresponding magnetic moment, we can simply say that:

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

where

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

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

In an external magnetic field \mathbf{B} , the magnetic moment has the energy

$$E = -\mu \cdot \mathbf{B} \quad (\text{III})$$

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

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

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

$$\Delta E = -\mu_B \cdot B \quad (\text{V}).$$

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). 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:

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

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

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

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

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 $B = 1 \text{ T}$ by only $\Delta f = 14 \text{ GHz}$, respectively $\Delta \lambda = 0,02 \text{ nm}$.

In the experiment a *Fabry-Perot* etalon is used. This is a glass plate which is coplanar 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. 2). 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):

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

(Δ = optical path difference, d = thickness of the etalon, n = refractive index of the glass, k = order of interference)).

Using the 4 mm fused silica plate, the so called free spectral range of the etalon is 35 pm. The resolution depends on the reflectivity of the aluminized surfaces, and also on the surface flatness of the fused silica. Typically, this is something like 3 pm.

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 (150 mm), the aperture angle α corresponds to a radius r in the focal plane of that lens and the change in the angle $\delta \alpha$ to a change in the radius δr . Using an ocular, we can observe several circles in the focal plane, without magnetic field they indicate the different orders for interference, with magnetic field we see the splitting due to $\delta \lambda$.

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 each of the the circular fringe patterns.

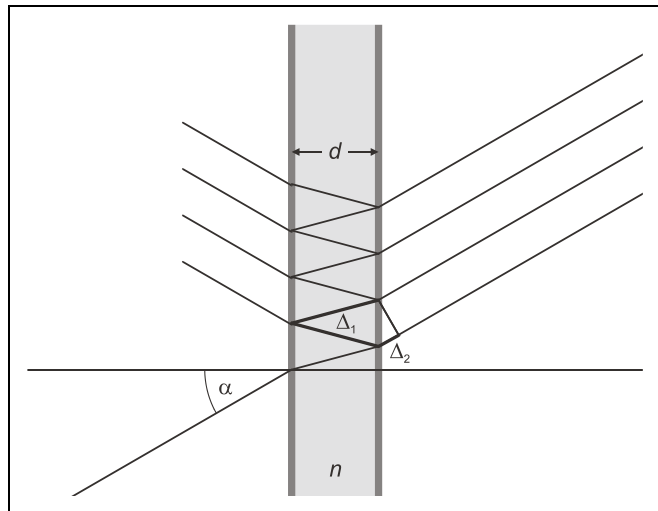


Fig. 2: *Fabry-Perot* etalon as an interference spectrometer.

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, the *Zeeman* splitting of the red cadmium line is measured as a function of the magnetic field B . The energy interval of the triplet components (see equations (II) and (V))

$$E = \frac{h}{4\pi} \frac{e}{m_e} \cdot B \quad (\text{VIII})$$

is used to calculate the specific electron charge.

To achieve spectroscopic separation of the *Zeeman* components of the red cadmium spectral line, the optical ring system of a *Fabry-Pérot* interferometer is first observed with the eye and then recorded using a webcam. The measurement of the splitting and ring diameters can be done both with the eye or later in the images recorded by the webcam.

Apparatus

1 Cadmium lamp	451 12
1 Universal choke in housing	451 30
1 High current power supply	521 55
1 U-core with yoke	562 11
2 Coils, 10 A, 480 turns	562 131
1 Pair of pole pieces with great bore	560 315
1 Fabry-Perot etalon.....	471 221
1 Precision optical bench, 1 m.....	460 32
1 Rider base with threads.....	460 381
6 Optics riders 60/50	460 373
2 Lenses, $f = +150$ mm.....	460 08
1 Holder for interference filters	468 41
1 Interference filter, 644 nm	468 400
1 WebCam USB	662 1584
1 Universal measuring instrument Physics.....	531 835
or	
1 Mobile-CASSY	524 005
1 Combi-B-sensor S	524 0381
1 Extension cable, 15-pole	501 11
1 Stand base, V-shape, 20 cm	300 02
1 Stand rod, 47 cm	300 42
1 LD-multiclamp	301 01
3 Connecting leads, 100 cm	501 33
<i>add. required</i> : PC with Windows 98 or higher	

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.

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.

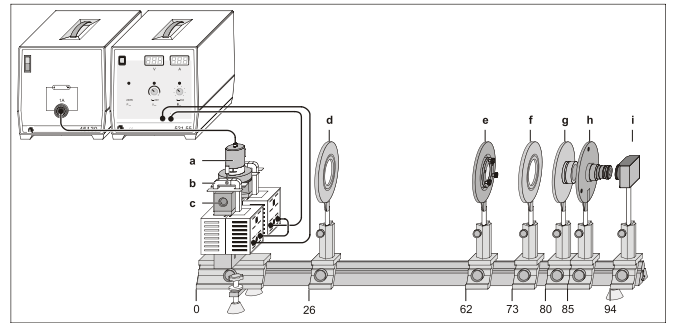
Set up

Fig. 3: 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 Interference filter in holder
- h Ocular
- i WebCam

The experimental setup in transverse configuration is illustrated in Fig. 3.

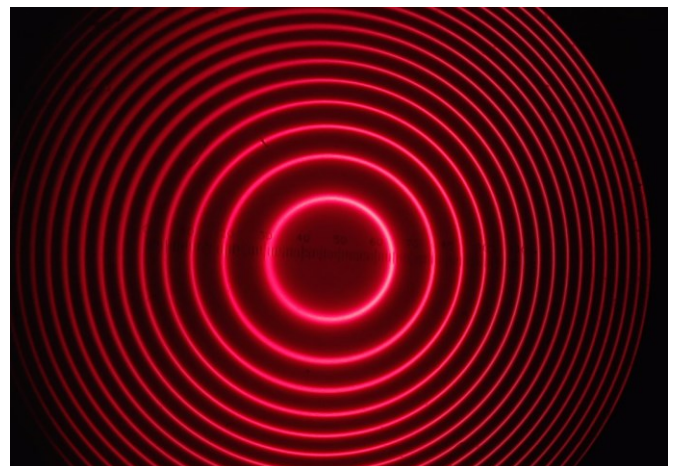


Fig.4: The ring system seen through the ocular at zero magnetic field. Note the horizontal measurement scale.

Mechanical 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. It must be possible to shift off and in the cadmium lamp with holding plate for measuring the magnetic field

Fix the pole pieces and the holding plate with the screws of the clamps.

Mount the B-sensor S with the help of the stand material, so that it is possible to hold the tangential probe vertically in the middle of the pole pieces.

Electrical connection:

Connect the coils of the electromagnet in series and then to the high current power supply.

Connect the B sensor S to the Universal measuring instrument Physics or the Mobile CASSY.

Connect the cadmium lamp to the universal choke.

Connect the WebCam to the computer. The computer will start to download the WebCam software and drivers automatically from the Internet.

Adjusting the observing optics:

Mount the optical components according to Fig. 3.

After switching on the universal choke wait 5 min until the light emission is sufficiently strong.

Use the ocular and your eye to adjust a sharp image of the ring system. First look through the ocular at any white surface and focus the ocular to see a sharp image of the measurement scale inside the ocular. Put the ocular in the setup and adjust the distance from the imaging lens (f) to the ocular to get a sharp image of the red ring system. Later the WebCam should replace your eye and look through the ocular.

WebCam:

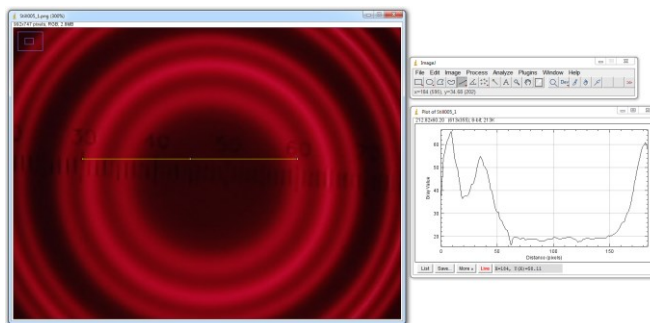
There are two different programs used in the evaluation. First, a so called Capture software (for example Logitech Capture when using a Logitech Webcam) is used to record the images taken by the webcam. This software is provided by the webcam manufacturer and automatically downloaded and installed upon the first connection. It can display the signals from the webcam, take snapshots and store them on disc. Verify the webcam works and normal pictures can be recorded and stored on disc.

Second, we use a software called ImageJ for evaluation of the red ring images stored on disc.

Go to <https://imagej.nih.gov/ij/download.html> and download the "ImageJ bundled with Java" package, extract that folder. Later we will run ImageJ.exe, which will start Java if necessary.

Calibration of Distance

Take an image of the red rings with the measurement scale clearly visible.



Start ImageJ and load that image. Use the line tool to draw a line at some clearly visible parts of the measurement scale (Here 30 and 60, so the focal plane separation is 3 mm). Select Analyze/Plot Profile and note the total width of the displayed Plot by moving the cursor to the rightmost position and reading the $X = 184$ value below the plot. In this example, we know that 184 pixels are equal to 3 mm distance and can use this value later.

Carrying out the experiment**a) Measuring the magnetic field**

Hold the tangential probe vertically in the center of the pole pieces, while the cadmium lamp is not mounted.

Increase the current through the coils and measure the magnetic field in dependency of the current, see. Table 1. This way, we created a calibration for the magnetic field.

b) Measuring the splitting of the cadmium line

Cautiously insert the cadmium lamp between the pole pieces without changing the distance of the pole pieces (see Mechanical setup). Any changes in the optic will invalidate the distance calibration described above.

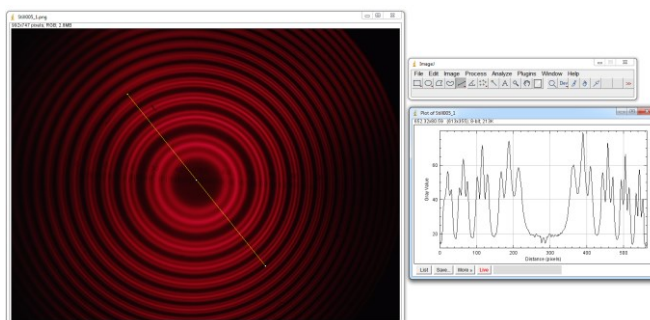
Make sure the pole pieces are securely fastened, they must not move when the magnetic field is switched on.

Using the Capture software, adjust the image in brightness and contrast to get a good looking picture.

Take several images at different current settings and therefore magnetic fields. Note the lamp will be brighter at high magnetic fields due to changes in the discharge, this is normal and might require some exposure corrections in the software.

Shut down the current through the magnet and the Cadmium lamp and start to evaluate the images recorded. Note the coils will heat up due to the high currents, so better shut down the current.

Use ImageJ to evaluate the images recorded.



The image shown was recorded at 3.5 A.

To calculate the splitting, we need to measure the diameter of each ring. Use the line tool first to draw a line through the center of the image and open the Analyze/Plot window. Then use the line tool in the plot window to draw a line from one

center peak to the other side, measuring the diameter of this ring.

In the example shown the diameter of the unsplit inner ring (π) is 200.9 pixels, while the smaller ring is 148.83 pixels wide, and the outer ring is 242.78 pixels in diameter ($\sigma+$ and $\sigma-$).

Using the distance scaling (184 pixel = 3 mm) and the focal length of the imaging lens (150 mm), we can calculate the angles α in air and using $\frac{\sin \alpha}{\sin \beta} = n = 1.46$ the angles β inside the fused silica etalon.

Diameter	Radius	Angle in air	Angle in silica
Pixels	mm	rad	rad
200,9	1,63777174	0,01091804	0,00747803
148,83	1,21328804	0,00808841	0,00553998
242,78	1,97918478	0,0131938	0,00903671

Now we use

$$\frac{\Delta \lambda}{\lambda} = \frac{\cos \beta_2}{\cos \beta_1} - 1$$

To calculate the splitting,

	$\delta\lambda/\lambda$	$\delta\lambda / \text{pm}$	$\Delta E / \mu\text{eV}$
149 – 201	-1,26E-05	-8,12	-24,29
243 – 201	1,29E-05	8,29	24,78

and

$$\Delta E \approx \frac{-\Delta \lambda}{\lambda} \cdot E = -hc \cdot \frac{\Delta \lambda}{\lambda^2} \text{ with } \lambda = 643.8 \text{ nm and}$$

1.9256779 eV for the Cd line to convert the measured splitting in either pm differences in wavelength or μeV differences in energy.

The same measurement could be done with the higher order rings visible in this image.

For the different magnetic fields, we need to measure the splitting in each of the recorded images.

.Measuring example

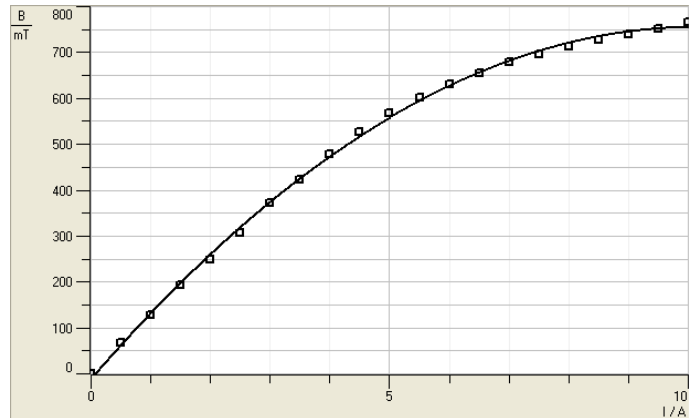
a) Calibrating the magnetic field

Tab. 1: Magnetic field B vs. current I

$\frac{I}{\text{A}}$	$\frac{B}{\text{mT}}$	$\frac{I}{\text{A}}$	$\frac{B}{\text{mT}}$
0.0	0		
0.5	68	5.5	601
1.0	127	6.0	631
1.5	194	6.5	655
2.0	249	7.0	678
2.5	307	7.5	695
3.0	373	8.0	713
3.5	423	8.5	728
4.0	479	9.0	739

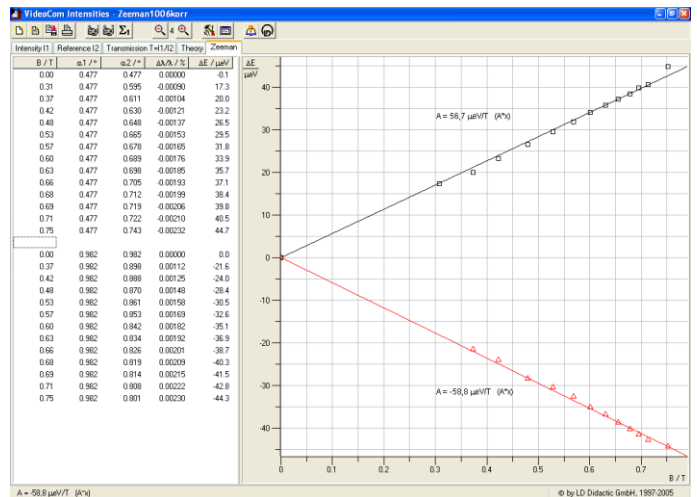
4.5	528	9.5	752
5.0	569	10.0	765

Diagramm 1: Magnetic field B vs. current I



b) Measuring the splitting of the cadmium line

Fig. 5: Screenshot “Zeeman” table with diagramm



Evaluation

The gradients A for $\sigma+$ or $\sigma-$ components of the curves are:

$$A = 56.7 \frac{\mu\text{eV}}{\text{T}} \text{ and } A = -58.8 \frac{\mu\text{eV}}{\text{T}}$$

The mean value gives Bohr’s magneton:

$$\mu_B = 57.8 \frac{\mu\text{eV}}{\text{T}} = 9.26 \cdot 10^{-24} \frac{\text{Js}}{\text{T}}$$

With $h = 6.626 \cdot 10^{-34} \text{ Js}$:

$$\frac{e}{m_e} = \frac{4\pi \mu_B}{h} = 1.76 \cdot 10^{11} \frac{\text{C}}{\text{kg}}$$

Literature values:

$$\mu_B = 57.9 \frac{\mu\text{eV}}{\text{T}}$$

$$\frac{e}{m_e} = 1.759 \cdot 10^{11} \frac{\text{C}}{\text{kg}}$$

Measuring the Zeeman splitting of the red cadmium line as a function of the magnetic field – spectroscopy using a Fabry-Perot etalon

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- Determining Bohr's magneton μ_B and the specific electron charge $\frac{e}{m_e}$

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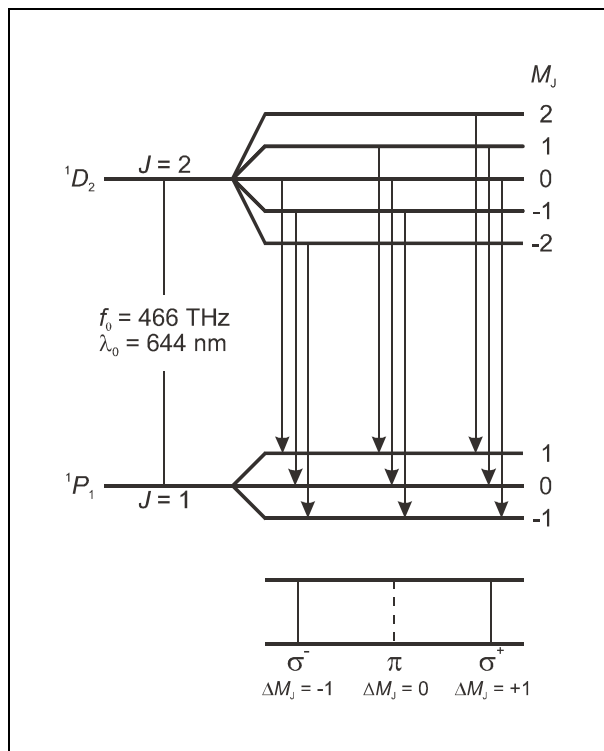


Fig. 1: Level splitting and transitions of the normal Zeeman effect in cadmium

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

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

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

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

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In the experiment a *Fabry-Perot* etalon is used. This is a glass plate which is coplanar 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. 2). 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):

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

(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.

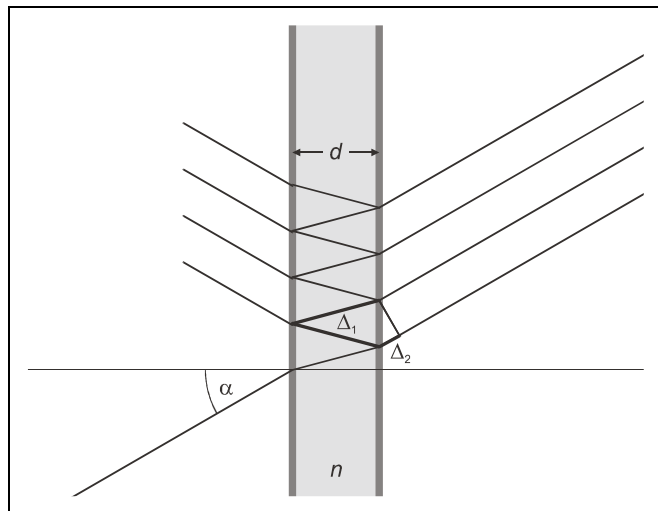


Fig. 2: *Fabry-Perot* etalon as an interference spectrometer.

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, the *Zeeman* splitting of the red cadmium line is measured as a function of the magnetic field B . The energy interval of the triplet components (see equations (II) and (V))

$$E = \frac{h}{4\pi} \frac{e}{m_e} \cdot B \quad (\text{VIII})$$

is used to calculate the specific electron charge.

To achieve spectroscopic separation of the *Zeeman* components of the red cadmium spectral line, the optical ring system of a *Fabry-Pérot* interferometer is imaged on the Video-Com CCD (without camera lens) using an imaging lens. The CCD detects a diametrical section through the optical ring system.

Apparatus

1 Cadmium lamp	451 12
1 Universal choke in housing	451 30
1 High current power supply	521 55
1 U-core with yoke	562 11
2 Coils, 10 A, 480 turns	562 131
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Do not touch any current-carrying (live!) parts.

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.

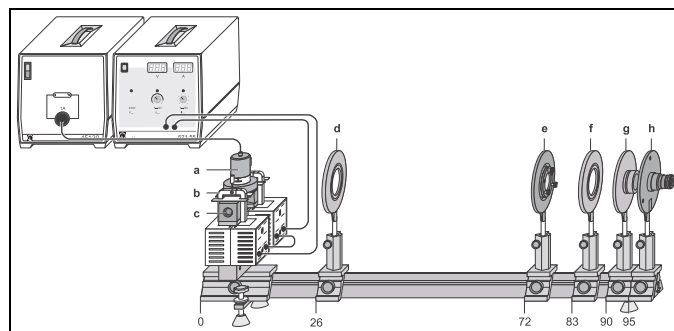
Set up

Fig. 3: 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 Interference filter in holder
- h VideoCom (it is helpful to use an ocular for adjustment)

The complete experimental setup in transverse configuration is illustrated in Fig. 3.

Mechanical 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. It must be possible to shift off and in the cadmium lamp with holding plate for measuring the magnetic field

Fix the pole pieces and the holding plate with the screws of the clamps.

Mount the B-sensor S with the help of the stand material, so that it is possible to hold the tangential probe vertically in the middle of the pole pieces.

Electrical connection:

Connect the coils of the electromagnet in series and then to the high current power supply.

Connect the B sensor S to the Universal measuring instrument Physics or the Mobile CASSY.

Connect the cadmium lamp to the universal choke.

Connect the VideoCom to the computer.

Adjusting the observing optics:

Mount the optical components according to Fig. 3.

After switching on the universal choke wait 5 min until the light emission is sufficiently strong.

If available, use first an ocular (e.g. 460 135 Ocular with scale) to get a sharp image of the ring system. Later on, the CCD of the VideoCom should be placed in the optical plane this image is located.

VideoCom:

It is possible to optimize the exposure time so that the peaks have an intensity of approximately 50 %.

To ensure that the CCD is in the focal plane of the imaging lens, move the imaging lens along the optical axis until the peaks of the observed curve are sharply imaged and show the maximum intensity. The center of the ring system must then be imaged on the CCD line. For this, you can either move VideoCom perpendicular to the optical axis or tilt the etalon slightly using the adjusting screws. You have found the center of the ring system when further adjustment does not cause any more peaks to emerge and the two central peaks (left and right intersections of the innermost rings) are the maximum distance apart.

Move the condenser lens until you obtain the most uniform possible illumination of the entire CCD line, so that the maxima in the middle are nearly at the same intensity (see Fig. 4).

Calibration of VideoCom

For angular calibration, the focal length of the imaging lens is specified (here $f = 150$ mm). To shift the zero point, determine the angles of the two central peaks using the function "Calculate Peak Center" and enter the negative mean value of the two peak centers manually. This sets the center of the ring system to 0° on the angular scale.

Carrying out the experiment**a) Measuring the magnetic field**

Hold the tangential probe vertically in the center of the pole pieces, while the cadmium lamp is not mounted.

Increase the current through the coils and measure the magnetic field in dependency of the current, see. Table 1.

b) Measuring the splitting of the cadmium line

Cautiously insert the cadmium lamp between the pole pieces without changing the distance of the pole pieces (see Mechanical setup). Start the software "VideoComInt" and adjust the observing optics.

The intensity of the peak should be around 50 % (adjust this if necessary as the luminance of the Cd lamp changes in the magnetic field).

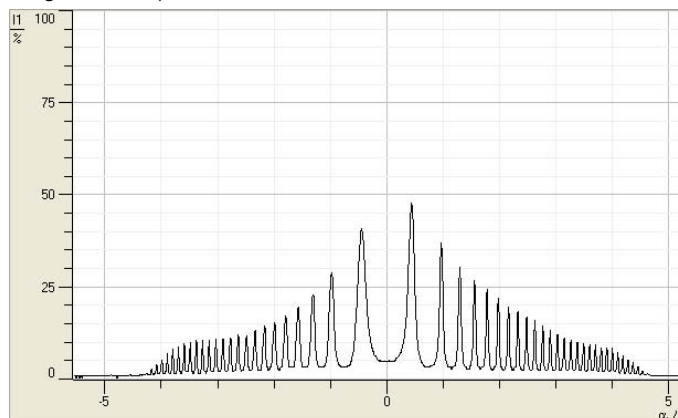


Fig.4: Intensity vs. angle without magnetic field

The table "Zeeman" is provided for evaluation; switch to this table by clicking on the corresponding tab. This table contains columns for the magnetic field B , the angle α_1 of the non-displaced line (π -component), the angle α_2 of the displaced line ($\sigma+$ or $\sigma-$) and the corresponding wavelength and energy shifts. These last two values are calculated automatically after entry of α_1 and α_2 using

$$\frac{\Delta\lambda}{\lambda} = \frac{\cos\beta_2}{\cos\beta_1} - 1 \quad \text{with} \quad \frac{\sin\alpha}{\sin\beta} = n = 1.46 \quad \text{for the etalon and}$$

$$\Delta E \approx \frac{-\Delta\lambda}{\lambda} \cdot E = -hc \cdot \frac{\Delta\lambda}{\lambda^2} \quad \text{with} \quad \lambda = 643.8 \text{ nm for the Cd}$$

line.

Start the evaluation by marking a peak (π) with "Calculate Peak Center". Transfer this value to the "Zeeman" table by dragging it from the status line to column α_1 of the table (drag and drop). To determine the origin in the diagram, drag the value to column α_2 as well and enter the value 0 in column B (non-displaced ring without magnetic field).

Next, examine the ring as it is split in the magnetic field ($\sigma+$ or $\sigma-$). Once again, determine the displaced angle α_2 using "Calculate Peak Center" and drag it to column α_2 in the "Zeeman" table. The non-displaced angle α_1 remains unchanged (you can e.g. import it from a previous measurement using drag and drop), and the magnetic flux density is entered. Using these values, the software calculates the percentage shift in wavelength and the energy split. Additionally, the corresponding point is plotted in the diagram. (To confirm the effect for other rings at equal flux densities or for repetition with different flux densities, it is necessary to examine peaks with identical components ($\sigma+$ or $\sigma-$) each time.)

To get the gradients of the line splitting fit straight lines through the measured points.

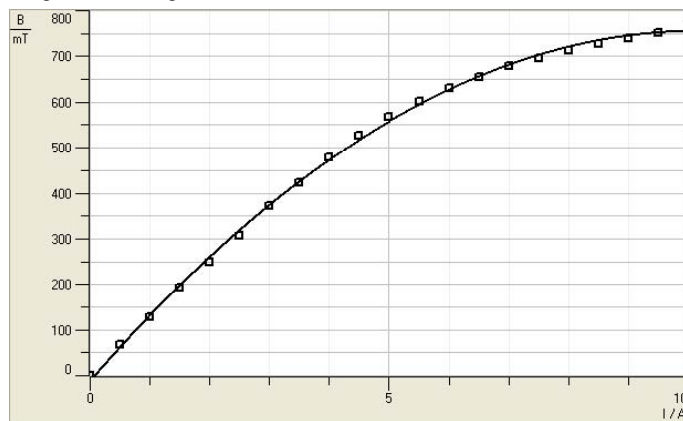
Measuring example

a) Measuring the magnetic field

Tab. 1: Magnetic field B vs. current I

$\frac{I}{A}$	$\frac{B}{mT}$	$\frac{I}{A}$	$\frac{B}{mT}$
0.0	0		
0.5	68	5.5	601
1.0	127	6.0	631
1.5	194	6.5	655
2.0	249	7.0	678
2.5	307	7.5	695
3.0	373	8.0	713
3.5	423	8.5	728
4.0	479	9.0	739
4.5	528	9.5	752
5.0	569	10.0	765

Diagramm 1: Magnetic field B vs. current I



Evaluation

The gradients A for σ_+ or σ_- components of the curves are:

$$A = 56.7 \frac{\mu\text{eV}}{\text{T}} \text{ and } A = -58.8 \frac{\mu\text{eV}}{\text{T}}$$

The mean value gives *Bohr's* magneton:

$$\mu_B = 57.8 \frac{\mu\text{eV}}{\text{T}} = 9.26 \cdot 10^{-24} \frac{\text{Js}}{\text{T}}$$

With $h = 6.626 \cdot 10^{-34} \text{ Js}$:

$$\frac{e}{m_e} = \frac{4\pi \mu_B}{h} = 1.76 \cdot 10^{11} \frac{\text{C}}{\text{kg}}$$

Literature values:

$$\mu_B = 57.9 \frac{\mu\text{eV}}{\text{T}}$$

$$\frac{e}{m_e} = 1.759 \cdot 10^{11} \frac{\text{C}}{\text{kg}}$$

b) Measuring the splitting of the cadmium line

Fig. 5: Screenshot "Zeeman" table with diagramm

