Optical pumping: measuring and observing the Zeeman transitions in the ground state of Rb-87 with σ^+- and σ^--pumped light

Objects of the experiment

- Observation of Zeeman transitions in the ground state of ^{87}Rb with σ^+- and σ^-- pumping light.
- Determination of the nuclear spin *I* of ^{87}Rb.
- Assignment of the transitions and determination of the transition frequencies.

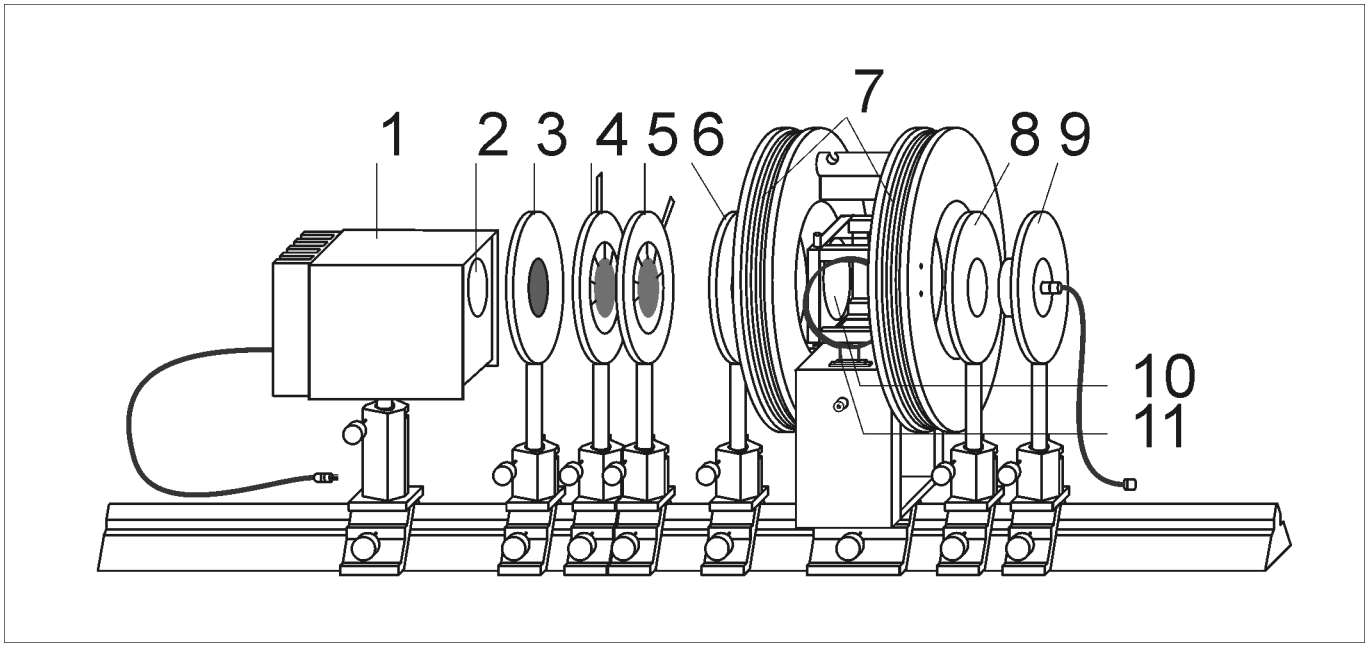

Fig. 1: Optical and magnetic components for the experiment "optical pumping"

1 Rubidium high-frequency lamp
2 Lens, f = + 50 mm
3 Line filter, 795 nm
4 Polarisation filter for red radiation
5 Quarter wavelength panel, 200 nm
6 Lens on brass stem, f = + 100 mm
7 Helmholtz coils, pair
8 Lens on brass stem, f = + 50 mm
9 Silicon photodetector
10 Absorption chamber with rubidium absorption cell
11 High-frequency coils

Method

Optical pumping [1,2,3] permits spectroscopic analysis of atomic energy states in an energy range not accessible to direct optical observation.

In weak magnetic fields, the differences in the population number between the Zeeman levels in the ground state of ^{87}Rb are extremely slight, as the energy interval is less than 10^{-8} eV. Optical pumping produces a population which deviates greatly from the thermal equilibrium population. To accomplish this, rubidium vapor is irradiated in an absorption cell with the circularly polarized component of the D_1 light from a rubidium lamp. The population of the Zeeman level depends on the polarity of the incident light. When the cell is irradiated with a high-frequency alternating magnetic field, we observe a change in the transparency of the rubidium vapor for rubidium-D_1 light.

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A rubidium high-frequency lamp is used as the pumping light source. Rubidium atoms in a glass ampule are excited in the electromagnetic field of an HF transmitter.

The combination of an interference filter, a polarisation filter and a quarter-wavelength panel separate the desired circularly polarized component of the D_1 line from the emission spectrum of the light source. Depending on the position of the quarter wavelength panel, we obtain either σ^+ or σ^- polarisation.

A system of convex lenses focuses the pumping light on the center of the absorption cell (also filled with rubidium vapor) and the transmitted component of the pumping light on a photodetector (cf. Fig.4).

The Zeeman magnetic field is generated using Helmholtz coils. Depending on the polarity of the coil current, the field lines are oriented either parallel or antiparallel to the optical radiation.

Using the high-frequency coil pair, it is possible to generate a high-frequency alternating field perpendicular to the Zeeman magnetic field. When its frequency corresponds to the energy difference of two adjacent Zeeman levels, transition between the levels can occur. The populations of the Zeeman levels, and thus the transparency of the rubidium vapor, change.

To determine the change in transparency, the intensity of the transmitted light is measured using a silicon photodetector. A current/voltage converter amplifies its output signal. The transmitted intensity is recorded as a function of the frequency of the irradiated high-frequency field. This frequency is varied in a linear fashion between a user-definable start frequency and stop frequency using a function generator.

Physical principles

In its ground state, rubidium, like all alkali metals, has a total spin of the electron shell with the spin quantum number $J = \frac{1}{2}$. The ground state thus splits into two hyperfine states with the total angular momenta $F = I + \frac{1}{2}$ and $F = I - \frac{1}{2}$ respectively.

In the magnetic field, the hyperfine states are each split into $2F+1$ Zeeman levels with the magnetic quantum numbers $m_F = -F,...,F$. Fig. 2 shows an example of the level diagram for ^{87}Rb.

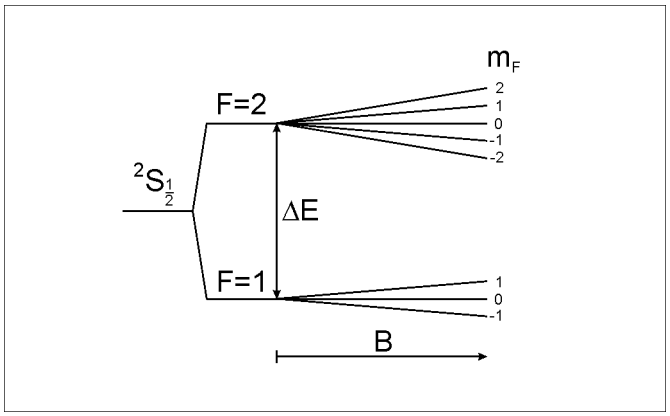

Fig. 2 Schematic representation of Zeeman levels in the ground state of ^{87}Rb Hyperfine splitting ΔE and Zeeman splitting are not drawn to scale.

The energy E of the Zeeman levels can be calculated for the magnetic fields used here with the help of the Breit-Rabi formula [4,5]:

For $F = I \pm \frac{1}{2}$

$$E(F,m_F) = -\frac{\Delta E}{2(2I+1)} + \mu_K g_I B m_F \pm \frac{\Delta E}{2}\left(1 + \frac{4m_F}{2I+1}\xi + \xi^2\right)^{\frac{1}{2}}$$

where $\xi = \frac{g_J \mu_B - g_I \mu_K}{\Delta E} B$ (I)

F : Total angular momentum

I : Nuclear spin

J : Angular momentum of the electron shell

m_F : Magnetic quantum number of the total angular momentum F

g_I : g-factor of the nucleus

g_J : g-factor of the electron shell

ΔE : Hyperfine structure spacing

μ_B : Bohr magneton

μ_K : Nuclear magneton

B : Magnetic flux density

When irradiated with σ^+ pumping light, the Zeeman levels within a hyperfine state which have positive quantum numbers m_F become enriched at the expense of the levels with negative quantum numbers. In the ground state ^{87}Rb for example, the level with $F = 2$, $m_F = +F$ has the greatest population. The result is a population which deviates from the thermal equilibrium population.

When irradiated with a linearly polarized alternating magnetic field of the correct frequency, more transitions take place from a higher Zeeman level m_F to the next lowest level with $m_F - 1$ than in the other direction. With σ^- pumping light, the situation is just the opposite, as the Zeeman levels with negative quantum numbers predominate.

The frequency f of these transitions is always

$$f(m_F \leftrightarrow m_F - 1) = \pm\frac{\mu_K g_I B}{h} + \frac{\Delta E}{2h}\left(\left(1 + \frac{4m_F}{2I+1}\xi + \xi^2\right)^{\frac{1}{2}} - \left(1 + \frac{4(m_F-1)}{2I+1}\xi + \xi^2\right)^{\frac{1}{2}}\right) \quad \text{(II)}$$

Safety notes

Protecting individuals

Danger of scalding: hot water can leak from insecurely fastened or defective water tubing between the circulation thermostat and the absorption chamber:

- Use only silicon tubing of the specified diameter.
- Clamp the tubes in the holder between the Helmholtz coils and secure them against slippage.

Protecting the equipment

The absorption chamber is made of acrylic glass and can be destroyed by heat:

- Fill the absorption chamber with distilled water only.
- Do not heat the absorption chamber above 80℃.
- Never clean the absorption chamber with solvents.

The homogeneity of the Helmholtz field is impaired if the Helmholtz coil cores become deformed:

- Protect Helmholtz coils from shocks or knocks.

The HF transmitter in the rubidium high-frequency lamp can be destroyed by excessive voltage levels:

- Only operate the rubidium high-frequency lamp with the operation device.

For best experiment results

The experiment setup is sensitive to interfering magnetic fields:

- Keep all power supplies and measuring instruments as far away from the experiment setup as possible.
- Remove ferromagnetic materials or devices which generate magnetic fields from the vicinity of the experiment setup.
- Use only lenses on brass stems (460 021 and 460 031).

Room lighting can drown out the measurement signal at the silicon photodetector. External light unnecessarily raises the DC component of the photodetector signal:

- Switch off the electric lighting in the room.
- Prevent the incidence of external light.
- Darken the experiment room.
- Turn the reflective side of the line filter so that it faces the rubidium high-frequency lamp.

The direction of flow of the heating water in the absorption chamber is determined by the experiment setup:

- Make sure the water inlets and outlets are connected in the proper direction.

High frequencies interfere with voltage-sensitive measuring instruments:

- Do not put a disassembled rubidium high-frequency lamp in operation.

Equipment list

1	Rubidium high-frequency lamp	558 823
1	Pair of Helmholtz coils on stand rider	558 826
1	Absorption chamber with rubidium absorption cell	558 833
1	Silicon photodetector	558 835
1	I/U converter for silicon photodetector	558 836
1	Operation device for optical pumping	558 814
1	Function generator 1mHz - 12 MHz	522 551
1	DC power supply, 0...±15 V	521 45
1	Circulation thermostat, +30℃ to +100℃	666 768
1	Digital storage oscilloscope, e.g.	575 294
1	Plug-in power unit, 9,2V-, regulated	530 88
1	Digital-Analog Multimeter MetraHit24S	531 281
1	Two-way switch	504 48
1	Optical bench, standard cross-section, 1m	460 32
1	Line filter, 795 nm	468 000
1	Polarisation filter for red radiation	472 410
1	Quarter wavelength panel, 200 nm	472 611
1	Lenses on brass stem, f = +50 mm	460 021
1	Lens on brass stem, f = +100 mm	460 031
6	Optical riders 60/34	460 370
1	Optical rider 95/50	460 374
2	Silicone tubing, 1,5 m long, 6,0x2,0	LN-Nr. 20066843
4	Connecting leads, black 50 cm	501 28
2	Connecting lead, black 200 cm	501 38
3	BNC cables, 1 m	501 02
1	BNC cables, 2 m	501 022

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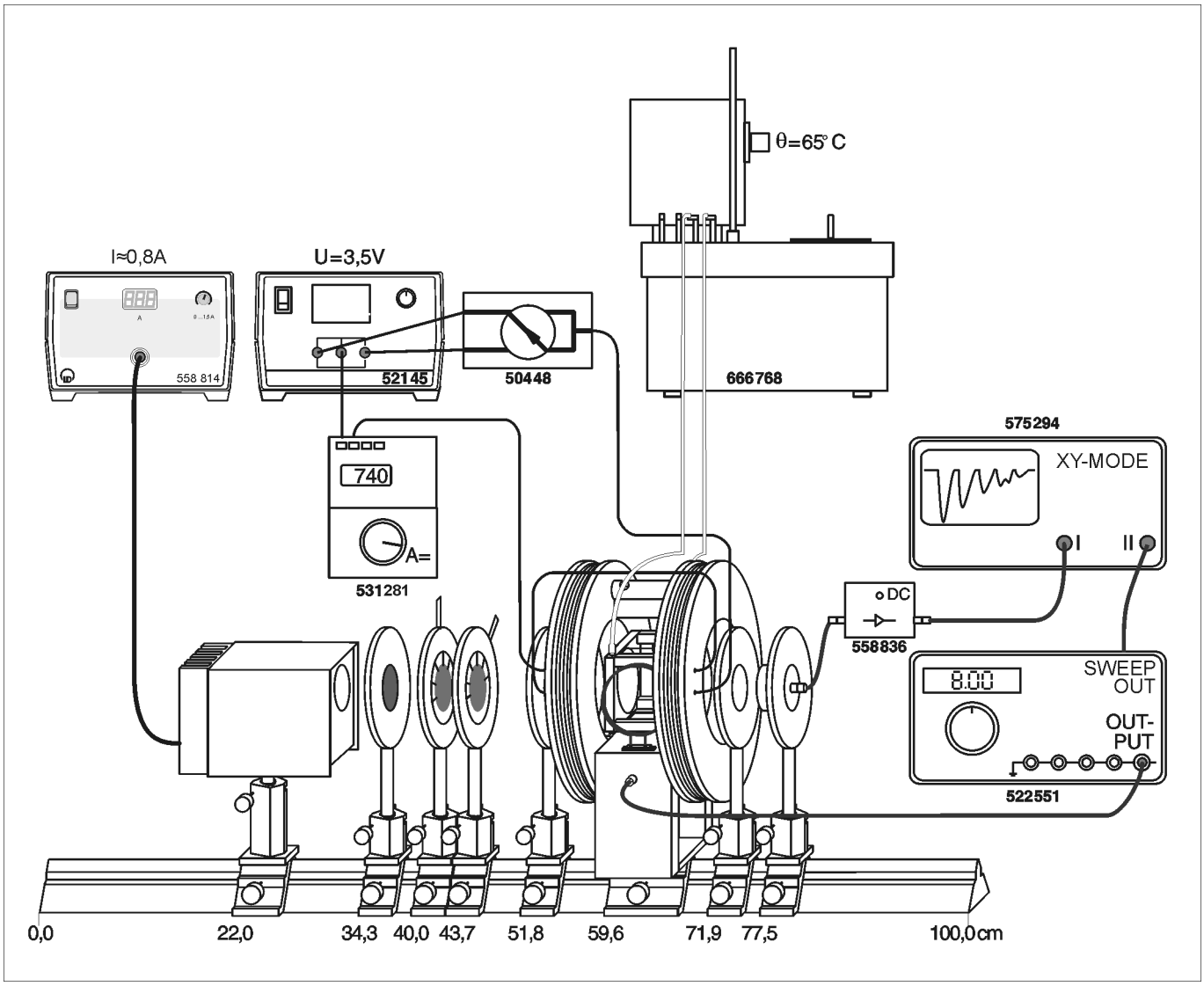

Fig.3: Overview diagram of the entire experiment setup; position specifications are measured from the left edge of the optical riders.

Setup

Optical and electrical setup

- Set up the optical and magnetic components on the optical bench with standard cross-section (460 32) as shown in Fig. 1 and Fig. 3.
- Connect the rubidium high-frequency lamp with the operation device for optical pumping (558 814).
- Connect the Helmholtz coils and the multimeter (531 281) in series to the power supply (521 45).
- Insert the two-way switch (504 48) in the circuit to permit easy reversal of the magnetic field.
- Connect the output of the function generator (522 551) to the HF coils.
- Connect the photodetector output to channel I of the oscilloscope (575 294) via the I/U converter (558 836).
- Connect Sweep Out of the function generator with channel II of the oscilloscope.

Warming up the system

- Using silicon tubing, set up a heating water circuit between the absorption chamber and the circulation thermostat (666 768) as shown in Fig.3.
- Switch on the circulation thermostat and set the temperature θ to 65°C.
- Switch on the operation device for optical pumping and set the operating current to approx. 0,8 A (cf. instruction sheet for the rubidium high-frequency lamp 558 823).
- Switch on the stabilized power supply.
- Wait at least 15 min. until the operating temperature is reached.

If the light output of the rubidium high-frequency lamp is unstable:

- Increase the operating current by approx. 0,1 A.

Initial optical adjustment

- Remove the optical riders with line filter, polarisation filter and quarter wavelength panel from the optical bench.
- Remove the absorption chamber from the stand rider for the Helmholtz coils.
- Hold a white piece of paper in place of the absorption cell at the midpoint between the Helmholtz coils.
- Move the lense (6) and the rubidium high-frequency lamp so that the smallest possible evenly illuminated light spot is obtained (cf. Fig. 4).
- Remove the optical rider with the silicon photodetector from the optical bench.
- Using the piece of paper, find the point with the smallest evenly illuminated light spot.
- Move lens (8) to improve the illumination (cf. Fig.4).
- Mount the silicon photodetector at the point where the piece of paper is.

When the initial adjustment is complete:

- Remount all components you have removed on the optical bench.

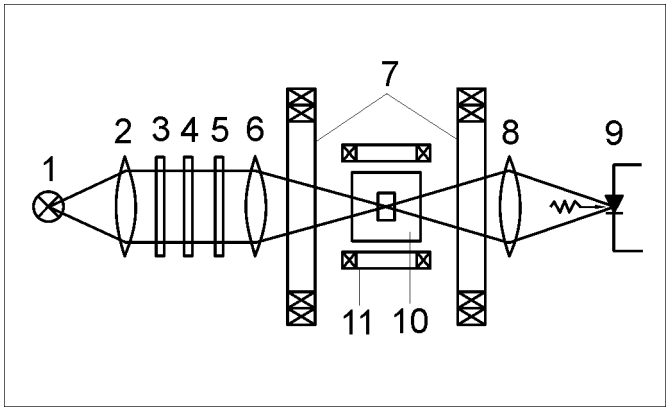

Fig. 4 Schematic representation of the radiation path in optical pumping. For designations of the optical and magnetic components see Fig. 1.

Fine adjustment

To obtain the maximum light intensity at the silicon photodetector:

- Observe the photodetector signal at the oscilloscope.
- Alternately adjust the height and position of the rubidium high-frequency lamp, lenses (6) and (8), the absorption chamber and the silicon photodetector so as to obtain the maximum photodetector signal.
- If necessary, use the offset potentiometer of the I/U converter to bring the signal back to the middle of the oscilloscope screen.

Settings:

Oscilloscope:

Channel I:	10-20 mV/DIV. (DC)

I/U converter:

Toggle switch:	DC

Finding the absorption signal

For ^{87}Rb the frequencies of the Zeeman transitions in the ground state in a Helmholtz field of 1.2 mT (coil current 740 mA) are around 8 MHz. When the setup is carefully adjusted, the absorption signal reaches an amplitude of approx. 20 mV (higher signals could be possible if the operating current of the rubidium-lamp is increased, it would shorten however the lamp life):

- Set the polarisation filter to 0° and the quarter wavelength panel to +45° or -45°.
- Set the desired operating mode and frequency range on the function generator.
- Start the function generator by pressing the button labeled MANUAL.
- Vary the Helmholtz coil current until the maximum (negative!) absorption signal appears on the oscilloscope.
- If necessary, set the toggle switch of the I/U converter to AC or use the offset potentiometer of the I/U converter to bring the signal back to the middle of the oscilloscope screen.
- Maximize the absorption signal by changing the operating parameters of the rubidium high-frequency lamp.

Settings:

Polarisation filter:

Angle:	0°

Quarter wavelength panel:

Angle:	+45° or –45°

I/U converter:

Toggle switch:	DC

Oscilloscope:

Operating mode:	X-Y Mode
Channel I:	≥10 mV/DIV. (DC)
Channel II:	0,5 V/DIV. (DC)

Function generator:

Function:	~ (sine)
Amplitude:	Middle position
Attenuation:	20 dB
DC-offset:	0 V (DC button pressed)
Sweep button:	Pressed
Mode*:	'C u
Stop*:	8,5 MHz
Start*:	7,5 MHz
Period*:	ca. 100 ms (fast sweep)

* Press button and set desired value with knob

Measuring

Preparation

Finding the signal:

- Operate the oscilloscope in XY-mode.
- Switch off the oscilloscope storage mode.
- If necessary, switch off the sensitivity of oscilloscope channel I.
- Set the toggle switch of the I/U converter to DC.
- Set the start and stop frequencies on the function generator (f_A = 9,0 MHz, f_E = 9,2 MHz).
- Switch the function generator to period 100 ms (fast sweep).
- Start the function generator by pressing the button labeled MANUAL.
- Set the Helmholtz coil current I ≈ 0,8 A and vary it until an absorption signal can be seen on the oscilloscope screen.

Oscilloscope storage mode:

- Switch on the storage mode of the oscilloscope.
- Press the START button of the function generator.
- Adjust the horizontal deflection of the oscilloscope with the knob Y-Pos.II to x_A = 1,0 scale division.
- Press the STOP button of the function generator.
- Adjust the horizontal deflection of the oscilloscope with the rotary switch and the knob VOLTS/DIV. of channel II to x_E = 9,0 scale divisions.

Fine adjustment:

- Start the function generator by pressing the button labeled MANUAL.
- Switch the function generator to period 10 ms (slow sweep).
- Switch the vertical deflection of the oscilloscope to sensitive.
- Turn the quarter wavelength panel back and forth between +45° and –45° and check whether all lines of t he absorption spectrum appear on the oscilloscope screen.
- If necessary, readjust the Helmholtz coil current *I* or the start frequency f_A and stop frequency f_E accordingly.

Procedure

Note: at σ^+-polarisation the absorption line with the lowest frequency is the most intense.

First run:

- Set the quarter wavelength panel to σ^+-polarisation.
- Start the function generator by pressing the button labeled MANUAL.
- Wait until the absorption spectrum has been completely recorded.
- Stop recording of the absorption spectrum by pressing the oscilloscope buttons HOLD I and HOLD II.
- Determine the position *x* of the absorption lines on the oscilloscope screen.
- Determine the amplitude *U* of the absorption lines.
- Check the start frequency f_A and the stop frequency f_E.
- Check the Helmholtz coil current *I*.

Second run:

- Set the quarter wavelength panel to σ^--polarisation.
- Start the function generator by pressing the button labeled MANUAL.
- Wait until the absorption spectrum has been completely recorded.
- Stop recording of the absorption spectrum by pressing the oscilloscope buttons HOLD I and HOLD II.
- Determine the position *x* of the absorption lines on the oscilloscope screen.
- Determine the amplitude *U* of the absorption lines.
- Check the start frequency f_A and the stop frequency f_E.
- Check the Helmholtz coil current *I*.

Settings:

Oscilloscope:

Operating mode:	X-Y Mode
	Storage mode
Channel I:	10 mV/DIV. (DC)
Channel II:	>0,5 V/DIV. (DC)
Recording range:	1.0 division - 9.0 divisions
Timebase:	1 s/DIV.

Function generator:

Stop:	9,0 MHz
Start:	9,2 MHz
Period:	10 s (slow sweep)
Amplitude:	3rd division mark
Attenuation:	20 dB

Measuring example:

Measuring parameters:

x_A = 1,0 div., x_E = 9,0 div., f_A = 9,05 MHz, f_E = 9,20 MHz

Tab. 1:Position x, relative amplitude *U* of the ^{87}Rb -absorption lines

left side: Measurement with σ^+ light, *I* =0,795 A

right side: Measurement with σ^- light, *I* =0,795 A

No.	$\frac{x}{\text{Div}}$	$\frac{U}{\%}$
1	2,5	100
2	3,8	39
3	5,1	14
4	5,8	13
5	6,4	4
6	7,1	3

No.	$\frac{x}{\text{Div}}$	$\frac{U}{\%}$
1	2,6	4
2	3,9	14
3	5,2	36
4	5,9	4
5	6,5	100
6	7,2	13

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Evaluation

Determining the nuclear spin *I* of ^{87}Rb

The irradiated alternating magnetic field makes possible transitions with the selection rules $\Delta F = 0,\pm 1$ and $\Delta m_F = \pm 1$. The available frequency range only permits $\Delta F = 0$. Thus, between the nuclear spin *I* and the number of transitions *n* there exists the relationship

$$n = 2F_+ + 2F_- = 4I \qquad \text{(III)}$$

We can observe six lines. According to equation (III), the nuclear spin of ^{87}Rb thus has the value $I = \frac{3}{2}$.

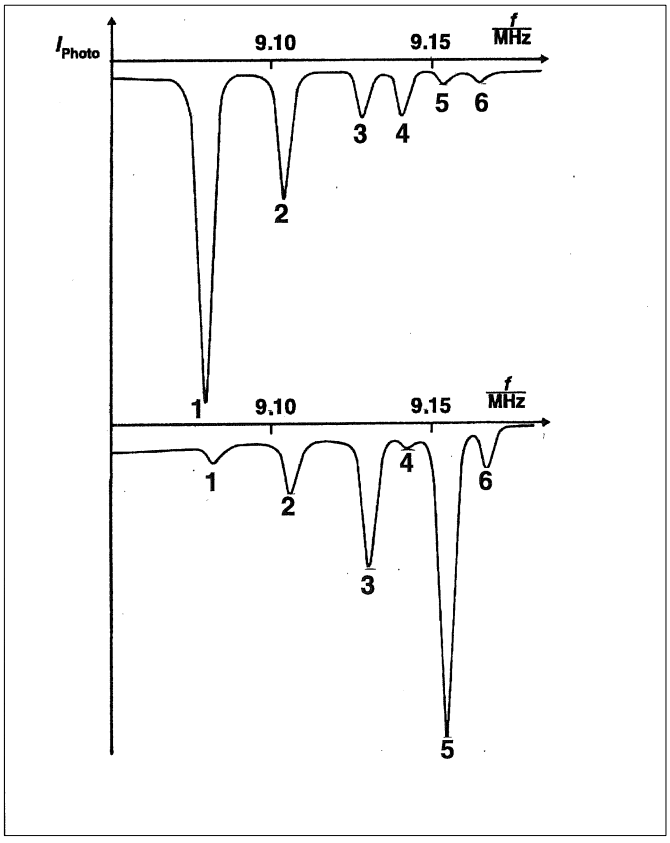

Fig. 5: Absorption spectrum ^{87}Rb with σ^+ light (top) and σ^- light (bottom). For identification of the absorption lines see Table 2.

Determining the transition frequencies

The position *x* on the oscilloscope screen allows us to determine the frequencies f_M of the absorption lines using the formula

$$f_M = f_A + (f_E - f_A)\frac{x - x_A}{x_E - x_A} \qquad \text{(IV)}$$

x_A : Start of scale (set with Y-POS.II)

x_E : End of scale (set with rotary switch VOLTS/DIV.)

f_A : Start frequency

f_E : Stop frequency

The results are summarized in Table 2 as the quantities $f_M(\sigma^+)$ and $f_M(\sigma^-)$. The standard deviation for these quantities is $\sigma_F = 0{,}002$ MHz.

Assignment of the transitions

The following numerical values can be found in the literature:

$\mu_K = 5{,}05083(4)\cdot 10^{-27}\,\mathrm{JT}^{-1}$ [9]

$\mu_B = 9{,}27410(7)\cdot 10^{-24}\,\mathrm{JT}^{-1}$ [9]

$g_J = 2{,}002332(2)$ [6]

$h = 6{,}6260(5)\cdot 10^{-34}\,\mathrm{Js}$ [9]

$\frac{\Delta E}{h} = 6834{,}682614(1)\,\mathrm{MHz}$ [8]

$g_I = -5{,}39155(2)$ [7]

Using (II), we obtain within the hyperfine $F = 2$ four transitions which have frequencies

$$f_{F=2} = -0{,}01393\,\mathrm{MHz}\cdot\frac{B}{\mathrm{mT}} + 3417{,}34\,\mathrm{MHz}\left(\left(1 + m_F\xi + \xi^2\right)^{\frac{1}{2}} - \left(1 + (m_F - 1)\xi + \xi^2\right)^{\frac{1}{2}}\right)$$

and within the hyperfine state $F = 1$ two transitions with the frequencies

$$f_{F=1} = 0{,}01393\,\mathrm{MHz}\cdot\frac{B}{\mathrm{mT}} + 3417{,}34\,\mathrm{MHz}\left(\left(1 + m_F\xi + \xi^2\right)^{\frac{1}{2}} - \left(1 + (m_F - 1)\xi + \xi^2\right)^{\frac{1}{2}}\right)$$

where $\xi = 4{,}10243(4)\cdot 10^{-3}\cdot\frac{B}{\mathrm{mT}}$.

By suitably varying the parameter *B* in (I) and (II) we can reproduce the measured transition frequencies mathematically. Table 2 compares the transition frequencies measured with σ^+ light, the transition frequencies measured with σ^- light and the calculated transition frequencies *f*. The values assigned to a line number agree to within a measuring error of $\sigma_F = 0.002$ MHz. The value for magnetic flux density used for calculation is $B = 1{,}3031$ mT. The quantum numbers *F* and m_F of the Zeeman levels involved in the transition are also shown in Table 2.

Table 2: ^{87}Rb transition frequencies at $B = 1{,}3031$ mT

No.	$\frac{f_M(\sigma^+)}{\mathrm{MHz}}$	$\frac{f_M(\sigma^-)}{\mathrm{MHz}}$	$\frac{f}{\mathrm{MHz}}$	*F*	$m_F(1)\leftrightarrow m_F(2)$
1	9,078	9,080	9,080	2	2 ↔ 1
2	9,103	9,104	9,104	2	1 ↔ 0
3	9,127	9,129	9,128	2	0 ↔ -1
4	9,140	9,142	9,140	1	1 ↔ 0
5	9,151	9,153	9,153	2	-1 ↔ -2
6	9,164	9,166	9,165	1	0 ↔ -1

When changing from σ^+ to σ^- pumping light, the amplitudes U of the absorption lines also change. Table 3 compares the intensities of the transitions. Within the measuring error for U the change from σ^+ to σ^- corresponds to a change from m_F to $-m_F$.

Tab. 3: Relative ^{87}Rb transition intensities at B=1,3031 mT

No.	$U(\sigma^+)$	$U(\sigma^-)$	F	$m_F(1) \leftrightarrow m_F(2)$
1	100%	4%	2	2 ↔ 1
2	39%	14%	2	1 ↔ 0
3	14%	36%	2	0 ↔ -1
4	13%	4%	1	1 ↔ 0
5	4%	100%	2	-1 ↔ -2
6	3%	13%	1	0 ↔ -1

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