Optics

Spectrometer
Grating spectrometer

Measuring the line spectra of inert gases and metal vapors using a grating spectrometer

Objects of the experiment

- ■ Adjusting the grating spectrometer.
- ■ Calibrating the grating spectrometer with an He-lamp.
- ■ Measuring an "unknown" line spectrum.
- ■ Identifying the "unknown" light source.

Principles

Inert gases and metal vapors which are excited to luminance emit spectral lines, i.e. a specific selection of wavelengths which are characteristic for the respective element. By precisely measuring these wavelengths, we can draw well-founded conclusions about the nature of these light sources.

We can use a grating to separate these spectral lines. The light is diffracted at the grating; light rays of the same wavelength are superposed on each other, producing sharp intensity maxima. long-wave light is deviated more than short-wave light.

In the grating spectrometer, emerging light propagates in a diverging manner though the vertical slit S, for which the width and height can be varied, and falls on the objective lens O_1; its distance from the slit is equivalent to its focal length (see Fig. 1). The slit and the lens together form a collimator. Behind the lens, the light falls on the grating G as a parallel beam, i.e. all rays are incident on the grating at the same angle. The grating diffracts the light, and each wavelength is deviated at a different angle. Finally, a second objective lens O_2 focuses all parallel rays of a specific wavelength to form an image of slit S in the focal plane of the lens. In this way, a pure spectrum is formed in the focal plane, and we can observe this using the ocular O'. Objective lens O_2 and ocular O' together form an astronomical telescope focused on infinity.

The telescope is mounted on a swivel arm so that the deviation angle can be measured. When the telescope is turned, crosshairs positioned in the focal plane of the ocular are placed on the individual spectral lines. To enable measurement of the angles and thus the relative position of the lines, the telescope is combined with a graduated circle (a disk with a scale with half-degree graduations) to form a goniometer. The vernier permits the position to be read off to within an angular minute.

The relationship between the diffraction and the wavelength is linear ($\sin \alpha \sim \lambda$, normal spectrum). When assigning the wavelengths of an unknown light source to the deviations through the grating, it is not necessary to first calibrate the spectrometer – in contrast to the prism spectrometer (dispersion spectrum). On the basis of the diffraction of the individual spectral lines, it is possible to assign these to the corresponding wavelengths. These are then compared with a suitable reference table to determine the light source.
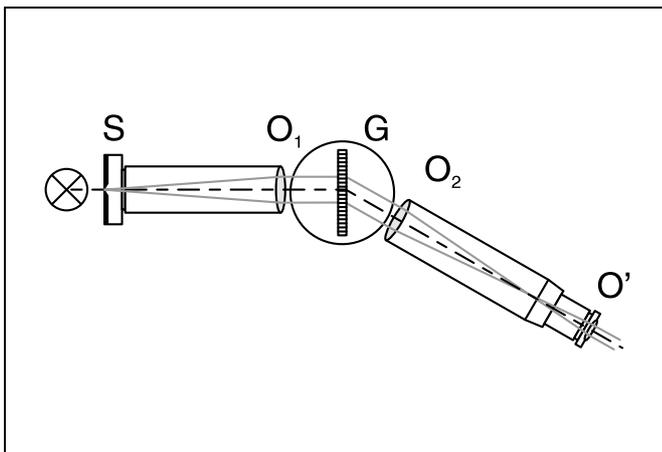
Fig. 1   Beam path in a grating spectrometer

Apparatus

1 Spectrometer and goniometer	467 23
1 Copy of a Rowland grating, approx. 5700 lines/cm	471 23
1 Spectral lamp He, pin contact	451 031
1 Spectral lamp Na, pin contact	451 111
1 Housing for spectral lamps with pin contact	451 16
1 Universal choke, 230 V, 50 Hz	451 30
1 Transformer, 6 V AC, 12 V AC	562 73
1 Stand base, small, V-shape	300 02

additionally usable:

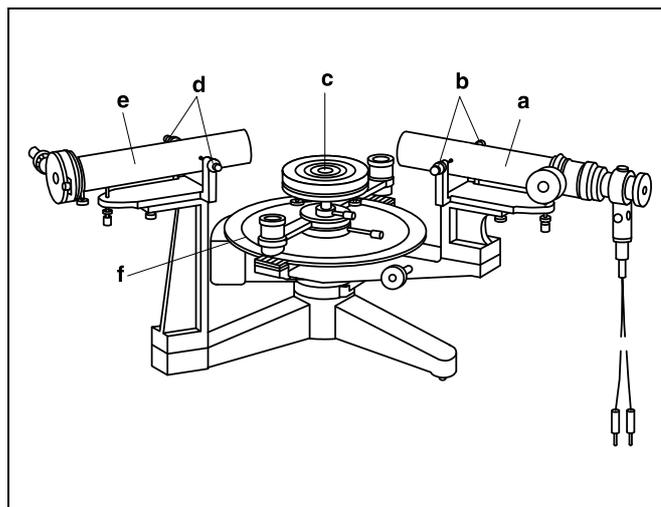|	
1 Spectral lamp Ne, pin contact	451 011
1 Spectral lamp Cd, pin contact	451 041
1 Spectral lamp Hg/Cd, pin contact	451 071
1 Spectral lamp Ti, pin contact	451 081

Fig. 2   Spectrometer
- **a** Telescope
- **b** Adjusting screw for laterally displacing the collimator
- **c** Prism table
- **d** Adjusting screw for laterally displacing the telescope
- **e** Collimator
- **f** Spectrometer base unit

Adjusting the spectrometer

In order to conduct precise measurements, the apparatus must be carefully adjusted.

The slit and the crosshairs must be positioned exactly in the focal plane of the respective objective lens (telescopic beam path).

The slit and the grating surfaces must be aligned parallel to the rotary axis of the telescope.

Some of the adjustment steps, as well as the measurements of line spectra, are more easily carried out when the room is darkened somewhat.

Preliminary adjustment:

The inclination of the prism table can be varied only to a limited extent. To ensure that enough play is left for adjustment, align the table as horizontally as possible (by eye) during preliminary adjustment.

- Align the telescope **(a)**, the prism table **(c)** and the slit tube (collimator) **(e)** horizontally by eye (see Fig. 2).
- Center the telescope and the collimator laterally using the screws for lateral adjustment **(b)**, **(d)** and then screw them tight. Do not loosen the adjusting screws too much on one side, as these support the telescope and the collimator.

Focusing the telescope to infinity:

*Note: Experimenters requiring vision correction can see distant objects clearly with the telescope; however, in this case the telescope by definition is not set precisely to infinity. It is still possible to carry out precise measurements when the collimator and the telescope are adjusted by the same experimenter. When other experimenters wish to observe the spectra, subsequent focusing may only be carried out by moving the ocular **(a4)**.*

- Remove ocular **(a4)**, mount illumination source **(a3)** in the telescope and replace the ocular with the opening for the illumination source **(a5)** facing downward (see Fig. 3).
- Focus the crosshairs by moving the ocular **(a4)** in the ocular tube and aligning it if necessary. Make sure that the opening for the illumination source **(a5)** is still facing downward.
- Focus the horizontally aligned telescope on a distant object (> 500 m) using the focus adjustment knob **(a1)**.

As the image of the observed object and the crosshairs must both be in the focal plane of the objective lens when the setting is correct, there should be if possible no parallax between the observed object and the crosshairs.

Adjusting the illumination source:

- Aim the telescope at the collimator (open the slit slightly).
- Connect the illumination source **(a3)** to the voltage U = 6 V.
- Using arresting screw **(a2)**, mount the illumination device on the telescope so that the inside of the slit is well illuminated, without altering the position of the ocular.
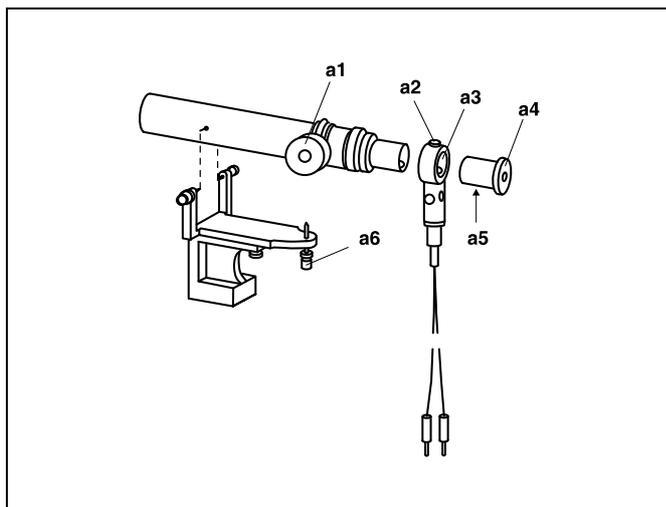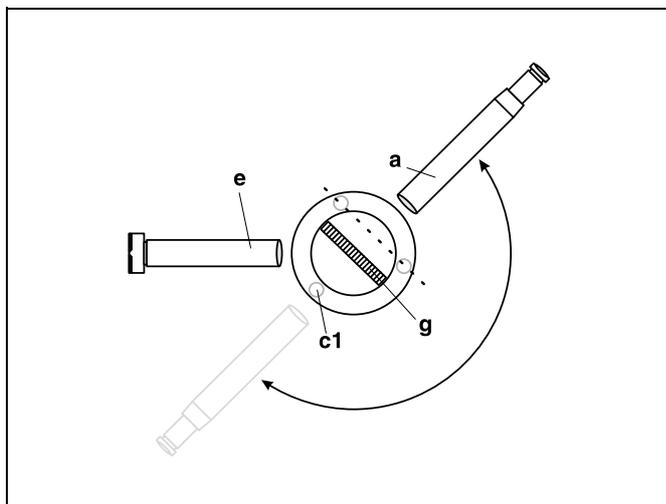
Fig. 3   Telescope with illumination source
   a1   Focus adjustment knob
   a2   Arresting screw for illumination source
   a3   Illumination source
   a4   Ocular
   a5   Opening for illumination source (not visible)
   a6   Height adjustment screw for telescope

Aligning the optical axis of the telescope perpendicular to, and the axis of the grating parallel to the spectrometer axis:

–   Place the grating in the holder for the flat glass plate **(g)** in the center of the prism table at an angle of 45° to the collimator **(e)** so that the (imaginary) line between two of the adjusting screws of the prism table is parallel to the side surfaces of the flat glass plate (see Fig. 4).

–   Align the telescope **(a)** perpendicular to one of the side faces of the grating so that the cross-hairs are reflected in this surface.

–   Adjust the horizontal cross-hair so that is coincident with its reflection. In making this adjustment, correct half the difference using the height-adjustment screw of the tele-

scope **(a6)** (see Fig. 3) and the other half using the leveling screw **(c1)** of the prism table.

–   Repeat the following two steps until the horizontal cross-hair and its mirror image coincide on both sides of the grating:
   1) Turn the telescope 180° as shown in Fig. 4 so that the cross-hairs are reflected on the opposite side of the grating.
   2) Check whether the cross-hair and its mirror image coincide. If not, correct half the difference using the height-adjustment screw of the telescope **(a6)** (see Fig. 3) and the other half using the leveling screw **(c1)** of the prism table, as described above.

–   Secure the height-adjustment screw of the telescope **(a6)** using a lock nut.

–   Remove the grating with holder from the prism table. Note the alignment of the grating with respect to the leveling screws of the prism table, as this is the only position in which the grating is parallel to the rotational axis of the telescope, and the grating must be replaced on the prism table when carrying out the experiment.

–   Disconnect the illumination source from its voltage supply.

Adjusting the collimator:

–   Illuminate the slit from the outside using e. g. a light bulb or one of the spectral lamps.

–   Aim the telescope at the collimator and open the slit slightly using the micrometer screw for slit width **(e1)**.

–   Set the slit to a suitable, observable slit height using the slide **(e5)**.

–   With the height adjustment screw of the collimator **(e4)**, align the middle of the slit with the horizontal cross-hair and lock the slit in position.

–   Loosen the arresting screw for the collimator tube **(e3)** and slide the collimator tube **(e2)** in the direction of the arrow (see Fig. 5) until a sharp image is obtained.

–   By turning the tube, align the slit vertically so that it is parallel to the vertical cross-hair, and then tighten the arresting screw for the collimator tube **(e3)**.

Fig. 4   Spectrometer with grating
   a   Telescope
   b   Leveling screws for prism table
   c1   Collimator
   d   Grating in holder

Fig. 5   Collimator
   e1   Micrometer screw
   e2   Collimator tube
   e3   Arresting screw for collimator tube
   e4   Height adjustment screw for collimator
   e5   Slide for adjusting slit height
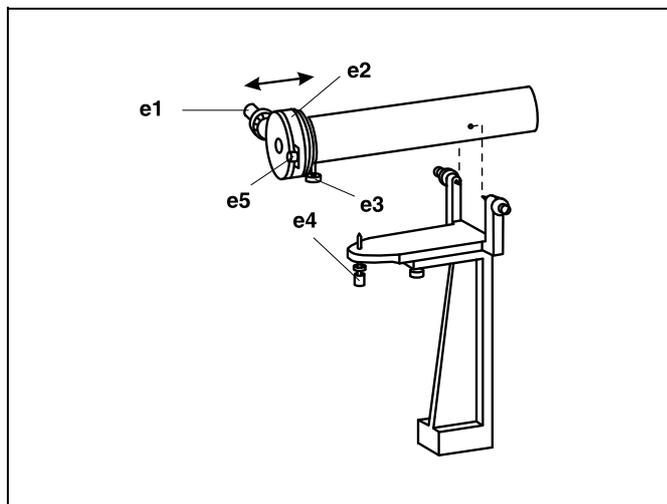
Setup

- Attach the He-spectral lamp in the housing, mount it in the stand base as shown in Fig. 8, connect it to the universal choke and switch it on.
- Illuminate the slit with the He-spectral lamp. Make sure that the He-lamp is positioned in the optical axis of the collimator.
- Position the grating on the prism table and align the telescope so that the light through the slit passes through the grating (when viewed from above, see Fig. 1) and the spectrum can be observed in the telescope.
- To permit more precise subsequent measurements, place the grating on the axis of rotation of the telescope and perpendicular to the optical axis of the collimator (center of prism table).

The resolution increases as the slit width narrows; at the same time, however, the light intensity of the spectrum is reduced.

- Set the slit to a suitable width using the slit micrometer screw **(e1)**.
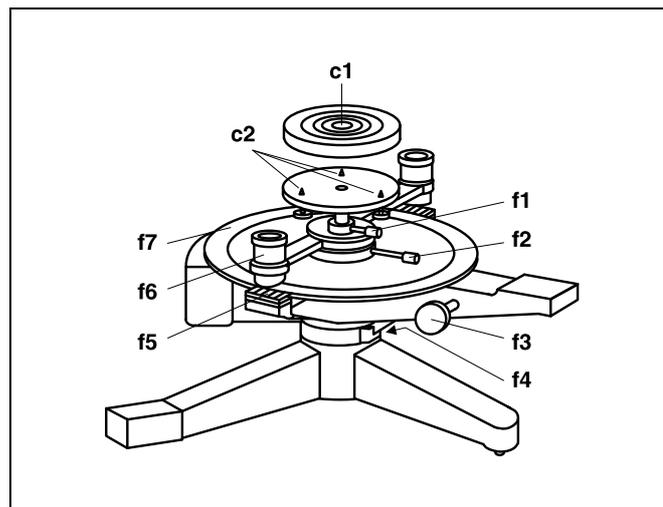

Fig. 6   Spectrometer base unit and prism table
   c1 Prism table
   c2 Leveling screws for prism table
   f1 Arresting screw for prism table
   f2 Arresting screw for graduated circle
   f3 Fine-adjustment screw for telescope rotation
   f4 Arresting screw for telescope (not visible)
   f5 Verniers
   f6 Magnifiers
   f7 Graduated circle

Carrying out the experiment

Note: the spectrometer is equipped with two opposing verniers. In order to minimize reading errors and compensate for any eccentricity of the circular graduation with respect to the axis of rotation, find the mean value of two readings.

a) Measuring the He-line spectrum:

- Tighten the telescope arresting screw **(f4)** and align the vertical cross-hair of the telescope with each of the spectral lines of equal diffraction orders on both sides of the main maximum in turn using the fine-adjustment knob **(f3)**. Read off the corresponding telescope position on the graduated circle using the magnifiers **(f6)** and the verniers **(f5)** and write this value in the experiment log.

b) Determining the interval between the two Na-D lines:

- Remove the He-spectral lamp and replace it with the Na-spectral lamp. When illuminating the slit, again make sure that the lamp is positioned in the optical axis of the collimator.
- Find the two yellow Na-D lines of the first diffraction order on both sides of the main maximum.
- Align the vertical cross-hair of the telescope with each of the spectral lines and read off and write these values in the experiment log.
- Repeat the measurement for the lines of the second order of diffraction.

Fig. 7   Complete experiment setup after adjustment
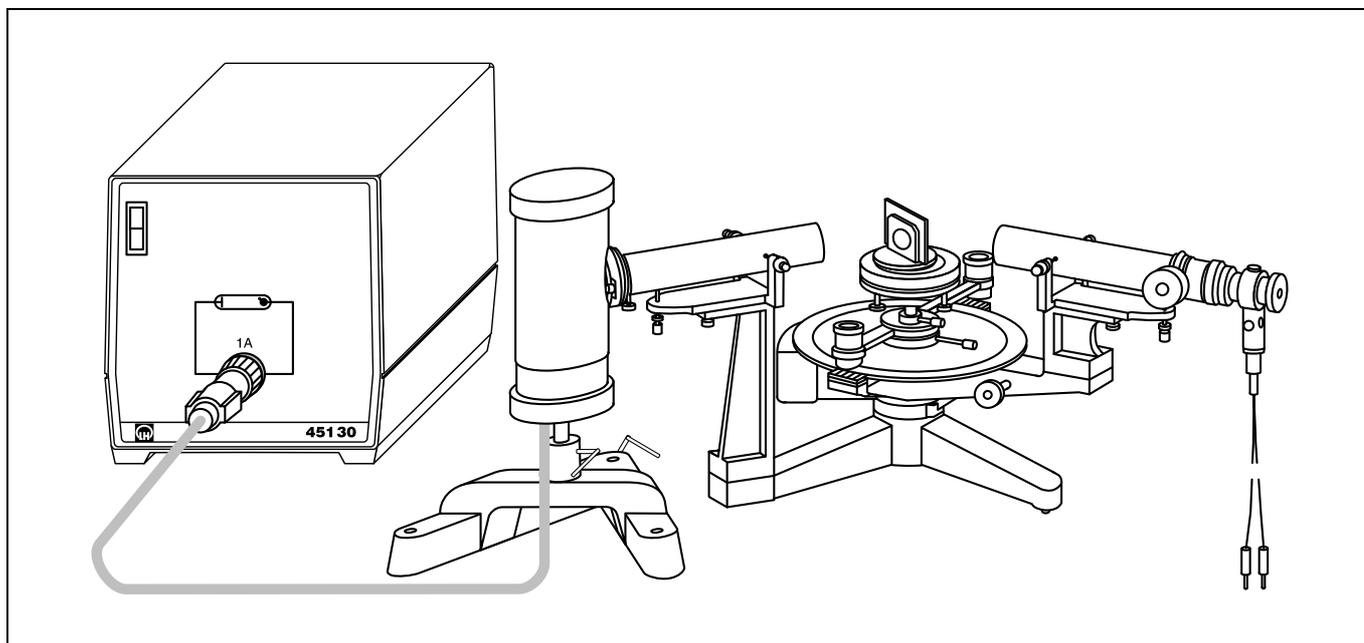
Measuring example and evaluation

Note: With the grating spectrometer it is also possible to see low-intensity lines which do not belong to the spectrum of the respective metal vapor or inert gas. Due to the manufacturing process, other gases may also be included in the light bulb. In metal vapor lamps, argon (Ar) is additionally used as a base gas.

The following formula applies:

$$\lambda = \frac{\sin\dfrac{\Delta\alpha}{2}}{n \cdot N} \qquad (I)$$

n: diffraction order,
Δ*a:* angular difference between the right and left spectral lines of nth order (see Fig. 8),
N: line count, λ: wavelength

With the given grating line count $N = 5700\ cm^{-1}$, we obtain from the measured angles $\Delta\alpha$ the wavelengths given in Table 1 for the observed spectral lines. These agree with the literature values for helium, but are an average of 1.0 ‰ above these values. If we calculate the wavelengths with a correspondingly greater grating line count ($N = 5706\ cm^{-1}$), we obtain excellent agreement with the literature values (see Table 1).

Table 1: Measured values for example with the He-spectral lamp, measured for the diffraction order $n = 1$
(The literature data refer to the wavelengths in air at standard temperature and pressure and in vacuum, for definition of $\Delta\alpha$ see Fig. 8)

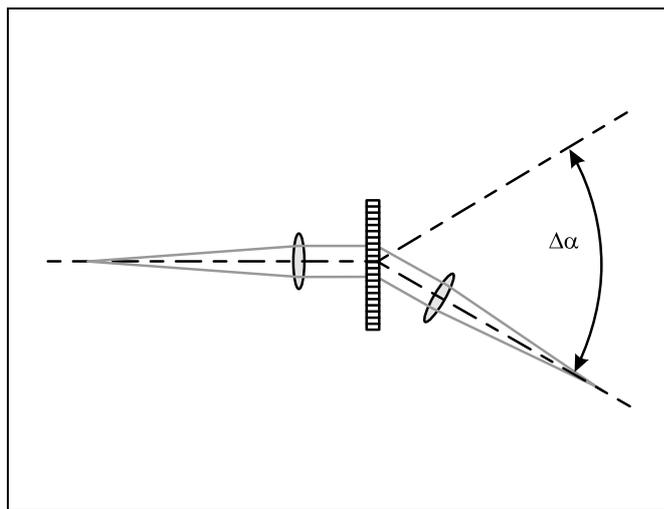| $\Delta\alpha$	$\dfrac{\lambda_{5700/cm}}{nm}$	$\dfrac{\lambda_{5706/cm}}{nm}$	$\dfrac{\lambda_{air}}{nm}$	$\dfrac{\lambda_{vacuum}}{nm}$
29.56°	447.6	447.1	447.0	447.1
31.18°	471.5	471.0	471.2	471.3
32.62°	492.7	492.2	492.1	492.2
33.24°	501.8	501.3	501.5	501.6
39.17°	588.1	587.5	587.4	587.6
44.79°	668.4	667.7	667.6	667.8
47.55°	707.3	706.5	706.3	706.5

Fig. 8   Schematic diagram for the definition of angle $\Delta\alpha$

Additional information

The spectrometer and goniometer can also be used as a prism spectrometer (see experiment description P5.7.1.2). As in this configuration the deviation is not linearly dependent on the wavelength, we require a calibration curve for carrying out measurements; this is created using a spectrum lamp with a known spectrum. Also, the resolution of a prism spectrometer is not as great as a good grating spectrometer.

However, the intensity of the prism spectra is greater, as a significant proportion of the radiation in a grating spectrometer is lost in the undiffracted 0th order, while the rest is distributed over several diffraction orders on both sides of the 0th order. As a result, the less intense lines are scarcely observable, or not observable at all, with a grating spectrometer.

b) Determining the interval between the two Na-D lines:

Table 2: Sodium D-lines, measured at the diffraction orders $n = 1$ and $n = 2$

Line	n	$\Delta\alpha$	$\dfrac{\lambda_{5706/cm}}{nm}$
D$_1$	1	39.300°	589.33
	2	84.542°	589.41
D$_2$	1	39.250°	588.61
	2	84.425°	588.74

From Table 2, we obtain for the interval between the two yellow sodium D-lines the values $\Delta\lambda = 0.72$ nm (measured at $n = 1$) and $\Delta\lambda = 0.67$ nm (measured at $n = 12$).

The mean value is $\lambda(D_1) - \lambda(D_2) = 0.70$ nm.

Literature value for wavelengths in air at standard temperature and pressure: $\lambda(D_1) - \lambda(D_2) = 589.418$ nm $- 588.821$ nm $= 0.597$ nm