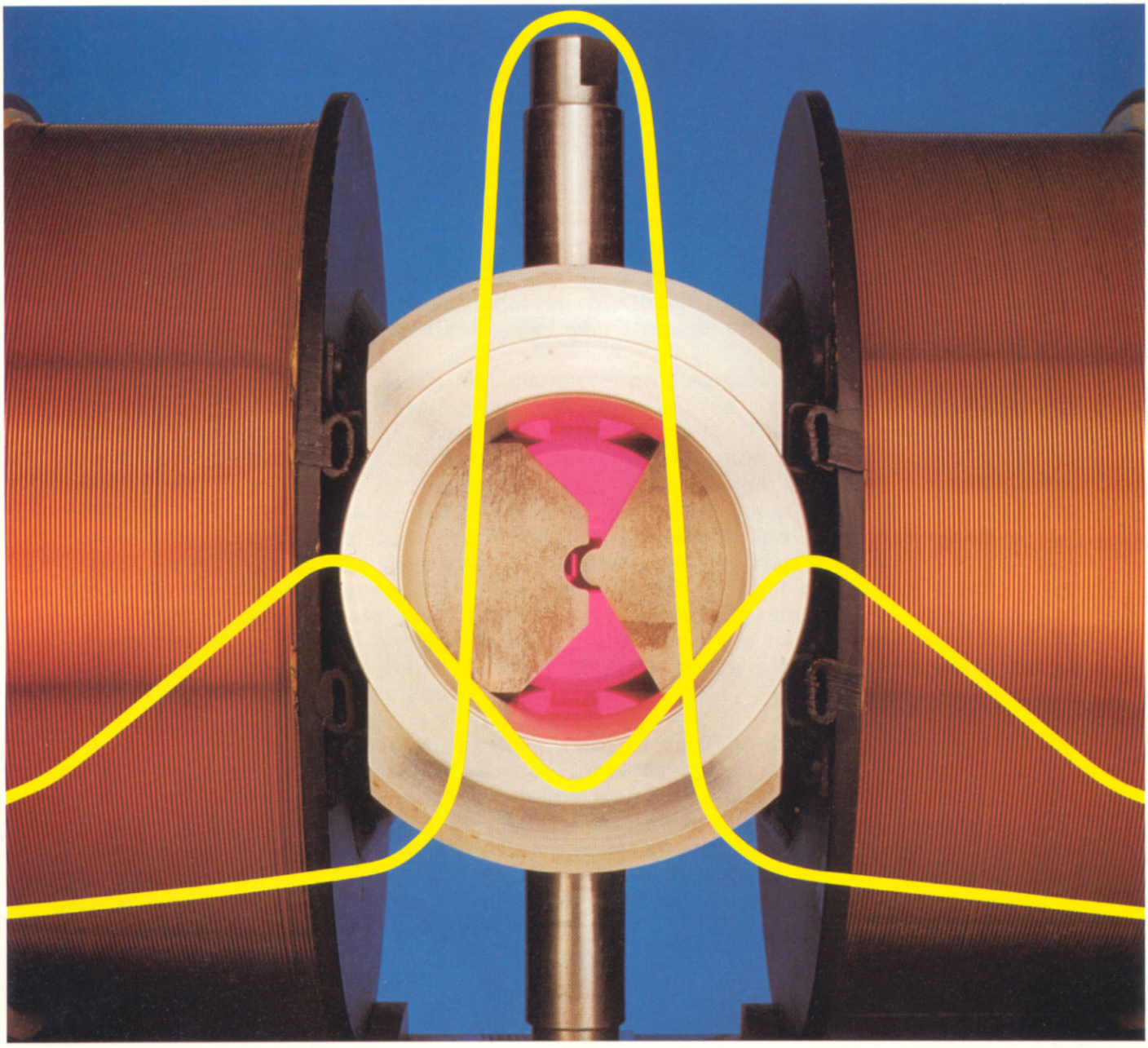
PHYWE

Operating Instructions

STERN-GERLACH APPARATUS
09054.88



Contents

1. INTRODUCTION

More than 50 years have elapsed since the experiment of Stern and Gerlach was first performed. Today's technical facilities now enable this experiment to be carried out with an apparatus which is both compact and easy to operate. PHYWE's apparatus for the Stern-Gerlach experiment has the following features:

- greatly simplified operation and handling
- clearly arranged layout
- easy adjustment
- standardized flanges to facilitate dismantling
- demonstrative results, measurable and calculable
- retention of the original measuring principle, but execution in keeping with the state of the art.

1.1 The original experiment

Although the principle of the Stern-Gerlach experiment is described in virtually every text book, details of the set-up are not so familiar. The following extract is taken from an issue of the "Zeitschrift für Physik" which was published in 1921:

> "A beam of silver atoms (1/20 mm diameter) produced in a highly evacuated vessel (10^{-4} to 10^{-5} mm Hg) travels past the edge of the knife-shaped pole-piece of an electromagnet (du Bois' half-ring electromagnet). The beam emerges from a small (1/2 cm^3) electric steel furnace through a circular aperture (1 mm^2) located in the lid. The furnace is surrounded by a water-cooled jacket. The beam passes through the first circular slit (1/20 mm diameter) located approximately 1 cm away from the furnace aperture in a platinum sheet and then, 3 cm behind the latter, through a second identical slit situated on the front end of the knife-edge pole of the electromagnet. The beam then travels along the 3 cm long pole edge and impinges on a glass plate immediately after emerging from the field. The silver deposited on this surface is still invisible to the naked eye even when the experiment is performed for a duration of eight hours, although it can be intensified by simple chemical methods."

The size of the apparatus had to be kept small in view of the short free path in the relatively poor vacuum attainable at that time. By having one pole in the form of a knife edge and the other in the form of a 3 mm wide and 30 mm deep channel above it, the magnetic field was of much greater intensity near the knife edge than anywhere else in the gap. Consequently, the deflecting force was high, a necessary requirement in view of the short magnet. Since the inhomogeneity decreased considerably with increasing distance from the knife edge, the deflected beam became distorted. The extremely critical alignment of the slits caused virtually unsolvable problems. The spatial distribution of the field inhomogeneity could not be calculated and had to be laboriously measured.

The precipitate detector necessitated a long experiment duration and did not allow any check to be made during the course of the experiments.

1.2 PHYWE's apparatus for the Stern-Gerlach experiment

The present state of vacuum technology now means that a considerably larger beam (length: 70 cm; cross-section 0.3 mm x 4 mm) can be used for the experiment and hence alignment problems no longer exist.

Flanges sealed with O-rings made of Viton allow the apparatus to be opened and closed again at several points. The atom beam is formed from potassium atoms which, like silver, have a free $^2S_{1/2}$ electron. A simple and sensitive detector is available

for potassium atoms. Potassium is also particularly suitable for this experiment in that it can be vaporised at low temperature (< 200°C) and deposits can be removed easily from the apparatus.

The magnetic field produced simulates a two-wire field: the pole-pieces lie on two equipotential surfaces of a fictitious field which can be thought of as being produced by two parallel conductors carrying currents in opposite directions. The field distribution of the two-wire field can be calculated. A good simulation of the two-wire field with iron pole-pieces of suitable shape is successful only at low field intensities. The length of the magnetic field is 7 cm and hence a measurable beam deflection can be obtained.

The Langmuir-Taylor detector comprises an incandescent (approx. 800°C) tungsten wire which vaporises impinging potassium atoms as ions. (The ionisation energy for potassium atoms is les than the work function of the electrons from tungsten). These potassium ions are accelerated to a collecting electrode by means of an electric field; the resulting current is proportional to the number of atoms impinging on the wire. By shifting this detector wire across the beam it is possible to measure the beam intensity at different positions.

This detector not only enables the beam profile to be measured accurately, but also allows the experimental findings to be demonstrated quickly and clearly on a recording instrument.

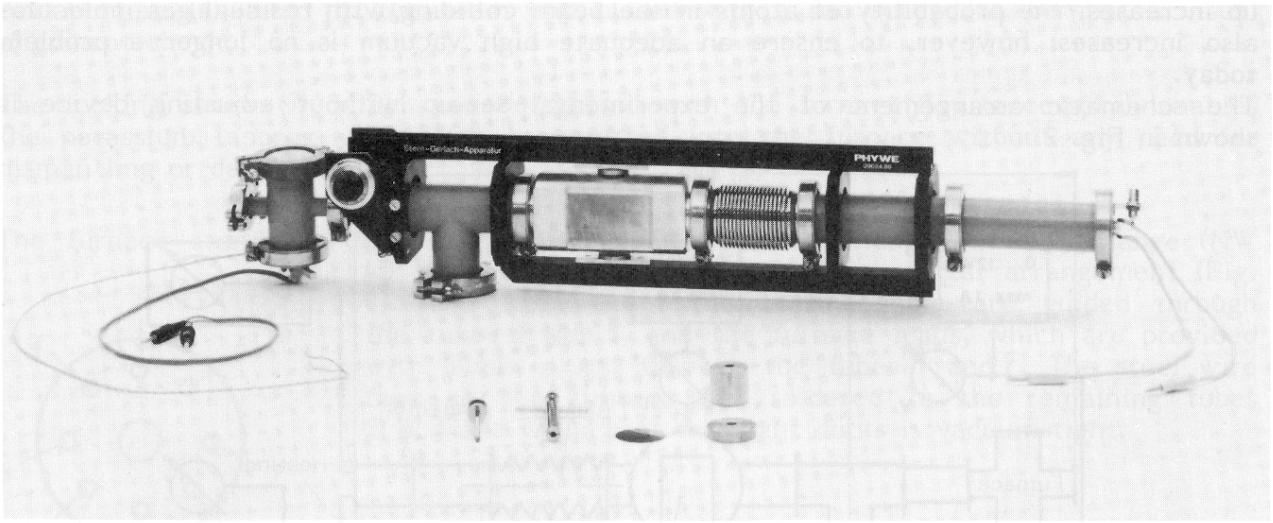


Figure 1: Stern-Gerlach apparatus 09054.88 with atom beam furnace, Langmuir-Taylor detector and magnetic analyzer.

2. DESCRIPTION OF THE STERN-GERLACH APPARATUS

2.1 Principle

Although the measuring principle of the original Stern-Gerlach experiment has been retained, its execution has been adapted in keeping with the present state of the art. A beam of potassium is produced by heating the metal in a small electric furnace and then defined as a thin beam by means of slits. The magnetic deflecting field produced between the specially shaped pole-pieces of an electromagmet simulates a two-wire field. The detector is a surface ionisation detector; it can be swivelled by means of a lever system and enables the intensity distribution in the beam to be measured electrically with good sensitivity. The vacuum container is provided with bellows. The length of the beam is considerably longer than in the original set-up; consequently, there are no problems concerning alignment. As the size of the set-

up increases, the probability of atoms in the beam colliding with residual gas molecules also increases; however, to ensure an adequate high vacuum is no longer a problem today.
The schematic arrangement of the experimental set-up without adjusting device is shown in Fig. 2.

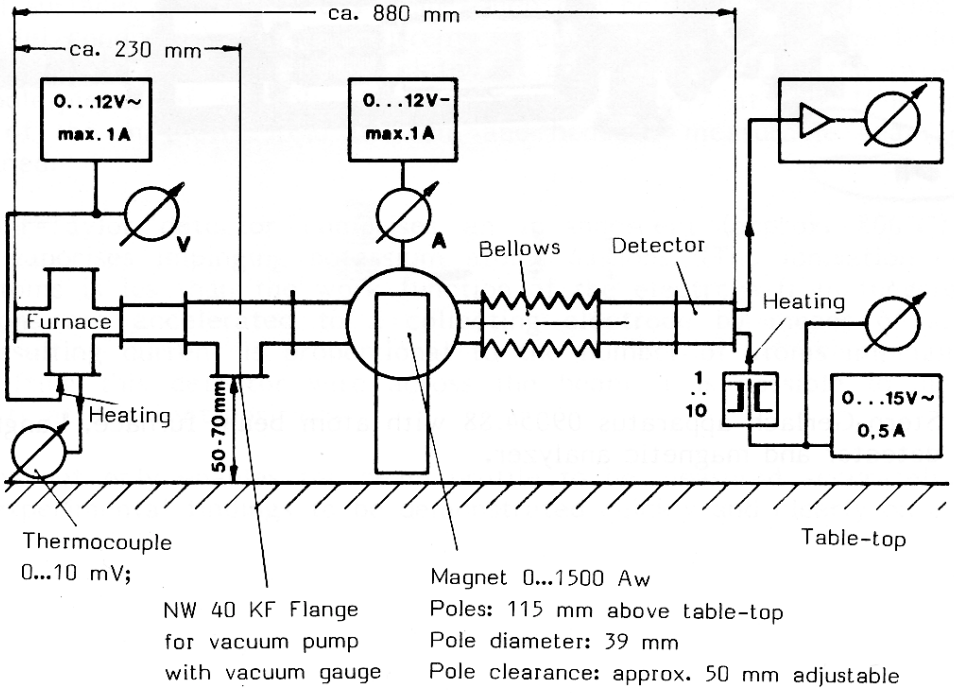


Figure 2: Schematic arrangement of the experimental set-up (without adjusting device).

2.2 Atom beam source (furnace)

An electric furnace (Fig. 3) supplied with potassium serves as the atom beam source; it is incorporated in a vacuum-tight housing with flanges in cross-shaped arrangement. The furnace itself comprises a closed metal container furnished with a slit-shaped aperture (1) in the direction of the beam. Provided that the apparatus is evacuated, the slit cannot become obstructed; the heating (2) is arranged so as to maintain the slit at a slightly higher temperature than that of the furnace chamber. When the furnace is cooled down, any potassium deposits are then vaporised again during the subsequent heating-up period. The thick walls give the furnace sufficient thermal inertia and ensure that slight fluctuations of filament during a measurement do not alter the intensity of the beam.

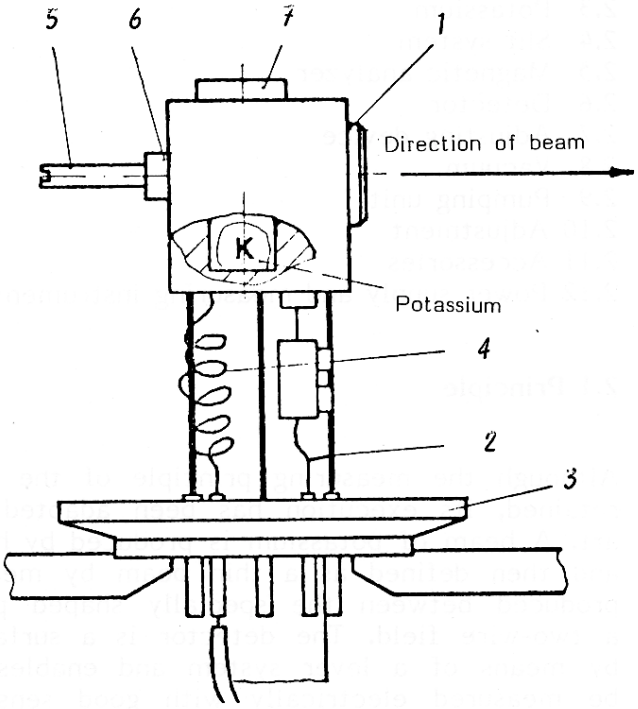


Figure 3: Furnace, side view.

The temperature of the furnace (approx. 170°C) is measured by means of a Fe-CuNi thermocouple (4). The wires of the thermocouple are led directly into the vacuum flange (3) to avoid measurement errors due to additional thermoelectric voltages. Measurement of the furnace temperature is necessary as a check on the furnace heating and for determining the mean velocity in the atom beam.

An aperture (6), axial to the beam and closed with a rod screw (5), permits a visual alignment check.

The locking screw (7), which can be opened with the furnace key (accessory), enables the potassium (approx. 50 mg) to be inserted into the furnace without any need for dismantling or de-alignment.

The furnace stands on four steel wires on the vacuum flange (3). This flange (NW 40 KF) has eight insulated ducts in octal arrangement (Fig. 4). The wires from the thermocouple are guided through the tubes 3 and 5, and the furnace leads, which are provided with 4 mm plugs, through the tubes 1 and 7. The steel wire feet of the furnace are soldered in the remaining tubes 2, 4, 6 and 8. Each of the eight ducts is vacuum-tight.

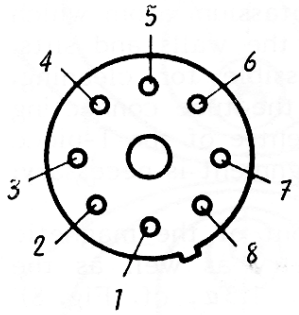


Figure 4: Base wiring, furnace.

2.3 Potassium

Potassium is stored under vacuum in ampoules; it oxidises rapidly in air. If, when filling the furnace, a compact piece of potassium is exposed to the air approximately one minute, only the outer layer is oxidised. Although this does not really matter, it does mean that the piece of potassium retains its form in the furnace even at temperatures above the melting point. Flat deposits of potassium which appear near the furnace after several hours' operation oxidise within 30 seconds when air is admitted. Potassium oxide reacts with atmospheric moisture to form potassium hydroxide which absorbs water from the air and then releases it again over long periods of time during evacuation.

Potassium deposits are removed from the apparatus after venting (see 3.8).

Fig. 5 shows the vapour pressure and free path of potassium. The curve is extrapolated; exact data could not be found in the temperature range of interest here.

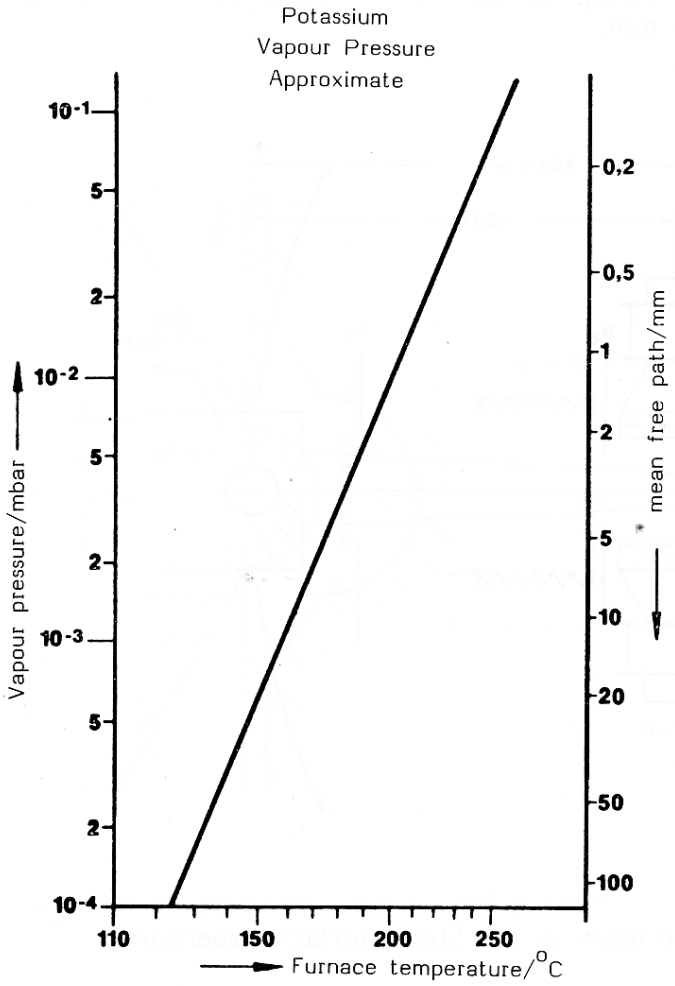


Figure 5: Potassium, vapour pressure and mean free path in the furnace.

Data

Density (at 20°C): 860 kg m^{-3}
Melting point: 63°C
Magnetic moment: 9.27 x 10^{-24} Am^2
= 1 Bohr magneton

Atomic mass: 64.92 x 10^{-27} kg

2.4 Slit system (cf. also Fig. 6)

A non-focussed beam of potassium atoms emerges from the furnace slit B_0 (0.10 mm x 2 mm) into the half space (cosine distribution). Beam focussing is not possible. A series of slits has to be used to define a thin beam. The arrangement and size of these slits are such as to prevent obstruction by potassium deposits. Potassium atoms must only reach the detector through the slits. The latter however must not reduce the tube cross-sections and render evacuation more difficult. The individual slits are therefore each provided with groups of tandem slits which cut off in the beam direction due to their shape. Roughly only every millionth potassium atom which leaves the furnace reaches the detector; the others condense on the walls and slits. The points at which appreciable deposits are formed are accessible for cleaning. Most of the potassium is deposited in the furnace housing and in the tube connecting it to the apparatus. The nearest slit is the vacuum divider in the centre of the T-piece which leads to the high vacuum pump. It is of ample size and no alignment is necessary.

The main slit B_H (0.3 mm x 4 mm) is located in the flange in front of the magnetic analyzer. It is not readjustable and determines the beam geometry as well as the passage of the beam through the pole-pieces (beam centre at $z = 1.3a$, cf. Fig. 8).

In the flange behind the magnetic analyzer a coarse slit covers those cross-sections which are not cut off by the main slit and pole-pieces.

A further slit in the centre of the detector tube prevents any scattered atoms from reaching the detector.

An aperture in the collecting electrode of the detector allows the beam to pass through and limits its height. As a result, and owing to the cross-section of the detector wire, the effective surface is 0.25 mm x 4 mm.

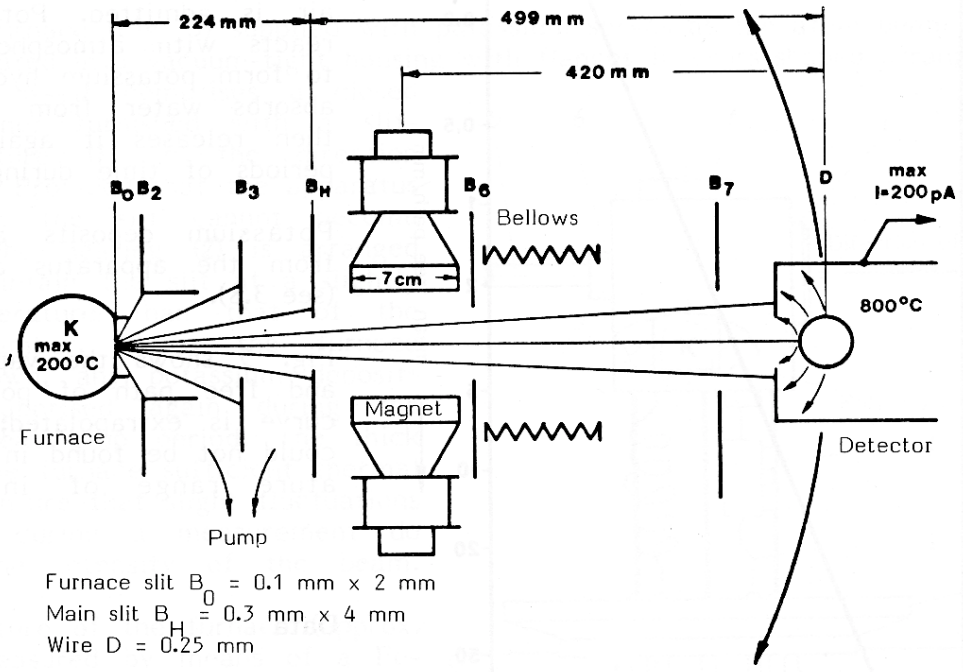


Figure 6: Slits and path of the beam in the Stern-Gerlach experiment.

2.5 Magnetic analyzer

The magnetic analyzer is crucial for the measuring accuracy of the apparatus. The magnetic field between the specially shaped pole-pieces (made of magnetic pure soft iron) simulates the field produced by two parallel conductors, separated by a distance $2a$ (Fig. 7), through which an equal current flows but in opposite directions. Provided that a two-wire field is produced in the gap and the centre of the beam is adjusted to $z = 1.3\,a$ (Fig. 8), the deflecting force can be readily calculated by measuring the magnetic flux density with a Hall probe.

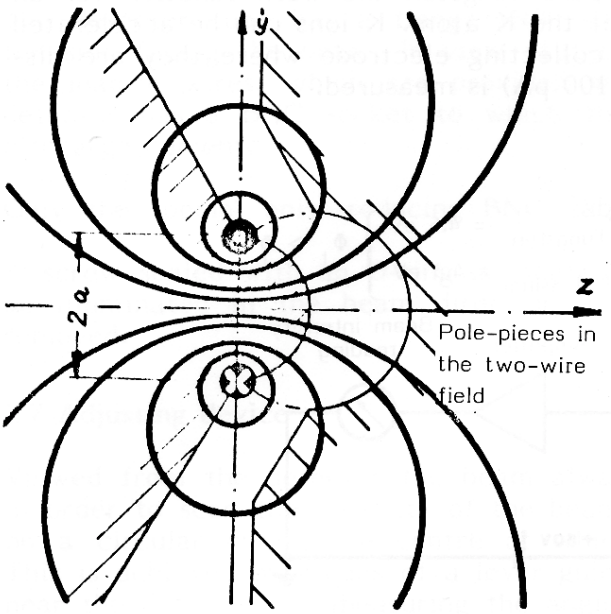


Figure 7: Two-wire field.

The following expression applies to a two-wire field:

$$\frac{\partial B}{\partial z}\,(z = 1.3\,a) \approx \frac{B_M}{a}$$

Use is made of this formula to determine the field gradient since the latter cannot be measured directly.

The simulation of a two-wire field with iron pole-pieces is however only ideal if the permeability of the iron is very much greater than 1. This is only the case at low field strengths. The deflection of the divided beam cannot then be determined exactly. In the case of large, readily-measurable beam deflections the two-wire field is no longer simulated exactly and the deflection is smaller than the theoretically expected value.

The pole-pieces are positioned by a special method and are hermetically sealed. The adhesive used has proven reliable, provided that temperatures below 0°C and excess pressure in the system are avoided.

The flat pole-pieces of the electromagnet are pressed on both sides onto the flat surfaces of the analyzer without any air gap.

The gap width is approximately 2 mm. The field gradient can be up to 300 Tesla/m.

Prior to assembling the apparatus the centre-gap magnetic flux B_M is measured as a function of the coil current of the electromagnet and the test certificate is enclosed with each instrument.

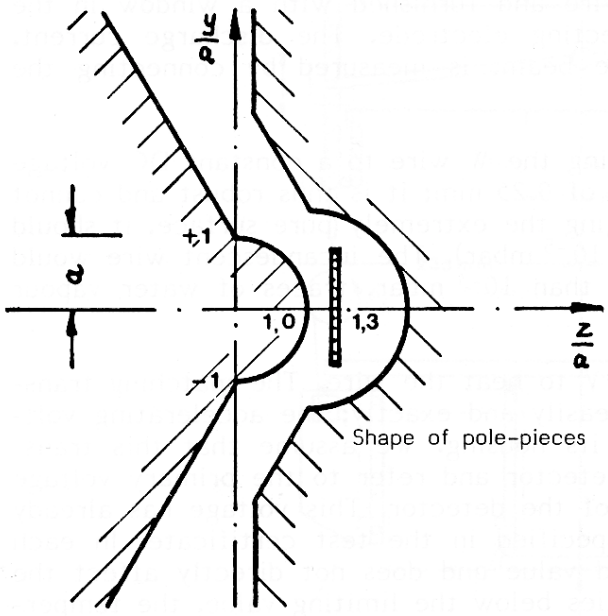


Figure 8: Shape of pole pieces and position of beam.

Data

Length of analyzer L: 7×10^{-2} m
Field parameter a: 2.5×10^{-3} m

2.6 Detector

The Langmuir-Taylor detector (see Fig. 9 for basic set-up and circuitry) comprises an incandescent tungsten wire (temperatures of 800-1000°C). K atoms impinging on this wire are vaporised as ions because for pure tungsten the work function for an electron is higher than the ionisation energy of the K atom. K ions can be accelerated in an electric field (accelerating field) to a collecting electrode where they are discharged; the resulting current (in the order of 100 pA) is measured.

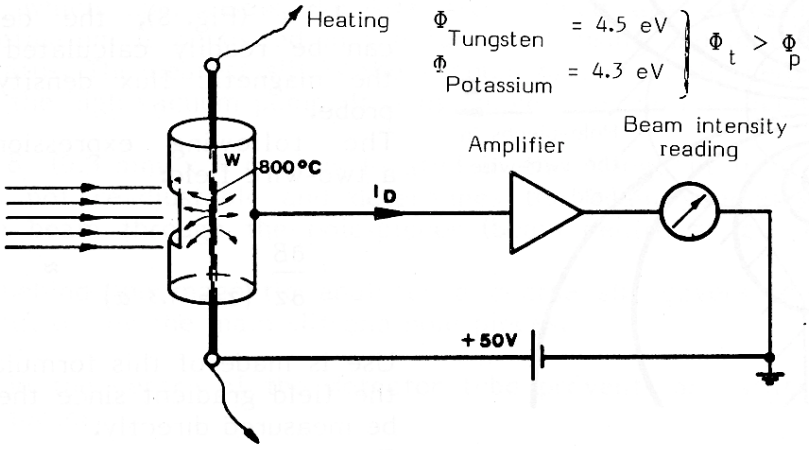


Figure 9: Langmuir-Taylor detector, basic set-up and circuitry.

A nickel cylinder surrounding the tungsten wire and furnished with a window in the direction of the beam constitutes the collecting electrode. The discharge current, which is proportional to the intensity of the beam, is measured by connecting the electrode to the amplifier.

The accelerating field is produced by connecting the W wire to a constant DC voltage of approx. +50 V. The W wire has a diameter of 0.25 mm; it is thus robust and cannot burn through easily. However, to avoid damaging the extremely pure surface, it should only be used in a good vacuum (better than 10^{-5} mbar). The incandescent wire would rapidly burn out in air. At pressures greater than 10^{-3} mbar, traces of water vapour lead to its destruction within hours.

Approximately 5 A are required at about 0.5 V to heat the wire. The matching transformer (09054.04) is used to set the voltage easily and exactly; the accelerating voltage source (about +50 V) is incorporated in its housing. We assume that this transformer is always connected in front of the detector and refer to the primary voltage of the transformer as the operating voltage of the detector. This voltage has already been determined for each detector and is specified in the test certificate. In each case it is in the order of ±10% of the rated value and does not directly affect the measuring result. When the filament voltage lies below the limiting value, the temperature of the W wire is too low and not all the K atoms impinging on it are vaporised. If the filament voltage is too high, impurities diffuse from inside the W wire to the surface; these impurities vaporise as ions and consequently superimpose an additional current on the one being measured. This effect, incidently, can be used to clean the wire when the apparatus is not being used ("Flashing"); see 3.9.1.

In normal operation the background current is 1-2 pA and can be disregarded with regard to the signal.

The adjusting device for the detector is described in 2.7.

The sensitivity and accuracy of the detector are more than sufficient to cover all the possibilities by the system.

The detector tube has a flange (NW 40 KF) with nine insulated ducts arranged on the side facing the beam. In view of the high filament current (5 A) for the W wire the lead-in wires, which are provided with 4 mm plugs, are soldered in place. The detector has a BNC socket to which the amplifier is connected for measuring the discharge current.

Only the special noise-reducing BNC cable supplied should be used for this purpose.

A screw sealed with an O-ring is located in the centre of the flange; the system can be illuminated in the beam direction and visually aligned once this screw has been removed.

2.7 Adjusting device

Viewed from the detector the beam always emanates from the centre of the magnet. In order to scan the intensity of the beam cross-section, the detector has to be guided on a circular curve, the centre of which is located at the centre of the magnet. This is achieved by means of a lever guide. Since there is no reference point available near the detector for measuring the angle of adjustment, the lever is extended beyond its pivot in the direction of the beam source where it is adjusted with the aid of a spindle; the latter is provided with a scale having 100 graduations. One revolution U of the spindle corresponds to an adjusting path s_S of 1 mm (10 revolutions possible).

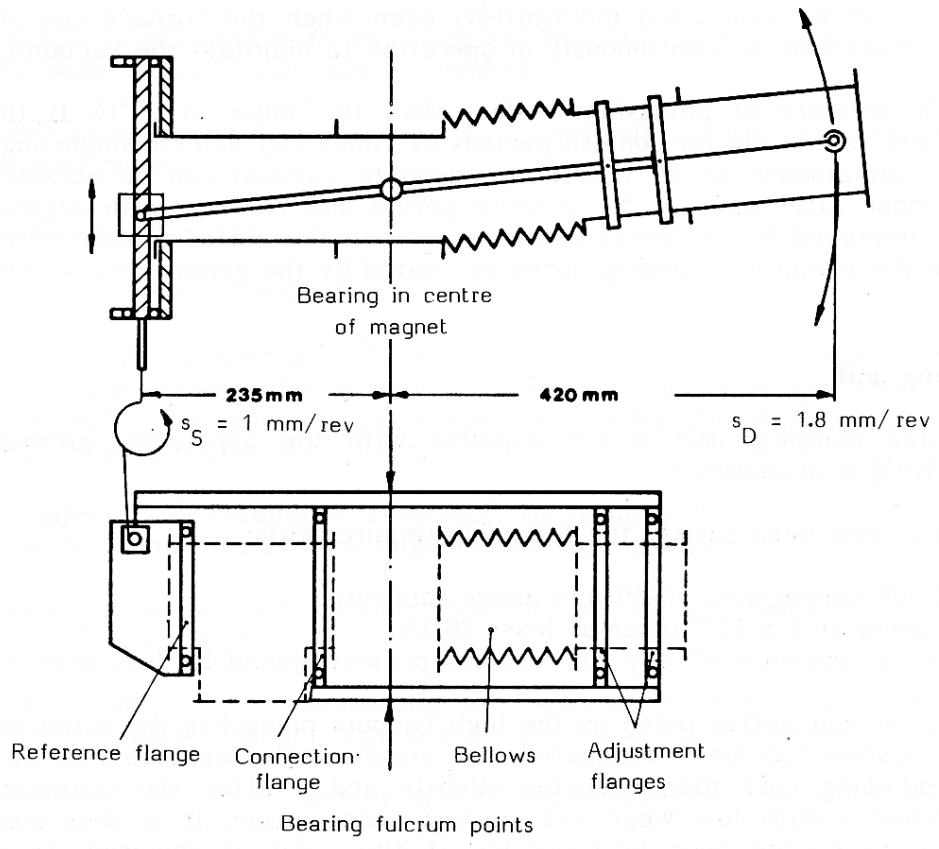


Figure 10: Principle and arrangement of the adjusting device.

The leverage is 1:1.8, i.e. one revolution of the spindle scale corresponds to a displacement s_D = 1.8 mm of the detector.

The adjusting device also enables the positioning of the movable part of the system, which contains the detector, to be reproduced.

Two rigid U-supports, which are connected by several flanges, have been used for this purpose. The detector tube is mounted in these flanges and can be adjusted.

Fig. 10 shows the principle of the adjusting device.

2.8 Vacuum

Potassium atoms which are scattered due to collision with residual gas molecules affect the measurement if they reach the detector. In order to exclude collisions as a source of error, the mean free path should therefore be a multiple of the beam length. Measurements have shown that an oil-free vacuum $<4 \times 10^{-6}$ mbar is sufficient for this purpose. Since large oil molecules in the residual gas have a greater collision probability, their partial pressure should be below 4×10^{-7} mbar.

This is the case when a Penning vacuum gauge indicates less than 4×10^{-6} mbar.

The unit is constructed from conventional aluminium components with small standardized flange connections. The seals are made of Viton and can be re-used even after the system has been dismantled. The connection to the pumping unit is made with a small NW 40 KF flange connection. The system should be assembled so that this flange is approximately 50-60 mm above the table-top (cf. also Fig. 2).

The system can be evacuated indefinitely, even when the furnace contains potassium. (The pump must then be continuously in operation to maintain the vacuum).

The vapour pressure of potassium is less than 10^{-7} mbar at 20°C. If the system has been exposed to the air for longish periods of time, e.g. after dismantling, the evacuation time can amount to 24 hours; an adequate vacuum can be obtained in approximately 1 hour after opening for a short period and flushing with argon. These times cannot be improved to any great extent even with the aid of a more efficient pumping unit, since the maximum pumping speed is limited by the given cross-sections.

2.9 Pumping unit

The required pumping unit is not supplied with the apparatus, although a suitable one (09059.93) is available.

The pumping unit must satisfy the following requirements:

- NW 40 KF connection, 50-60 mm above table-top,
- pump speed at 3×10^{-6} mbar at least 20 l/s,
- the partial pressure of any oil residues present should be less than 3×10^{-7} mbar.

The use of an ion getter pump as the high vacuum pump has the following advantages: after the system has been evacuated, the mechanical forepump can be switched off and the pumping unit then operates silently and - after the ultimate vacuum has been obtained - with low wear and current consumption. It is thus possible to keep the system evacuated over long periods of time and, if required, to set the pump temporarily in motion again.

No problems are encountered in starting up the pump again after the power has been switched off, e.g. for 30 min (transport).

2.10 Adjustment (see 3.6ff)

The apparatus has been designed in such a way than only a visual adjustment is necessary during assembly to ensure good measuring results.

To allow the adjustment to be checked visually, the furnace and detector are provided with holes which lie in the beam axis. These holes are accessible once the locking screws have been removed.

The main slit B_H in the magnetic analyzer has already been adjusted at the factory. The beam axis is thus defined. The flange which carries the spindle with scale to the adjusting device for the detector is secured with four screws on the T-tube in such a way as to ensure that the mechanism is of easy action, and is not then altered again.

The detector tube is centered about the beam axis when the upper level of the adjusting device is parallel to the beam axis. The four screws in each of the two flanges carrying the detector tube are used for this purpose.

The detector has already been adjusted at the factory; this can be checked with the aid of the hole in the flange. To position the W wire exactly vertically, the last tube with detector is turned. A slight inclination only reduces the sensitivity of the detector.

The detector is adjusted so that the slit is centered about, and positioned perpendicular to, the axis of the beam. The position of the plane of the slit is not important.

The height of the furnace has also been adjusted at the factory. The supporting wires fit in holes in the furnace and are secured with grub screws. These wires are bendable and allow the furnace to be centered in its housing.

The furnace flange is provided with two toggles. By rotating the flange the slit shifts laterally to the beam axis and can thus be centered.

Finally, the slit can be positioned so as to be perpendicular to the beam axis by turning the entire furnace housing.

2.11. Accessories (see Fig. 11)

2.11.1 Accessories included with 09054.88

The **ampoule opener** (1) consists of a 30 mm high steel cylinder provided with an axial 8 mm hjole to accommodate the K ampoule, and a slightly larger steel disk with a central 8 mm hole. The ampoule is opened by placing the disk over the neck of the ampoule and tapping it with a hammer.

The **potassium injector** (2) resembles a syringe. By using a "cannula", a 10-40 mg plug of potassium can be removed and then squeezed into the furnace.

The **furnace key** (3) has an M3 through screw to secure the furnace locking screw. This is the lid locking screw (4).

The **special BNC cable** (5) for connecting the detector to the amplifier is a noise-reducing type; the capacity changes only slightly when the cable is moved.

The **slit** (6) can be inserted in one of the flange connections to define the axis of the beam.

The **screw plate** (7) serves as the screw driver when setting up the furnace slit.

The **supporting plate** (8) is placed under the electromagnet to position the pole-pieces correctly.

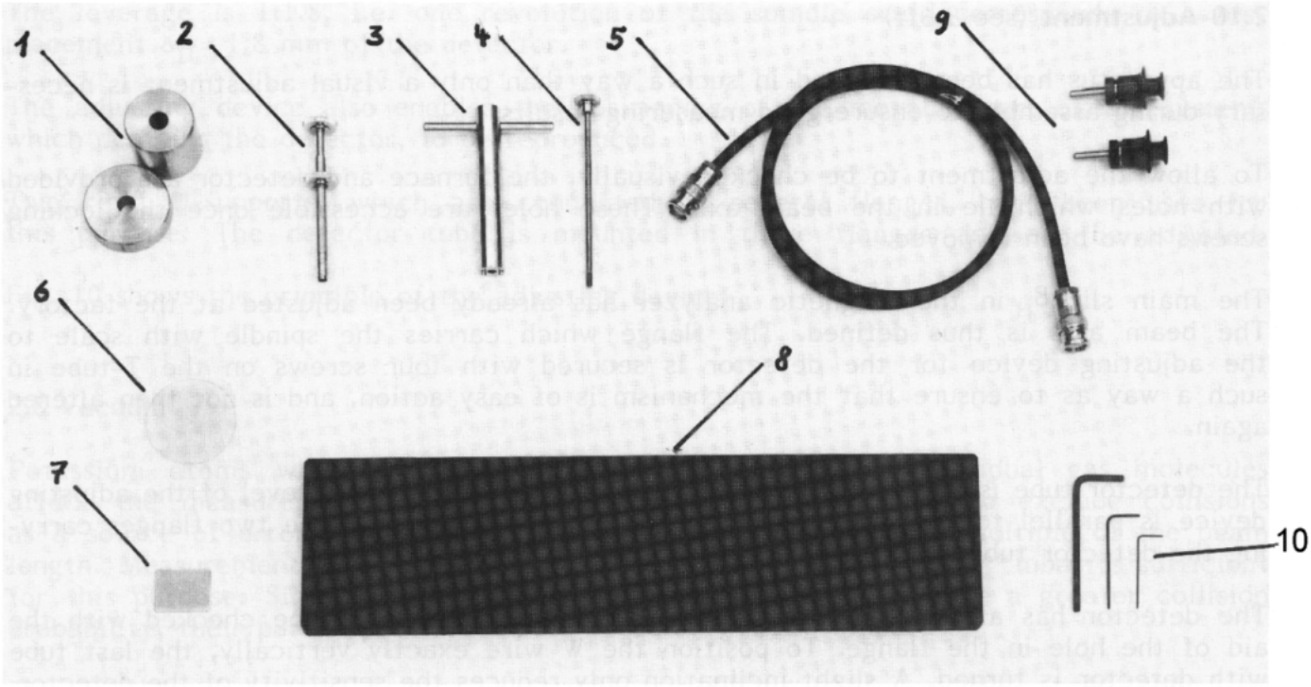


Figure 11: Accessories supplied.

Two **terminal plugs** (*9*) for connecting the terminals of the thermocouple to the measuring instrument.

Three **hexagonal pin spanners** (*10*):

- 0.9 mm for grub screws on furnace and detector,
- 1.3 mm for the scale on the adjusting device,
- 4 mm for the screws on the adjustment flange.

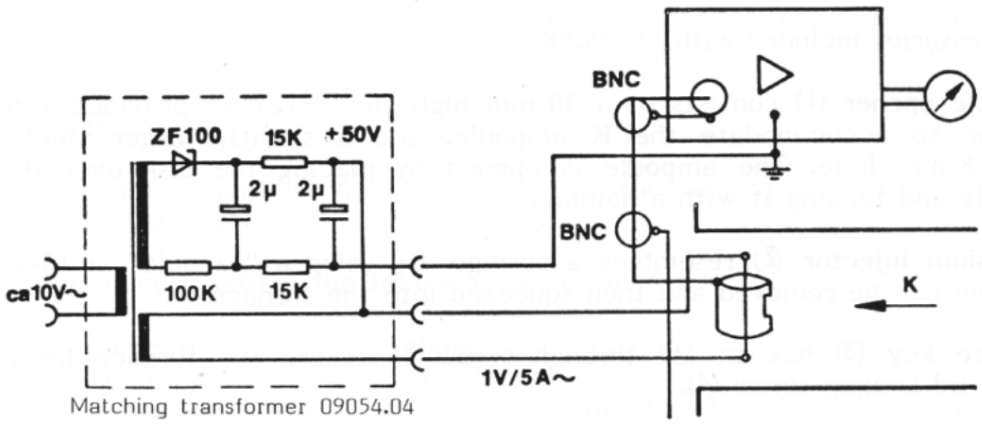


Figure 12: Circuitry and connections of the matching transformer.

2.11.2 Required accessories

Matching transformer 09054.04

The unit, which serves as the power supply for the detector, contains a transformer with a turns ratio of 10:1 to match the filament voltage, and a stabilized 50 V DC source as the accelerating voltage for the detector.

Data

Primary:	0-16 V AC/max 0.6 A
Secondary:	0-1.5 V AC/max 5 A and 50 V DC between earth socket and heating filament terminal
Circuitry:	see Fig. 12

Potassium ampoules, set of 6 09054.05

Each ampoule contains a sufficient quantity of vacuum-distilled potassium to fill the furnace.

Electromagnet, without pole-pieces 06480.01
Pole-piece, flat, 2 06480.02

U-shaped iron core with two coils (can be connected either in series or in parallel). Cylindrical pole-pieces to vary the gap width which are finely adjustable with two adjustment screws to ensure that the flat pole surfaces are parallel.

Data

Number of turns per coil	842
Diameter of pole surface	39 mm
Width of gap	0-50 mm
Coil terminals	4 mm sockets
Coil current	max 4 A
Operating current for Stern-Gerlach experiment	0-1 A; coils in series

2.12 Power supply and measuring instruments

The circuit diagram on the rear cover sheet shows the connections for the following instruments.

The **power supply** can be taken centrally from the
UNIVERSAL POWER SUPPLY UNIT. 11704.93

As shown on the circuit diagram, two different voltages can be led out using the selector switch. (In this case, the short-circuit plug is inserted in the 2-15 V AC output socket).

In each case one
RHEOSTAT, 10 Ω 06110.01

Connected as a voltage divider for setting the **operating voltages** for **furnace** and **detector.**

In each case a
VOLTMETER, 0.3-300 V 07035.00

serves to check the voltages on the furnace and detector.

To determine the **furnace temperature,** the terminals of the thermocouple are connected via the terminal plugs (accessories) to the
MEASURING INSTRUMENT, 10/30 mV, 200°C 07019.00

The temperature is shown in °C.

The **electromagnet** is supplied from the adjustable and regulated DC voltage of the universal power supply via a
AMMETER 07036.00

to measure the current, and via the
COMMUTATOR SWITCH. 06034.03

The commutator switch is required to reverse the polarity of the magnet during magnetization.

To attain zero current the circuit has to be broken at one point.

To measure the **detector current,** the detector is connected via the special BNC cable (accessory) to the
UNIVERSAL AMPLIFIER. 11761.93

A
RESISTANCE IN PLUG-IN BOX, 1 MΩ 06067.10
is required as measuring resistance.

A
VOLTMETER 07035.00

is connected to the output of the amplifier to indicate the **detector current.**

3. HANDLING THE STERN-GERLACH APPARATUS

3.1 Assembly

Assemble the Stern-Gerlach apparatus on a table of suitable size (0.7 m x 1 m, or larger) with the power supply and measuring instruments arranged behind it (cf. Fig. 13). Place the high vacuum pumping unit underneath the table and connect it to the apparatus through the gap in the table-top; distance from the left-hand edge and front edge of the table: approx. 25 cm and 35 cm respectively. Arrange an NW 40 KF connection about 50-60 mm above the surface of the table.

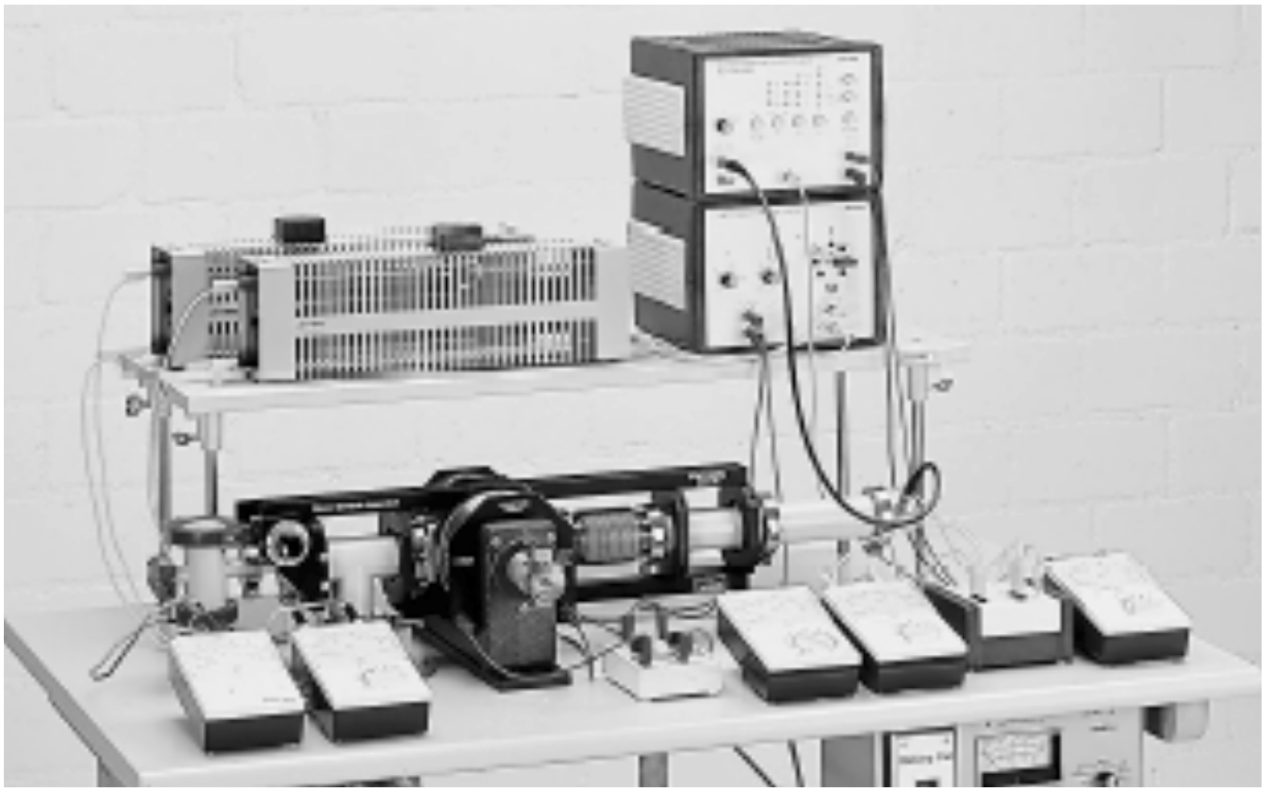


Figure 13: The Stern-Gerlach experiment. Stern-Gerlach apparatus on pumping unit with connected power supply and measuring instruments.

The electromagnet 06480.00 is on the supporting plate to the right of, and next to the pump flange. Its poles are screwed far apart.

The Stern-Gerlach apparatus is filled with argon when supplied. In order to avoid long evacuation times, it should be quickly evacuated after assembly. Check that the pumping unit is functioning correctly beforehand.

Remove the covers on the pump connection and on the Stern-Gerlach apparatus, and check for damage and contamination. Insert a clean seal and attach the apparatus to the pump flange. Check that the magnet poles are pointing approximately towards the centre of the pole-pieces, and then unscrew the SW 10 hexagonal screw on the lower bearing of the adjusting device until it lies on the yoke of the magnet and supports the set-up. **In doing so, ensure that the system is not under stress as a result of turning the screw too far.**

Using the two adjustment screws, now press the poles of the magnet symmetrically against the pole-pieces of the apparatus so that they lie flat against each other; if necessary, move the magnet slightly.

It is important that there is no air gap between the poles of the magnet and the pole-pieces of the analyzer. It may be necessary to rotate the analyzer about the beam axis, in which case loosen the tightening rings on the two analyzer flanges and then force the gripping jaws apart slightly.

Now evacuate the system to about 10^{-6} mbar and check that it is clean and leak-proof. The time required for evacuation can be shortened considerably by warming parts of the system carefully; details in 3.2.

Meanwhile, position the power supply and measuring instruments as shown in Fig. 15 and connect them to the apparatus.

3.2 Evacuation

The vacuum of at least 4×10^{-6} mbar is required for the Stern-Gerlach apparatus (reading of a Penning vacuum gauge). The partial pressure of any oil residues present should be lower than this by a factor of 10. This is generally the case when a Penning vacuum gauge indicates 4×10^{-6} mbar.

The operating instructions for the pumping unit are described in a separate brochure. Various types of pumping unit can be used, provided that they satisfy the following minimum requirements:

- Coupling flange: NW 40 KF, 5-6 cm above table-top
- Pumping speed at 10^{-6} mbar: >15 l/s on the coupling flange
- Partial pressure of any oil vapours: $< 10^{-7}$ mbar.

When putting into operation for the first time, check initially that the pumping unit is functioning correctly. To do this, close the coupling flange and evacuate. If the specified ultimate vaccum of the pumping unit is attained within a reasonable period of time, the unit and connecting parts are free from leaks and contamination.

After the Stern-Gerlach apparatus has been correctly assembled and connected to the pumping unit, the latter is set in operation again. The ultimate vacuum will be attained relatively quickly if everything is in order. The remaining part of this section describes how this procedure can be speeded up, and how faults can be recognized and avoided.

Generally, the pumping unit consists of two different pump systems: one pump for the forevacuum, and a high-vacuum pump which is switched on once the characteristic vacuum of the pumping unit has been attained. The volume of the Stern-Gerlach ap-

paratus is slightly greater than 1 Litre. The pumping speed of the forepump is usually greater than 0.3 l/s, whereas that of the high-vacuum pump is greater than 20 l/s. Provided that no gas sources are present, it is possibe to evacuate the system to 10^{-6} mbar in 15 minutes, even when the additional volumes of the lines and throttling of the pumping speed due to narrow cross-sections are taken into account. Short evacuation times such as these can only be realized when a clean and intact system has been evacuated and then re-evacuated after admission of argon. After venting, evacuation takes a considerably longer time since gas residues (primarily water vapour) adhere to all surfaces and are then released again only slowly. For this reason it is advantageous to exclude the admission of air when opening the system by, for instance, flooding and flushing with argon. An alternative and less expensive method is to flood via a dry filter (but only for the shortest possible time).

If the system has been vented for longish periods of time or dismantled, it can take 20-40 hours to attain the ultimate vacuum despite the absence of leaks.

Gas residues which adhere to the inside walls can be removed rapidly by a baking-out process (see 3.3).

Extreme cleanliness should be observed when dismantling the system. Avoid contact with oil or grease; the use of high vacuum grease as a sealing agent is not recommended. On the other hand, impressions made by a clean finger are not critical in the 10^{-6} mbar range. It is recommended to wipe the sealing surfaced of flanges with a clean finger, but do not use fibrous cloths.

After wiping, oven-dry (60 -100 °C) any parts that have been cleaned with a solvent or water.

3.3 Degassing

Depending on their nature, all surfaces inside a vacuum system absorb water to some extent from the atmosphere and release it again very slowly during evacuation. Cleansing solvents can also penetrate into gaps and then vaporise slowly. These adsorbed gases are released more readily at elevated temperatures.

It is expedient to heat the furnace in the medium-high vacuum range until the pressure remains constant. Gas can also be released by wafting a flame around the bellows.

Take care when using a flame. To avoid thermal stress, do not heat just on one side. Since the temperature is not measured, only heat to about 60°C; this is approximately the temperature at which the finger can be place on the surface for 0.5 s without any sensation of pain. A temperature of 80°C is permissible, but this cannot be tested so easily.

Do not warm the magnetic analyzer on account of the gluing seams.

Heating is particularly effective at the following positions:

- bellows
- transition pieces to the furnace housing
- furnace (by switching on the electric heating).

The degassing process is finished when only a slight increase in pressure is obtained during heating.

3.4 Detection of leaks

If, when the forepump has been running for 15 min, a pressure of 10^{-3} mbar has not been attained or, in the case of longer pumping times, the pressure has not fallen below this value, a leak could be present.

A simple method for detecting leaks takes advantage of the fact that the reading indicated by a Pirani or Penning vacuum gauge is dependent on the type of gas. Using a brush, apply 2-propanol in turn to all points which could conceivably leak and observe the vacuum reading. If the reading changes considerably, then 2-propanol has made its way through the leak into the system.

If this method proves unsuccessful, consider whether there are any sources of gas in the system.

Is the pump oil clean? Let the pump run for 15 min with gas ballast; if necessary, change the oil.

Has the sorption trap been baked out and cooled down?

Have any parts been inserted which could still contain traces of water or solvent?

Have any materials which could give off gas, such as plastics, soldering flux etc. been introduced into the system?

It is improbable that the flange seals will leak, unless foreign bodies have been incorporated when they were screwed down. If the vacuum reading does not improve when the pumping time is increased, then any leaks can be detected by brushing propan-2-ol in turn onto the suspected points. If a leak is present, the reading on the vacuum gauge will change after propan-2-ol has been brushed onto the point in question, since the reading indicated by vacuum gauges depends to a large extent on the type of gas.

Small leaks up to 10^{-4} mbar x l/s can be sealed permanently by brushing the relevant point with a sealing lacquer called "Epple 22"; dilute this with a little nitro thinner before use.

An extremely fine leak could conceivably lead to a slight increase of the ultimate pressure attainable. Sometimes it is not absolutely certain that there is a fault in the system. Such leaks are detected using propan-2-ol. The current shown by the VacIon is a suitable indicator. Be patient! After applying propan-2-ol it can take some time before the final reading is obtained. Check for any leaks at the following positions:

- electrical lead-in holes on the furnace
- O-ring of the M3 screw in the centre of the detector
- gluing seam of the pole-pieces on the magnetic analyzer.

If a leak is detected at any of these positions, it can be readily sealed without interrupting the operation by brushing with Epple 22 (dilute first with nitro thinner).

The small 0-ring on the detector can be renewed as the occasion demands.

3.5 Flooding

If the system has to be opened, for example to fill the furnace, vent it beforehand or, better still, flush it with argon.

The following points **must** be observed:

- Switch off the detector heating to prevent the tungsten wire from burning out.
- Cool the furnace down to below 50°C if it still contains potassium. Hot potassium is extremely dangerous.
- Remove the red tightening ring on the furnace to prevent excess pressure forming in the apparatus (to protect the gluing seams on the magnetic analyzer).

Further details are given in the operating instructions for the pumping unit.

3.6 Adjustment

The Stern-Gerlach apparatus has already been adjusted at the factory. A re-adjustment may be necessary after the apparatus has been dismantled. The beam axis passes through the centre of the apparatus and is fixed by the magnetic analyzer (MA) with incorporated main slit. The centering of the fixed tubes is sufficiently accurate due to the type of design. The furnace, adjusting device with movable tubes, and detector must all be adjusted.

The alignment slit (supplied), which has a central hole approximately 1 mm in diameter, is a useful aid for adjustment purposes.

3.6.1 Adjustment of the furnace

The furnace must be adjusted so that the greatest beam intensity is produced in the axis of the beam. Since the beam has a rectangular cross-section, the furnace slit and the main beam slit must be parallel. There is no need to adjust the other slits.

The following adjustments must be made to the furnace:

a) Height
b) Side
c) Parallelism of the slits.

To define the beam axis, insert the alignment slit behind the magnetic analyzer.

For a):
The furnace is supported by four vertical wires which stand vertically on the furnace flange. These wires extend into four holes located on the furnace and are held with grub screws. These screws can be loosened to adjust the height of the furnace (once-only adjustment by the factory).

For b):
The furnace slit is located 6 mm in front of the centre line of the furnace flange. Turn the latter to effect a lateral displacement of the slit.

For c):
Turn the entire furnace housing on the flange to the vacuum container to align the furnace slit parallel to the main beam slit.

The furnace housing has a KF 10 flange on the side opposite the beam direction. Take off the blank flange to gain access to a rod screw which closes a hole in the furnace. After this screw has been removed, it is possible to look into the system in the beam direction through the furnace slit. A visual alignment check can be made by illuminating the other end with a lamp (since the detector is also provided with a corresponding hole).

After the above-mentioned adjustments have been made, the furnace slit, main slit and magnetic analyzer all lie on one axis. Now remove the alignment slit behind the MA.

3.6.2 Adjustment of the adjusting device

Adjust the flange carrying the adjustment spindle so that the spindle is perpendicular to the axis of the apparatus and ensure that the mechanism is of easy action over the entire range of adjustment. In addition, ensure that the levers of the adjusting device are approximately parallel to the beam axis in the centre of the adjustment range (mid-scale).

Press the bellows together slightly so that the two adjustment flanges on the tube behind the bellows are mounted symmetrically. The detector can be replaced by the alignment slit.

The two tubes on the end of the Stern-Gerlach apparatus orientated towards the detector are first roughly centred by eye about the beam axis with the eight screws on the two adjustment flanges. The levers of the adjusting device should be parallel to the beam direction. Now illuminate the apparatus from the furnace side (lamp with ground glass plate, possibly a laser) and then adjust further to give maximum brightness (the scale can be moved slightly for this purpose).

To ensure that the tension of the bellows does not cause the adjustment flanges to slip out of place, always adjust in opposite directions two screws which face each other.

3.6.3 Adjustment of the detector

Coarsely adjust the detector on the flange by loosening the four screws for the heating filament mounting, shifting the filament to the centre, and then re-tightening the screws. Additional fine adjustments to the wire and, if necessary, to the cylindrical electrode can be made by bending at the connection points. In order to better judge the correct position, insert the detector flange into one tube and look through it from each side in turn.

Finally, assemble the detector; check the verticality of the tungsten wire visually and make any adjustent by turning the detector tube.

3.7 Filling the furnace

It is expedient to evacuate the apparatus prior to filling the furance in order to check that the vacuum system is functioning correctly (see 3.2 Evacuation). In the meantime, ensure that the following accessories and instruments are handy:

- Ampoule opener (2 parts)
- Potassium ampoule
- Safety glasses
- Hammer, 400 g
- Tweezers
- Potassium injector
- Furnace key with lid locking screw
- Petri dish or paper, for any parts to which potassium may adhere.

Wear safety glasses when handling potassium!

Loosen the locking ring on the furnace housing. Close the forevacuum valve on the pumping unit. Flood the apparatus; then set the argon flow to approx. 2 l/min. Remove the lid of the furnace housing. Screw out the furnace locking screw with the furnace key; leave the locking screw on the furnace key and place to one side.

Insert a potassium ampoule, point upwards, into the hole in the steel cylinder of the ampoule opener and place the steel disk on the neck of the ampoule. Hit the disk with a hammer to open the ampoule. Remove glass splinters with the tweezers.

Push the tube of the potassium injector into the potassium; move it to and fro (tilt) and then pull it out. Check that the injector tube contains potassium. Now squeeze the potassium into the furnace chamber as if using a syringe. When withdrawing the injector from the furnace, ensure that the plug of potassium does not stick on the injector. Use the pin of the potassium injector to pack down the potassium in the furnace.

Close the furnace locking screw. Do not over-tighten. The furnace should still have some play.

Remove the key from the furnace locking screw. Place the lid with seal loosely on the furnace housing. Arrest the argon flushing. Press the lid firmly with the hand. Open the forevacuum valve (forepump running).

Evacuate in accordance with the operating instructions for the pumping unit. The apparatus is ready for the use when a vacuum of 4 x 10^{-6} mbar has been attained.

EXTREME CAUTION should be exercised when disposing of potassium residues.

3.8 Cleaning the furnace

The furnace must be cleaned when the potassium has been consumed or when the apparatus is not to be left under vacuum on completion of an experiment.

Since potassium reacts with air to form potassium hydroxide, any deposits should be removed immediately as a safeguard against corrosion.

The following procedure is recommended:

- Switch off the power supply for the furnace heating and the detector
- Check that the furnace temperature is below 50°C; if not, wait
- Switch off VAC-ION
- Remove the tightening ring on furnace housing
- Flood the apparatus with argon and allow to flow at a rate of 3 l/min as long as the apparatus is open
- Remove the lid and seal on the furnace housing. Carefully screw out the furnace locking screw with lid locking screw with the furnace key
- Remove KF 10 flange on the left-hand end of the apparatus and screw out the adjustment locking screw
- Dismantle the furnace together with furnace housing on the other KF 10 flange
- Wipe the tube piece (Ø approx. 15 mm) left on the apparatus with a cloth
- Close the flooding valve
- Shut the aperture of the apparatus (KF 16)
- Take the furnace with flange out of the furnace housing
- Put on safety glasses
- Fill the furnace with absolute alcohol, wait until effervescence ceases, then shake out and rinse with distilled water
- Remove the slit screw and slit using the screw plate, wash with water and dry
- Rinse the furnace housing with distilled water and dry; do the same for all other small parts which have been dismanted so far. Take the seals off their support rings
- Oven-dry (approx. 80°C) all parts that have been cleaned with water for 1/2 hour Reassemble the furnace parts. Check that the slit is not obstructed; clean with a needle if necessary.
- Insert the furnace into its housing and centre it visually
- Insert the adjustment locking screw; screw down loosely. Secure the KF 10 flange.
- Attach the furnace housing with furnace to the apparatus
- Commence flushing with argon
- Screw down the furnace locking screw so that the furnace still has a little play
- Place the lid with seal on the furnace housing
- Close the flooding valve and argon valve.

3.9 Detector

A small and constant dark current is set up after some time. Therefore, if the pressure is less than 10^{-4} mbar, always switch on the heating and leave it switched on. Switch if off when the pressure rises above 10^{-4} mbar.

Before flooding the apparatus, it is essential to switch off the heating. The incandescent tungsten wire would burn out in air within a few minutes.

The filament voltage on the input of the matching transformer can fluctuate between ±10 % of the recommended value without affecting the measuring accuracy. If the

filament voltage is lower than this, the detector reacts increasingly slowly to changes in measured values.

Flashing:

To reduce the dark current it can be advantageous to increase the detector heating for 10-30 seconds to 16 V on the matching transformer. When the filament voltage is taken back to the operating value, the dark current is then particularly low for some time. This procedure does not damage the tungsten wire.

3.9.1 Replacing the tungsten wire

Provided the tungsten wire is used in accordance with the instructions, it will not be subjected to considerable wear. When connected correctly to the recommended power supply, it is only possible for it to burn out if exposed to air or water vapour $>10^{-4}$ mbar. If this value is exceeded only slightly, this process takes 50 seconds, and several minutes at atmospheric pressure.

The tungsten wire has a purity of 99.97% and a diameter of 0.25 mm. This commercial purity is not sufficient for the operation. The surface of the wire has to be purified further in high vacuum by heating to glowing. Not every wire is equally suitable; some portions of the same batch even vary.

Tungsten wire is extremely hard and difficult to cut. The diagonal cutting pliers used should be sufficiently hard and sharp to ensure that the wire is not squeezed off, otherwise it could exhibit longitudinal cracks and thus be unusable. (Check the cutting points with a magnifying glass; after becoming incandescent, the wire becomes even harder and can then only be broken).

Loosen the attachment screws and take out the old wire.

It is advantageous to clean the surface of the wire before insertion:

- Immerse a piece of the wire (approx. 80 mm in length) in a bath containing 2N KOH to a depth of about 40 mm.
- Pass an alternating current (approx. 10 mA) for about 30 min through the wire and an additional nickel electrode of large area. Meanwhile, stir the KOH solution with a magnetic stirrer.
- Then wash the wire with distilled water and allow to dry.

Fix the cleaned wire to the attachment pieces of the detector; do not touch the bare wire. Tension the wire slightly using the plate springs.

Insert the pull electrode and centre it visually. Adjustment check after removal of the M3 screw on the flange and insertion in the detector tube. To do this, dismantle the latter from the apparatus.

Now attach the detector; it can be set in operation once the vacuum is greater than 10^{-5} mbar. The detector now has an extremely high dark current, but this can be reduced by heating the wire to glowing in a vaccum.

The matching transformer is not adequate for the initial phases of this programme. The filament voltage for the wire and the pulling voltage (approx. 50 V loadable with 10 µA must be taken from suitable instruments.

The equilibrium between several phenomena in the wire shifts at different wire temperatures. Experience has shown that it is advantageous to commence the wire cleaning process at high temperature.

Apply 1.2 V (approx. 6 A) to the wire for about 3 min. Then allow it to cool down for at least 15 min. Apply the pulling voltage during the heating. Repeat this procedure about 50 times.

Finally, heat the glowing for 24 hours at 0.5 V; for this operation, the original circuit with the matching transformer can be set up again.

To determine the operating voltage, set the previous voltage with the potassium beam on. If the detector current reacts too slowly towards changes, select a higher operating voltage. In the absence of the potassium beam, the current should not exceed 1-2 pA; if it does, then reduce the operating voltage.

In the case of a correctly "burnt-in" detector and an optimum operating voltage, the dark current is reduced further during longer periods of operation.

3.10 Magnet

Screw the poles of the magnet firmly against the pole-pieces of the Stern-Gerlach apparatus and connect the coils of the magnet in series. The current range used is 0-1 A; this is equivalent to 0-5.5 V on the magnet coils.

In view of the hysteresis of magnetic iron, carry out all measurements with increasing current values.

It is not possible to demagnetize the magnet using 50 Hz alternating current. The time constant for coils in series is about 0.3 s.

To demagnetize the magnet, reverse the coil current starting at the highest current used, reduce the current by about 10%, reverse the polarity again, etc. Do not reverse the polarity faster than one second.

3.11 Adjusting device

All measurements should be made for the same direction of rotation of the micrometer screw (1 mm/rev) to exclude any end play.

The leverage is 420/235 = 1.79, i.e. 1.8 mm/rev on the detector.

If a cord pulley is attached to the back shaft of the adjustment spindle and actuated via a synchronous motor, the measuring results can be recorded with a y,t plotter. 20 seconds per revolution on the adjustment spindle is a suitable value.

Adjust the stops on the adjustment spindle so that the scale extends from 0 to 1000. The beam maximum will be near the 500 setting.

3.12 Furnace temperature

A suitable heating voltage for the furnace has already been determined during the acceptance test of the Stern-Gerlach apparatus and is specified in the test certificate. This value is only intended as a guide when putting into operation for the first time. In practice, the beam current and the furnace temperature are selected with the heating voltage.

In order to bring the furnace to the desired temperature more quickly, heat it (max. 10 min) with 12 V, max. 1 A.

The furnace temperature can be measured with the aid of the built-in Fe-CuNi thermocouple. R_i = 2.2 Ω.

Fig. 14 shows the thermocouple voltage as a function of its temperature. The internal resistance of the millivoltmeter used should be taken into account.

If the instrument 07019.00 is used, the temperature can be measured directly. The internal resistance of the thermocouple has already been taken into account. The ambient temperature (equivalent to the temperature of the reference junction) can be set on the instrument when the test terminals are short-circuited.

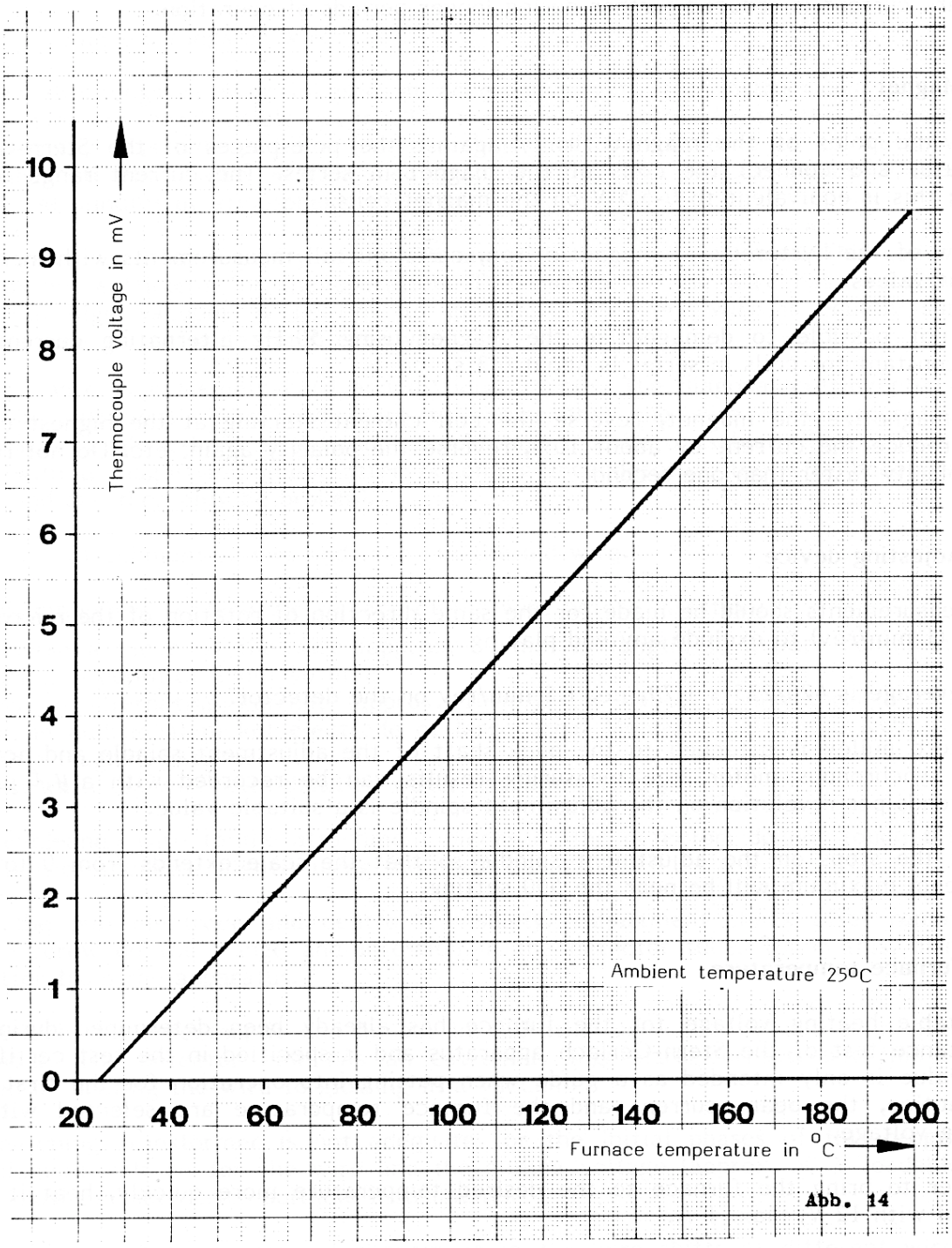


Figure 14: Thermocouple voltage.

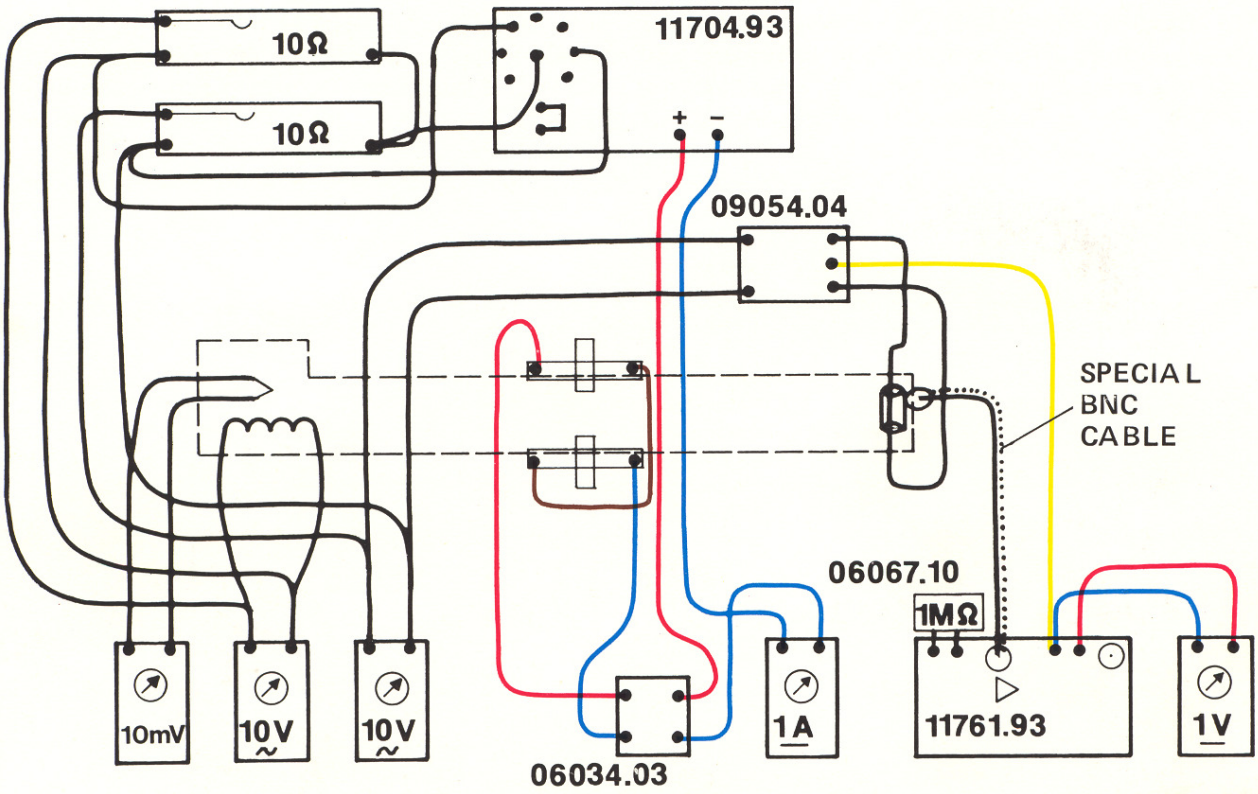


Figure 15: Instrument connections in the Stern-Gerlach experiment.

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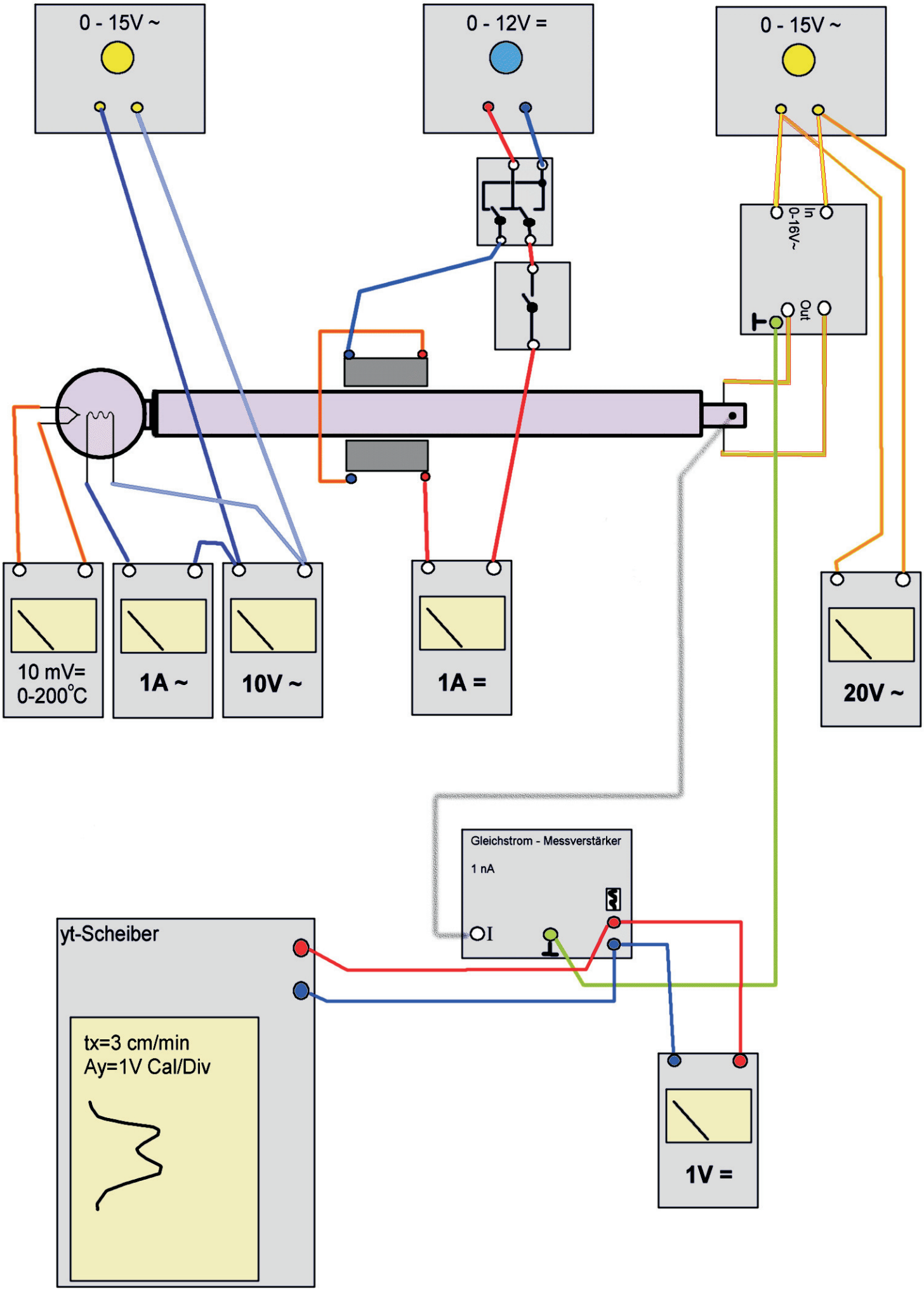
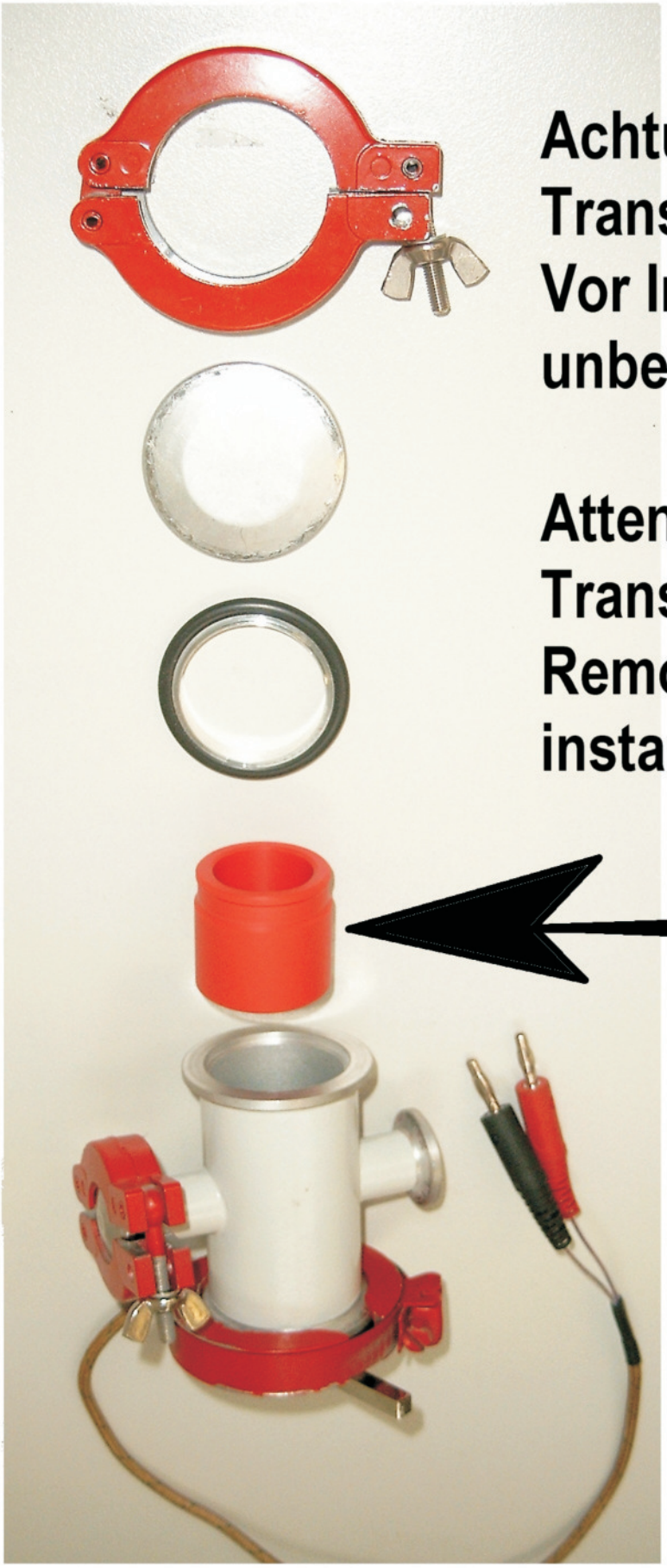
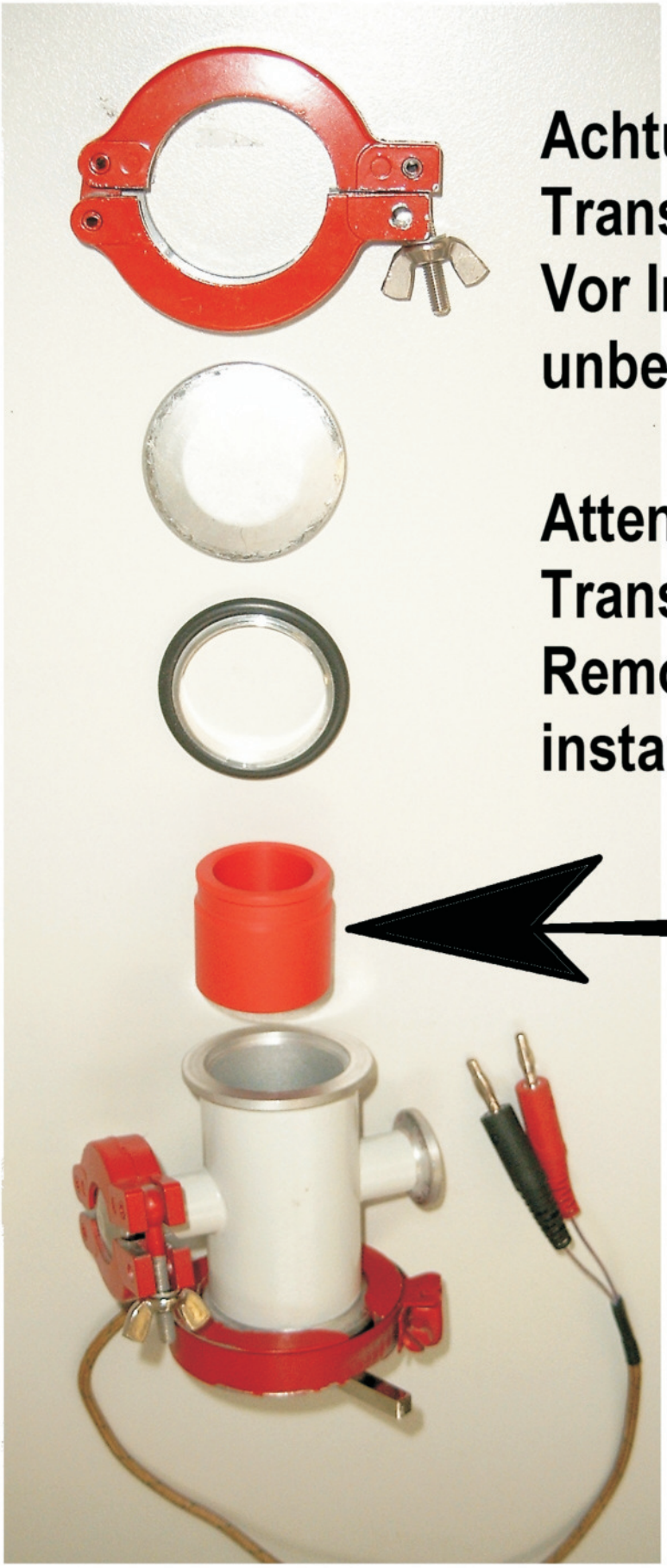

0 - 15V ~
0 - 12V =
0 - 15V ~
In
0-16V~
Out
10 mV=
0-200°C
1A ~
10V ~
1A =
20V ~
Gleichstrom - Messverstärker
1 nA
OI
yt-Scheiber
tx=3 cm/min
Ay=1V Cal/Div
1V =



Achtung !
Transportsicherung.
Vor Inbetriebnahme
unbedingt entfernen !

Attention !
Transportation Lock.
Remove before
installation !



Achtung !
Transportsicherung.
Vor Inbetriebnahme
unbedingt entfernen !

Attention !
Transportation Lock.
Remove before
installation !