UNIVERSIDAD AUTÓNOMA DE CHIHUAHUA

FACULTAD DE INGENIERÍA

ELECTRICITY AND MAGNETISM PRACTICE MANUAL

PHYSICS LABORATORY

LD DIDACTIC

ELECTRICITY

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Electricity

Electrostatics
Basic experiments on electrostatics

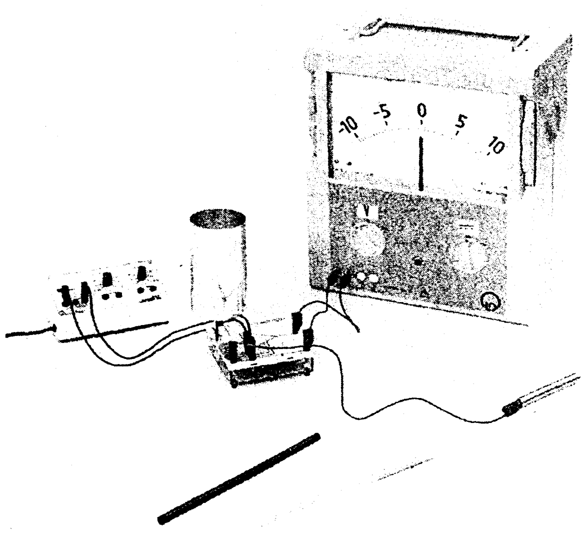
LD Physics Leaflets

P3.1.1.2

Basic electrostatics experiments with the electrometer amplifier

Objects of the experiment

- Investigating charge separation when two friction rods are hit together
- Detecting charge separation when a friction rod is rubbed with a friction foil
- Investigating the polarity of charged friction rods after they have been rubbed with various friction foils



Principles

Charges can be separated through hitting or rubbing two materials together.

This experiment shows that one of the materials carries positive charges, and the other material negative charges. It demonstrates also that the absolute values of the charges are equal.

If the charges of both materials are measured at the same time they cancel each other out. The sign of the charge of the material does not depend on the material alone, but also on the properties of the other material.

To determine the charge separated, e.g. by hitting two materials, the electrometer amplifier is used. This device is an impedance converter with an extremely high-ohm voltage input ($10^{13}\ \Omega$) and a low-voltage output ($1\ \Omega$).
By means of capacitive connection of the input and using a Faraday's cup to collect charges, this device allows to measure extremely small charges. Thus charges found in experiments of contact and friction electricity can be conducted with a high degree of reliability.

Fig. 1: Experimental setup with power supply 450 V (see also Fig. 2)

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Apparatus

1 Electrometer amplifier 532 14
with
1 Plug-in power supply 12 V AC 562 791
or with
1 power supply, 450 V, 230 V 522 27
1 pair of cables, 50 cm, black 501 451

1 connecting rod 532 16
1 Coupling plug... 340 89
1 Faraday's cup 546 12
1 clamping plug... 590 011
1 capacitor, 1 nF, STE 2/19 .... 578 25
1 capacitor, 10 nF, STE 2/19 .... 578 10

1 pair of friction rods PVC and acrylic..................... 541 00
1 Induction plate 542 51

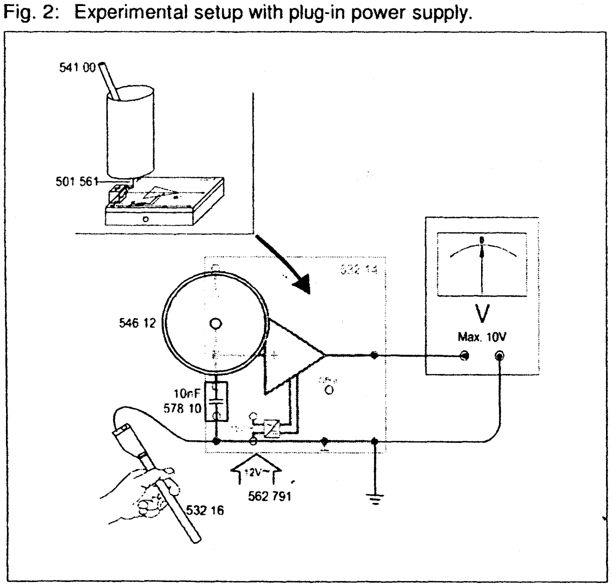
with
1 Multimeter LDanalog 20....................................... 531 120
or with
1 Demo-multimeter, passive 531 905

1 Pair cables 100 cm, red/blue 501 46
1 Connecting Lead 50 cm Black 500 424

additionally recommended:
1 cartridge burner DIN type 666 714

1 leather.. 541 21
1 polyethylene friction foils............................... 200 70 750

Fig. 2: Experimental setup with plug-in power supply.



Setup

The experimental setup with power supply, 450 V and plug-in power supply 12 V AC is shown in Fig. 1 and Fig. 2, respectively.

Further hints of how to measure the charge with the electrometer amplifier can be found in the instruction sheet 523 14.

Carrying out the experiment

Remark:

Before carrying out the experiment discharge the friction rods and the Faraday's cup in order to obtain exact experiment results.

Further hints:

For discharging the friction rods it is recommend quickly move them longitudinally through the non-luminous flame of the cartridge burner several times.
The Faraday's cup is discharged by touching it with the connecting rod until the multimeter displays a voltage of U = 0 V.

- Hit the discharged friction rods together several times. Then hold them apart in your hands.
- Hold the PVC rod in the Faraday's cup so that about a quarter of its length is inside the cup and observe the deflection of the multimeter pointer.
- Do the same with the acrylic rod.
- Then hold the two rods in the Faraday's cup simultaneously and observe the deflection of multimeter pointer again.

The induction plate can be used to demonstrate the transfer of charge from a friction rod to the Faraday's cup., e.g. by touching the friction rod with the induction plate and holding the induction plate into the Faraday's cup the charges can be transferred and measured.

Measuring example

Table. 1: Measured polarity of charges after hitting the PVC and acrylic friction rods

Friction rod in the Faraday's cup	Polarity of the charge
PVC	-
Acrylic	+
PVC and acrylic	0

Evaluation and results

When two friction rods are hit together, charge separation takes place.

In the course of charge separation electrons are transferred from one friction rod (e.g. acrylic) to the other (e.g. PVC).

The friction rod which has lost electrons (acrylic) carries a positive charge after the process of friction.

The friction rod which has acquired electrons (PVC) carries a negative charge.

The polarities of the charged friction rods are always of opposite signs.

The magnitudes of the charges are equal.

Supplementary information

Instead of hitting the friction rods to separate the charges a friction rod can be rubbed with various materials to generate charge separation.

a) Detecting charge separation when a friction rod is rubbed with a friction foil

- Rub the discharged acrylic rod with the leather, hold it in the Faraday's cup so that about a quarter of its length is inside the cup, and observe the deflection of the multimeter pointer.
- Remove the acrylic rod.
- If necessary, discharge the Faraday's cup, hold the leather over the opening of the cup, and observe the deflection of the multimeter pointer.
- Remove the leather.

Table. 2: Polarity of the friction rod and the friction foil after charge separation.

Friction rod	Polarity of the friction rod	Friction foil	Polarity of the friction foil
Acrylic	-	Leather	+

b) Investigating the polarity of charged friction rods after they have been rubbed with various friction materials

- One after another rub the PVC and the acrylic rod with leather and paper. Each time hold the respective rod in the Faraday's cup so that about a quarter of its length is inside the cup.
- Observe the deflections of the multimeter pointer, each time taking down the polarity of the charged friction rods.

Table. 3: Polarity of friction rods after being rubbed with various friction foils.

Friction rod	Friction foil	Polarity of the friction rod
Acrylic	Polyethylene	+
PVC	Polyethylene	+
Acrylic	Leather	-
PVC	Leather	-
Acrylic	Paper	+
PVC	Paper	-

The results of Table 2 and Table 3 can be summarized as follows:

When a friction rod is rubbed with a friction foil, charge separation takes place.

In the course of charge separation electrons are transferred from one body (friction rod or friction foil) to the other.

The body which has lost electrons (friction rod or friction foil) carries a positive charge after the process of friction.

The body which has acquired electrons (friction rod or friction foil) carries a negative charge.

The polarities of the charges on the friction rod and the associated friction foil are always of opposite signs.

The polarity of the charges carried by a friction rod after being rubbed depends on the materials the friction rod and the friction foil are made from.

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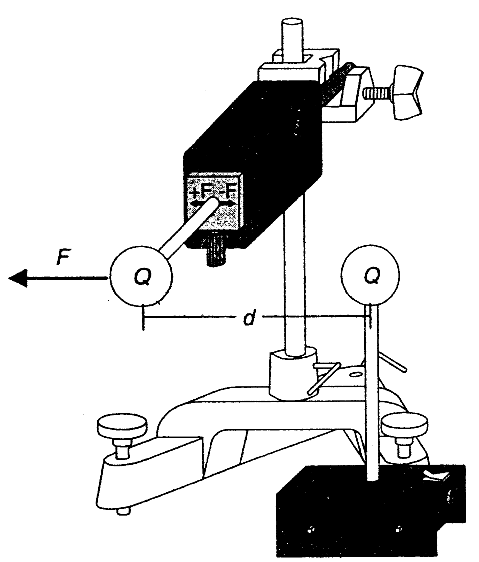
Confirming Coulomb's law

Measuring with the force sensor and newton meter

Objects of the experiments

- Measuring the force F between two charged balls as a function of the distance d between the balls.
- Measuring the force F between two charged balls as a function of their charges Q_1 und Q_2.
- Estimating the permittivity of free space ε_0.



Principles

According to Coulomb's law, the force between two pointlike charges Q_1 and Q_2 at a distance d is

$$F = \frac{1}{4\pi \cdot \varepsilon_0} \cdot \frac{Q_1 \cdot Q_2}{d^2} \qquad \text{(I)}$$

with $\varepsilon_0 = 8.85 \cdot 10^{-12} \frac{\text{As}}{\text{Vm}}$: permittivity of free space

The force F is positive, that is repulsive, if both charges have the same sign. If the signs of the charges are different, the force is negative, that is attractive.

The force between two charged spheres is approximately the same if the distance d between the centres is considerably larger than the radii r of the spheres so that the uniform charge distribution on the spheres remains undistorted. At smaller distances d, measuring results are changed by an "image force" caused by mutual electrostatic induction.

The force between two charged balls will be measured in the experiment by means of a force sensor. You will study the proportionalities

$$F \propto \frac{1}{d^2},\ F \propto Q_1 \text{ and } F \propto Q_2 \qquad \text{(II).}$$

The device for measuring the force contains two parallel flection elements and four strain gauges connected in bridge circuit. The electric resistance of the strain gauges changes under mechanical stress. This change in resistance is proportional to the acting force, which is directly displayed by a newtonmeter.

An electrometer operated as a coulombmeter enables the charges on the balls to be measured almost without current. Any voltmeter may be used to display the output voltage U_A. From the reference capacitance C

$$Q = C \cdot U_A \qquad \text{(III)}$$

is obtained. For example, at C = 10 nF, U_A = 1 V corresponds to the charge Q = 10 nAs. If other capacitances are used, other measuring ranges are accessible.

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Apparatus

1 set of bodies for electric charge	314 263
1 trolley 1.85 g	337 00
1 precision metal rail, 0.5 m	460 82
1 force sensor	314 261
1 newtonmeter	314 251
1 multicore cable, 6-pole, 1.5 m	501 16
1 high voltage power supply 25kV	521 721
1 high voltage cable, 1 m	501 05
1 insulated stand rod, 25 cm	590 13
1 saddle base	300 11
1 electrometer amplifier	532 14
1 plug-in unit 230 V/12 V AC/20 W	562 791
1 STE capacitor 1 nF, 630 V	578 25
1 STE capacitor 10 nF, 100 V	578 10
1 voltmeter, up to U = ±8 V f.e.	531 100
1 Faraday's cup	546 12
1 clamping plug	590 011
1 connection rod	532 16
1 stand base, V-shape	300 02
1 stand rod, 25 cm	300 41
1 Leybold multiclamp	301 01
connection leads	

Safety notes

The high voltage power supply 25 kV fulfills the safety requirements for electrical equipment for measurement, control and laboratory. It supplies a non-hazardous contact voltage. Observe the following safety measures.

- Observe the instructions of the high voltage power supply.
- Always make certain that the high voltage power supply is switched off before altering the connections in the experimental setup.
- Set up the experiment so that neither non-insulated parts nor cables and plug can be touched inadvertently.
- Always set the output voltage to zero before switching on the high voltage power supply (turn the knob all the way to the left).
- In order to avoid high-voltage arcing, lay the high voltage cable in a way that there are no conductive objects near the cable.

Preliminary remark

Carrying out this experiment requires particular care because "leakage currents" through the insulators may cause charge losses and thus considerable measuring errors. Moreover, undesirable effects of electrostatic induction may influence the results.

The experiment must be carried out in a closed, dry room so as to prevent charge losses due to high humidity.

Cleaning the insulated rods, which hold the balls, with distilled water is recommended because distilled water is the best solvent of conductive salts on the insulators. In addition, the insulated rods should be discharged after every experiment by quickly passing them through a non-blackening flame several times; for example, that of a butane gas burner.

The high voltage power supply and the point of the high voltage cable must be at a sufficient distance from the rest of the experimental setup so as to avoid interference by electrostatic induction.

For the same reason, the experimenter – particularly while measuring charges – must keep the connection rod of the electrometer amplifier in his hand in order to earth himself.

Setup

The experimental setup has two parts. In Fig. 1, the setup for charging the balls and for measuring the force is illustrated. Fig. 2 shows the connection of the electrometer amplifier for the charge measurement.

High voltage supply:

- Connect the high voltage cable to the positive pole of the high voltage power supply and the negative pole to earth.
- Put the free point of the high voltage cable **(a)** through the uppermost hole of the insulated stand rod.

Arrangement of the force sensor and the balls:

- Put the trolley **(b)** onto the precision metal rail, and attach ball 1 by means of the connector.
- Attach the force sensor **(c)** to the stand material so that its "-"-side points at ball 1 (repulsive forces are considered to be positive).
- Attach ball 2 with the insulated rod to the force sensor and lock with the screw.
- Align the two balls at the same height.
- Connect the force sensor to the newtonmeter with the multicore cable.
- Move the trolley so that its left edge coincides with the scale mark 4.0 cm, and set the distance between the balls to 0.2 cm (distance between the centres d = 4.0 cm).

Setup for the charge measurement:

- Supply the electrometer amplifier with voltage from the plug-in unit.
- Attach the Faraday's cup **(d)** with the clamping plug.
- Attach the capacitor 10 nF **(e)**.
- Use a connection lead to connect the connection rod **(f)** to ground and, if possible, the ground to the earth of the high voltage power supply through a long connection lead.
- Connect the voltmeter to the output.

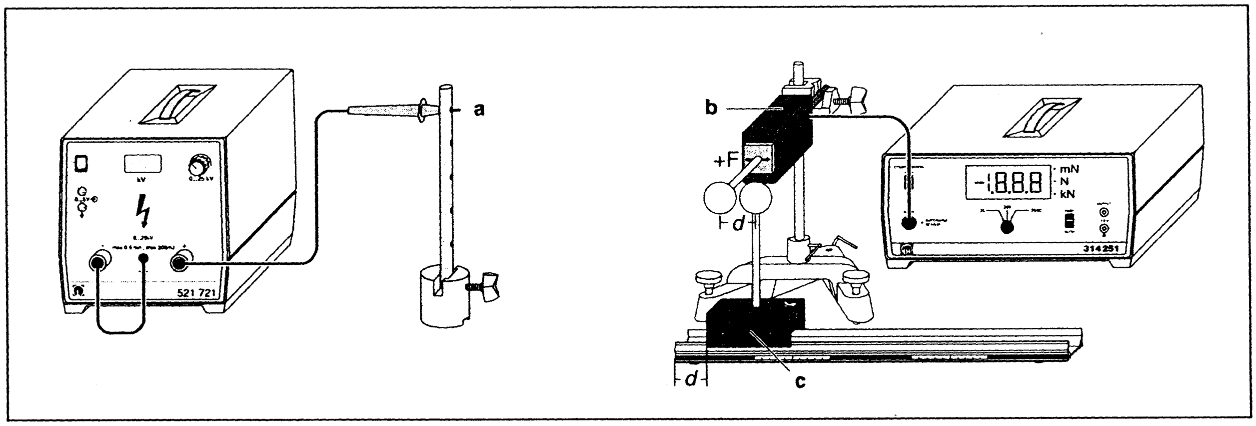


Fig. 1 Setup for measuring the force between two electrically charged balls as a function of their distance.

Carrying out the experiment

Notes:

The measurement is liable to being influenced by interferences from the vicinity because the forces to be measured are very small: Avoid vibrations, draught and variations in temperature.

The newtonmeter must warm up at least 30 min before the experiment is started: switch the newtonmeter on at the mains switch on the back of the instrument to which the force sensor is connected.

a) Measurement at various distances *d* between the balls:

a1) Measurement with equal charges:

- Move ball 1 with the trolley to the maximum distance.
- Switch the high voltage power supply on, and set the output voltage to U = 25 kV.
- Touch the two balls successively with the point **(a)** of the high voltage cable.
- Set the high voltage back to zero.
- Make the zero compensation by setting the pushbutton COMPENSATION of the newtonmeter to SET.
- Move ball 1 towards ball 2, measure the force F as a function of the distance d and take it down.

a2)Measurement with opposite charges:

- Move ball 1 back to maximum distance.
- Make the compensation of the newtonmeter again.
- Charge ball 2 again.
- Set the high voltage back to zero, and change the polarity (high voltage cable at negative pole, positive pole at earth).
- Set the output voltage to U = 25 kV and charge ball 1 negatively.
- Move ball 1 towards ball 2, measure the force F as a function of the distance d and take it down.

b) Measurement with various charges Q_1 and Q_2:

b1) Measurement of the charge on the balls

- Move ball 1 back to maximum distance.
- Set the high voltage back to zero, and change the polarity.
- Charge ball 1 positively with U = 25 kV, and set the high voltage back to zero.
- While measuring charges keep the connection rod **(f)** in your hand. Move the ball into the Faraday's cup with the insulated rod (see Fig. 3).

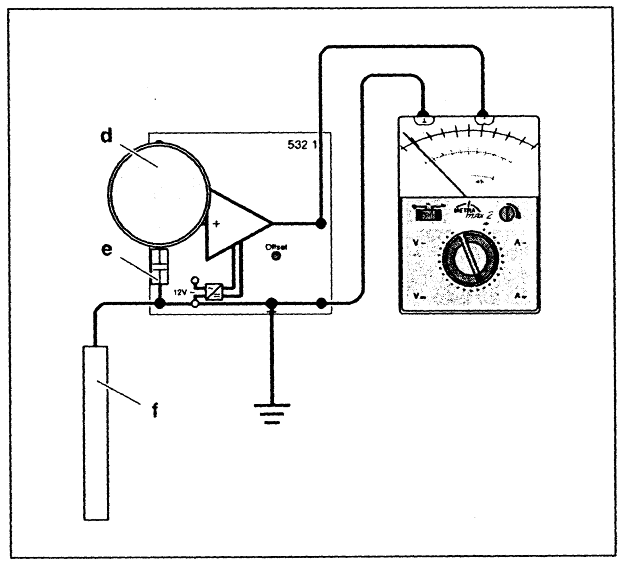
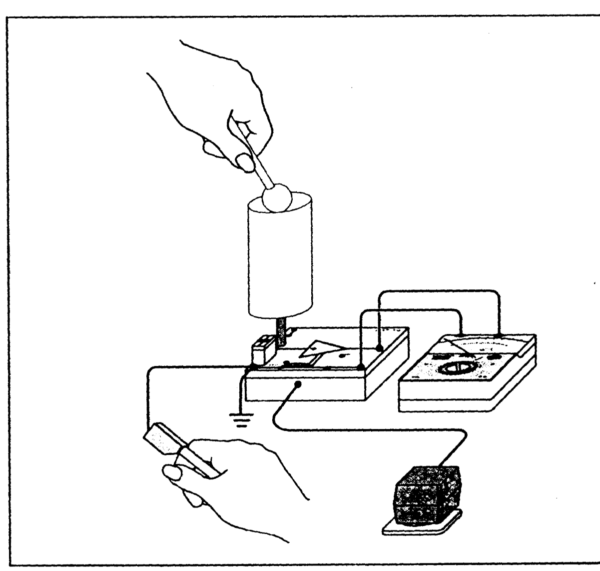


Fig. 2 Connection of the electrometer amplifier for the charge measurement.

Fig. 3 Measurement of the charge on a ball.



- Repeat the measurement at U = 20 kV, U = 15 kV, 10 kV and 5 kV (before each measurement discharge the ball by contact with the connection rod).
- Record the same series of measurements with ball 2.

b2) Measurement of the force F as a function of Q_2 (Q_1 >0, Q_2 >0):

- Mount the two balls again and move ball 1 back to maximum distance.
- Provide for compensation of the newtonmeter again.
- Charge ball 1 with U = 25 kV.
- Charge ball 2 successively with 5 kV, 10 kV, 15 kV, 20 kV and 25 kV with the balls at maximum distance, set the high voltage back to zero each time, choose the distance d = 6 cm and measure the force F.

b3) Measurement of the force F as a function of Q_1 (Q_1 < 0, Q_2 >0):

- Move ball 1 back to maximum distance.
- Provide for compensation of the newtonmeter again.
- Charge ball 2 with U = 25 kV.
- Set the high voltage back to zero and change the polarity.
- Charge ball 1 successively with –5 kV, –10 kV, –15 kV, –20 kV and –25 kV with the balls at maximum distance, set the high voltage back to zero each time, choose the distance d = 6 cm and measure the force F.

Measuring example

a) Measurement at various distances *d* between the balls:

Table 1: The Coulomb force F between two balls as a function of the distance d

$\frac{d}{\text{cm}}$	$\frac{F(Q_1 > 0, Q_2 > 0)}{\text{mN}}$	$\frac{F(Q_1 < 0, Q_2 > 0)}{\text{mN}}$
4	3.41	–3.6
5	2.73	–2.95
6	2.40	2.49
7	1.94	–2.11
8	1.33	–1.56
9	0.95	–1.36
10	0.84	–0.96
15	0.41	–0.42
20	0.21	–0.17
25	0.11	–0.12

b) Measurement with various charges Q_1 and Q_2:

Table 2: The Coulomb force F acting on ball 2 as a function of its charge Q_2 (Q_2 >0, Q_1 = 36 nAs, d = 6 cm)

$\frac{U}{\text{kV}}$	$\frac{Q_2}{\text{nAs}}$	$\frac{F}{\text{mN}}$
5	7	0.32
10	14	0.91
15	22	1.4
20	28	2.01
25	36	2.76

Table 3: The Coulomb force F acting on ball 2 as a function of the charge Q_1 of ball 1 (Q_2 < 0, Q_2 = 36 nAs, d = 6 cm)

$\frac{U}{\text{kV}}$	$\frac{Q_1}{\text{nAs}}$	$\frac{F}{\text{mN}}$
–5	–7	–0.4
–10	–14	–0.96
–15	–22	–1.39
–20	–28	–2.1
–25	–36	–2.65

Evaluation and results

a) Measurement at various distances *d* between the balls:

Fig. 4 shows a graph of the measuring values of Table 1. The magnitude of the Coulomb force has a non-linear dependence on the distance d and is independent of the signs of the charges Q_1 and Q_2. If both charges have the same (opposite) sign, the Coulomb force is positive (negative).

In Fig. 5, the magnitudes of the forces are plotted against $1/d^2$. The straight line drawn through the origin agrees with the data points at small values of $1/d^2$. Thus, for large distances d the proportionality

$F \propto \frac{1}{d^2}$ is valid.

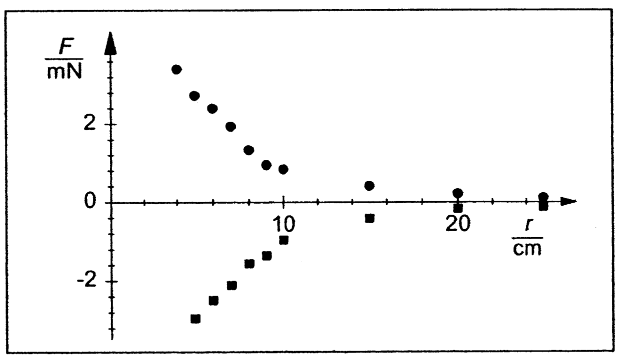
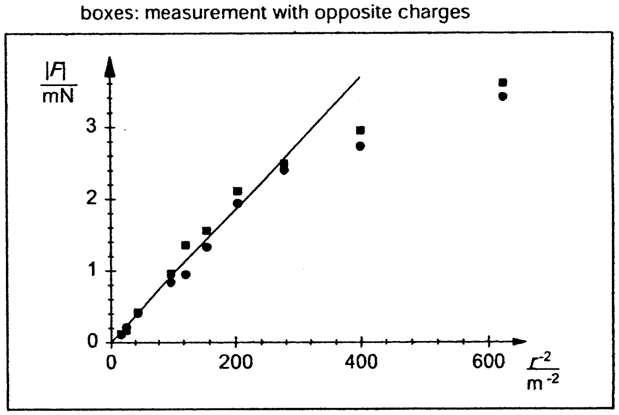


Fig. 4 The Coulomb force F between two charged balls as a function of the distance d between the balls
circles: measurement with equal charges
boxes: measurement with opposite charges

Fig. 5 The magnitude of the the Coulomb force F between two charged balls as a function of $1/d^2$
circles: measurement with equal charges
boxes: measurement with opposite charges



b) Measurement with various charges Q_1 and Q_2:

In Fig. 6, the measuring values of Tables 2 and 3 are summarized in one graph. The measuring values lie in a good approximation)) on a straight line through the origin. So the two proportionalities $F \propto Q_1$ and $F \propto Q_2$ are verified.

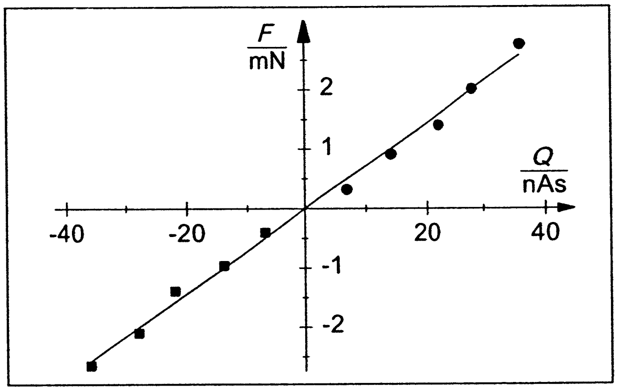


Fig. 6 The Coulomb force F acting on ball 2 at a fixed distance d = 6 cm
circles: measurement of F as a function of Q_2 (Q_1 = 36 nAs)
boxes: measurement of F as a function of Q_1 (Q_2 = 36 nAs)

c) Estimating the permittivity of free space:

Converting Eq. (I) leads to

$$\varepsilon_0 = \frac{\frac{1}{4\pi} \cdot \frac{Q_1}{d^2}}{\frac{F}{Q_2}}$$

The permittivity of free space can, therefore, be estimated from the slope of the straight line drawn through the origin in Fig. 5. The slope is

$$\frac{F}{Q_2} = 0.072 \frac{\text{mN}}{\text{nAs}}.$$

With the values Q_1 = 36 nAs and d = 0.06 m the result

$$\varepsilon_0 = 11 \cdot 10^{-12} \frac{\text{As}}{\text{Vm}}$$

is obtained.

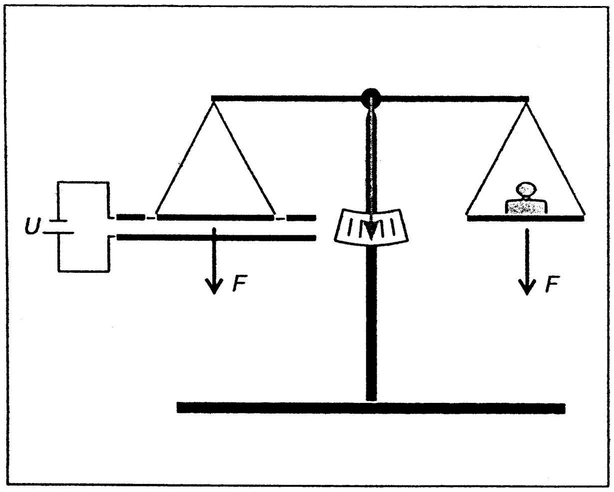
The value quoted in the literature is:

$$\varepsilon_0 = 8.85 \cdot 10^{-12} \frac{\text{As}}{\text{Vm}}$$

Kirchhoff's voltage balance: Measuring the force between two charged plates of a plate capacitor

Objects of the experiments

- Measuring the force F between the charged plates as a function of the voltage U at a constant distance d between the plates.
- Determining the permittivity of free space ε_0.
- Measuring the force F between the charged plates at a constant ratio between the voltage U and the distance d.



Principles

A voltage U applied to a plate capacitor gives rise to a homogeneous electric field

$$E = \frac{U}{d} \qquad \text{(I)},$$

d: distance between the plates,

between the plates. This field is generated by the charges Q and $-Q$ on the capacitor plates. On the other hand, the field exerts a force on the charges. However, the more the field penetrates into the plate, the more it is attenuated. On the surface of the plates the field strength is E, but inside it is zero. On average, only half the field strength $E/2$ acts on the charges. Therefore, the plates attract each other with the force

$$F = -\frac{1}{2} \cdot Q \cdot E \qquad \text{(II)}.$$

The charge Q on the plates is

$$Q = \varepsilon_0 \cdot \frac{A}{d} \cdot U \qquad \text{(III)},$$

$\varepsilon_0 = 8.85 \cdot 10^{-12} \frac{\text{As}}{\text{Vm}}$: permittivity of free space,

A: area of the plates.

Thus from (I) and (II)

$$F = -\frac{1}{2} \cdot \varepsilon_0 \cdot A \cdot \left(\frac{U}{d}\right)^2 \qquad \text{(IV)}$$

follows. F, A, d and U are directly measurable quantities. Eq. (IV) can, therefore, be considered as the determining equation of the permittivity of free space ε_0. This is the principle of Kirchhoff's voltage balance, the setup of which is the object of the present experiment. The proportionality

$$F \propto \frac{U^2}{d^2} \qquad \text{(V)},$$

which is stated by Eq. (IV), will be confirmed experimentally.

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Apparatus

1 electrostatic accessories for current balance	516 37
1 vertically adjustable stand	516 31
1 newtonmeter	314 251
1 force sensor . . . 524060	~~314 261~~
1 support for conductor loops	314 265
1 multicore cable 6-pole, 1.5 m long	~~501 16~~
1 high voltage power supply 10 kV	521 70
1 high voltage cable, 1 m	~~501 05~~
1 stand rod, 47 cm	300 42
1 stand base, V-shape, 20 cm	300 02
1 Leybold multiclamp	301 01
connection leads	

Safety notes

The high voltage power supply 10 kV fulfills the safety requirements for electrical equipment for measurement, control and the laboratory. It supplies a non-hazardous contact voltage. Observe the following safety measures.

- Observe the instructions of the high voltage power supply.
- Always make certain that the high voltage power supply is switched off before altering the connections in the experimental setup.
- Set up the experiment so that neither non-insulated parts nor cables and plug can be touched inadvertently.
- Always set the output voltage to zero before switching on the high voltage power supply (turn the knob all the way to the left).
- In order to avoid high-voltage arcing, lay the high voltage cable in a way that there are no conductive objects near the cable.

Setup

The experimental setup is illustrated in Fig. 1. The plate capacitor consists of the capacitor plate on an insulator, the capacitor plate with a pair of plugs, and the screening ring from the set of electrostatic accessories (516 37).

Mechanical setup:

- Set the screening ring **(a)** with the stand up.
- Set the stand rod up in the stand base, and attach the force sensor (+F direction upward) to the stand rod with the Leybold multiclamp.
- Connect the force sensor to the newtonmeter with the multicore cable.
- Attach the support for conductor loops to the force sensor, connect the capacitor plate with the pair of plugs **(b)**, and align it concentrically with the screening ring without contact.
- Put the capacitor plate on the insulator **(c)** onto the vertically adjustable stand, lock with the knurled screw **(d)**, and align the plate **(c)** parallel to the capacitor plate **(b)** by means of the leveling screws **(f)**.
- Check the adjustment, and set the distance d to 20 mm by means of the adjusting screw **(e)**.

Electrical setup:

- Connect the capacitor plate **(c)** to the positive pole of the high voltage power supply, plugging the high voltage cable into the 4-mm hole in the socket of the plate.
- Connect the screening ring **(a)** to the capacitor plate **(b)**, then connect both to the negative pole of the high voltage power supply, plugging the connection lead into the 4-mm hole in the stand or into the support for conductor loops.
- Connect the negative pole to the earth of the of the high voltage power supply.
- Connect the high voltage power supply 10 kV to the mains and switch it on.

Carrying out the experiment

Notes:

The measurement is susceptible to impact through interferences from the vicinity because the forces to be measured are very small: Avoid vibrations, draught and variations in temperature.

The newtonmeter must warm up at least 30 min before the experiment is started: the force sensor being connected, switch the newtonmeter on at the mains switch on the back of the instrument.

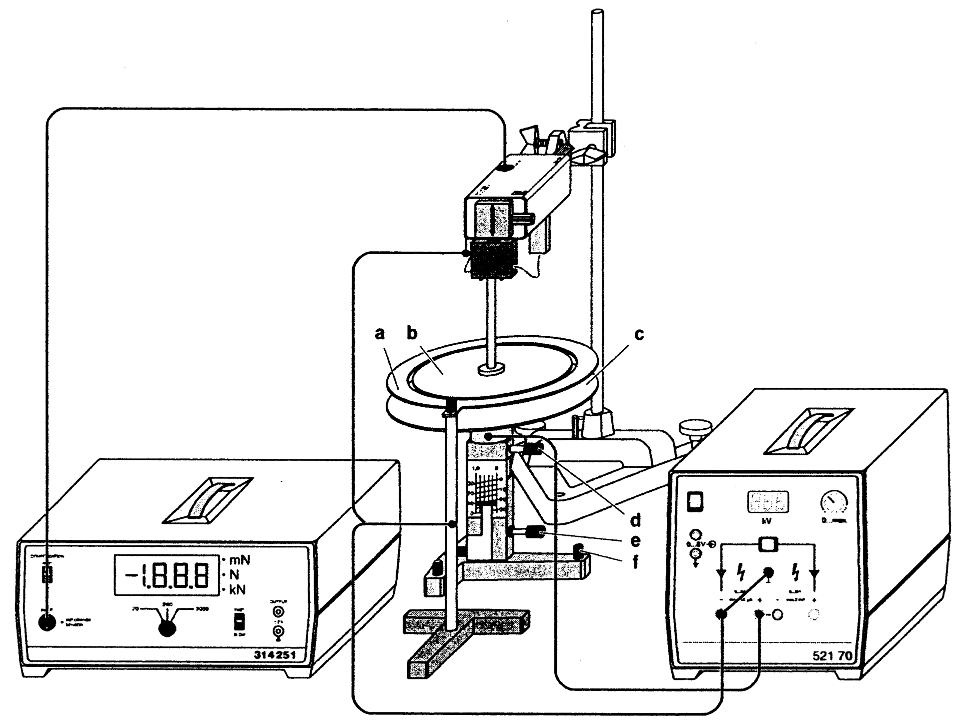

Fig. 1 Experimental setup for Kirchhoff's voltage balance

a) The force *F* as a function of the voltage *U*:

- Make zero compensation by setting the pushbutton COMPENSATION of the newtonmeter to SET.
- Switch on the high voltage power supply, and set the output voltage to U = 2 kV.
- Read the force F from the newtonmeter and record it.
- Increase the high voltage in steps of 0.5 kV up to 5 kV. In each case, read the force F and record it together with the voltage U.

b) The force *F* at a constant ratio between the voltage *U* and the distance d between the plates:

- Set the high voltage back to zero, and make zero compensation of the newtonmeter again.
- Set the high voltage to U = 5 kV and read the force F from the newtonmeter.
- Set the high voltage to U = 4 kV, and reduce the distance d between the plates to 16 mm; make sure that the capacitor plates and the screening ring do not touch.
- Read the force F from the newtonmeter and record it together with the values U, d and .
- Repeat the measurement at U = 3 kV, d = 12 mm and at U = 2 kV, d = 8 mm.

Measuring example

a) The force *F* between the charged plates as a function of the voltage *U*:

radius of the capacitor plate: 15 cm

Table 1: The force F between the charged plates as a function of the high voltage U (d = 20 mm)

$\frac{U}{\text{kV}}$	$\frac{F}{\text{mN}}$
5.0	–4.0
4.5	–3.2
4.0	–2.5
3.5	–2.0
3.0	–1.5
2.5	–1.0
2.0	–0.6

b) The force *F* at a constant ratio between the voltage *U* and the distance d between the plates:

Table 2: The force F between the charged plates at a constant ratio $E = U/d$

$\frac{U}{\text{kV}}$	$\frac{d}{\text{mm}}$	$\frac{E}{10^6 \frac{\text{V}}{\text{m}}}$	$\frac{F}{\text{mN}}$
5.0	20	0.25	–4.0
4.0	16	0.25	–4.0
3.0	12	0.25	–4.0
2.0	8	0.25	–4.0

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Evaluation

a) The force F as a function of the voltage U:

Fig. 2 is a plot of the measuring values from Table 1. The curve drawn in is a parabola with its maximum in the origin. It can be seen that the attractive force increases with the square of the high voltage U, that is,

$F \propto U^2$.

In Fig. 3, the measuring values are plotted in the linearized form $F = f(U^2)$. The data points lie to a good approximation on a straight line through the origin.

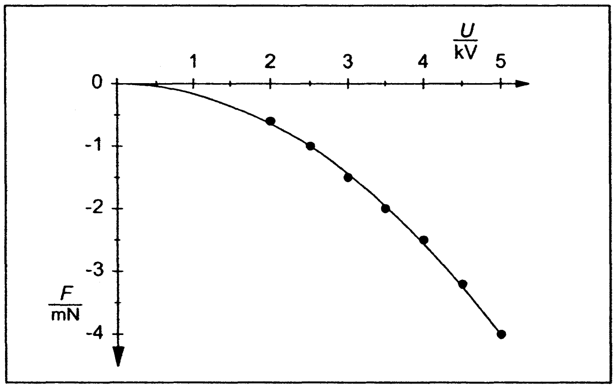


Fig. 2 The force F between the charged plates as a function of the voltage U at a constant distance d = 20 mm between the plates.

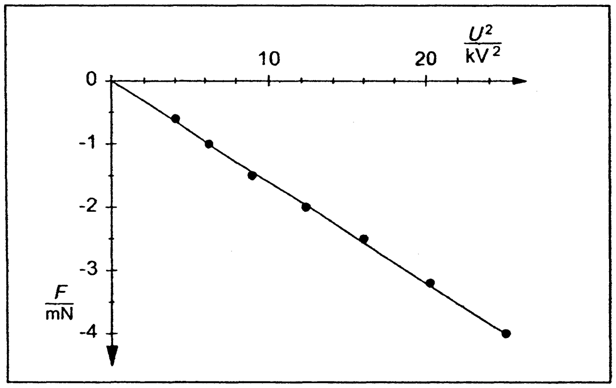


Fig. 3 Graph of the measuring values of Fig. 2 in the linearized form $F = f(U^2)$

Determining the permittivity of free space ε_0:

According to Eq. (IV), the permittivity of free space can be determined from the slope

$$\frac{F}{U^2} = -0.16 \frac{\mathrm{mN}}{\mathrm{kV}^2}$$

of the straight line through the origin in Fig. 4:

$$\varepsilon_0 = -\frac{F}{U^2} \cdot \frac{2d^2}{A}.$$

The distance d between the plates is 20 mm.

The area A is calculated with the radius r = 7.5 cm of the smaller capacitor plate since the force F acting on this plate has been measured: $A = 1.7 \cdot 10^{-2} \mathrm{m}^2$.

The result is: $\varepsilon_0 = 7.5 \cdot 10^{-12} \frac{\mathrm{As}}{\mathrm{Vm}}$.

Value quoted in the literature: $\varepsilon_0 = 8.85 \cdot 10^{-12} \frac{\mathrm{As}}{\mathrm{Vm}}$.

b) The force F at a constant ratio between the voltage U and the distance d between the plates:

The measuring values of Table 2 show that the force F depends on the electric field strength when the voltage U and the distance d between the plates are varied. The force remains constant as long as the field strength remains constant.

From $F \propto U^2$ thus the proportionalities

$F \propto E^2$, at constant distance, and

$F \propto \frac{1}{d^2}$, at constant voltage,

follow.

Results

An attractive force, which depends quadratically on the electric field strength, acts between the charged plates of a plate capacitor.

12

12,

Measuring the force between a charged sphere and a metal plate

Objects of the experiments

- Measuring the force F between a charged sphere and an earthed metal plate as a function of the distance d between the centre of the sphere and the metal plate.
- Measuring the force F between a charged sphere and an earthed metal plate as a function of the charge Q on the sphere.

Principles

By electrostatic induction (displacement of charges), a pointlike charge Q at a distance d from an earthed metal plate generates an excess charge of the opposite sign on the surface of the metal plate. The charge Q is, therefore, acted upon by an attractive force towards the metal plate.

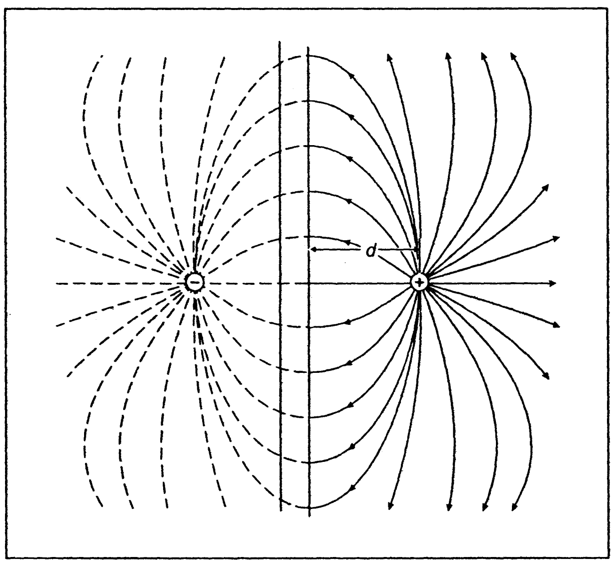


Fig. 1 The field lines of a pointlike charge Q in front of a metal plate in comparison with the field lines of two charges Q and $-Q$.

This attractive force F is equal to the force that a pointlike charge $-Q$ at a distance $2d$ would exert on the charge Q, that is,

$$F = \frac{1}{4\pi \cdot \varepsilon_0} \cdot \frac{-Q^2}{(2d)^2} \quad \text{(I)}.$$

This relation is illustrated in Fig. 1: In the case of an equilibrium, the electric field lines starting from Q meet the metal plate perpendicularly because a field component parallel to the surface of the plate would lead to a displacement of the charge distribution on the metal plate, which cannot occur in a state of equilibrium. The same shape of the field lines is generated by a "mirror" charge $-Q$ placed at the mirror image of the point where Q is located with respect to the plate.

In the experiment, the force between a charged sphere and a metal plate is measured with the aim of confirming the proportionalities

$$F \propto \frac{1}{d^2} \quad \text{(II)}$$

and

$$F \propto Q^2 \quad \text{(III)}.$$

In the experiment, however, the mutual electrostatic induction between the sphere and the metal plate leads to a displacement of charges on the sphere as well – which shows up particularly at small distances d. This displacement has the same effect that a reduction of the distance d would have, and it leads to an enhancement of the force F.

Apparatus

1 electrostatic accessories for current balance	516 37
1 vertically adjustable stand	516 31
1 newtonmeter	314 251
1 force sensor	314 261
1 multicore cable 6-pole, 1.5 m long	501 16
1 stand rod, 47 cm	300 42
1 stand base, V-shape, 20 cm	300 02
1 Leybold multiclamp	301 01
1 plastic rod	541 04
1 leather	541 21
connection leads	

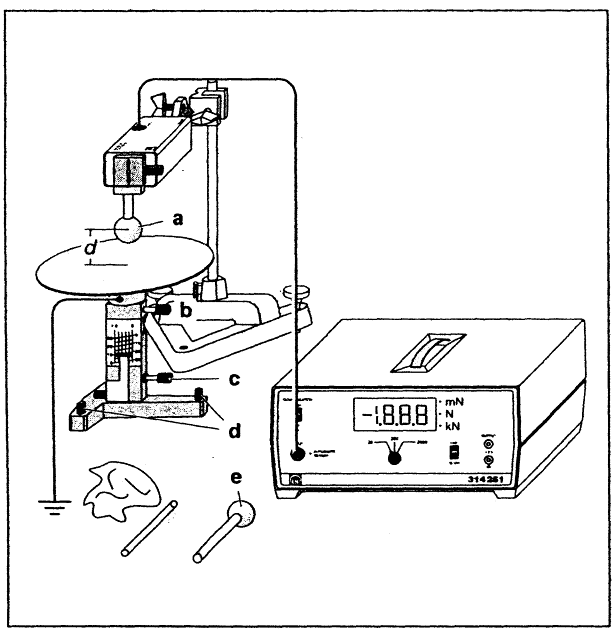
Preliminary remarks

Carrying out this experiment requires particular care because "leakage currents" through the insulators may cause charge losses and thus considerable measuring errors. Moreover, undesirable effects of electrostatic induction may influence the results.

The experiment must be carried out in a closed, dry room so as to prevent charge losses due to high humidity.

Cleaning the insulators of the spheres with distilled water is recommended because distilled water is the best solvent of conductive salts on the insulators. In addition, the insulators should be discharged before every experiment by passing them several times quickly through a non-blackening flame, for example of a butane gas burner. The plastic rod and the leather too must be dry and clean.

Fig. 2 Experimental setup for the measurement of the force between a charged sphere and an earthed metal plate



Setup

The experimental setup is illustrated in Fig. 2.

- Put the capacitor plate on the insulator from the electrostatic accessories (516 37) onto the vertically adjustable stand, lock with the knurled screw **(b)**, and align the plate horizontally with the levelling screws **(d)**.
- Plug a connection lead into the 4-mm hole on the socket of the capacitor plate and connect it to the earth.
- Extend the vertically adjustable stand to maximum height by turning the height adjustment screw **(c)**, and adjust to zero.
- Set the stand rod up in the stand base, and attach the force sensor (+F direction upward) to the stand rod with the Leybold multiclamp.
- Plug the sphere on an insulator with a pair of plugs **(a)** into the socket of the force sensor.
- Connect the force sensor to the newtonmeter with the multicore cable.
- Adjust the height of the force sensor so that the distance between the metal plate and edge of the sphere is 15 mm (distance d to the centre of the sphere: 30 mm).

Carrying out the experiment

Notes:

The measurement is susceptible to impact through interferences from the vicinity because the forces to be measured are very small: Avoid vibrations, draught and variations in temperature.

The newtonmeter must warm up at least 30 min before the experiment is started: the force sensor being connected, switch the newtonmeter on at the mains switch on the back of the instrument.

a) The force F as a function of the distance d:

- Make the zero compensation by setting the pushbutton COMPENSATION of the newtonmeter to SET.
- Charge the plastic rod by rubbing it with the leather.
- Charge the sphere **(a)** by touching it with the plastic rod.
- Read the force F and record it together with the distance d.
- Increase the distance d with the height adjustment screw **(c)** in steps of 2.5-mm up to d = 45 mm. In each case, read the force from the newtonmeter and record it together with the distance.

b) The force F as a function of the charge Q:

- Set the distance d to 35 mm.
- Make the zero compensation of the newtonmeter again.
- Recharge the plastic rod by rubbing it with the leather, and charge the sphere **(a)** by touching it with the plastic rod.
- Read the force from the newtonmeter and record it as $F(Q)$.
- Halve the charge by touching the sphere **(a)** with the sphere **(e)**, which has the same size.
- Read the force again and record it as $F(Q/2)$.
- Calculate the ratio of the two forces.
- Discharge the two sphere at the capacitor plate, and repeat the experiment several times.

Measuring example

a) Measuring the force F as a function of the charge Q:

Table 1: The force F as a function of the distance d

$\frac{d}{\text{mm}}$	$\frac{F}{\text{mN}}$
30	–5.9
32.5	–4.3
35	–3.1
37.5	–2.4
40	–1.9
42.5	–1.6
45	–1.3

b) Measuring the force F as a function of the charge Q:

Table 2: The force F measured with the total charge Q and with the halved charge (d = 35 mm)

n	$\frac{F(Q)}{\text{mN}}$	$\frac{F(Q/2)}{\text{mN}}$	$\frac{F(Q/2)}{F(Q)}$
1	-3.2	–0.9	0.28
2	-5.0	–1.2	0.24
3	-3.4	–0.8	0.24
4	–4.0	–1.2	0.30
5	-3.0	–0.7	0.23
6	-3.6	–0.9	0.25
7	–4.6	–1.1	0.24
8	-3.7	–1.0	0.27
9	-3.9	–0.9	0.23
10	–4.2	–1.0	0.24

Evaluation

a) The force F as a function of the distance d:

In Fig. 3, the measuring values of Table 1 are plotted. The attractive force F between the charged sphere and the earthed metal plate ((turns out to nonlinearly)) when the distance d is increased.

Fig. 4 shows the measuring values in the linearized form $|F|^{-\frac{1}{2}} = f(d)$. The measuring values lie to good approximation on a straight line, which, however, does not go through the origin, but intersects the x-axis at d_0 = 17 mm. Thus the proportionality

$$|F|^{-\frac{1}{2}} \propto d - d_0 \text{ or } F \propto \frac{1}{(d-d_0)^2}$$

is found. This effect corresponds to a shift of the distance, which goes back to a charge displacement on the sphere towards the metal plate due to electrostatic induction.

b) Measuring the force F as a function of the charge Q:

According to Eq. (III), the force should be reduced by a factor of four after the charge Q has been halved, that is, one expects

$$\frac{F(Q/2)}{F(Q)} = 0.25 \qquad \text{(IV)}.$$

The mean value of the result in Table 2 is $\bar{x}$ = 0.252, and the standard deviation is σ = 0.008. Thus (IV) is confirmed.

Results

An attractive force arises between a charged sphere and an earthed metal plate due to electrostatic induction. This force is equal to the force exerted by a mirror charge.

Fig. 3 The force F between a charged sphere and a metal plate as a function of the distance d

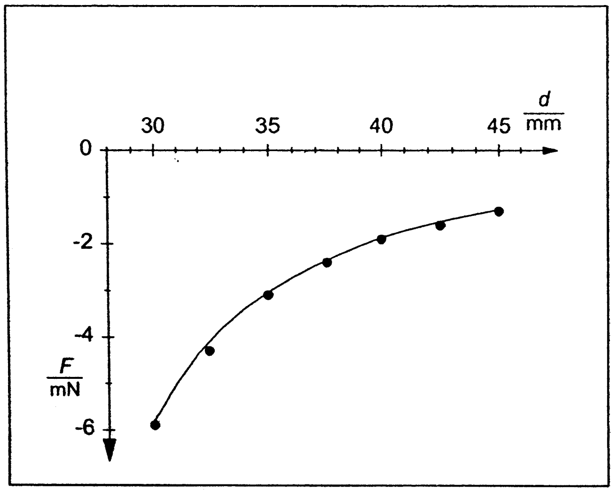
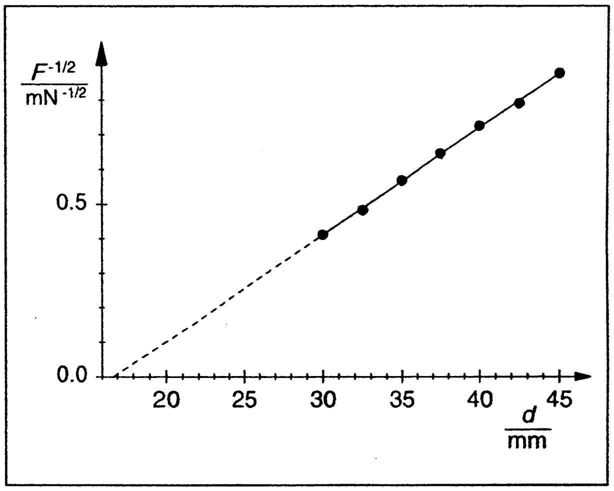


Fig. 4 Linearization of the curve in Fig. 3 in the form $|F|^{-\frac{1}{2}} = f(d)$



15

Electricity

Electrostatics

Charge distributions on electrical conductors

Investigating the charge distribution on the surface of electrical conductors

Objects of the experiments

- Investigating the charge distribution on the outside surface of a Faraday's cup and a conical conductor as a function of the curvature of the surface.
- Measuring the charge on the inside surface of a Faraday's cup and a conical conductor.

Principles

In an electrical conductor, excess charges can move freely. In the case of electrostatic equilibrium the charges are, therefore, arranged on the surface of the conductor only; there are no free charges in the interior of the conductor.

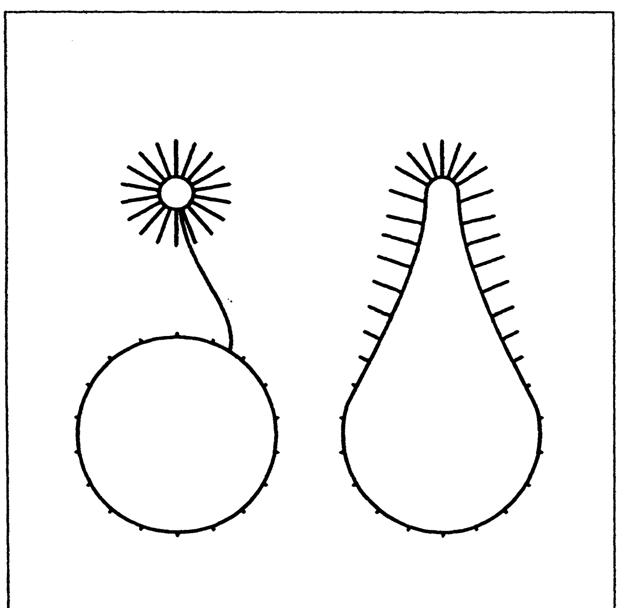
More precisely, the charges are distributed on the surface so that they are not subject to an electric field or a gradient of the potential along the surface. The electric field is perpendicular to the surface at every point of the surface, and the potential is the same everywhere on the surface and in the interior of the conductor. The charge density and the electric field are particularly high at places on the surface with a strong curvature.

Hollow conductors carry electric charges only on their outside surface. There is no electric field in the cavity and the electric potential is constant. If charge is to be completely removed from a conductor, the interior of a metallic hollow body should be touched with the conductor.

In the experiment, electric charge is picked up with an insulated metal plate from charged hollow conductors in order to investigate the charge distribution. The charges picked up are measured with an electrometer amplifier operated as a coulombmeter. The electrometer amplifier itself is equipped with a hollow conductor, namely a Faraday's cup. Any voltmeter may be used to display the output voltage U_A. From the reference capacitance C_A

$$Q = C \cdot U_A \qquad \text{(I)}$$

is obtained. For example, at C_A = 10 nF, U_A = 1 V corresponds to the charge Q = 10 nAs. If other capacitances are used, other measuring ranges are accessible.



If two charged metal spheres of different sizes are on the same potential, the electric field strength near the smaller sphere is larger than the field strength near the bigger sphere. Therefore, electric fields at sharp points can be very strong.

1009-Wei

Apparatus

1 conical conductor on insulated rod . . .	543 07
2 Faraday's cup	546 12
1 metal plate on insulating rod	542 52
1 high voltage power supply 10 kV	521 70
1 high voltage cable, 1 m	501 05
1 electrometer amplifier	532 14
1 plug-in unit 230 V/12 V~/20 W . . 562 792	~~562 791~~
1 STE capacitor 1 nF, 100 V	578 25
1 STE capacitor 10 nF, 100 V	578 10
1 voltmeter, DC, until $U = \pm 8$ V for example	~~531 100~~ 531 120
1 clamping plug	590 011
1 connection rod	532 16
1 demonstration insulator	540 52
1 saddle base	300 11
1 set of 6 croc-clips, polished	501 861
connection rods	

Safety notes

The high voltage power supply 10 kV fulfils the safety requirements for electrical equipment for measurement, control and laboratory. It supplies a non-hazardous contact voltage. Observe the following safety measures.

- Comply with the instruction sheet of the high voltage power supply.
- Always make sure that the high voltage power supply is switched off before altering the connections in the experimental setup.
- Set up the experiment so that neither non-insulated parts nor cables and plug can be touched inadvertently.
- Always set the output voltage to zero before switching on the high voltage power supply (turn the knob all the way to the left).
- In order to avoid high-voltage arcing, lay the high voltage cable in such a way that there are no conductive objects near the cable.

Preliminary remark

Carrying out this experiment requires particular care because "leakage currents" through the insulators may cause charge losses and thus considerable measuring errors. Moreover, undesirable effects of electrostatic induction may influence the results.

The experiment must be carried out in a closed, dry room so as to prevent charge losses due to high humidity.

Cleaning the insulators with distilled water is recommended because distilled water is the best solvent of conductive salts on insulators. In addition, the insulators should be discharged after every experiment by passing them several times quickly through a non-blackening flame, for example of a butane gas burner.

The experimenter – particularly while measuring charges – must keep the connection rod of the electrometer amplifier in his hand to earth himself.

Setup

The experimental setup has two parts. In Fig. 1, the setup for electrostatic charging of the hollow bodies and picking up a test charge is illustrated. Fig. 2 shows the connection of the electrometer amplifier for the charge measurement.

Electrostatic charging of the hollow bodies:

- Attach the Faraday's cup **(a)** to the demonstration insulator and mount it in the saddle base.
- Connect the high voltage cable to the positive pole of the high voltage power supply and the negative pole to earth.
- Plug the free end of the high voltage cable into the *upper (!)* 4-mm bore of the demonstration insulator.

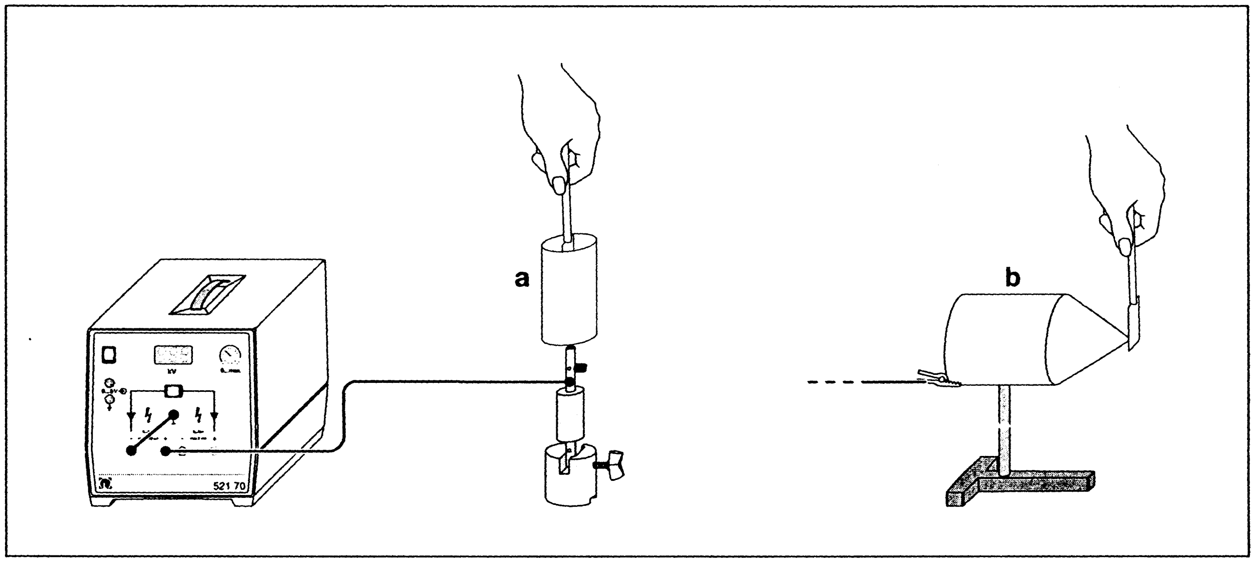
Setup for the measurement of the test charge:

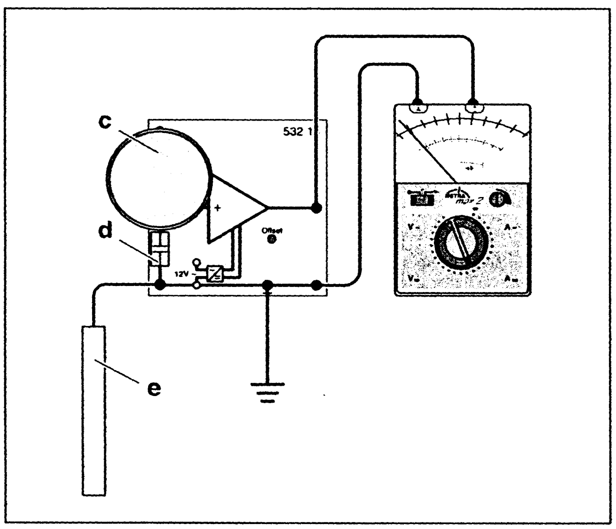
- Supply the electrometer amplifier with voltage from the plug-in unit.
- Attach the other Faraday's cup **(c)** with the clamping plug.
- Attach the STE capacitor 10 nF **(d)**.
- Use a connection lead to connect the connection rod **(e)** to earth and, if possible, a long connection lead to connect the earth to the earth of the high voltage power supply through.
- Connect the voltmeter to the output.

Carrying out the experiment

Note:

The Faraday's cup and the conic conductor remain connected to the high voltage source during the experiment: Do not touch the hollow bodies under investigation even though there is a non-hazardous contact voltage.





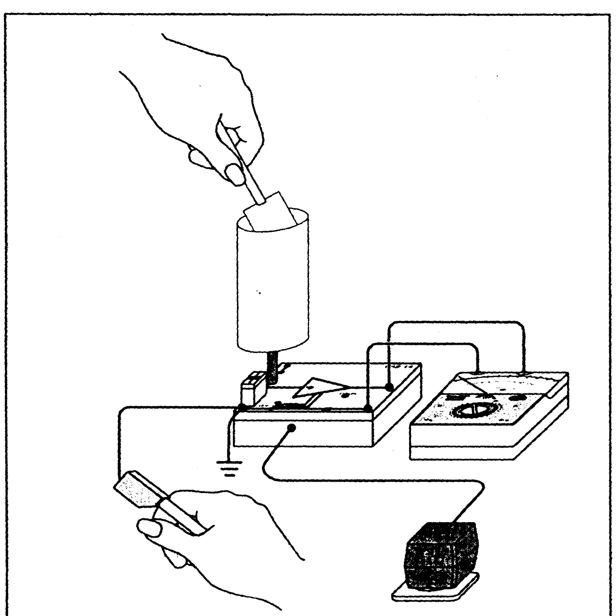


Fig. 1 Experimental setup for the measurement of the charge distribution on a Faraday's cup **(a)** and on a conic conductor **(b)**

Fig. 2 Experimental setup for the measurement of the charge on the insulated metal plate

Fig. 3 Measurement of the charge on the insulated metal plate.

a) Charge distribution on the Faraday's cup:

- Switch the high voltage power supply on, and set the high voltage U to 5 kV.
- Discharge the insulated metal plate with the connection rod **(e)**.
- Touch the outer wall of the Faraday's cup **(a)** to pick up charge.
- To measure the charge, discharge the Faraday's cup **(c)** of the electrometer amplifier by touching it with the connection rod **(e)**, then take the connection rod in your hand, and move the insulated metal plate to the inner wall of the Faraday's cup (see Fig. 3).
- Repeat the investigation for several places on the outer and inner wall of the Faraday's cup **(a)**; each time discharge the insulated metal plate with the connection rod **(e)**.

b) Charge distribution on the conic conductor:

- Switch off the high voltage power supply and replace the Faraday's cup with the conic conductor **(b)**; to do so, attach the high voltage cable to the conic conductor with a croc-clip.
- Switch on the high voltage power supply and set the high voltage U to 5 kV.
- Move the insulated metal plate towards the apex of the conic conductor from the front and measure the charge on the plate.
- Repeat the investigation for several places on the outer and inner wall of the conic conductor; each time discharge the insulated metal plate with the connection rod **(e)**.

Measuring example

a) Charge distribution on the Faraday's cup:

Place	$\frac{Q}{\text{nAs}}$
Outer wall	6.0
Inner wall	0.1

b) Charge distribution on the conic conductor:

Place	$\frac{Q}{\text{nAs}}$
Outer wall	
apex	8.6
conic part	7.8
cylindrical part	6.2
Inner wall	0.4

Evaluation

Almost no charges can be detected on the inner walls of the Faraday's cup and of the conic conductor. The total charge is on the outer wall.

On the conic conductor, the charge picked up from the outside surface depends on the curvature of the surface. The smaller the radius of curvature, the more charge is found. The radius of curvature of the apex of the conic conductor is particularly small and there is an accumulation of charge.

Since the electric field strength near the surface is proportional to the charge, the field strength near the apex is large as well. This phenomenon is called needle effect or point effect and is of practical significance, for example, in lightning conductors.

Supplementary information

The dependence of the charge density on the radius of curvature can be explained as follows: The potential of a charged metal sphere with radius R and charge Q is

$$U = \frac{1}{4 \cdot \pi \cdot \varepsilon_0} \cdot \frac{Q}{R} \qquad \text{(II).}$$

ε_0: permittivity of free space

As the charge is equally distributed on the surface of the sphere, the charge density is

$$\sigma = \frac{Q}{4\pi \cdot R^2} \qquad \text{(III).}$$

From (II) and (III)

$$U = \frac{\sigma \cdot R}{\varepsilon_0} \qquad \text{(IV)}$$

follows.

Two spheres or, more general, two surfaces with different radii of curvature are on the same potential if their charge densities σ fulfil the proportionality

$$\sigma \propto \frac{1}{R} \qquad \text{(V).}$$

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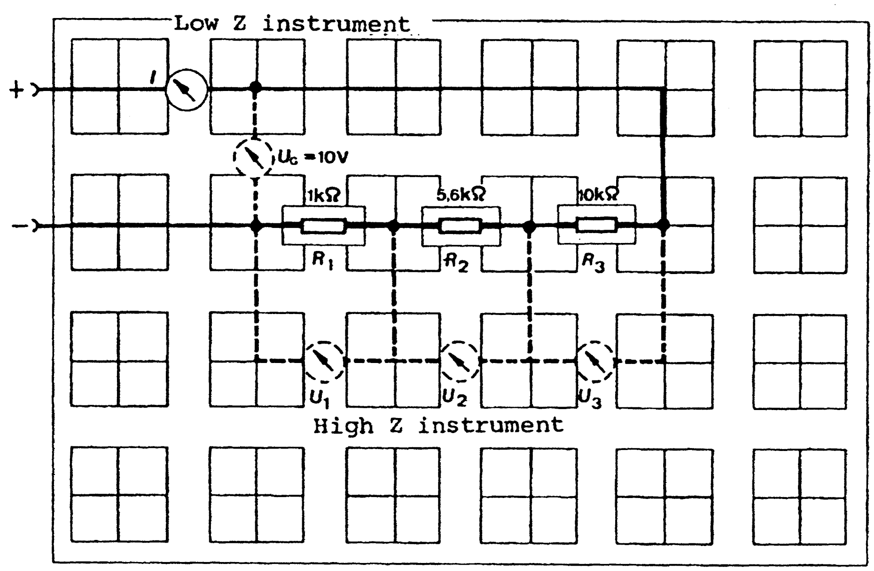
P3.2.3.1

Series connection of resistors

1. Aim of the Experiment

Measurement of the total voltage U and the voltage drops U_1, U_2 and U_3 across the resistors and the current I flowing through the circuit.

2. Circuit



3. Equipment and Components

	S	D
1 Rastered socket panel	576 74	580 10
1 Resistor R_1, 1 kΩ	577 44	580 74
1 Resistor R_2, 5.6 kΩ	577 53	580 83
1 Resistor R_3, 10 kΩ	577 56	580 37
1 Low Z instrument	-	-
1 High Z instrument	-	-
1 D.C. power supply unit	~~522 30~~	~~522 30~~ 52145
Bridging plugs	501 48	501 48
Connecting leads		

4. Conducting the Experiment

4.1 Assemble the circuit and connect a multimeter in series for measurement of the current.

4.2 Adjust U_G = 10 V. Measure all voltages with the high Z instrument !

Then measure, one after the other, the voltage drops U_1, U_2 and U_3 across the corresponding resistors R_1, R_2 and R_3.

Total current I_G = 0.60 mA

Voltage U_G = 10 V

R_1 : 1 kΩ	U_1 : 0.60 V
R_2 : 5.6 kΩ	U_2 : 3.36 V
R_3 : 10 kΩ	U_3 : 6. 0 V

N o t e s :

a) The voltage drop across the current measuring instrument is not included in the measurement.

b) The paralleling of the voltmeter with the component resistances introduces an error of approx. 0.5%.

(Tolerances of the resistors: ± 5%).

5. Exercises

5.1 The total resistance of the circuit can be calculated from

$$R = \frac{U}{I} \; ; \quad R = \frac{10\ \text{V}}{0.60\ \text{mA}}$$

The total resistance R = 16.6 kΩ.

5.2 From the results the values of the individual resistors can be calculated as follows:

$R_1 = 1 \ k\Omega$

$R_2 = 5.6 \ k\Omega$

$R_3 = 10 \ k\Omega$

5.3 What is the relationship between $U:U_1:U_2:U_3$ to $R:R_1:R_2:R_3$

10 V : 0.60 V : 3.36 V : 6.0 V

1 : 0.060 : 0.336 : 0.60

16.6 kΩ : 1 kΩ : 5.6 kΩ : 10 kΩ

1 : 0.0602 : 0.337 : 0.602

The partial voltages are proportional to the partial resistances.

or :

$U_G = U_1 + U_2 + U_3 = I \ (R_1 + R_2 + R_3)$

$0 = U_1 + U_2 + U_3 - U_G$

$\Sigma \ U = 0$

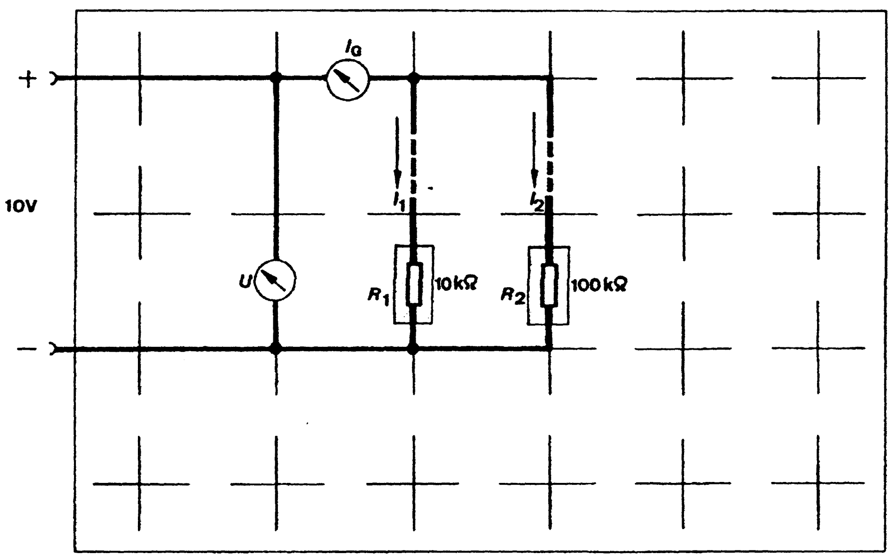
The sum of all voltage drops equals 0
(2nd law of Kirchhoff).

Parallel connection of resistors

1. Aim of the Experiment

Measurement of the current I and the voltage U in a circuit and a number of circuit variations.

2. Circuit



3. Equipment and Components

	S	D
1 Rastered socket panel	576 74	580 10
1 Resistor R_1, 10 kΩ	577 56	580 37
1 Resistor R_2, 100 kΩ	577 68	580 40
1 Low Z instrument	-	-
1 High Z instrument	-	-
1 D.C. power supply unit	522 30	522 30
Bridging plugs	501 48	501 48
Connecting leads		

4. Conducting the Experiment

4.1 Assemble the circuit step by step (the single stages are indicated by dotted lines).

4.2 Measure the current I and the voltage U as given in the table below.

Circuit with	$\frac{U}{V}$	$\frac{I}{mA}$	$\frac{R}{k\Omega}$
R_1	10	1	10
R_2	10	0.1	100
$R_G = \frac{R_1 \cdot R_2}{R_1 + R_2}$	10	1.1	9.1

5. Exercises

5.1 Enter the resistance values into the table for each of the circuits.

5.2 Calculate the total resistance R_G of the circuit from the separate stages.

$$\frac{1}{R_G} = \frac{1}{R_1} + \frac{1}{R_2} \qquad R_G = \frac{R_1 \cdot R_2}{R_1 + R_2} \qquad R_G = 9.1\ k\Omega$$

5.3 1st law of Kirchhoff: $I_G = I_1 + I_2$

Because $I = \frac{U}{R}$ it follows from the 1st law of Kirchhoff:

$$\frac{U}{R_G} = \frac{U}{R_1} + \frac{U}{R_2}$$

$$\frac{10\ V}{9.1\ k\Omega} = \frac{10\ V}{10\ k\Omega} + \frac{10\ V}{100\ k\Omega}$$

$$1.1\ mA = 1\ mA + 0.1\ mA$$

$$1.1\ mA = 1.1\ mA$$

5.4 What is the ratio of the partial currents compared to the ratio of the partial resistances ? (refer to the table)

1st law of Kirchhoff: $I_1 : I_2 = R_2 : R_1$

$$1 : 0.1 = 100 : 10$$

$$1 : 0.1 = 10 : 1$$

The partial currents are inversely proportional to the resistances.

≙ P3.2.3.2

The voltage divider under no-load conditions

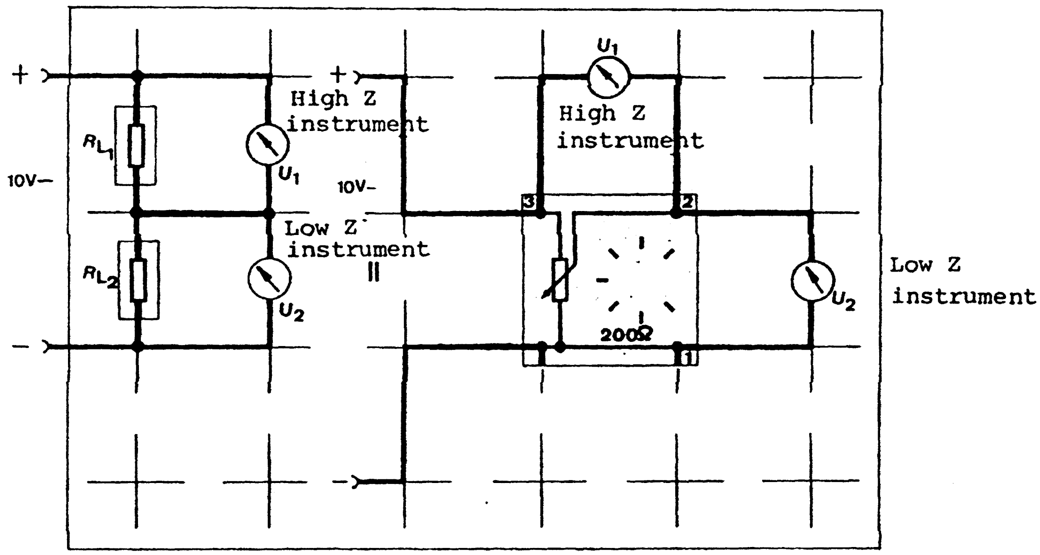
1. Aim of the Experiment

Measurement of U_1 and U_2 for different combinations of resistors, filling in of a table and graphical representation of the measured values

Measurement of U_1 and U_2 for different settings of the potentiometer

2. Circuit

I



3. Equipment and Components

	S	D
1 Rastered socket panel	576 74	580 10
1 Resistor R_{L_1} , 100 Ω	577 32	580 62
1 Resistor R_{L_2} , 100 Ω	577 32	580 62
1 Resistor R_{L_1} , 47 Ω	577 28	580 58
1 Resistor R_{L_2} , 150 Ω	577 34	580 64
1 Resistor R_{L_1} , 150 Ω	577 34	580 64
1 Resistor R_{L_2} , 47 Ω	577 28	580 58
1 Potentiometer, 200 Ω	577 90	581 40
1 Low Z instrument	-	-
1 High Z instrument	-	-
1 D.C. power supply unit	~~522 30~~	~~522 30~~ 52145
Bridging plugs	501 48	501 48
Connecting leads		

4. Conducting the Experiment

4.1 Assemble circuit I.

4.2 Measure the values of U_1 and U_2 for different combinations of resistors, fill in a table and make a diagram:

a) $U_1 = f\ (R_{L1})$

b) $U_2 = f\ (R_{L1})$

Total voltage: 10 V

$\frac{R_{L1}}{\Omega}$	$\frac{R_{L2}}{\Omega}$	$\frac{U_1}{V}$	$\frac{U_2}{V}$
150	47	7.6	2.4
100	100	5.0	5.0
47	150	2.4	7.6

4.3 Assemble circuit II.

4.4 Measure the values of U_1 and U_2 for 7 different settings of the potentiometer, fill in a table and draw a diagram:

a) $U_1 = f$ (position of potentiometer)

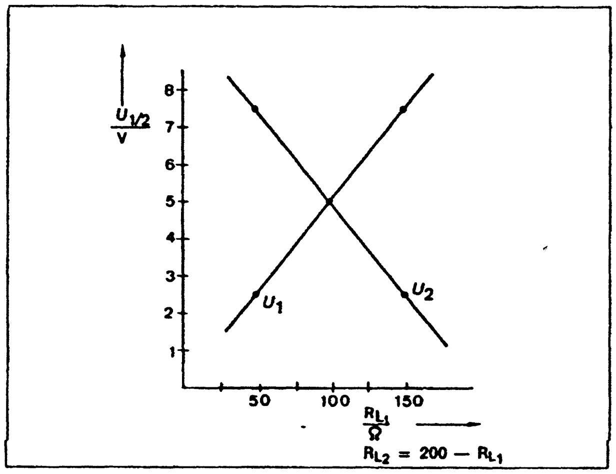
b) $U_2 = f$ (position of potentiometer)

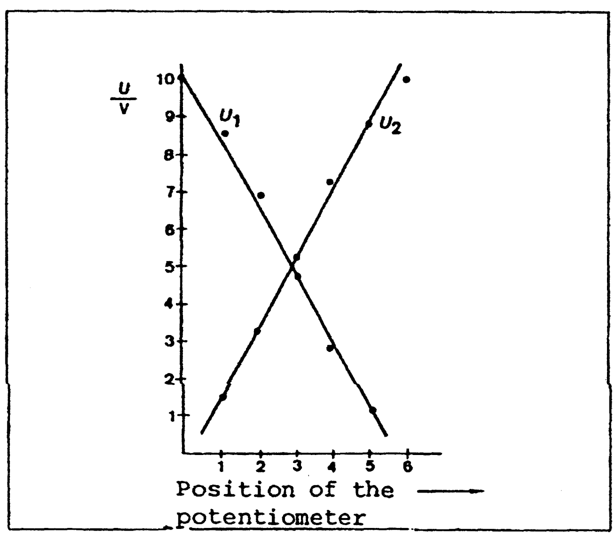
Total voltage: 10 V

Position of the potentiometer	$\frac{U_2}{V}$	$\frac{U_1}{V}$
0	0	10
1	1.5	8.5
2	3.2	6.8
3	5.2	4.8
4	7.2	2.8
5	8.9	1.1
6	10	0

5. Evaluation

5.1 Graphical display of the results as measured in 4.2 and 4.4.



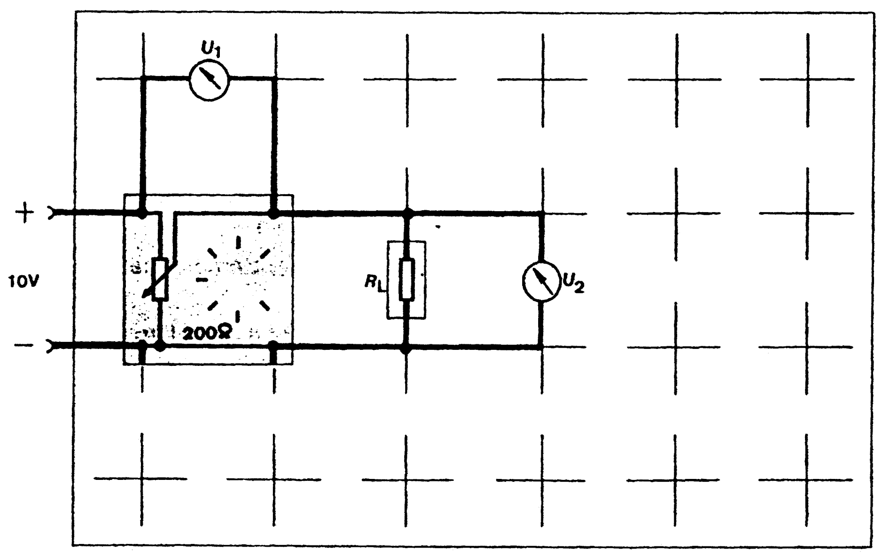


The loaded voltage divider

1. Aim of the Experiment

Measuring U_1 as a function of the potentiometer setting for a number of different load resistors (resistance remains constant for each series of measurements)

2. Circuit



3. Equipment and Components

	S	D
1 Rastered socket panel	576 74	580 10
1 Potentiometer, 200	577 90	581 40
1 Load resistor R_L, 100	577 32	580 62
1 Load resistor R_L, 470	577 40	580 70
1 Low Z instrument	-	-
1 High Z instrument	-	-
1 D.C. power supply unit	522 30	522 30
Bridging plugs	501 48	501 48
Connecting leads		

4. Conducting the Experiment

4.1 Assemble the circuit.

4.2 Measure the voltage U_1 and U_2 for different settings of the potentiometer as a function of $R_L = \infty$; $R_L = 470\ \Omega$; $R_L = 100\ \Omega$.

4.3 Tabulate the results.

Total voltage: 10 V

Position of the potentiometer	$R_L = \infty$		$R_L = 470\ \Omega$		$R_L = 100\ \Omega$	
	$\frac{U_2}{V}$	$\frac{U_1}{V}$	$\frac{U_2}{V}$	$\frac{U_1}{V}$	$\frac{U_2}{V}$	$\frac{U_1}{V}$
0	0	10.0	0	10.0	0	10.0
1	1.5	8.5	1.3	8.6	1.1	8.9
2	3.1	6.9	2.8	7.2	2.1	7.9
3	5.0	5.0	4.7	5.3	3.4	6.6
4	6.8	3.2	6.5	3.5	5.0	5.0
5	8.5	1.5	8.3	1.7	7.5	2.5
6	10.0	0	10.0	0	10.0	0

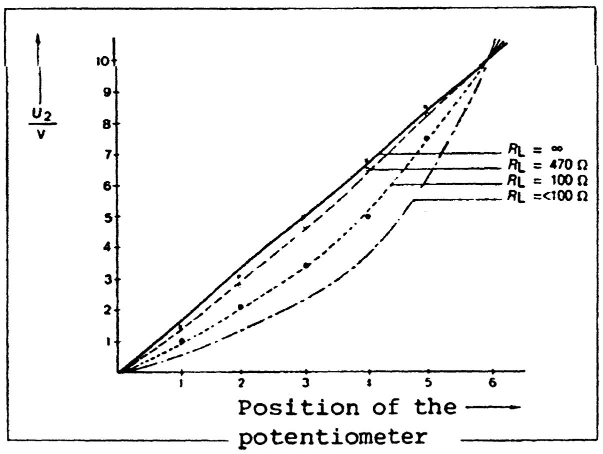
N o t e : Due to the residual resistance of the potentiometer, the measured values may deviate somewhat from the theoretical values.

5. Exercises

5.1 What is the total voltage $U = U_1 + U_2$ for each measurement ?

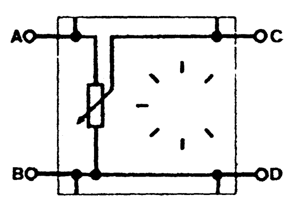
$$U_1 + U_2 = 10\ V$$

5.2 Graph of the voltage U_2 as a function of the potentiometer setting P for constant values of R_L.



5.3 What curve would you expect for a resistor < 100 Ω ?
Draw the expected curve into the graph.

5.4 A potentiometer consists of a fixed-value resistor with a wiper with which it is possible to set any intermediate value.



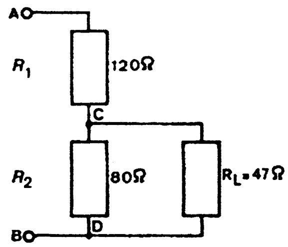
Consider the following settings of the potentiometer:

Resistance between A and B: 200 Ω

A and C: 120 Ω

C and D: 80 Ω

A load resistor $R_L = 47\ \Omega$ is connected between C and D so that the following combination of resistances results:



What is the value of the voltage between C and D when a voltage of 10 V is applied between A and B ?

1.) without the load resistor R_L

$U_{C-D} = 4\ V$

2.) with the load resistor $R_L = 47\ \Omega$

$$\frac{1}{R_{C-D}} = \frac{1}{R_L} + \frac{1}{R_2}$$

$$R_{C-D} = \frac{R_L \cdot R_2}{R_L + R_2}$$

$$R_{C-D} = 30\ \Omega$$

$$U_{C-D} = 2\ V$$

P3.2.6.1

2. The DANIELL Cell

Problem

a) Use a DANIELL cell to generate an electric current.
b) Measure the voltage of an "unloaded" DANIELL cell.
c) Determine the voltage of 3 DANIELL cells connected in series.

Apparatus and chemicals

4 Copper electrodes	Copper sulfate solution, 1 M and 0.1 M
4 Zinc electrodes	Zinc sulfate solution, 1 M and 0.1 M

Conducting the experiment

Arrange the cell blocks of the experimental electrochemistry unit to form double cells as described on page 2.

Construct the following cells in the four double cells:

Cell 1:	$Zn/ZnSO_4$ (1 M)	//	$CuSO_4$ (1 M)	/ Cu
Cell 2:	$Zn/ZnSO_4$ (0.1 M)	//	$CuSO_4$ (0.1 M)	/ Cu
Cell 3:	$Zn/ZnSO_4$ (0.1 M)	//	$CuSO_4$ (0.1 M)	/ Cu
Cell 4:	$Zn/ZnSO_4$ (0.1 M)	//	$CuSO_4$ (0.1 M)	/ Cu

Conduct the following experiments in sequence:

a) Connect the electrodes of the first DANIELL cell to the inputs of the electric motor.

b) Connect the Cu electrode of the second DANIELL cell to the +pole and the Zn electrode to the -pole of the inputs "galv. Messung" (measuring range: 2V). (You may adjust the extent to which the electrodes are submerged in the electrolyte solutions.)

c) Connect three DANIELL cells in series as shown in Illustration 5.1 and measure the voltage (measuring range: 5V).

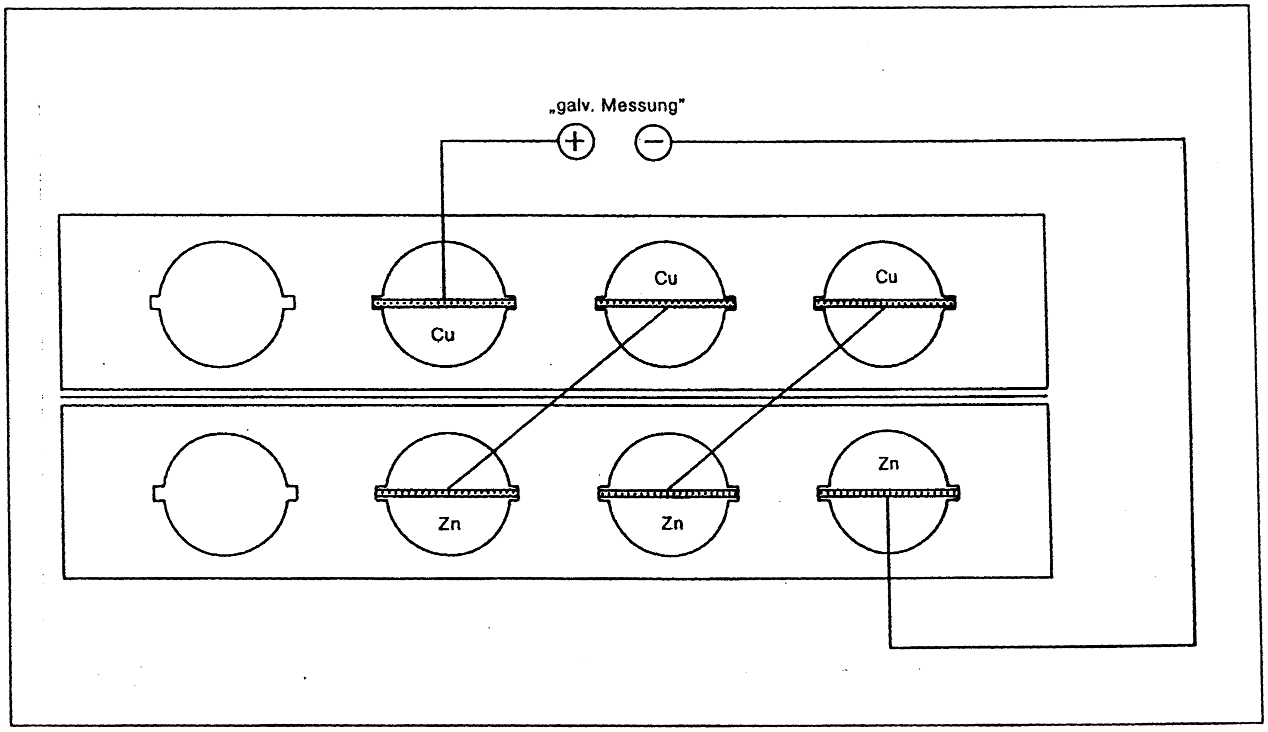


Fig. 5.1 Three DANIELL cells connected in series

Evaluation and results

a) When the electrodes of a DANIELL cell are connected to an electric motor, an electric current is generated which is sufficient to drive the electric motor.

b) The voltage of the cell $Zn/ZnSO_4$(0.1 M) // $CuSO_4$(0.1 M)/Cu is 1.08 V. The voltage of the cell is independent of the dimensions of the electrodes. (Note: When using this cell the electric motor cannot be driven.)

c) When three DANIELL cells are connected in series, the voltage is 3.24 V, i.e., the sum of the individual voltages.

When the cells are connected in parallel, the total voltage is the same as the voltage of each of the individual cells because the set-up in this case is simply one very large cell.

If cells connected in series are short-circuited, the short-circuit current produced is the same as the short-circuit current of a single cell. When the cells are connected in parallel, however, the total short-circuit current equals the sum of the individual short-circuit currents.

P3.2.6.2

3. Measuring the Voltages of Simple Galvanic Cells

Problem

Combine the half-cells Ag/Ag^{+}, Cd/Cd^{2+}, Cu/Cu^{2+}, Pb/Pb^{2+} and Zn/Zn^{2+} to produce galvanic cells.

Determine

a) which metal is the +pole and which is the -pole
b) which voltage ΔE (in V) exists between the half-cells.

Apparatus and chemicals

1 lead electrode	lead nitrate solution, 0.1 M
1 cadmium electrode	cadmium sulfate solution, 0.1 M
1 copper electrode	copper sulfate solution, 0.1 M
1 silver electrode	silver nitrate solution, 0.1 M
1 zinc electrode	zinc sulfate solution, 0.1 M

Conducting the experiment

Fill one chamber of a double cell with one 0.1 molar salt solution; fill the other chamber with another 0.1 molar salt solution. Then insert the appropriate electrodes in the chambers. Example: Combine Cu in a 0.1 molar $CuSO_4$ solution with Cd in a 0.1 molar $CdSO_4$ solution. Create the other galvanic cells by the same method (see table). We suggest starting out the series of measurements with four galvanic cells that are each composed of the same half-cell. Change the diaphragm each time the four double cells have been used.

To measure the voltage, set the measuring range selector to 1000 mV. Select the measuring range 2 V when working with the combinations Zn/Ag, Zn/Cu and Cd/Ag. Plug one end of each of two connecting cables into the inputs "galv. Messung". Touch the electrodes with the other ends of the cables to determine which metal is the +pole and which is the -pole. The indicator of the gauge will swing to the right when the polarity is correct.

In this and all subsequent experiments, always select the *most appropriate* measuring range for a given voltage measurement. (Example: When measuring a voltage of 650 mV, select the measuring range 1000 mV, not 2 V.)

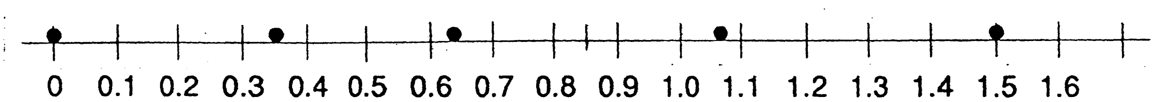
Warning: Cadmium sulfate and lead nitrate are poisonous! Do not let silver nitrate come into contact with hands or clothing!

Evaluation and results

No.	Galvanic Cell	Voltage $\frac{\Delta E}{V}$	-pole	+pole
1	$Zn/ZnSO_4//CdSO_4/Cd$			
2	$Zn/ZnSO_4//Pb(NO_3)_2/Pb$			
3	$Zn/ZnSO_4//CuSO_4/Cu$			
4	$Zn/ZnSO_4//AgNO_3/Ag$			
5	$Cd/CdSO_4//Pb(NO_3)_2/Pb$			
6	$Cd/CdSO_4//CuSO_4/Cu$			
7	$Cd/CdSO_4//AgNO_3/Ag$			
8	$Pb/Pb(NO_3)_2//CuSO_4/Cu$			
9	$Pb/Pb(NO_3)_2//AgNO_3/Ag$			
10	$Cu/CuSO_4//AgNO_3/Ag$			

In all combinations, zinc is always the -pole and silver is always the +pole of the galvanic cells. When the electrodes of the various galvanic cells are connected with a connecting cable ("short-circuit"), the electrons always flow from the -pole to the +pole, e.g., in cell 3 from zinc to copper and in cell 10 from copper to silver. The metals (or the appropriate corresponding redox pairs) can be lined up so that the metal acting as the -pole in all experiments is located at the left end and the metal always functioning as the +pole is located at the right end. Arrange the other metals so that the metals for which they function as the +pole are located to their left and the other metals for which they function as the -pole of the corresponding galvanic cell are located to their right. It is thus possible to obtain - taking into account the measured voltages of the galvanic cells - an *electrochemical series* of corresponding redox pairs of the type metal/metal cation. The zero point of this electrochemical series may be selected as desired.

For example:



From the table it may be determined that, for example:

$\Delta E\ (2) = \Delta E\ (1) + \Delta E\ (5)$
$\Delta E\ (3) = \Delta E\ (1) + \Delta E\ (5) + \Delta E\ (8)$
$\Delta E\ (3) = \Delta E\ (1) + \Delta E\ (6)$
$\Delta E\ (3) = \Delta E\ (2) + \Delta E\ (8)$

etc.

P3.2.6.3

3. Potenciales estándar de los pares redox correspondientes, del tipo catión metálico/metal

Problema

Establecer los potenciales estándar de los pares redox correspondientes Ag/Ag^+, Cd/Cd^{2+}, Cu/Cu^2, Pb/Pb^{2+} y Zn/Zn^{2+} con ayuda de un electrodo de hidrógeno "estándar" simplificado.

Aparatos y substancias químicas

1	electrodo de platino (platinado) (ver Apéndice 4)	ácido clorhídrico, 1 M
1	electrodo de plomo	solución de nitrato de plomo, 1 M
1	electrodo de cadmio	solución de sulfato de cadmio, 1 M
1	electrodo de cobre	solución de sulfato de cobre, 1 M
1	electrodo de plata	solución de nitrato de plata, 1 M
1	electrodo de cinc	solución de sulfato de cinc, 1 M

asimismo: 1 fuente de alimentación de CC o batería plana de 4,5 V.

Evaluación y resultados

Par redox correspondiente	Zn/Zn^{2+}	Cd/Cd^{2+}	Pb/Pb^{2+}	Cu/Cu^{2+}	Ag/Ag^+
Potencial estándar (valor medido) $\frac{E°}{V}$ -	-0,76	-0,40	-0,125	+0,34	+0,80

4. Potenciales estándar de los pares redox correspondientes, del tipo anión no metálico/no metal

Ejercicio

Establecer los potenciales estándar de los pares redox correspondientes Cl^-/Cl_2 , Br^-/Br_2 y I^-/I_2 con ayuda de un electrodo de hidrógeno "estándar" simplificado.

Aparatos y substancias químicas

1 electrodo de platino (platinado)
1 electrodo de grafito

ácido clorhídrico, 1 M
solución de cloruro de sodio, 1 M
solución de bromuro potásico, 1 M
solución de yoduro potásico, 1 M

asimismo: 1 fuente de alimentación de CC o una batería plana de 4,5 V

Resultados

Par redox correspondiente	Cl^-/Cl_2	Br^-/Br_2	I^-/I_2
Potencial estándar (valor medido) $\frac{E°}{V}$ -	+1,36	+1,06	+0,53

Puesto que el yodo en una solución acuosa de potasio forma el compuesto aditivo $KI \cdot I_2 = KI_3$, el par redox correspondiente adecuado deberá formularse en realidad de la siguiente manera:

$$\underset{\text{ion yoduro}}{3\,I^-} \rightleftharpoons \underset{\text{ion triyoduro}}{J^-_3 + 2\,e^-}$$

5. Potencial estándar correspondiente al par redox Fe^{2+}/Fe^{3+}

Ejercicio

Establézcase el potencial estándar correspondiente al par redox Fe^{2+}/Fe^{3+} con ayuda de un electrodo de hidrógeno "estándar" simplificado.

Aparatos y substancias químicas

1 electrodo de platino (platinado)	ácido clorhídrico, 1 M
1 electrodo de grafito	hierro (II)/solución salina de hierro (III), Fe^{2+} y Fe^{3+} (solución clorhídrica)

asimismo: 1 fuente de alimentación de CC o batería plana de 4,5 V

Evaluación y resultados

Par redox correspondiente	Fe^{2+}/Fe^{3+}
Potencial estándar (valor medido) $\frac{E^\circ}{V}$	+0,75

6. Evaluación de los resultados de los experimentos 4, 5 y 6

Los potenciales estándar pueden ordenarse en una *escala de potenciales electroquímicos* (utilizar los valores que se dan en las tablas de las páginas 18 y 19)

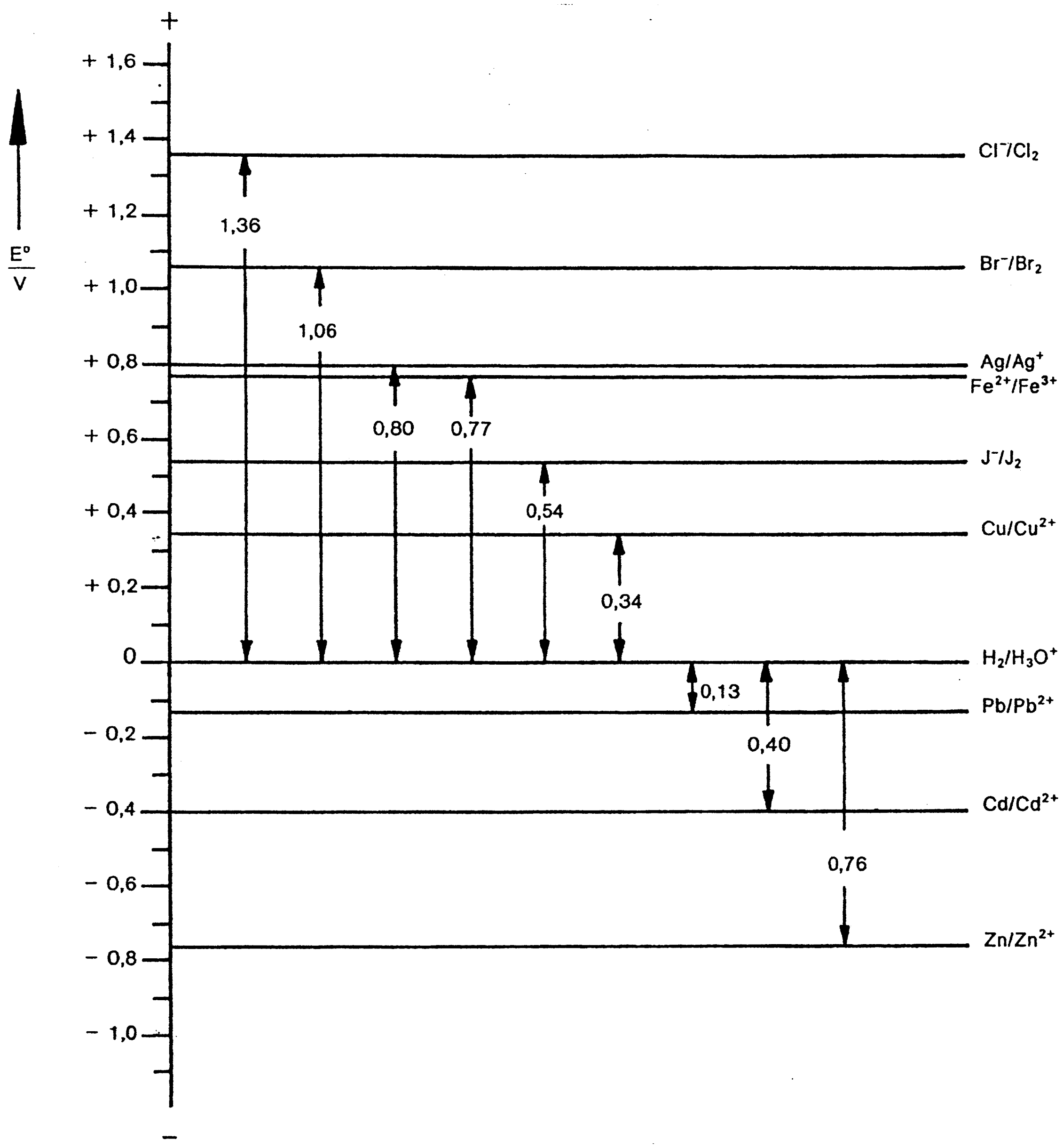


Fig. 2 Escala de potenciales electroquímicos

Model of a moving coil movement

The deflection of a current-carrying coil in the field of a horseshoe magnet

Apparatus:

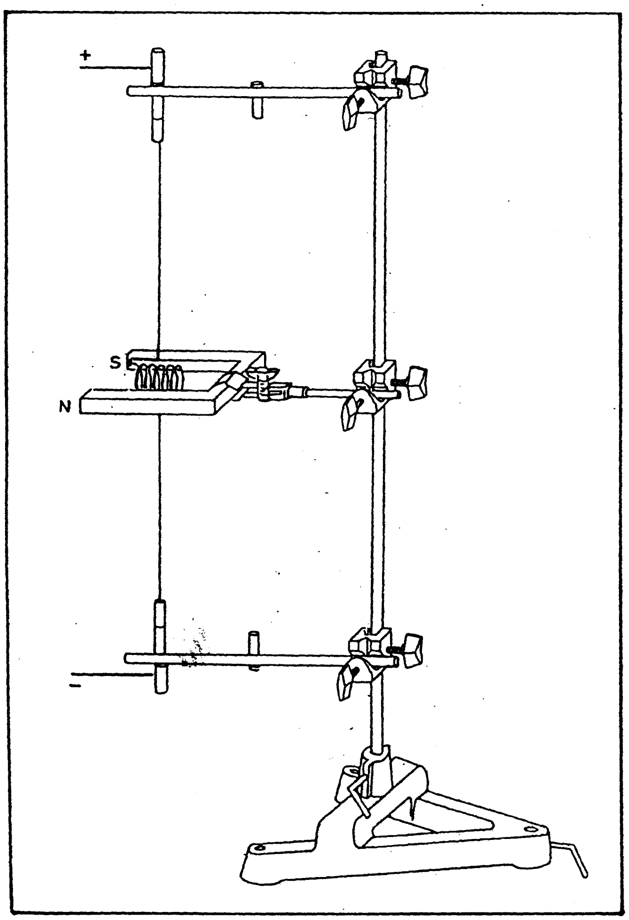
1 Equipment for electromagnetism 560 00
1 Power supply unit, 10 to 20 A AC/DC ..... ~~522 29~~ 52155
1 Connecting lead, 1 m, red 501 30
1 Connecting lead, 1 m, blue 501 31

Setting up:

Set up the apparatus as in Fig. 1 with the north pole of the magnet (marked red) on the right when viewed from the front.

The coil axis must be perpendicular to the lines of force of the permanent magnet.

Connect the positive terminal of the power source to the top plug of the coil and the negative terminal to the bottom plug.



Carrying out the experiment:

Increase the voltage slowly, starting at zero. Watch the coil.

Repeat the experiment with reversed polarity.

Repeat the experiment with AC voltage.

Evaluation and results:

The larger the current, the greater the rotation of the coil. The wires become more and more twisted. The coil turns by a maximum of 90° (coil axis parallel to the lines of force of the horseshoe magnet).

The coil rotates in the opposite direction when the polarity is reversed.

There is no rotation when an AC voltage is applied.

Note:

A magnetic field is created in the coil which is like that of a bar magnet outside the coil. The field in the coil is perpendicular to the magnetic field of the horseshoe magnet.

Both magnetic fields exert forces on each other. Consequently, the rotatable magnetic field (coil) turns in the fixed magnetic field (horseshoe magnet) so that opposite poles are facing each other.

The coil does not turn by 90° for small currents because the torsion force of the wires with respect to the coil grows with increasing rotation.

If alternating current flows through the coil, the magnetic field changes with the frequency of this current. The coil cannot keep up with this rate of change due to its inertia and therefore remains at rest.

The degree of coil rotation is a measure of the direct current flowing.

Fig. 1: Experiment setup "Model of a moving-coil measurement instrument"

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(see section 4)

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Gebrauchsanweisung **560 15**
Instruction Sheet

Elektromagnetisches Versuchsgerät
Equipment for Electromagnetism

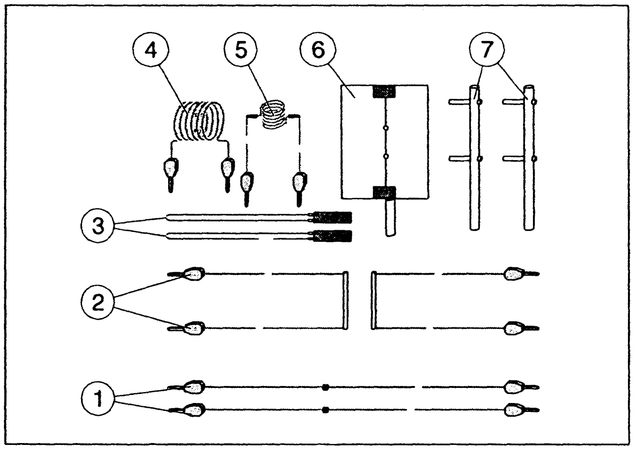


Fig. 1

Das Gerät dient dazu, die magnetischen Felder um stromdurchflossene Leiter und die Kraftwirkungen dieser Felder auf permanente Magnete oder stromdurchflossene Leiter zu zeigen.

1 Sicherheitshinweis

Maximal zulässiger Strom

dauernd:	12 A
max. 5 min:	15 A
max. 1 min:	20 A

2 Lieferumfang (Fig. 1)

① 2 bewegliche biegsame Leiter mit Steckern
② 2 gerade Leiter an je 2 biegsamen Zuleitungen mit Steckern
③ 2 Weicheisenstücke mit Schlaufen
④ 1 feste Spule mit Steckern
⑤ 1 bewegliche Spule mit Steckern
⑥ 1 zweiteilige Kunststoffplatte zum Aufstreuen von Eisenpulver für Feldlinienbilder;
mit 2 Durchführungen für Kabel
⑦ 2 Haltestangen mit Isolierbuchsen

3 Zusätzlich erforderliche Geräte

- Stativmaterial:

1 kleiner Stativfuß	300 02
1 Stativstange, 75 cm	300 43
3 Leybold-Muffen	301 01
1 Stativklemme	302 61
1 Stativlochstab	590 13
2 Sockel	300 11

- Magnete:

1 Magnetnadel	513 11
1 Fuß dazu	513 51
1 Hufeisenmagnet mit Joch	510 21
1 Paar Rundstabmagnete	510 12
1 Streuer für Eisenpulver	514 72
1 x Eisenpulver	514 73

This apparatus is used to demonstrate the magnetic fields surrounding current-carrying conductors and the forces exerted by these fields on permanent magnets or other current-carrying conductors.

1 Safety note

Maximum permissible current:

Sustained:	12 A
Max. 5 min:	15 A
Max. 1 min:	20 A

2 Scope of supply (Fig. 1)

① 2 Movable, flexible conductors with plugs
② 2 Straight conductors, each on two flexible leads with plugs
③ 2 Soft-iron pieces with loops
④ 1 Fixed coil with plugs
⑤ 1 Movable coil with plugs
⑥ 1 Two-piece plastic plate for scattering iron filings to illustrate lines of force;
with two lead-throughs for leads
⑦ 2 Holding rods with insulated sockets

3 Additionally required equipment

- Stand material:

1 Stand base, small	300 02
1 Stand rod, 75 cm	300 43
3 Leybold multiclamps	301 01
1 Clamp	302 61
1 Insulated stand rod	590 13
2 Saddle bases	300 11

- Magnets:

1 Magnetic needle	513 11
1 Base for magnetic needle	513 51
1 Horse-shoe magnet with yoke	510 21
1 Pair of round magnets	510 12
1 Shaker for iron filings	514 72
1 x Iron filings	514 73

- Spannungsquelle und Experimentierkabel; Mindestbelastbarkeit 10 A, empfehlenswert 15 A bis 20 A

z.B. für max. 10 A	
Kleinspannungsstelltrafo	521 39
oder für max. 20 A	
Hochstrom-Netzgerät	521 55
Sicherheitsexperimentierkabel	

- Voltage source and connecting leads: minimum load capacity 10 A, recommended: 15 A to 20 A

e.g. for max. 10 A	
Variable extra-low voltage transformer	521 39
or for max. 20 A	
High current power supply	521 55
Safety connecting leads	

4 Versuchsbeispiele

4 Experiment examples

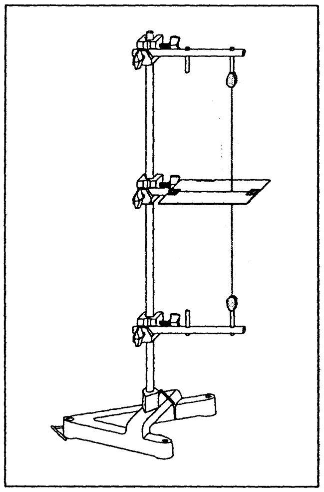


Fig. 2

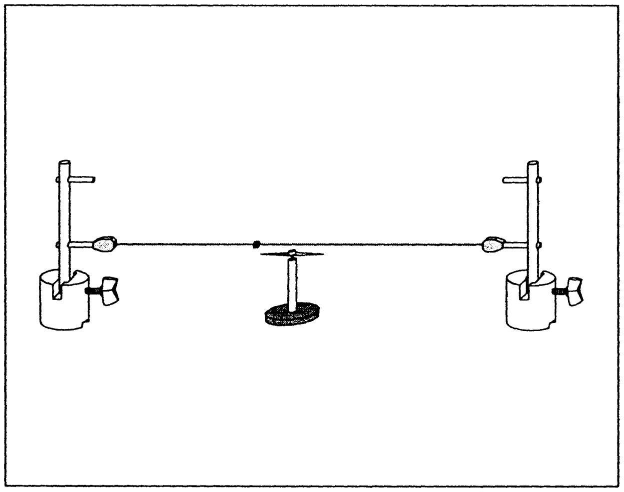


Fig. 3

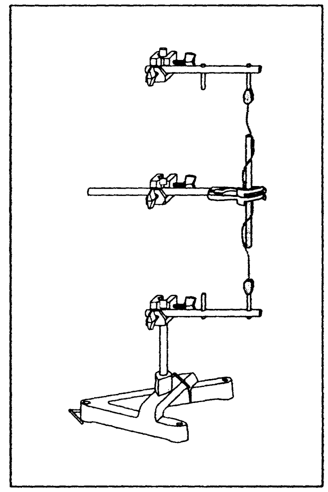


Fig. 4

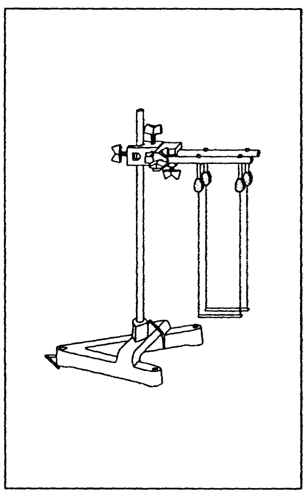


Fig. 5

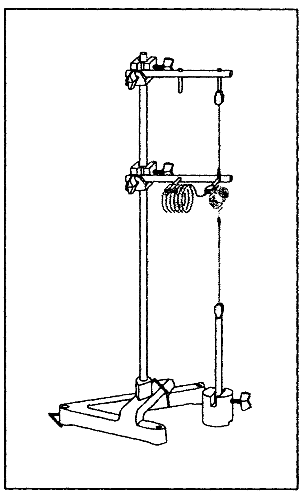


Fig. 6

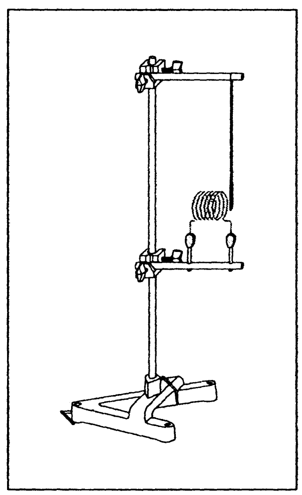


Fig. 7

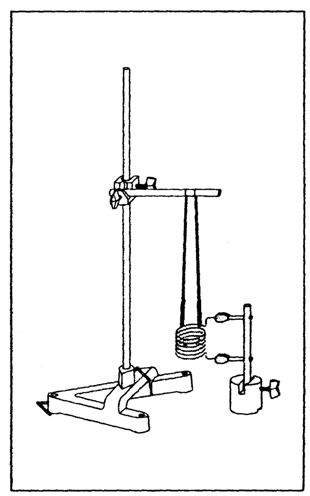


Fig. 8

Fig. 2 Nachweis des Magnetfeldes um einen stromdurchflossenen Leiter mit Eisenpulver

Fig. 3 Ablenkung einer Magnetnadel durch das Feld eines stromdurchflossenen Leiters

Fig. 4 Ablenkung eines beweglichen Leiters durch das Feld eines feststehenden Stabmagneten

Fig. 5 Kraftwirkung zweier beweglicher stromdurchflossener Leiter aufeinander

Fig. 6 Ablenkung einer beweglich gehalterten stromdurchflossenen Spule im Magnetfeld einer zweiten Spule (Wattmeter-Modell)

Fig. 7 Anziehung eines Weicheisenstückes im magnetischen Gleich- oder Wechselfeld einer stromdurchflossenen Spule (Modell eines Weicheiseninstrumentes)

Fig. 8 Abstoßung zweier Weicheisenstücke im magnetischen Gleich- oder Wechselfeld einer stromdurchflossenen Spule

Fig. 2 Demonstrating the magnetic field surrounding a current-carrying conductor using iron filings

Fig. 3 Deflection of a magnetized needle by the field of a current-carrying conductor

Fig. 4 Deflection of a movable conductor by the field of a fixed bar magnet

Fig. 5 The action of the forces of two movable current-carrying conductors on each other

Fig. 6 Deflection of a moveably mounted current-carrying coil in the magnetic field of a second coil (wattmeter model)

Fig. 7 Attraction of a piece of soft iron in the constant or alternating magnetic field of a current-carrying coil (model of a moving-iron instrument)

Fig. 8 Repulsion of two soft-iron pieces in the constant or alternating magnetic field of a current-carrying coil

Coulomb's Law of Magnetostatics

Quantitative proof of Coulomb's Law of Magnetostatics

The force acting between two magnetic poles is described quantitatively in Coulomb's Law of Magnetostatics. In the experiment carried out here, two long magnetizable steel needles are used so that only the force between two magnetic poles can be measured in good approximation. Using a torsion balance, the force is measured with which two magnetic poles attract or repel each other as a function of distance between the two poles (part a) and then as a function of pole strength p (part b).

A magnetizable steel needle is secured in a rotary body mounted between two torsion wires. One pole of the second needle is brought close to one pole of the first needle on a special stand. The force acting between the two poles causes torsion of the wires. The rotational motion is made visible using a concave mirror on the rotary body, with a light pointer being projected onto a scale via the mirror. The torsion angle α (or the deflection a of the light pointer on the scale) is a measure of the force acting between the poles.

Apparatus:

1 Torsion balance 516 01
1 Accessories for magnetostatics 516 21
1 Scale on stand 516 04
1 Lamp housing 450 60
1 Lamp 6 V/30 W 450 51
1 Condensor with diaphragm holder 460 20
1 Transformer 6 V/12 V, 30 W 562 73
1 Small stand base, v-shaped 300 02
1 Stand rod 47 cm 300 42
1 Leybold multiclamp 301 01
1 Bar magnet 60 x 13 x 5 mm 510 50

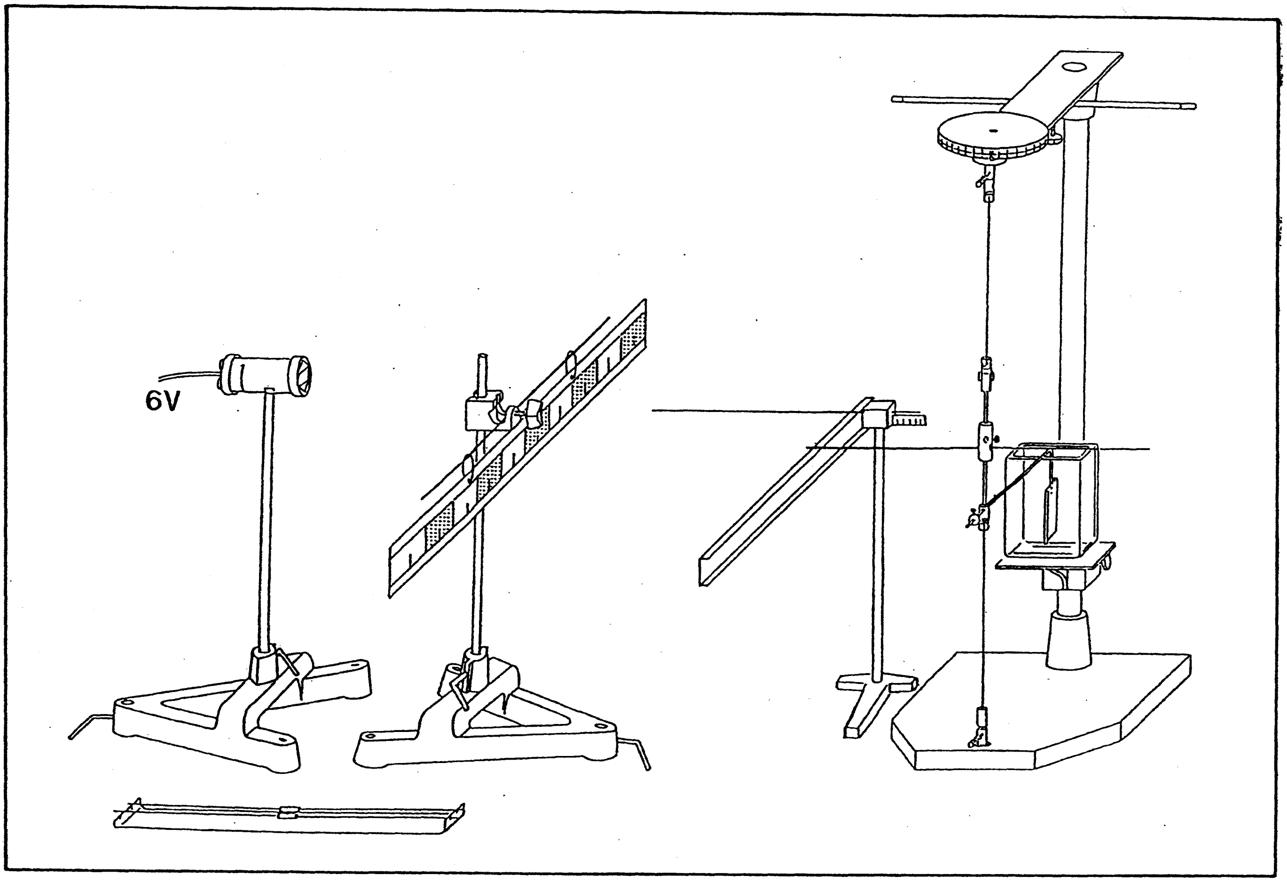


Fig. 1: Experiment setup for confirming Coloumb's Law of Magnetostatics using the torsion balance with damping vane and light pointer.

Setting up:

Mount the damping vane on the torsion balance, compensate with the counterweight and set up (see the Instructions for Use for the Torsion Balance 516 04 and the Instructions for Use for the Accessories for Magnetostatics 516 21).

The lamp housing (460 20 with lamp 450 51) with condenser and diaphragm slider 460 20 are used to project the light pointer. Use the Leybold multiclamp 301 01 to mount the lamp on a stand (320 02/42) at a distance of approximately 30 - 40 cm away from the concave mirror on the rotary body of the torsion balance. Project a "light pointer" (with "light pointer diapositive") onto the scale via the mirror The distance between the scale and mirror should be at least 2 m (see Fig. 1).

Note:

The long, thin needles do not remain permanently magnetized. For this reason, they are supplied unmagnetized. It is recommended to magnetize them again before each series of experiments. To do this, stroke the appropriate pole of a powerful magnet (e.g. a bar magnet 510 50) from the center to the ends of the needle. The needles should only be magnetized in coils if the latter are at least 10 cm longer than the needles. If this is not the case, extremely extensive pole regions will be obtained.

Place one of the magnetic needles in the rotary body so that its holder is flush with the bore on both sides. Place the stand with needle mount in front of the torsion balance so that the tip of the rotatable needle is 1-2 mm over the long scale (Fig. 1).

Carrying out the experiment:

a) Force as a function of the distance between the poles (distance large with respect to the extent of the pole region):

After setting the light pointer to zero, place a second magnetic needle through one of the three holes in the needle holder. It should project by 5 cm from the other side (read off on the depth scale). It does not matter whether you use holes which attract or repel. Now, move the assembled stand setup on the bench so that the tip of the needle supported in the balance is exactly over the 15 cm scale division of the scale secured to the stand, ensuring that the needle itself is perpendicular to the scale. After reading off the light pointer deflection, increase the distance r between the needles in arbitrary steps from 15 cm to approximately 30 cm by moving the stand setup on the bench. For each distance, align the stand setup so that the needle mounted in the torsion balance is perpendicular to the scale secured to the stand. Make a note of the light pointer deflection on the scale after each adjustment.

Measurement example:

Table 1

Pole distance r/cm	15	20	15 $\sqrt{2}$	25	30
Light pointer deflection a/cm	7.5	4.3	3.7	2.7	1.9
$\frac{1}{r^2}$/cm^{-2} · 10^{-3}	4.44	2.5	2.22	1.6	1.11
r^2a/cm³	1687.5	1720	1662.9	1687.5	1710

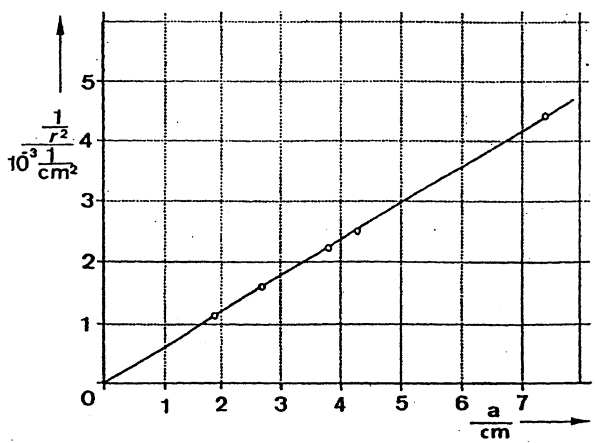


Fig. 2: Deflection of the light pointer a as a function of $\frac{1}{r^2}$; r = pole distance.

b) Force as a function of magnetic flux (pole strength) of the poles:

First place one needle in the stand setup, and measure the light pointer deflection a_1 for a certain distance r between the poles. Replace this in the frame, take a second needle and measure the deflection a_2 for the same r. Now, place both needles in the stand setup, set the same distance r, and measure the deflection of the light pointer. (The pole strength of "one" magnet is therefore approximately doubled). If necessary, repeat the measurement with a third steel needle, and measure the deflection of the light pointer with three needles placed in the stand setup for the same distance r.

Measurement example 2:

Force as function of pole magnetic flux.

b_1) r = 15 cm

a_1 = 6.8 (cm)

a_2 = 7.0 (cm)

Total deflection a = 13.2 (cm) for two steel needles

$a_1 + a_2$ = (6.8 + 7.0) cm = 13.8 (cm)

b_2) As for b_1, but with opposing poles

r = 15 cm

a = - 6.8 (cm)

a = + 6.9 (cm)

Total deflection a = + 0.3 (cm) for two steel needles

$a_1 + a_2$ = (-6.8 + 6.9) cm = 0.1 (cm)

Evaluation and results:

For a)

The force acting between two magnetic poles decreases with increasing pole distance r. The product of light pointer deflection a and r² is approximately constant. Since the light pointer deflection is proportional to the force acting between the poles, we obtain the following relationship:

$$F \sim \frac{1}{r^2}.$$

If $\frac{1}{r^2}$ is plotted against a, the values form a straight line (see Fig. 2).

Ideally, the value r² · A should be the same in all cases. Excepting unavoidable measurement errors, the actually observed deviations are due to the fact that the magnetic poles of the fixed or rotatable needles which are furthest apart also cause forces to act. However, these are several orders of magnitude smaller than the mainly effective pair of poles.

For b)

The deflection of the light pointer for two magnetized steel needles in the stand setup is approximately the same as the total of the individual deflections:

$a = a_1 + a_2$.

If $a_1 = a_2$, the deflection would be doubled if the pole strength p of a magnet were doubled.

It follows from experiments a) and b) that the force acting between the poles of two permanent magnets is proportional to the product of their pole strengths p and inversely proportional to the square of the pole distance:

$$F \sim \frac{p_1 \, p_2}{r^2}$$

(Where r ≫ extent of the pole region).

Measuring the force acting on current-carrying conductors in the field of a horseshoe magnet

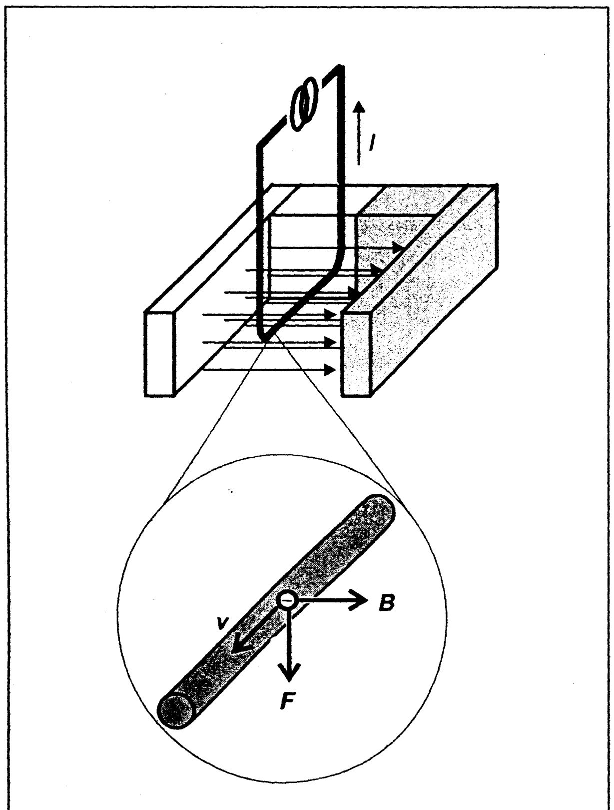
Objects of the experiment

- Measuring the force acting on a current-carrying conductor in the magnetic field as a function of the current intensity.
- Measuring the force acting on a current-carrying conductor in the magnetic field as a function of the conductor length.
- Measuring the force acting on a current-carrying conductor in the magnetic field as a function of the angle between the magnetic field and the direction of the current.
- Calculating the magnetic field.

Principles

Magnetic induction, or more simply the magnetic field $\boldsymbol{B}$, is a vector quantity. A force is exerted on a given charge q moving with a velocity $\boldsymbol{v}$ in the magnetic field $\boldsymbol{B}$, which depends on the magnitude and direction of the velocity and on the strength and direction of the magnetic field. The following relationship applies:

$$\boldsymbol{F} = q \cdot (\boldsymbol{v} \times \boldsymbol{B}) \qquad \text{(I)}$$



The so-called *Lorentz* force $\boldsymbol{F}$ is also a vector quantity acting perpendicular to the plane defined by $\boldsymbol{v}$ and $\boldsymbol{B}$.

The force exerted on a current-carrying conductor in a magnetic field may be understood as the sum of the individual force components acting on the moving charge carriers which make up the current. In accordance with (I), the *Lorentz* force $\boldsymbol{F}$ acts on each individual charge carrier q moving with the drift velocity $\boldsymbol{v}$. For a straight conductor, this means a total force of

$$\boldsymbol{F} = q \cdot nAs \cdot (\boldsymbol{v} \times \boldsymbol{B}) \qquad \text{(II)},$$

as the number of charged particles in the conductor is the product of the charge-carrier density n, the conductor cross-section A and the length s of the section of the conductor within the magnetic field.

It is common to introduce the vector $\boldsymbol{s}$, which points in the direction of the conductor section. In addition, the product $qnAv$ is equivalent to the current I. Thus, the force of a magnetic field on a straight, current-carrying conductor segment is given by the equation

$$\boldsymbol{F} = I \cdot (\boldsymbol{s} \times \boldsymbol{B}) \qquad \text{(III)}$$

and the absolute value of the force by

$$F = I \cdot s \cdot B \cdot \sin\alpha \qquad \text{(IV)},$$

whereby α is the angle between the magnetic field and the direction of the current.

In this experiment, rectangular conductor loops carrying currents of up to 20 A are placed in the horizontal magnetic field of a horseshoe magnet. The force acting on the horizontal section is measured. The forces acting on the two vertical sections cancel each other out.

The conductor loops are mounted on a force sensor. This contains a bending member to which strain gauges are mounted; the electrical resistance of these elements changes under load. The change in the resistance is proportional to the originating force. A connected newtonmeter measures the change in resistance and displays the corresponding force.

Title picture: schematic illustration of the force acting on a current-carrying conductor in a magnetic field

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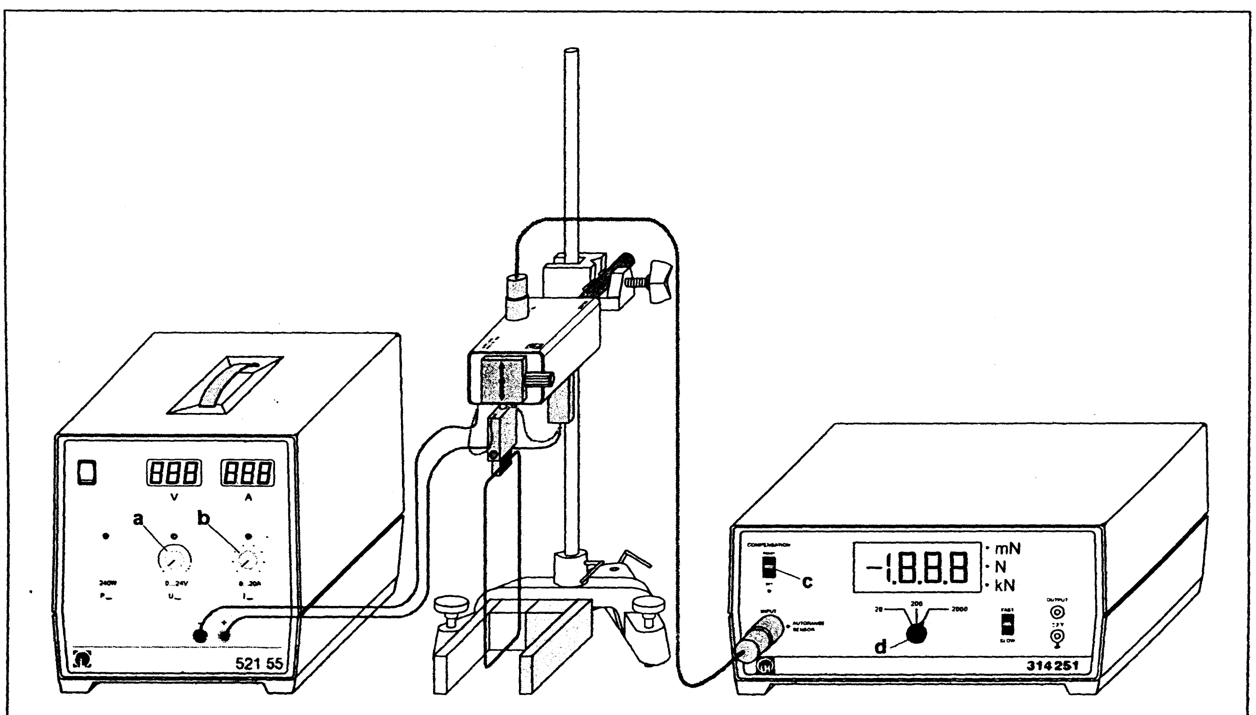
Apparatus

1 Horseshoe magnet with yoke	510 21
1 Force sensor	314 261
1 Set conductor loops for force measurement	516 34
1 Support for conductor loops	314 265
1 Newtonmeter	314 251
1 Multicore connecting cable, 6-pole	501 16
1 High current power supply	521 55
1 Stand base, small, V-shape	300 02
1 Stand rod, 47 cm	300 42
1 Leybold multiclamp	301 01

Connecting leads with conductor cross-section 2.5 mm^2

Fig. 1 Experiment setup for measuring the force acting on current-carrying conductors in a magnetic field



Setup and carrying out the experiment

Notes:

As the measurement quantity is very small, the measurement is easily affected by ambient interfering effects:
Avoid shocks, drafts and temperature variations in the vicinity.

The newtonmeter must warm up for at least 15 minutes before starting the experiment:
Switch on the newtonmeter with the force sensor connected using the mains switch on the rear of the device.

Subject the support and the conductor loops to loads of 20 A only for brief periods at a time (just a few minutes).

The magnetic field of the horseshoe magnet is not homogeneous:
For all measurements, center the conductor loop between the two arms of the magnet so that the effect of the magnetic field is as uniform as possible.

- Set up the experiment as shown in Fig. 1.
- To avoid short-circuits, make sure that the non-insulated cable sections of the support for conductor loops do not touch.
- Set the measuring range switch **(d)** on the newtonmeter to 2000.

The experiments are carried out using only the conductor loops without narrow section. The easiest way to set the current is to use only the current control knob **(b)**. The voltage control knob **(a)** is turned all the way to the right.

a) Measuring as a function of current:

- First, attach the 8 cm wide conductor loop to the force sensor.
- Turn the current control knob **(b)** all the way to the left and the voltage control knob **(a)** all the way to the right. Then switch on the high current power supply.

– To compensate the zero point of the newtonmeter, select the SET position with the COMPENSATION switch **(c)**.
– Using the current control knob **(b)**, increase the current to 20 A in steps of 2 A; for each current level, read off the force from the newtonmeter and write these values in your experiment log.
– Set the current to I = 0 A and check the zero point of the force display.

b) Measuring as a function of the conductor length:

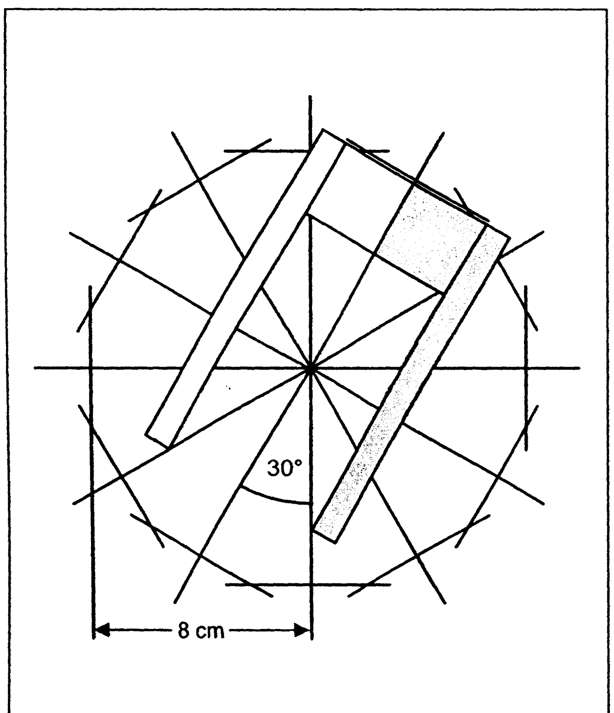
– Attach the 4 cm wide conductor loop to the force sensor.
– To compensate the zero point of the newtonmeter, select the SET position with the COMPENSATION switch **(c)**.
– Set the current level I = 20 A, read off the force from the newtonmeter and write this value in your experiment log.
– Set the current to I = 0 A and check the zero point of the force display.
– Repeat the measurement for the 2 cm and the 1 cm conductor.

c) Measuring as a function of the angle between the magnetic field and the direction of the current:

Recommendation: to compensate for the non-homogeneous nature of the magnetic field, and to set the proper rotational angle, make a template (see Fig. 2). This makes positioning the horseshoe magnet easier and more accurate.

– Turn the current control knob all the way to the left and attach the 4 cm wide conductor loop to the force sensor.
– Place the template underneath the conductor loop so that the center of the template is exactly underneath the midpoint of the horizontal conductor section and one of the template lines is parallel to this conductor section.

Fig. 2 Using the template as an aid in positioning the horseshoe magnet



– Set up the horseshoe magnet so that the magnetic field and the conductor section are parallel.
– To compensate the zero point of the newtonmeter, select the SET position with the COMPENSATION switch **(c)**.
– Set the current level I = 10 A.
– Turn the magnet through 360° in steps of 30° and read off the force from the newtonmeter for each angle.
– Set the current to 0 A and check the zero point of the force display.

Measuring example and evaluation

a) Measuring as a function of current:

Table 1: Force F as a function of the current I (s = 8 cm)

$\frac{I}{A}$	$\frac{F}{mN}$
0	0.0
2	4.5
4	9.3
6	13.5
8	18.0
10	22.5
12	27.0
14	31.4
16	35.9
18	40.4
20	45.6

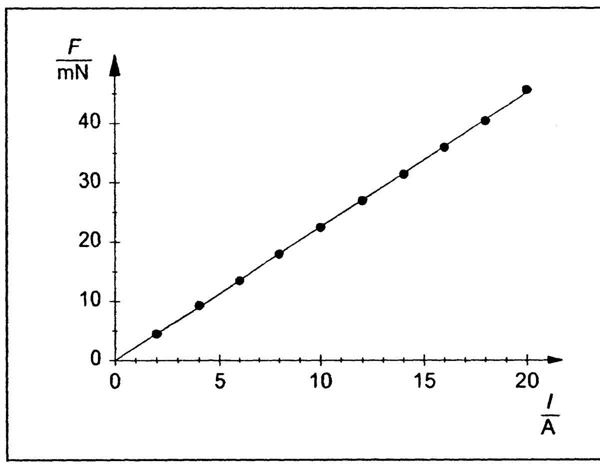


Fig. 3 Force F acting on a current-carrying conductor as a function of the current I (cf. Table 1)

In the graph in Fig. 3, the measured values show a close approximation of a straight line with the slope

$$\frac{F}{I} = 2.26\,\frac{\text{mN}}{\text{A}}$$

Given that $\sin 90° = 1$, equation (IV) gives us the following value for the magnetic field:

$$B = \frac{F}{I \cdot s} = \frac{2.26\ \text{mN}}{\text{A} \cdot 0.08\,\text{m}} = 28.5\ \text{mT}$$

The linear relationship between the force and the current for a constant conductor length formulated in equations (III) and (IV) is confirmed.

b) Measuring as a function of the conductor length:

Table 2: Force F as a function of the length s (I = 20 A)

$\frac{s}{\text{cm}}$	$\frac{F}{\text{mN}}$
8	45.6
4	23.0
2	11.7
1	6.2

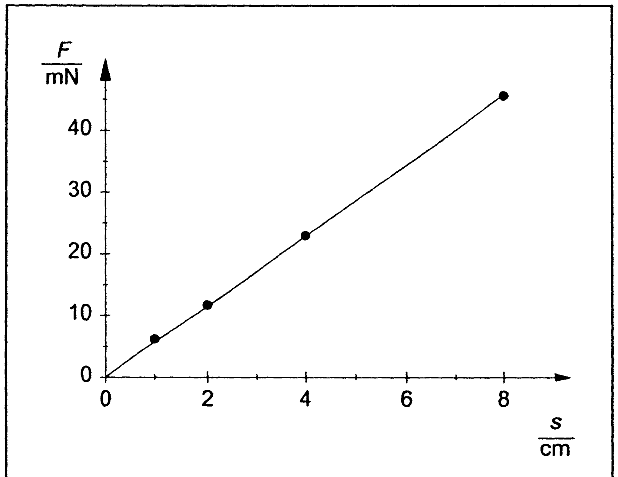


Fig. 4 Force F acting on a current-carrying conductor as a function of the conductor length s (cf. Table 2)

In Fig. 4, the measured values are also a close approximation of a straight line through the origin with the slope

$$\frac{F}{s} = 572 \frac{\text{mN}}{\text{m}}$$

For the magnetic field, we obtain the value

$$B = \frac{F}{s \cdot I} = \frac{572\ \text{mN}}{\text{m} \cdot 20\,\text{A}} = 28.6\,\text{mT}$$

The linear relationship between the force and the conductor length for a constant current formulated in (III) and (IV) is confirmed.

c) Measuring as a function of the angle between the magnetic field and the direction of the current:

Table 3: Force F as a function of the angle α (s = 4cm, I = 10A)

α	$\frac{F}{\text{mN}}$
0	0.0
30	5.6
60	9.9
90	11.6
120	10.4
150	6.3
180	0.1
210	-5.8
240	-9.9
270	-11.5
300	-10.1
330	-6.0
360	0.1

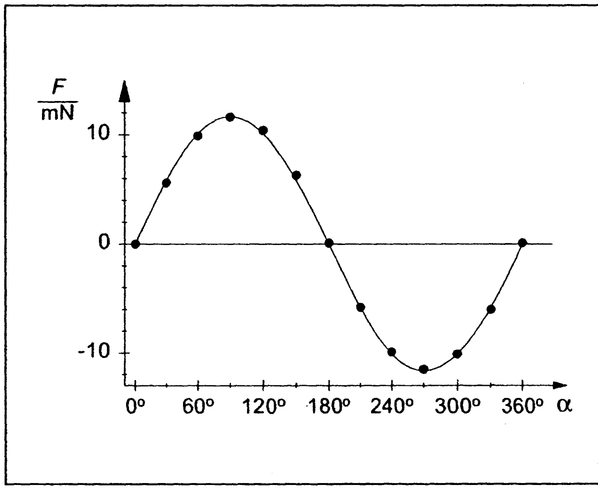


Fig. 5 Force F acting on a current-carrying conductor as a function of the angle α between the magnetic field and the direction of current (cf. Table 3)

The measured values in Fig. 5 are a close approximation of a sine curve calculated using (IV) for a magnetic field B = 28.5 mT.

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Teoría de la electricidad

Magnetismo
Ley de Biot-Savart

#12

Medición del campo magnético en conductores rectilíneos y y espiras conductoras circulares

Objetivos del experimento

- Medición del campo magnético en un conductor rectilíneo y en espiras conductoras circulares en función de la intensidad de corriente.
- Medición del campo magnético en un conductor rectilíneo en función de la distancia al eje del conductor
- Medición del campo magnético en espiras conductoras en función del radio de la espira y de la distancia al eje central.

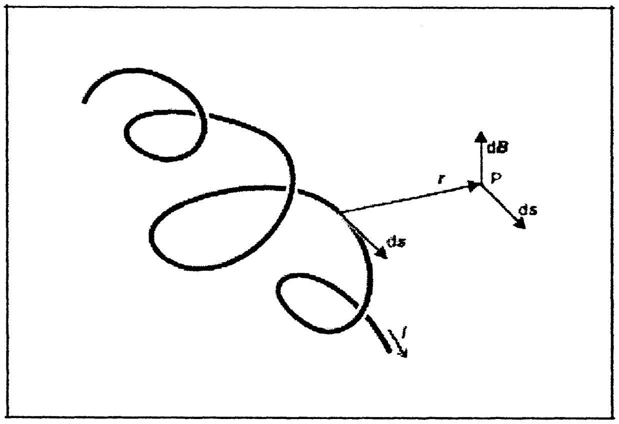
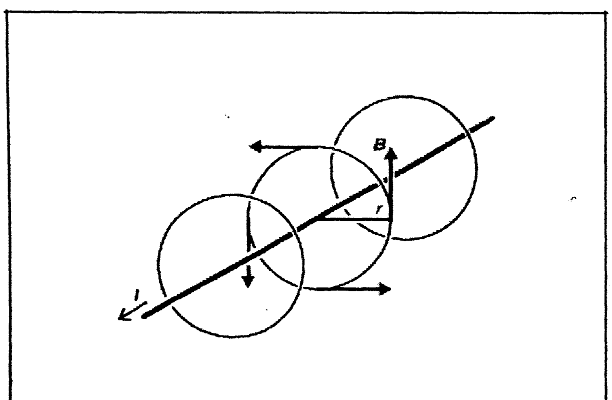


Fig. 1 Cálculo del campo magnético en un conductor atravesado por una corriente mediante una integral a lo largo del mismo

Fig. 2 Campo magnético en un alambre de longitud infinita



Fundamentos

La inducción magnética $\boldsymbol{B}$ en un cierto conductor atravesado por la corriente I en un punto P se compone, según la ley de *Biot-Savart*, de los aportes diferenciales

$$d\boldsymbol{B} = \frac{\mu_0}{4\pi} \cdot \frac{I}{r^2} \cdot d\boldsymbol{s} \times \frac{\boldsymbol{r}}{r} \qquad \text{(I)}$$

$\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$: permeabilidad magnética del vacío

de cada porción diferencial de conductor; su dirección y sentido se describen mediante el vector $d\boldsymbol{s}$. El vector $\boldsymbol{r}$ es el vector posición de la porción de conductor que va hasta el punto P (ver figura 1).

El cálculo de la inducción magnética total supone, entonces, la solución de una integral. Las soluciones analíticas son sólo posibles para conductores con una determinada simetría. De esta manera, la inducción magnética para un alambre de longitud infinita a distancia r del eje es

$$B = \frac{\mu_0}{4\pi} \cdot I \cdot \frac{2}{r} \qquad \text{(II)}$$

y las líneas de campo son concéntricas con el eje del cilindro (ver figura 2). La inducción magnética de una espira conductora circular de radio R a una distancia x medida sobre un eje que pasa por el centro de la espira es

$$B = \frac{\mu_0}{4\pi} \cdot I \cdot 2\pi \cdot \frac{R^2}{\left(R^2 + x^2\right)^{\frac{3}{2}}} \qquad \text{(III)}$$

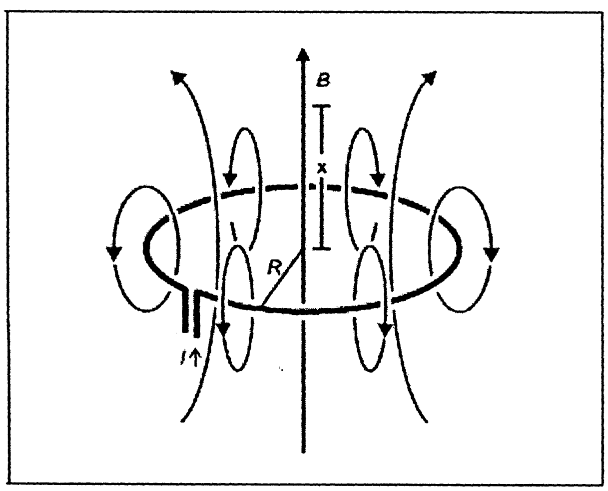
Equipo

1 juego de cuatro conductores	516 235
1 teslámetro	516 62
1 sonda axial B 52403G2	516 61
1 sonda tangencial B .....multiusos..........	516 60 52403
1 cable de 6 polos	501 16
1 fuente de alimentación de alta corriente	521 55
1 banco óptico pequeño	460 43
1 soporte	460 21
2 manguitos Leybold	301 01
1 base de soporte grande en forma de V ..	300 01
1 juego de seis juntas ...Acopladores...	501 644
cables, Ø 2,5 mm^2	

Sus líneas de campo corren paralelas al eje (ver figura 3).

En el experimento se mide la inducción magnética del conductor mencionado con una sonda axial o una tangencial B. Sus delgados sensores planos de efecto Hall son sensibles verticalmente a su superficie, esto es, no sólo se puede determinar la intensidad de la inducción magnética sino también su dirección. Se verifica, en un conductor rectilíneo, la dependencia de la inducción magnética B con la distancia r y, en las espiras circulares, la dependencia del radio R y de la coordinada espacial x. En sendos conductores se verifica la proporcionalidad entre la inducción magnética B y la intensidad de corriente I.

Fig. 3 Campo magnético de una espira conductora circular



Montaje y desarrollo

a) Campo magnético en un conductor rectilíneo:

El montaje del experimento se muestra en la figura 4.

- Ubicar el pequeño banco óptico sobre la base de soporte y disponerlo horizontalmente.
- Montar el soporte **(a)** con el manguito Leybold.
- Ubicar el soporte para el conductor rectilíneo **(b_1)**, sujetar el conductor rectilíneo y conectarlo a la fuente de alta corriente.
- Conectar la sonda axial B al teslámetro y realizar su ajuste a cero (ver instrucciones del teslámetro).
- Luego montar la sonda tangencial B en el manguito Leybold (canto izquierdo del manguito sobre la marca de 50,0 cm de la escala) y disponerla de costado, por encima, sobre el centro del conductor rectilíneo.
- Llevar el conductor rectilíneo hacia el sensor de efecto Hall **(c_1)** hasta dejarlo casi pegado a él (distancia $s = 0$).
- Aumentar la corriente I de 0 a 20 A en intervalos de 2 A, medir la inducción magnética B y anotar los valores.
- Con $I = 20$ A desplazar la sonda B por pasos a la derecha, medir la inducción B en función de la distancia s y anotar los valores.

b) Campo magnético en espiras conductoras circulares:

El montaje del experimento se muestra en la figura 5.

- Cambiar el soporte para el conductor rectilíneo por un adaptador para espiras conductoras **(b_2)** y alzar 40 mm la espira conductora.
- Conectar los cables en los casquillos del soporte **(a)** a fin de alimentar la espira con corriente.
- Conectar la sonda axial B al teslámetro y realizar su ajuste a cero (ver instrucciones del teslámetro).
- Luego montar la sonda axial B en el manguito Leybold (canto izquierdo del manguito sobre la marca de 70,0 cm de la escala) y disponerla sobre el centro de la espira conductora.
- Alinear lo más exactamente posible la espira conductora con el sensor de efecto Hall **(c_2)**.
- Aumentar la corriente I de 0 a 20 A en intervalos de 2 A, medir la inducción magnética B y anotar los valores.
- Con $I = 20$ A desplazar la sonda B por pasos a la derecha y a la izquierda, medir la inducción B en función de la coordenada espacial x, y anotar los valores.
- Cambiar la espira de 40 mm por la de 80 mm y luego por la de 120 mm midiendo siempre la inducción magnética en función de la coordenada espacial x.

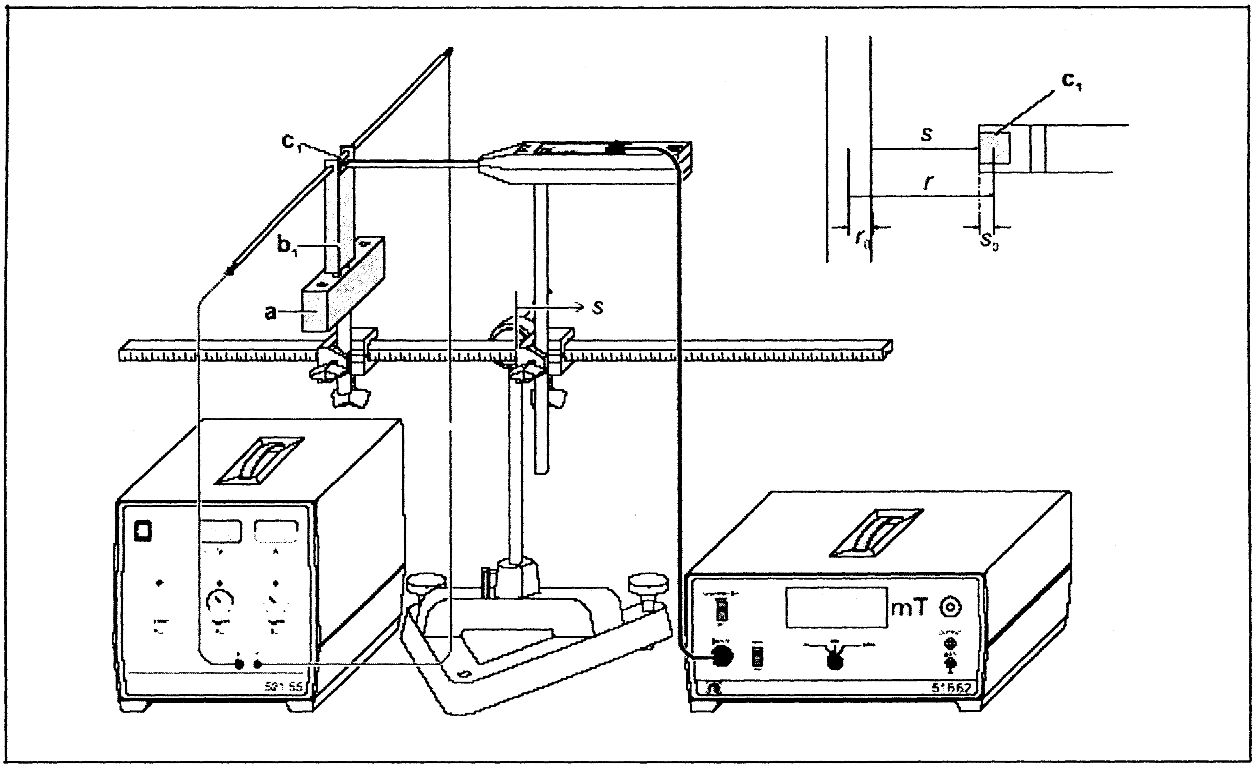
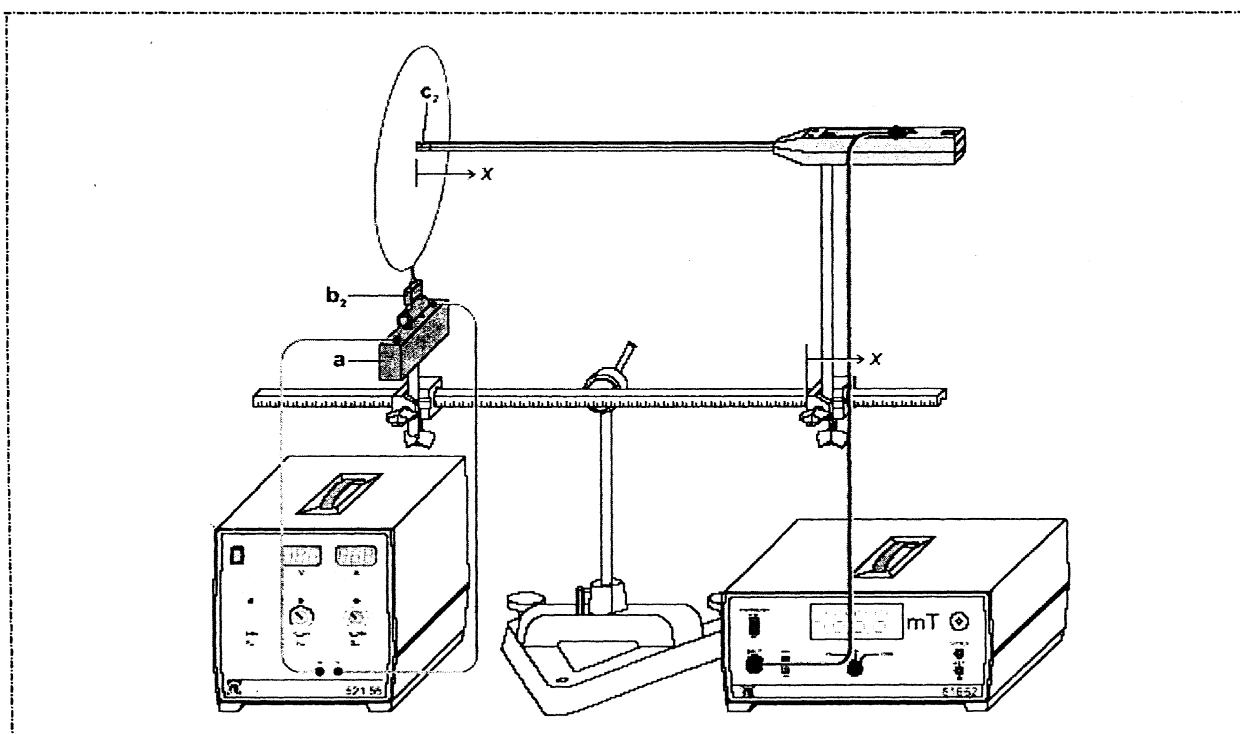


Fig. 4 Montaje del experimento para medir el campo magnético en un conductor rectilíneo

Fig. 5 Montaje del experimento para medir el campo magnético en espiras conductoras circulares



Ejemplo de medición

a) Campo magnético en un conductor rectilíneo:

Tabla 1: Inducción magnética *B* del conductor rectilíneo en función de la intensidad de corriente eléctrica *I* (distancia *s* = 0).

$\frac{I}{\mathrm{A}}$	$\frac{B}{\mathrm{mT}}$
0	0,00
2	0,13
4	0,27
6	0,40
8	0,51
10	0,64
12	0,76
14	0,91
16	1,025
18	1,15
20	1,28

Tabla 2: Inducción magnética *B* del conductor rectilíneo en función de la distancia *s* entre la superficie del conductor y la sonda B (intensidad de corriente *I* = 20 A)

$\frac{s}{\mathrm{mm}}$	$\frac{B}{\mathrm{mT}}$
0	1,28
1	0,97
2	0,77
3	0,64
4	0,55
5	0,48
6	0,43
7	0,395
8	0,35
9	0,33
10	0,31
15	0,21
20	0,17
25	0,14
30	0,11
40	0,085

b) Campo magnético en espiras conductoras circulares:

Tabla 3: Inducción magnética *B* de la espira conductora de 40 mm de diámetro en función de la intensidad de corriente *I*

$\frac{I}{\mathrm{A}}$	$\frac{B}{\mathrm{mT}}$
0	0
2	0,07
4	0,13
6	0,19
8	0,26
10	0,32
12	0,38
14	0,45
16	0,51
18	0,58
20	0,64

Tabla 4: Inducción magnética *B* de las espiras conductoras en función de la distancia *x*

$\frac{x}{\mathrm{mm}}$	$\frac{B}{\mathrm{mT}}$	$\frac{x}{\mathrm{mm}}$	$\frac{B}{\mathrm{mT}}$	$\frac{x}{\mathrm{mm}}$	$\frac{B}{\mathrm{mT}}$
2*R* = 40 mm		2*R* = 80 mm		2*R* = 120 mm	
−10	0,005	−10	0,015		
−7,5	0,015	−9	0,02		
−5	0,035	−8	0,03		
−4	0,06	−7	0,04	−9	0,04
−3	0,11	−6	0,05	−7,5	0,06
−2,5	0,14	−5	0,08	−6	0,08
−2	0,21	−4	0,11	−4,5	0,11
−1,5	0,33	−3	0,16	−3	0,15
−1	0,45	−2	0,23	−1,5	0,19
−0,5	0,58	−1	0,29	0	0,21
0	0,64	0	0,32	1,5	0,19
0,5	0,58	1	0,3	3	0,15
1	0,46	2	0,24	4,5	0,11
1,5	0,32	3	0,17	6	0,07
2	0,22	4	0,11	7,5	0,05
2,5	0,15	5	0,08	9	0,03
3	0,1	6	0,05		
4	0,05	7	0,04		
5	0,035	8	0,025		
7,5	0,01	9	0,02		
10	0,005	10	0,015		

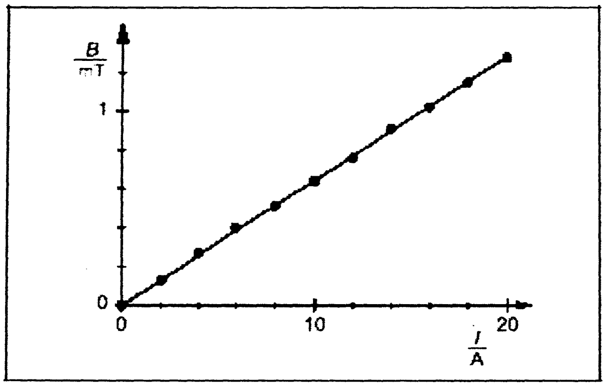


Fig. 6 Inducción magnética B del conductor rectilíneo en función de la intensidad de corriente I

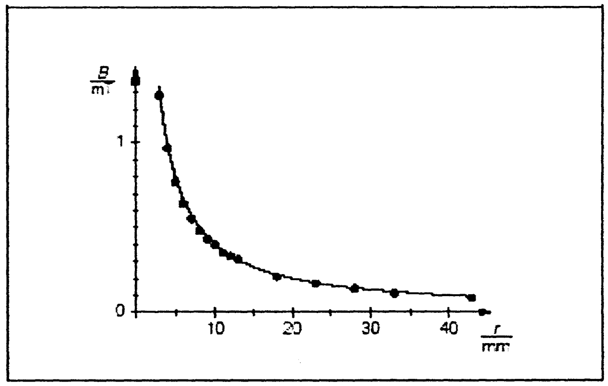


Fig. 7 Inducción magnética B del conductor rectilíneo en función de la distancia r al eje del conductor

Análisis y resultado

a) Campo magnético de un conductor rectilíneo:

En la figura 6 se representa gráficamente la inducción magnética B en función de la intensidad de corriente I para el conductor rectilíneo. Los valores medidos (ver tabla 1) se encuentran, tomando en cuenta el rango de precisión, sobre la recta trazada que pasa por el centro de coordenadas, o sea, la inducción magnética B es proporcional a la intensidad de corriente I.

La figura 7 muestra la representación gráfica de los valores de medición de la tabla 2. Ahí puede observarse que la distancia s entre la superficie del conductor y el borde de la sonda B se diferencian de la distancia r al eje del alambre, que aparece en (I). La diferencia $r - s = 3$ mm es la suma de radio $r_0 = 2$ mm del conductor rectilíneo y la distancia $s_0 = 1$ mm entre el borde de la sonda B y el centro del sensor de efecto Hall (ver figura 4). La curva trazada en la figura 7 se calculó, de acuerdo a (I), para $I = 20$ A. La curva de la figura 8 corresponde a una recta que pasa por el centro de coordenadas.

b) Campo magnético en espiras conductoras circulares:

La figura 9 muestra la inducción magnética B en función de la intensidad de corriente I para una espira conductora circular. También aquí la coincidencia de los valores medidos (cf. tabla 3) con la recta trazada por el centro de coordenadas verifica la proporcionalidad entre la inducción magnética B y la intensidad de corriente eléctrica I.

En la figura 10 se representa gráficamente la inducción magnética B en función de la coordenada espacial x para las tres espiras conductoras circulares. Las curvas trazadas fueron calculadas, según (II), para la intensidad de corriente I = 20 A.

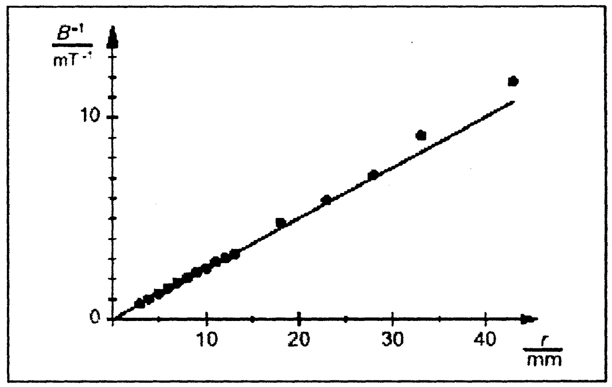


Fig. 8 Inducción magnética B en el conductor rectilíneo representada como $1/B = f(r)$

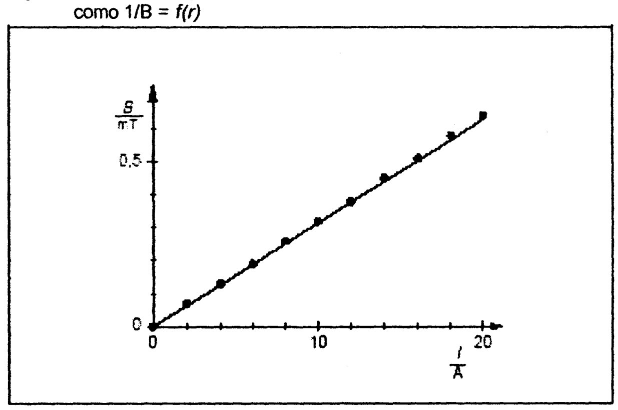


Fig. 9 Inducción magnética B de la espira conductora circular (diámetro 40 mm) en función de la intensidad de corriente I

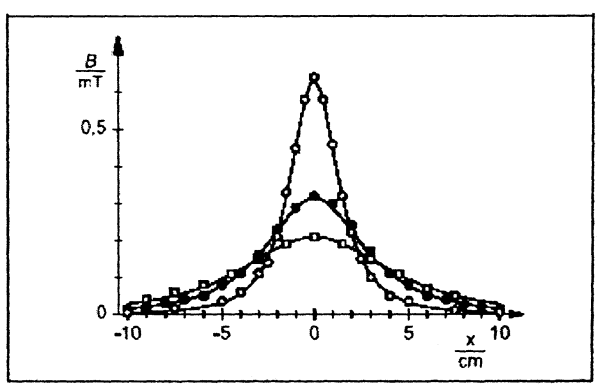


Fig. 10 Inducción magnética B para espiras conductoras circulares de radio R en función de la coordenada espacial x
O R = 60 mm, ● R = 40 mm, (◻) R = 20 mm

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Measuring the induction voltage in a conductor loop moving within a magnetic field

Objects of the experiment

- To measure the induction voltage as a function of the speed of the conductor loop.
- To measure the induction voltage as a function of the width of the conductor loop.
- To measure the induction voltage as a function of the magnetic flux density.

Principles

When a conductor loop is placed within a magnetic field B, the magnetic flux permeating the loop is

$$\Phi = B \cdot A \qquad \text{(I)}$$

Here, A is the area enclosed by the conductor loop, which is oriented perpendicular to the magnetic field. When this loop is withdrawn from the magnetic field, the area A permeated by the magnetic field is reduced. When a rectangular conductor loop with the width b is moved by the distance dx, its area changes by the value $dA = -b \cdot dx$ and its magnetic flux density changes correspondingly by $d\text{hi} = B \cdot b \cdot dx$. Thus, the change in the magnetic flux per time interval dt is

$$\frac{d\Phi}{dt} = -B \cdot b \cdot \frac{dx}{dt} \qquad \text{(II)}$$

when an open conductor loop is used, the electrons are displaced until their own electrical opposing field compensates the lorentz force. A voltage U is induced at the ends of the loop which ist porportional to the change in the magnetic flux:

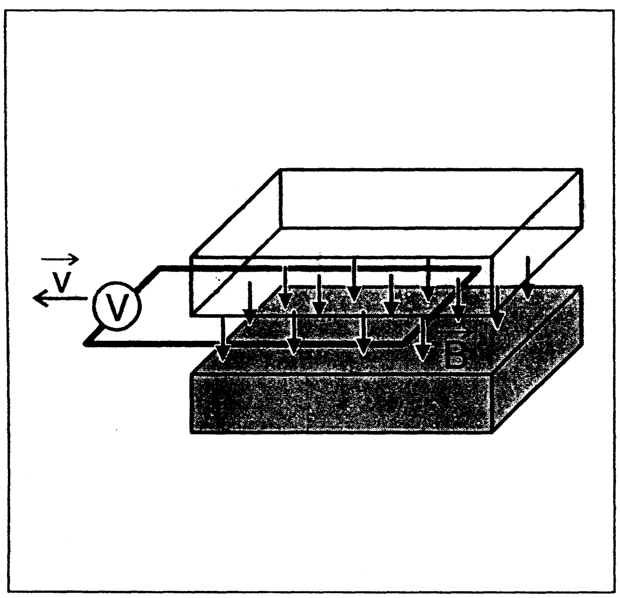
$$U = -\frac{d\Phi}{dt} \qquad \text{(III)}$$

The speed

$$v = \frac{dx}{dt} \qquad \text{(IV)}$$

of the conductor loop ultimately gives us the value of the induction voltage

$$U = B \cdot b \cdot v \qquad \text{(V)}$$



In this experiment, three induction loops of different widths are mounted on a sliding carriage. Two of the conductor loops are rectangular and have the widths b = 4 cm and b = 2 cm. The third is trapezoidal in shape and has an effective width b = 4 cm · cos 45° = 2.8 cm. The sliding carriage with the conductor loops is pulled though a magnetic field by a thread attached to an electric motor. You can vary the speed with which the sliding carriage is pulled through the magnetic field by winding the thread around a clutch with a stepped axle, i.e. one with different diameters, while running the motor at a constant speed. In this experiment, we do not measure the absolute motor speed of the sliding carriage; for a constant motor speed, the sliding carriage speeds have a ratio of 1 : 2 : 4.

The magnetic field is generated using paired cylindrical permanent magnets placed between two large parallel iron plates. Pole pieces are placed in the gaps between the magnets over the entire length of the plate, which ensure a sufficiently homogeneous magnetic field when the magnets are evenly distributed. You can vary the magnetic field strength by changing the number of permanent magnets.

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Apparatus

1 Induction apparatus	516 40
6 Pairs of magnets, cylindrical	510 48
1 Experiment motor	347 35
1 Control unit for experiment motor	347 36
1 Microvolt meter	532 13

Setup

The induction apparatus is marked for the positions of the magnets. When using n magnet pairs (n = 2, 3, 4, 5, 6, 8), be sure to place one magnet at each of the points designated n.

Slight variations in the magnetic field B cannot be prevented entirely. To improve the homogeneity of the magnetic field, first place all magnets in the middle of the base unit and then slide them evenly to the position marks designated "8".

Make sure that the magnets' polarity between the iron plates is always the same. The poles are color-coded.

Set up the experiment as shown in Fig. 1.

- Extend the guide rail **(c)** for the sliding carriage of the induction apparatus.
- Place the pairs of magnets to the left and right of the sliding carriage, making sure that the polarity between the iron plates **(e)** is always the same.
- Mount the clutch **(a)** in the chuck of the experiment motor.
- Set up the experiment motor in front of the front end of the guide rail as shown in Fig. 1 and connect the control unit.
- Insert the thread attached to the sliding carriage **(d)** through the guide hole of end stop **(b)** and then lay it in slit **(a)** of the clutch (see Fig. 2).
- Wind the thread approx. one turn around the axle segment of the clutch with the smallest diameter. Be sure to observe the rotational direction of the motor and make sure that the thread runs as smoothly as possible.
- Make a test run to be sure that the thread turns wind next to each other and not on top of each other, as otherwise the diameter of the axle, and thus the speed of the sliding carriage, will not remain constant during the experiment.
- Connect the screened cable **(f)** of the sliding carriage to the microvolt meter and select the measuring range 10^{-4} V.

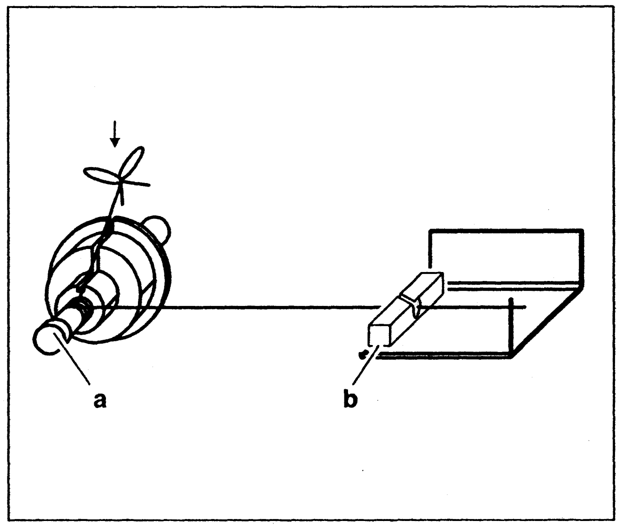
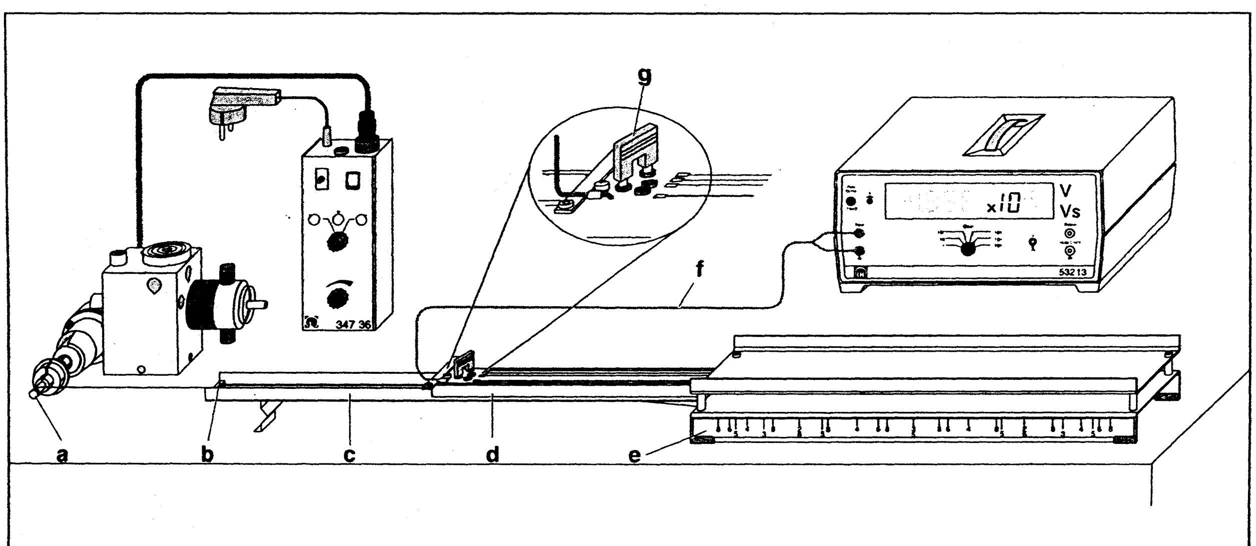


Fig. 2 Inserting the thread through the guide hole of the end stop and attaching it to the slip friction clutch

Fig. 1 Experiment setup



Carrying out the experiment

To protect the microvolt meter from voltage overloads when the sliding carriage is pushed back fast, a microswitch **(h)** *is* attached to the front of the sliding carriage to disconnect the measuring instrument from the induction loops (see Fig. 3). Always hold down the microswitch when pushing the sliding carriage back.

The clutch slips when the sliding carriage strikes the stop at the end of the guide rail. This prevents the thread from tearing and the experiment setup from being upset.

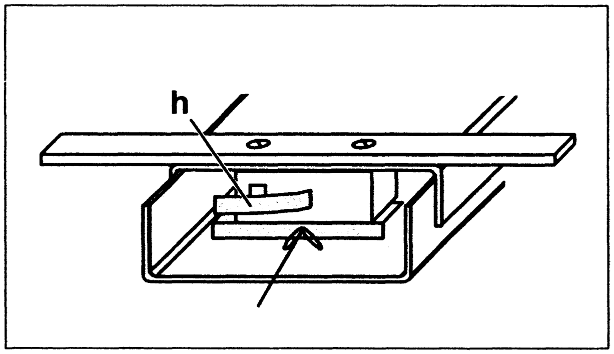


Fig. 3 Press the microswitch to electrically disconnect the microvolt meter and the conductor loops before pushing the sliding carriage back.

a) Measuring the induction voltage as a function of the speed of the conductor loop:

Check the offset of the microvolt meter at the start of every experiment. If necessary, zero the instrument by pressing the AutoComp key (you may also need to carry out fine adjustment using the offset potentiometer; see the Instruction Sheet for your microvolt meter).

- Connect the widest conductor loop (b = 4 cm) by plugging in bridging plug **(g)** on the sliding carriage (see Fig. 1).
- Select the smallest axle diameter of the clutch, switch on the experiment motor and set the speed so that the microvolt meter shows an induction voltage of about 50 mV. Switch off the experiment motor without changing the setting of the speed control knob; then hold down the microswitch on the sliding carriage and push the sliding carriage back to the starting point. Then write down the exact voltage value.
- Select the medium axle diameter, switch on the experiment motor and measure and write down the induction voltage.
- Repeat the measurement with the large axle diameter.

b) Measuring the induction voltage as a function of the width of the conductor loop:

- Connect the trapezoidal conductor loop (b = 2.8 cm) by changing the position of the bridging plug **(g)**.
- Use the largest axle diameter and switch on the experiment motor, then measure and write down the induction voltage.
- Connect the narrow conductor loop (b = 2 cm) by changing the position of the bridging plug and repeat the measurement.

c) Measuring the induction voltage as a function of the magnetic flux density:

The homogeneity of the field decreases with the number of magnet pairs used. To keep the field as homogeneous as possible, be sure to place the permanent magnets exactly on the position marks.

- Connect the wide conductor loop (b = 4 cm) by cnanging the position of the bridging plug **(g)**.
- Remove two magnet pairs from the induction apparatus and place the remaining six magnet pairs at the position marks with the designation "6".
- Use the largest axle diameter and switch on the experiment motor, then measure and write down the induction voltage.
- Repeat the measurement for n = 5, 4, 3 and 2 magnet pairs; be sure to place the magnets at the appropriate markings each time!

Measuring example and evaluation

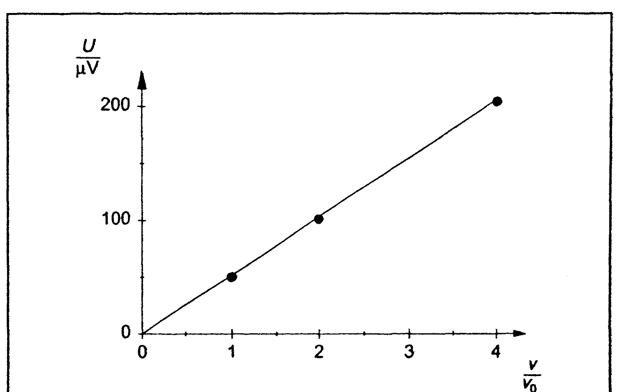
a) Induction voltage as a function of the speed v of the conductor loop:

Table 1: Induction voltage U as a function of the speed v of the induction loop (n = 8 , b = 4 cm)

$\frac{v}{v_0}$	$\frac{U}{\mu V}$
1	50
2	101
4	204

Fig. 4 confirms the proportionality between the induction voltage U and the speed v of the loop.

Fig. 4 Induction voltage as a function of the speed



b) Induction voltage as a function of the width *b* of the conductor loop:

Table 2 : Induction voltage U as a function of the width b of the conductor loop ($n = 8$, $v = 4\ v_0$)

$\frac{b}{\text{cm}}$	$\frac{U}{\mu V}$
4	204
2.8	146
2	108

Fig. 5 confirms the proportionality between the induction voltage U and the width b of the loop.

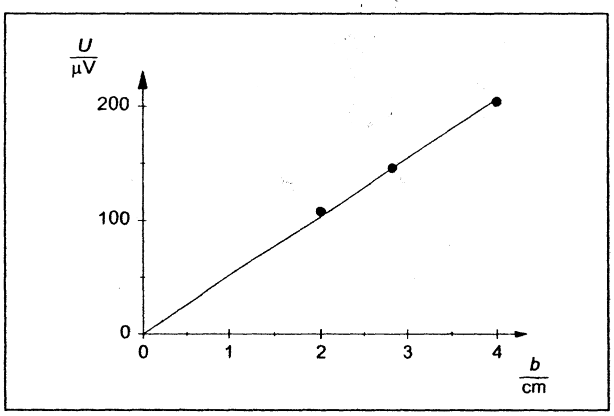


Fig. 5 Induction voltage as a function of the loop width

c) Induction voltage as a function of the magnetic flux density:

Table 3 : Induction voltage U as a function of the number of magnet pairs n ($v = 4\ v_0$, $b = 4$ cm)

n	$\frac{U}{\mu V}$
8	204
6	160
5	138
4	108
3	80
2	54

Fig. 6 confirms the proportionality between the induction voltage U and the magnetic field B.

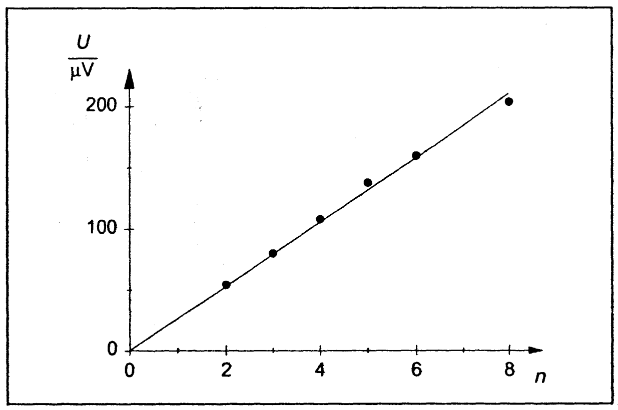


Fig. 6 Induction voltage as a function of the number of magnet pairs

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Electricity

Electromagnetic induction
Transformer

Physics Leaflets

P3.4.5.2

Voltage transformation with a transformer under load

Objects of the experiment

- Measuring the secondary voltage and current of a 'soft' and a 'hard' transformer as function of the load
- Determination of the output power of a transformer under load as function of the current in the secondary coil
- Investigation of the lines of the magnetic flux in a 'soft' and a 'hard' transformer

Principles

A transformer usually consists of two coils which are inductively coupled by an iron core. They are used to change alternating currents. The frequency is not changed by the voltage conversion.

The relationship between the input voltage U_1 and the output voltage U_2 of a transformer depends on the ratio of the number of turns N_1:N_2. The voltage transformation without load and the current transformation of a transformer under full load (short-circuited operation) is investigated in the related experiment P3.4.5.1.

On the other hand the output voltage (secondary voltage) of a transformer depends on the load. The output voltage U_2 decreases with increasing current I_2 in the secondary coil due to an increasing voltage drop across the internal resistance of this power source (i.e. the secondary coil).

Further, the current-voltage characteristic of a transformer under load depends also on the physical design of the transformer. In this experiment the relationship between the secondary voltage U_2 and the secondary current I_2 of a loaded transformer is investigated when the primary and secondary windings

a) are distributed symmetrically on both limbs of the iron core (fixed-ratio or 'hard' transformer) and

b) are wound separately on each limb of the iron core (high-reactance or 'soft' transformer).

In both cases the lines of the magnetic flux of the transformer are investigated by using iron filings on a transparent plate placed on top of the transformer.

The output power P of the two transformer types can be determined by using the relation (assuming low losses):

$$P_2 = U_2 \cdot I_2 \qquad \text{(I)}$$

Thus the current-power characteristic is obtained from which the maximum attainable output power can be determined.

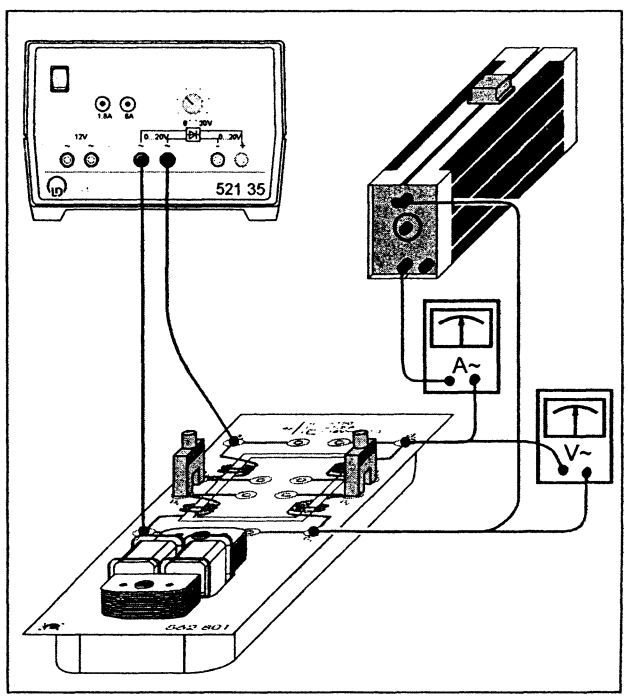

Fig. 1: Experimental setup to investigate the current-voltage characteristic of a transformation with load.

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Apparatus

1 Transformer for student's experiments	562 801
1 Variable extra low-voltage transformer S	521 35
1 Rheostat 100 Ohm	537 34
2 Multimeter LDanalog 20	531 120
1 Acrylic glass screen on rod	459 23
1 Shaker for iron filings	514 72
1 Iron filings	514 73
7 Connecting Lead 100 cm Black	500 444

Setup

a) current-voltage characteristic of a 'soft' transformer

The setup for measuring the output voltage and output current of a 'soft' transformer (primary and secondary coils on separate limbs) under load is shown in Fig. 1. The variable low voltage power supply is connected to the primary coils. The ammeter is connected in series with the load to the secondary coils. The output voltage of the transformer is measured with the voltmeter (Fig. 2).

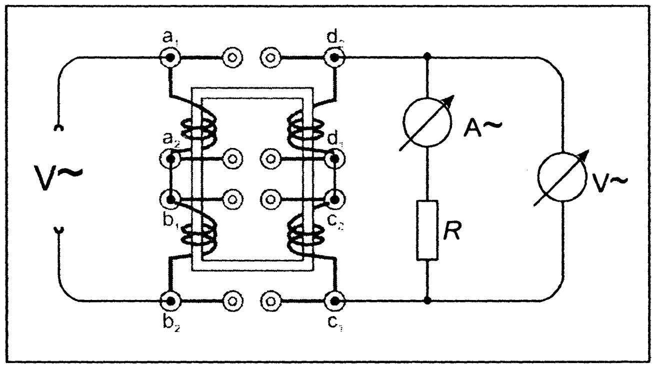

Fig. 2: Experimental setup to measure the current-voltage characteristic of a 'soft' transformer under load. Primary side: coils a and b connected in series, secondary side: coils d and c connected in series, $N_1 : N_2 = 300 : 300$.

b) current-voltage characteristic of a 'hard' transformer

The setup for measuring the output voltage and output current of a 'hard' transformer (primary and secondary coils on the same limbs) under load is shown in Fig. 3. The variable low voltage power supply is connected to the primary coils. The ammeter is connected in series with the load to the secondary coils. The output voltage of the transformer is measured with the voltmeter.

c) magnetic field of a 'soft' and a 'hard' transformer

A schematic representation of the setup for revealing the lines of magnetic flux of a loaded soft transformer is schematically depicted in Fig. 4.

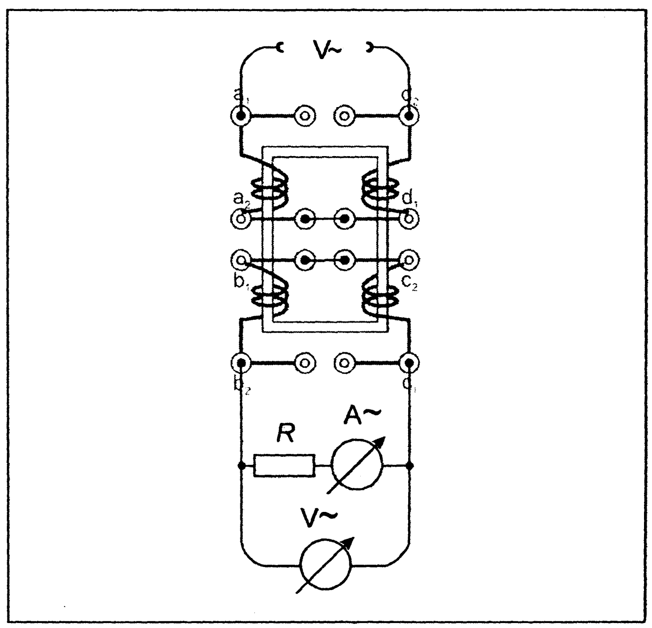

Fig. 3: Experimental setup to measure the current-voltage characteristic of a 'hard' transformer under load. Primary side: coils a and d connected in series, secondary side: coils b and c connected in series, $N_1 : N_2 = 300 : 300$.

Safety notes

Increase AC voltages on the transformer only gradually; do not apply higher voltages directly! (danger of damage to connected measuring instruments due to high currents – 100-fold excess currents).

Avoid overheating of the transformer – Mind the maximum applied voltages and currents listed in the instruction sheet 562 801 of the transformer for student's experiments.

- Maximum permissible AC voltage per winding 15 V AC.
- Maximum permissible power consumption 40 W.

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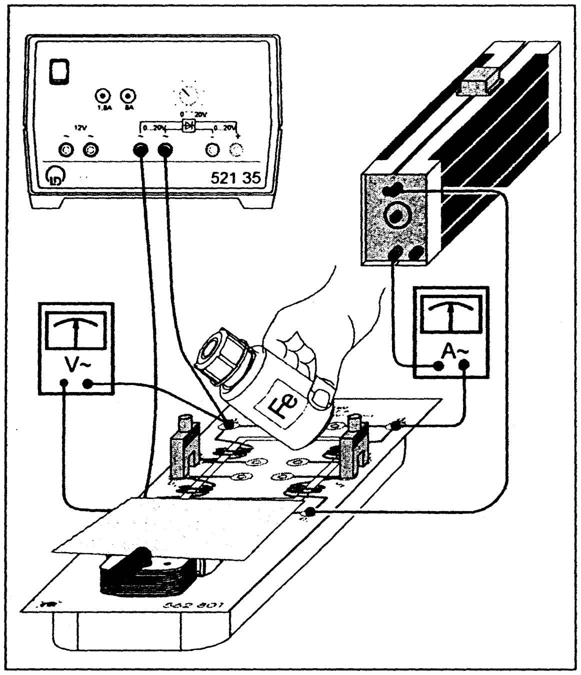


Fig. 4: Schematic representation of the experimental setup to reveal the lines of the magnetic flux using iron filings on a transparent plate on top of the 'soft' transformer under load.

Carrying out the experiment

a) current-voltage characteristic of a 'soft' transformer

- Connect the low voltage power supply, Rheostat (i.e. the load), the ammeter and the voltmeters to the Transformer for student's experiments as shown in Fig. 1. To realize a symmetrical transformer design choose the ratio $N_1 : N_2$ of 300 : 300 as depicted in Fig. 2.
- Set the voltage U_1 to 4 V.
- Measure the voltage U_2 and the current I_2 by varying the load.

b) current-voltage characteristic of a 'hard' transformer

- Connect the low voltage power supply, Rheostat (i.e. the load), the ammeter and the voltmeters to the Transformer for student's experiments as shown in Fig. 3. To realize a symmetrical transformer design the ratio $N_1 : N_2$ is be chosen to 300 : 300.
- Set the voltage U_1 to 4 V.
- Measure the voltage U_2 and the current I_2 by varying the load.

c) magnetic field of a 'soft' and a 'hard' transformer

- Setup the 'soft' transformer with load according Fig. 4.
- Place the Acrylic glass screen on rod on top of the transformer (Fig. 4.)
- Using the shaker, spread a thin uniform layer of iron filings on the Acrylic glass.
- Set the current I_2 to 1.5 A by adjusting the load or the applied voltage U_1 and observe the resulting pattern. It might be necessary to tap gently the glass plate.
- Repeat this experiment for the 'hard' transformer.

Measuring example

a) current-voltage characteristic of a 'soft' transformer

Table. 1: Voltage U_2 as function of current I_2.

$\frac{I_2}{A}$	$\frac{U_2}{V}$
0.00	4.0
0.04	3.8
0.08	3.6
0.13	3.4
0.17	3.2
0.22	3.0
0.26	2.8
0.30	2.6
0.33	2.4
0.36	2.2
0.40	2.0
0.42	1.8
0.45	1.6
0.48	1.4
0.50	1.2
0.53	1.0
0.55	0.8
0.59	0.4
0.63	0.0

b) current-voltage characteristic of a 'hard' transformer

Table. 2: Voltage U_2 as function of current I_2.

$\frac{I_2}{A}$	$\frac{U_2}{V}$
0.00	4.0
0.10	3.8
0.16	3.6
0.22	3.4
0.28	3.2
0.34	3.0
0.40	2.8
0.45	2.6
0.53	2.4
0.58	2.2
0.62	2.0
0.70	1.8
0.75	1.6
0.80	1.4
0.86	1.2
0.93	1.0
0.95	0.8
1.00	0.6
1.05	0.3
1.15	0.0

c) magnetic field of a 'soft' and a 'hard' transformer

A schematic sketch of magnetic field of the 'soft' transformer is depicted in Fig. 5. For the 'hard' transformer no field lines are observed.

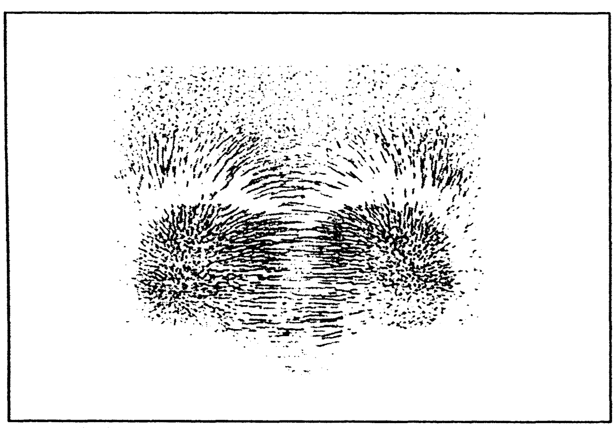


Fig. 5: Schematic sketch of the observed magnetic flux lines of a 'soft' transformer under load.

Evaluation and results

a) current-voltage characteristic of a 'soft' transformer

Fig. 6 summarizes the results of the table 1 and 2. The output voltage (secondary voltage) U_2 falls from its maximum value, i.e. off-load voltage ($R \to \infty$), with increasing current in the secondary coils. U_2 reaches zero at a maximum load (short-circuit operation: $R = 0$).

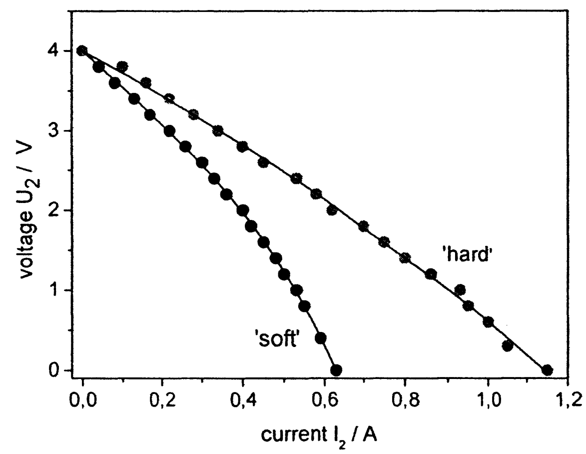


Fig. 6: Output voltage U_2 as function of the output current I_2 of 'soft' (black) and 'hard' (grey) transformer under load ($N_1 : N_2$ = 300:300). The solid lines are guides to the eye.

Using equation (I) the power P_2 can be calculated from the measured output voltage U_2 and the current I_2. Plotting P_2 as function of I_2 gives the current power characteristic of the transformers (Fig. 7). The power produced at the secondary side is zero where the transformer is operated with no load; in short-circuited operation the power output is zero again due to the breakdown of voltage. The maximum value is reached approximately in the middle between these extreme values. From Fig. 7 follows that the maximum output power of a 'hard' transformer is larger than for the 'soft' transformer.

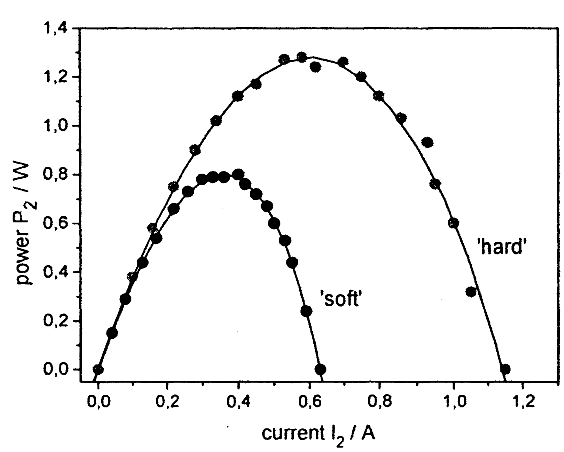


Fig. 7: Output power P_2 as function of the current I_2 of 'soft' (black) and 'hard' transformer (grey) under load ($N_1 : N_2$ = 300:300). The solid lines are guides to the eye.

b) current-voltage characteristic of a 'hard' transformer

The current-voltage characteristic of the 'hard' transformer is compared in Fig. 6 with the 'soft' transformer.

For the 'hard' transformer the losses are mainly due to the internal resistance of the secondary coil. Since the primary and secondary windings are distributed symmetrically on both limbs of the core the other losses (i.e. due a stray field) are largely eliminated. As a result this type of transformer possesses a relatively high electric strength. Therefore this type of transformer is named 'hard' transformer or 'fixed-ratio' transformer.

In contrast to the 'hard' transformer the losses of the 'soft' transformer are larger for the same ratio of the number of turns $N_1 : N_2$. The reason for this behaviour can be found in the design of this transformer where the primary and secondary windings are on different limbs of the iron core. As a result, a strong magnetic stray field is produced (Fig. 5). This stray field causes heat and magnetization losses which are added to the voltage drop across the internal resistance of the secondary coils. Therefore, due to this 'soft' voltage behaviour, this type of transformer is named 'soft' transformer or 'high-reactance' transformer.

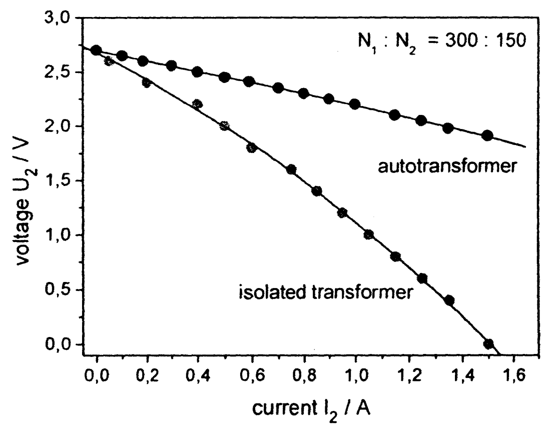


Fig. 8: Output voltage U_2 as function of the output current I_2 of the autotransformer (black) and the isolated transformer (grey) under load ($N_1 : N_2$ = 300:150). The solid lines are guides to the eye.

c) magnetic field of a 'soft' and a 'hard' transformer

The field pattern depicted in Fig. 5 shows a magnetic field around the 'soft' or 'high-reactance' transformer. The energy of this magnetic field is lost with respect to the power balance between primary and secondary coils of the transformer (i.e. so-called stray field losses).

No magnetic field can be observed around the 'hard' or 'fixed-ratio' transformer. Losses due to a stray field are therefore largely eliminated for this type of transformer.

Supplementary information

The disadvantage of the 'hard' transformer is its high short-circuit current which may damage the windings under certain circumstances.

The advantage of the 'soft' transformer (high-reactance transformer) is its low short-circuit current. This is exploited, e.g. for bell or toy transformers, which require short-circuit resistance.

In experiment P3.4.5.1 the voltage and the current transformation of a isolating transformer and an autotransformer have been investigated. The isolated transformer investigated in this experiment corresponds to the 'soft' transformer and, thus, it has a 'soft' voltage behaviour.

On the other hand, the autotransformer has a current-voltage characteristic of a 'hard' transformer as can be seen in Fig. 8.

Note: The measurement of the current-voltage characteristic of the autotransformer in Fig. 8 was limited by the maximum admissible current I_2 = 1.5 A of the Transformer for student's experiments, i.e. the short-circuit operation could not be reached for the initial off-load voltage $U_2 \approx 2.7$ V.

1.4 The principle of AC voltage generation

1.4.1 The external pole generator

Problem:

Voltage generation in a rotating coil

A coil rotates in a magnetic field of two permanent magnets in such a way that its windings are intersected by the magnetic field lines.

Place the drive belt over the belt pulley of the rotor and over one pulley of the hand-cranked machine and tauten it.

Plug carbon brushes into the adjacent guides of the brush holder for connection to the slip rings.

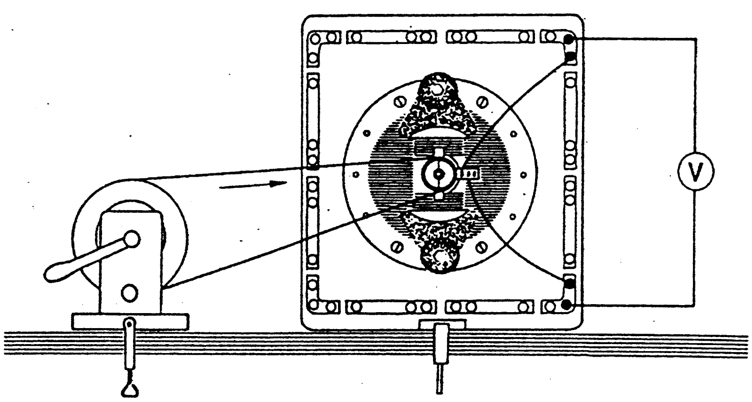


Fig. 7

Apparatus:

From basic kit A, 563 50

1 Baseboard with vertical holder	563 261
2 Brushes with cable and plug	563 13
1 Brush holder	563 18
1 Pair of magnets	510 48
2 Pole pieces for magnets	563 091
1 Two-pole rotor	563 22

From accessories kit Z, 563 52

1 Centering disk	563 17
1 Allen wrench	563 16
1 Simple bench clamp	301 07
1 Hand-cranked machine	563 301

Additionally required

1 Measuring instrument, e.g. E-measuring instrument D	531 88
2 Connecting leads, red, 50 cm	501 25

Setup:

Set up the apparatus as shown in Fig. 7.

Assemble the pole pieces only after fitting the centering disk.

Fit the magnets so that the hole pieces form opposite poles, e.g. top pole piece as the north pole (secure the magnet with its north pole to the bare side of the pole piece) and bottom pole piece as south pole.

Experiments:

1. Measuring instrument range: 1 V DC

   Place your hand flat on one pulley of the hand-cranked machine and slowly and smoothly turn the pulley. Carry on and continue the movement with your other hand.

   Observe the measuring instrument and position of the rotor.

2. Measuring range: 10 V AC

   Slowly and smoothly turn the crank of the hand-cranked machine.

Observations:

1. The measuring instrument shows a voltage with an alternating polarity.

   No voltage is produced when the spindle of the coil is in the direction of the field. The voltage reaches a maximum value when the coil spindle is vertical with respect to the field direction.

2. The measuring instrument indicates an alternating voltage with a frequency depending on the speed.

Result:

If a coil rotates in a magnetic field, an AC voltage can be tapped from the ends of the coil (the slip rings).

Note:

The external pole generator has no great technical significance because the entire power is removed through the brushes. The maximum obtainable power is thus limited by the maximum brush current which, in the case of brushes (563 13) for instance, does not exceed 1.5 A.

Note:

An oscilloscope can also be used instead of the measuring instrument in order to indicate the tapped alternating voltage.

1.4.2 The internal pole generator

Problem:

Voltage generation by a rotating magnet

A permanent magnet is rotated in such a way that its magnetic field intersects with the windings of two coils.

What task do the pole pieces fulfill?

and smoothly turn the pulley. Carry on and continue motion with your other hand. Observe the measuring instrument and position of the rotor.

2. Measuring instrument range: 10 V AC

   Slowly and smoothly turn the crank of the hand-cranked machine.

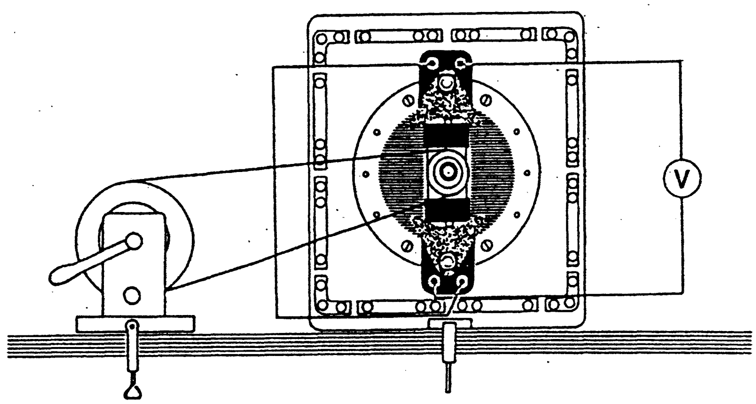


Fig. 8

Apparatus:

From basic kit B, 563 51
1 Baseboard with vertical holder 563 261
1 Magnetic rotor 563 19
2 Coils with 250 turns 563 11
2 Wide pole pieces for coils ... 563 101

From accessories kit Z, 563 52
1 Centering disk 563 17
1 Allen wrench 563 16
1 Simple bench clamp 301 07
1 Hand-cranked machine 563 301

Additionally required
1 Measuring instrument, e.g. E-measuring instrument D 531 88
3 Connecting leads, red, 50 cm .. 501 25

Setup:

Set up the apparatus as shown in Fig. 8.

Fit the pole pieces only with the centering disk fitted.

Place the drive belt over the belt pulley of the rotor and over one pulley of the hand-cranked machine and tauten it.

Experiments:

1. Measuring instrument range: 1 V DC

   Place your hand flat on one pulley of the hand-cranked machine and slowly

Observations:

1. The measuring instrument indicates a voltage with an alternating polarity.

   When the spindle of the rotor is in the direction of the field, no voltage is produced. The voltage reaches a maximum value when the rotor's spindle is vertical with respect to the field direction.

2. The measuring instrument indicates an alternating voltage with a frequency depending on the speed.

Results:

The amount of induced voltage depends on the speed and particularly on the strength of the rotor's magnetic field. In technically applied machines, an electromagnet is used for field generation in order to obtain a strong magnetic field (see experiment 1.5).

The purpose of the pole pieces is to concentrate the field lines emitted by the magnetic rotor and to guide them into the coil.

Note:

An oscilloscope can also be used instead of the measuring instrument to indicate the tapped alternating voltage.

4.4 Types of DC voltage motors

Problem:

Setting up three different DC voltage motors.

Apparatus:

From basic kit B, 563 51
1 Baseboard with vertical holder 563 261
2 Brushes with cable and plug ... 563 13
1 Brush holder 563 18
1 Three-pole rotor 563 23
2 Coils with 250 turns 563 11
2 Wide pole pieces for coils ... 563 101

From accessories kit Z, 563 52
1 Centering disk 563 17
1 Allen wrench 563 16

Additionally required
1 Transformer, extra low voltage. 591 09
5 Connecting leads, red, 50 cm .. 501 25

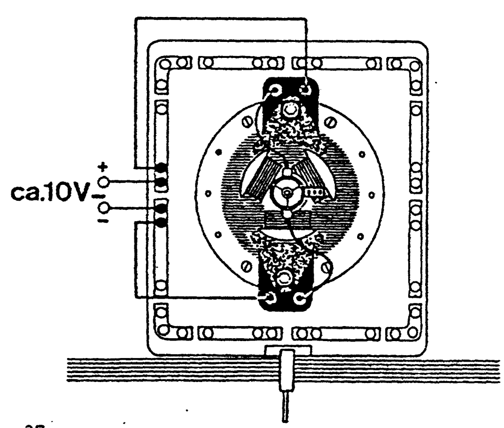


Fig. 37

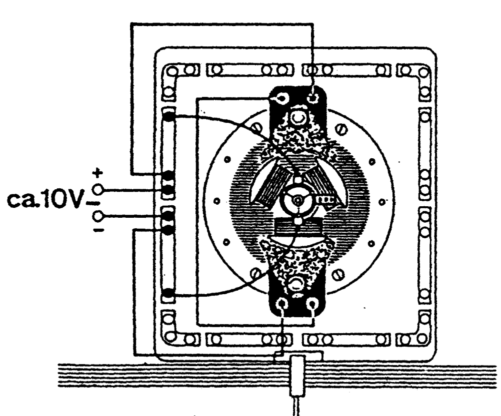


Fig. 38

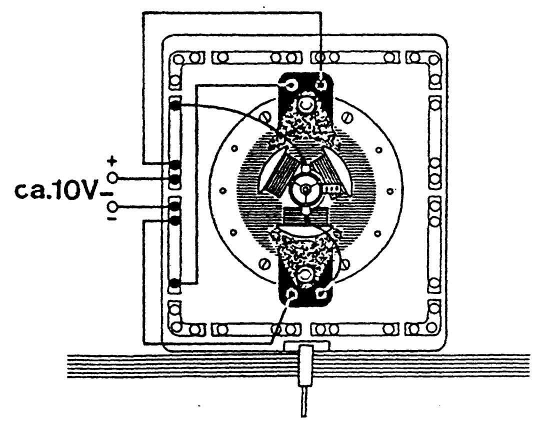


Fig. 39

Setup:

Do not fit the pole pieces until a centering disk is fitted.

Plug the carbon brushes into the opposite guides of the brush holder and align them vertically.

1. Series-wound motor:

   Set up the apparatus as shown in Fig. 37.

   Series-connect the stator coils and rotor.

2. Shunt motor:

   Set up the apparatus as shown in Fig. 38.

   Parallel-connect the stator coils and rotor.

3. Compound motor:

   Set up the apparatus as shown in Fig. 39.

   Connect one stator coil directly to the power supply unit and series-connect the second one to the rotor.

Experiments:

Set up all three motor types one after the other and apply an operating voltage of approximately 10 V DC in each case.

Turn the brush holder slightly in the direction opposite to rotation until the motor runs smoothly.

Important note:
Carry out these experiments only briefly.
The coils and brushes are subjected to multiple loads.

Observations:

All three motors start on their own after the operating voltage is applied.

The motors reach their maximum speed and run most smoothly at a specific brush position.

4.5 Possibilities of wiring motors for right- and left-hand rotation

Problem:

Setting up three different DC voltage motors with a reversible direction of rotation.

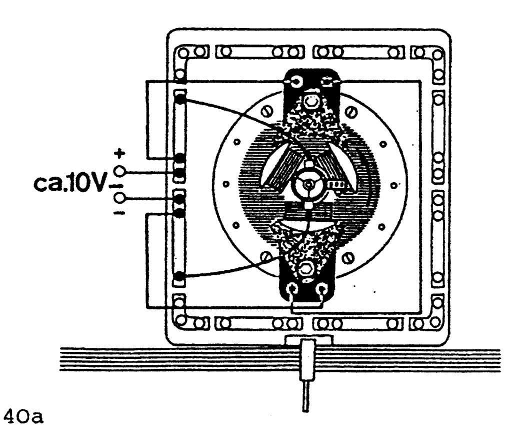


Fig. 40a

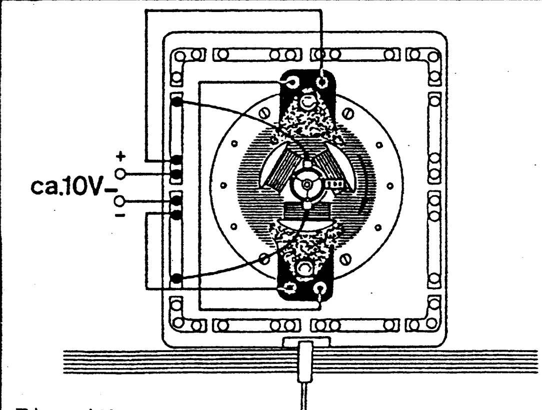


Fig. 40b

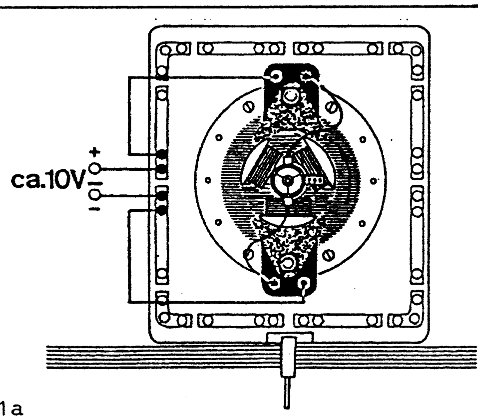


Fig. 41a

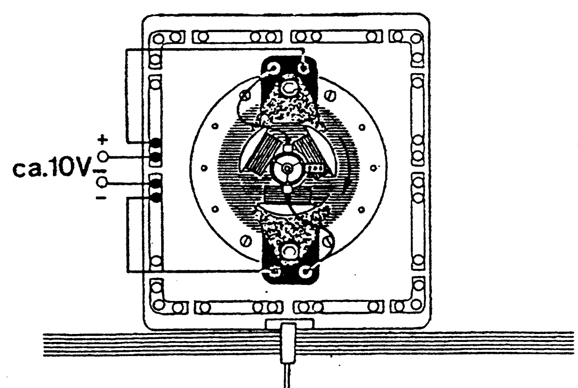


Fig. 41b

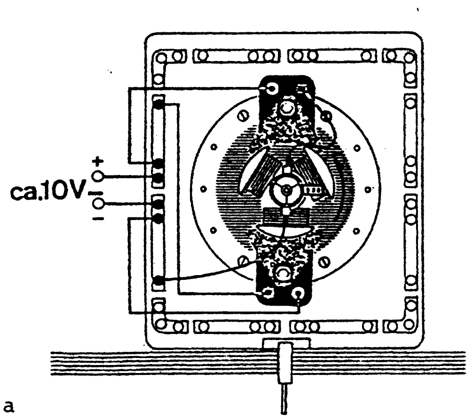


Fig. 42a

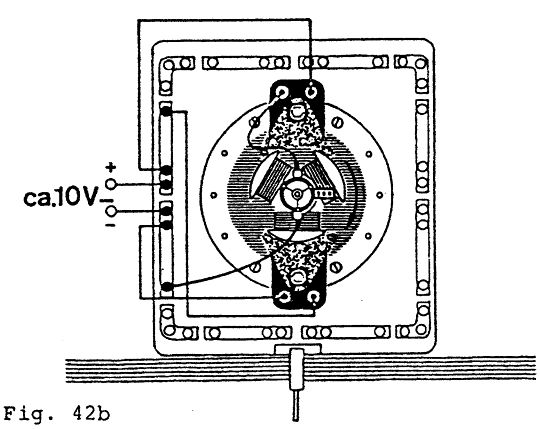


Fig. 42b

Apparatus:

From basic kit B, 563 51
1 Baseboard with vertical holder 563 261
2 Brushes with cable and plug ... 563 13
1 Brush holder 563 18
1 Three-pole rotor 563 23
2 Coils with 250 turns 563 11
2 Wide pole pieces for coils ... 563 101

From accessories kit Z, 563 52
1 Centering disk 563 17
1 Allen wrench 563 16

Additionally required
1 Transformer, extra low voltage. 591 09
5 Connecting leads, red, 50 cm .. 501 25

Setup:

Do not fit the pole pieces until a centering disk is fitted.

Plug the carbon brushes into the opposite guides of the brush holder and align them vertically.

1. Series-wound motor:

   Set up the apparatus as shown in Fig. 40.a and then as shown in Fig. 40.b.

   Series-connect the stator coils and rotor.

2. Shunt motor:

   Set up the apparatus as shown in Fig. 41a and then as shown in Fig. 41b.

   Parallel-connect the stator coils and rotor.

3. Compound motor:

   Set up the apparatus as shown in Fig. 42.a and then as shown in Fig. 42.b.

   Connect one stator coil directly to the power supply unit and series-connect the other to the rotor.

Experiments:

Set up all six variants in consecutive order and apply an operating voltage up to a maximum of 10 V DC in each case.

Slightly turn the brush holder in the direction opposite to rotation until the motor runs smoothly.

Reverse the polarity of the operating voltage once for each variant you have set up.

Important note:
Carry out these experiments only very briefly.
The coils and brushes are subjected to multiple overloads.

Observations:

It is not possible to reverse the direction of rotation of DC voltage motors by simply reversing the polarity of the operating voltage.

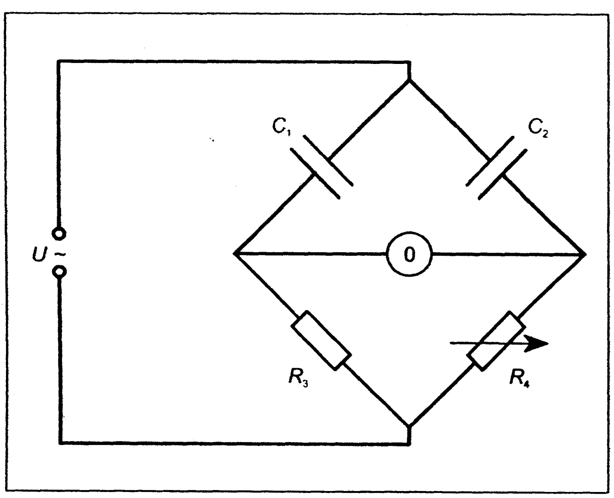
The direction of rotation depends on the direction of the current flowing through the stator coils and the rotor.

Determining capacitive reactance with a Wien measuring bridge

Objects of the experiments

- Determining the capacitances of capacitors by adjusting a Wien measuring bridge.
- Demonstrating that the balance condition is independent of the frequency of the AC voltage.

Fig. 1 Diagram of a Wien measuring bridge for determining a capacitive reactance Z_1



Principles

The Wheatstone measuring bridge is used to determine ohmic resistance in DC and AC circuits. In an analogue bridge circuit, the Wien measuring bridge (see Fig. 1), capacitive reactance can be determined. This measuring bridge, too, consists of four passive bridge arms, which are connected to one another in a square, an indicator arm with a balance indicator and a supply arm with the voltage source. The current in the indicator arm is made zero by adjusting variable elements in the bridge arm. Then the involved complex reactances fulfil the fundamental balance condition

$$Z_1 = Z_2 \cdot \frac{Z_3}{Z_4} \qquad \text{(I)},$$

from which the quantity to be measured

$$Z_1 = \frac{1}{i \cdot 2\pi \cdot f \cdot C_1} \qquad \text{(II)}$$

C_1: capacitance
f: frequency of the applied AC voltage

can be determined.

Z_2 is a capacitive reference reactance, Z_3 is a fixed ohmic resistance and Z_4 is a variable ohmic resistance. Therefore,

$$Z_2 = \frac{1}{i \cdot 2\pi \cdot f \cdot C_2} \qquad \text{(III)}$$

and

$$Z_3 = R_3 \text{ and } Z_4 = R_4 \qquad \text{(IV)}.$$

In the case of zero balance, the relation

$$C_1 = C_2 \cdot \frac{R_4}{R_3} \qquad \text{(V)}$$

holds regardless of the frequency f. In this experiment an earphone, an oscilloscope or a Sensor-CASSY can be used as a balance indicator.

1114-Sel

Apparatus

1 capacitor, 1 µF, 100 V, STE 2/19	578 15
1 capacitor 4.7 µF, 63 V, STE 2/19	578 16
1 plug-in board, A4	576 74
1 resistor 100 Ω, 0.5 W, STE 2/19	577 01
1 potentiometer 1 kΩ, 2 W, STE 4/50, 10-turn	57793
1 set of 10 bridging plugs	501 48
1 function generator S 12, 0.1 Hz-20 kHz	522 621
Connection leads	
1 earphone 2 kΩ	579 29
or	
1 two-channel oscilloscope 303	575 211
1 screened cable BNC/4 mm	575 24
or	
1 Sensor-CASSY	524 010
1 CASSY Lab	524 200

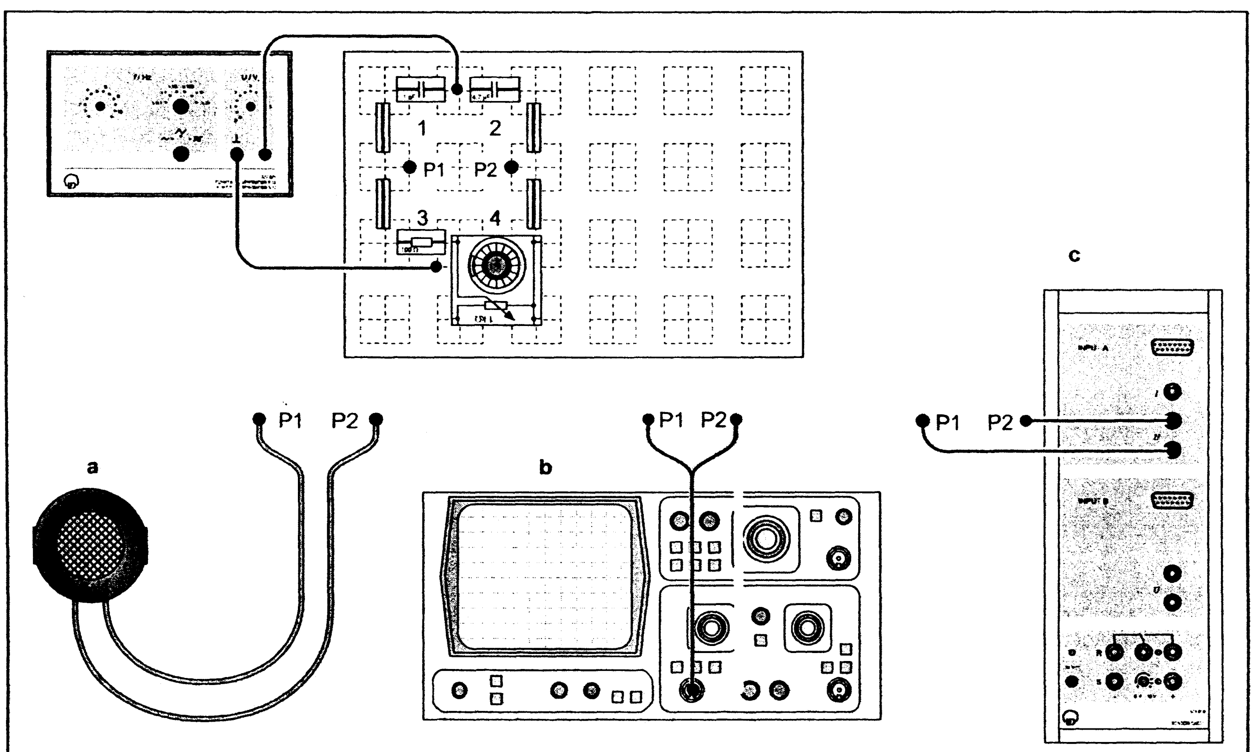
Setup

The experimental setup is illustrated in Fig. 2.

– Connect the function generator as an AC voltage source, and set the maximum output voltage and the signal shape ∿.

– Connect the earphone, the oscilloscope or the Sensor-CASSY between the connection points P1 and P2 as a balance indicator.

Fig. 2 Experimental setup for determining capacitive reactance by means of a Wien measuring bridge



Carrying out the experiment

Remark concerning the selection of the frequency of the AC voltage:

If the Sensor-CASSY is used as a balance indicator, the frequency f should not exceed 500 Hz because otherwise the r.m.s. value is not determined correctly. If the earphone is used, higher frequencies are recommendable in order to ensure sufficient aural sensitivity.

Oscilloscope settings:

Coupling:	AC
Deflection:	10 mV/DIV.
Trigger:	AC
Time base:	5 ms/DIV. (f = 100-500 Hz)

Sensor-CASSY settings:

Sensor input settings A1:

Measurement quantity: U_{A1}, r.m.s. values, measuring range: 0 V ... 0.21 V

Measuring parameters:

automatic recording, repeating measurement

Trigger:	U_{A1} 0.0000 V rising
Interval:	1 ms (f = 50 Hz), 500 µs (f = 100 Hz), 200 ms (f = 250 Hz, 100 µs (f = 500 Hz)
Number:	1000

a) Reference capacitance 4.7 µF:

- Insert the 1-µF capacitor as capacitance C_1 and the 4.7-µF capacitor as reference capacitance C_2.
- Switch the function generator on by connecting the plug-in power supply.
- Set a frequency that fits the balance indicator used.
- Vary the resistance R_4 carefully until the signal at the balance indicator is minimal (zero).
- Vary the frequency in the minimum to check the balance.

b) Reference capacitance 1 µF:

- Exchange the two capacitors, and repeat the measurement.

Measuring example

a) Reference capacitance 4.7 µF:

C_2 = 4.7 µF, R_3 = 100 Ω

R_4: scale value 0.225

Balance checked for f = 50, 100, 200 and 500 Hz

b) Reference capacitance 1 µF:

C_2 = 1.0 µF, R_3 = 100 Ω

R_4: scale value 4.440

Balance checked for f = 50, 100, 200 and 500 Hz

Evaluation

a) Reference capacitance 4.7 µF:

$$R_4 = \frac{0{,}225}{10} \cdot 1\,\mathrm{k\Omega} = 22{,}5\,\Omega$$

Eq. (V) gives: $C_1 = 4{,}7\mu\mathrm{F} \cdot \frac{22{,}5\,\Omega}{100\,\Omega} = 1{,}06\mu\mathrm{F}$

Value imprinted on the capacitor: C_1 = 1 µF

b) Reference capacitance 1 µF:

$$R_4 = \frac{4{,}440}{10} \cdot 1\,\mathrm{k\Omega} = 444{,}0\,\Omega$$

Eq. (V) gives: $C_1 = 1\mu\mathrm{F} \cdot \frac{444{,}0\,\Omega}{100\,\Omega} = 4{,}44\mu\mathrm{F}$

Value imprinted on the capacitor: C_1 = 4.7 µF

c) Comparison of the results with the values imprinted on the capacitors:

In both cases, the deviation of the measuring results from the values imprinted on the capacitors is approximately 6 % and thus somewhat greater than the tolerance indicated by the manufacturer. Note, however, that in either case the reference capacitance is only known within the tolerance of 5 % as well.

Result

With the aid of a Wien measuring bridge, the capacitance of a capacitor can be determined. The balance parameter is independent of the frequency of the applied AC voltage.

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A model of a relay with make contact

How a relay functions; the effect of the control circuit on the open circuit. Relay with make contact, relay with break contact, relay with make and break contacts

Apparatus:

1	Bell/relay set, complete	561 07
1	STE toggle switch, single-pole	579 13
1	Socket E10 on transparent base	594 72
1	Incandescent lamp E10; 6 V, 5 W	505 13
3	Connecting leads, 50 cm, black	501 28
1	Connecting lead, 50 cm, red	501 25
1	Connecting lead, 50 cm, blue	501 26
1	Power supply unit, DC and AC voltages, isolated, each 0 to 12 V .... e.g.	522 16

Fig. 1: Model of a relay with make contact;
(a): contact.
Model with break contact, drawn with dotted line;
Refer to the text for details of the model with make and break contacts

Setting up:

Plug the apparatus into the plate as in Fig. 1. Set the adjustable contact (a) so that there is a gap of approx. 1 mm through the contact on the armature.

Connect a DC voltage supply to the coils via the switch. The switch should be in position 0 (OFF).

Connect the incandescent lamp to the AC voltage output of the power supply unit.

Set a voltage of 6 V on the power supply unit (step 2).