# Hot-cathode emission in a vacuum: determining the polarity and estimating the specific charge of the emitted charge carriers

## Objects of the experiments

- Determining the polarity of the charge carriers emitted from a heated cathode
- Estimating the specific charge of the emitted charge carriers

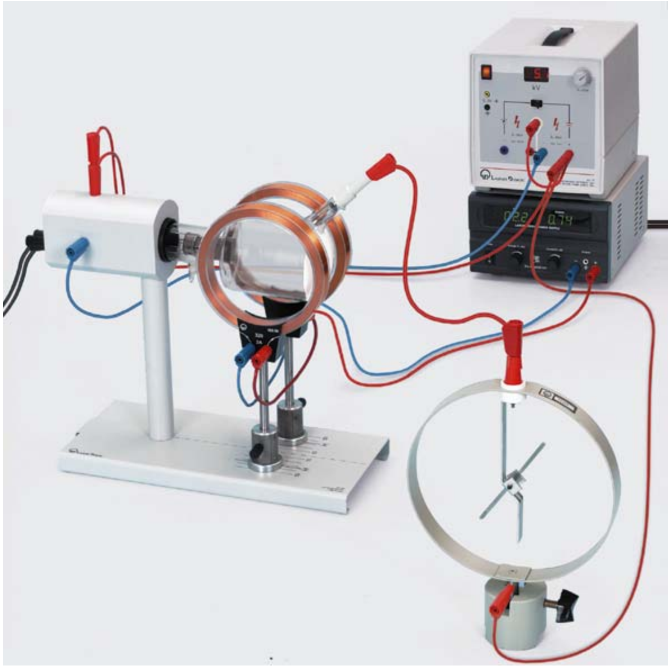
## Principles

A Perrin tube can be used for investigating the properties of cathode rays. The existence of cathode rays, the straight-line movement in field-free space and the deflection in electric and magnetic fields was qualitatively investigated in experiments with the vacuum tube diode, the vacuum tube triode and the Maltese cross tube.

In the Perrin tube the cathode rays are deflected by an electric or magnetic field into a Faraday cylinder which is located at an angle of 45° relative to the electron beam and which is charged by the cathode rays. The charge can be made visible by an electroscope and the polarity of the cathode rays is determined by comparison with a charge of known polarity. If the deflection is made by a field of known strength, the specific charge can also be estimated from the acceleration voltage $U_A$ and the geometric tube data.

In the Perrin tube the electrons emitted from a heated cathode are accelerated by the high voltage connected between the cathode and the anode. Through a hole aperture in the anode a narrow electron beam is generated which hits a fluorescent screen on the front of the tube and appears there as a green luminous spot. By means of deflection plates directly behind the anode the electron beam can be electrostatically deflected in horizontal direction. A Faraday cylinder arranged at a 45° angle to the beam axis can be charged up by the electrons which are deflected vertically upwards in a magnetic field.

In the experiment the properties of the cathode rays are investigated in more detail. First of all the polarity of the charge carriers is determined by comparison with a charge of known polarity. To do this the beam is deflected upwards in the magnetic field of a Helmholtz pair of coils arranged in parallel to the cathode rays, until it hits the Faraday cylinder. The deflection in a magnetic field is caused by the Lorentz force $\vec{F} = q \cdot \vec{v} \times \vec{B}$ acting on the charge carrier and occurs vertically both with respect to the direction of movement of the charge carrier and the field lines of the magnetic field. If the Faraday cylinder is connected to an electroscope pre-charged with a charge of know polarity, the change of the deflection will give information on the polarity of the charge carriers.



In addition, the specific charge of the charge carriers can be estimated. The beam is deflected by the magnetic field onto a circular path with the radius given by the speed of the electrons and the strength of the magnetic field. If the beam hits the Faraday cylinder, the radius of the circular path of $r$ = 16 cm in the experiment is fixed by the geometry of the tube and the coils, and the specific charge can be estimated from the applied anode voltage $U_A$ and the magnetic field $B$ using

$$\frac{e}{m} = \frac{2U_A}{(B \cdot r)^2} .$$

The magnetic field density B can be calculated from the current in the pair of Helmholtz coils using

$$B = \mu_0 \cdot \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{N \cdot I}{R}$$

where the number of windings $N$ = 320, the median coil radius $R$ = 6.7 cm and the applied current $I$.

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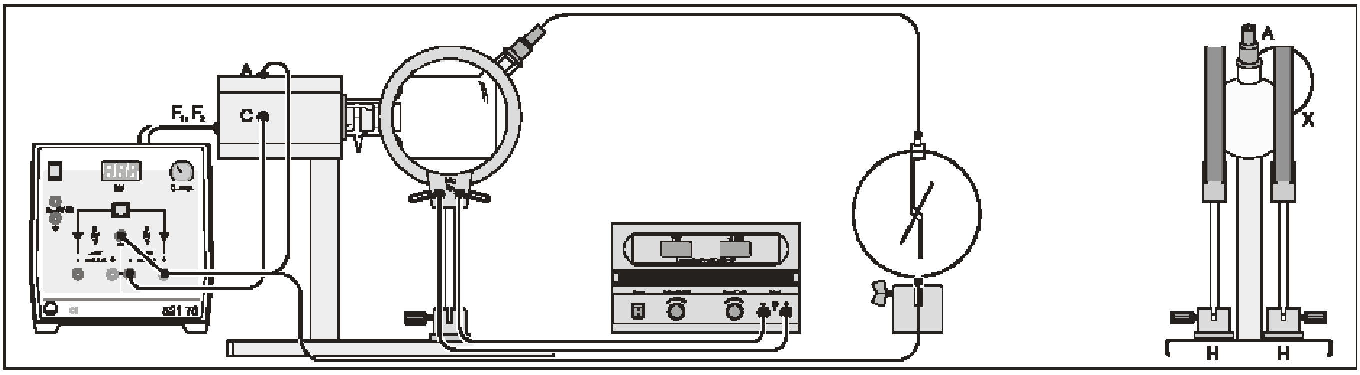
## Experimental setup:




### Apparatus

| | |
|---|---|
| 1 Perrin tube | 555 622 |
| 1 tube stand | 555 600 |
| 1 Helmholtz pair of coils | 555 604 |
| 1 high voltage power supply 10 kV | 521 70 |
| 1 DC power supply 0...16 V, 5 A | 521 545 |
| 1 electroscope | 540 091 |
| 1 support [0] | 300 11 |
| 1 high voltage connection cab[0]le | 501 05 |
| 1 safety connection lead, 25 cm, red | 500 611 |
| 2 safety connection leads, 50 cm, red | 500 621 |
| 1 safety connection lead, 50 cm, blue | 500 622 |
| 4 safety connection leads, 100 cm, red | 500 641 |
| 2 safety connection leads, 100 cm, blue | 500 642 |
| 2 safety connection leads, 100 cm, black | 500 644 |

### Safety notes

The Perrin tube is a thin-walled evacuated glass cylinder. Danger of implosion!

During the operation of the tube, voltages are applied which are dangerous when touched!

- Do not expose the tube to any mechanical loads.
- Only connect the Perrin tube by means of safety connection cables.
- Observe the operating instructions for the Perrin tube (555 622) and the tube stand (555 600).

### Setup

For setting up, the steps described below are required (see figure):

- Carefully insert the Perrin tube into the tube stand.
- Connect sockets $F_1$ and $F_2$ on the tube stand for the cathode heater to the 10 kV output at the rear of the high voltage power supply.
- Connect socket C on the tube stand (cathode cap) to the negative pole and socket A (anode) to the positive pole of the 10 kV high voltage power supply and in addition earth the positive pole.
- Connect socket X (deflection plates) to socket A (anode).
- Place the Helmholtz pair of coils at the positions marked with H (Helmholtz geometry) on the tube stand. A deviation from the Helmholtz geometry will lead to systematic errors in the calculation of the magnetic field. For this reason such a deviation should be kept as small as possible. Adjust the height of the coils in such a way that the centre of the coils is aligned with the beam axis. Connect the coils in series to the direct current power supply so that the current flows through the coils in the same direction. Ensure that the current flows in the same direction through the coils.
- Connect the electroscope to the Faraday cylinder and additionally earth the electroscope holder.

### Carrying out the experiment

- Switch on the high voltage power supply. Now the cathode is being heated.
- Select an anode voltage between 2.5 and 5 kV. A green luminous spot will appear on the fluorescent screen.

Determining the polarity of the charge carriers

- Pre-charge the electroscope with a negative charge by briefly connecting the negative pole of the high voltage power supply to the electroscope.
- Slowly increase the magnetic field by increasing the current in the coils until the electron beam precisely hits the Faraday cylinder. At the same time observe the electroscope.

Estimating the specific charge

- When the electron beam hits the Faraday cylinder precisely, read the values for the current $I$ through the pair of Helmholtz coils and the anode voltage $U_A$.

### Example of a measurement and evaluation

The electroscope is negatively pre-charged, the indicator of the electroscope is deflected.

Increase the magnetic field by slowly increasing the current in the coils; the green luminous spot on the screen will move upwards. Once the electron beam hits in the Faraday cylinder the deflection of the indicator on the electroscope will increase. The charge carriers have therefore the same polarity, i.e. they are charged negatively.

The electron beam hits the Faraday cylinder at a coil current of $I$ = 0.34 A and at a cathode voltage of $U_A$ = 3.5 kV. For the specific electron charge this formula applies:

$$\frac{e}{m} = \frac{2 \cdot U_A}{(r \cdot B)^2} \text{ with } B = \mu_0 \cdot \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{N \cdot I}{R}.$$

With the values $U_A$ = 3.5 kV, $r$ = 16 cm, $\mu_0 = 1{,}26 \cdot 10^{-6}\,\frac{\text{Vs}}{\text{Am}}$, $N$ = 320, $I$ = 0.34 A and $R$ = 6.7 cm, one obtains

$$\frac{e}{m_e} = 1{,}28 \cdot 10^{11}\,\frac{\text{As}}{\text{kg}}$$

The value estimated in this way for the specific charge is smaller than the value in the literature of $\frac{e}{m_e} = 1{,}28 \cdot 10^{11}\,\frac{\text{As}}{\text{kg}}$, the deviation is approx. 27 %.

One reason for the deviation is the assumption that the magnetic field between the Helmholtz coils is homogenous and can be calculated using $B = \mu_0 \cdot \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{N \cdot I}{R}$ . This is, however, only reasonably true for a range of $\pm\frac{R}{2}$ around the centre. Further out the magnetic field will continually decrease and just outside the coils it reaches a value of zero. The electron therefore initially moves through an area with a smaller magnetic field and therefore on a path with a larger radius.

Only when the distance $\frac{R}{2}$ from the centre is reached will the magnetic field have the value calculated for the Helmholtz geometry. After the electron has passed through the area with the homogeneous magnetic field around the centre will it again enter an area with a decreasing magnetic field. For this reason the magnetic field is systematically overestimated for the calculation of the specific charge, the deviation lies within the range of 10 %.

An additional deviation from the literature value results if the measurements deviates from the Helmholtz geometry. If e.g. instead of the optimum distance $a$ = 6.7 cm a distance of only $a^*$ = 7.3 cm is set, this also leads to a weaker field within the electron beam area; in this case this deviation is of the magnitude of 6 %.

A more precise determination of the specific charge without any correction terms is possible by using a fine beam tube (555 571). Here the Helmholtz coils are dimensioned so that in the area of the beam a homogeneous field is present which can be correctly described using the formula $B = \mu_0 \cdot \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{N \cdot I}{R}$.

In addition the distance between the pair of Helmholtz coils is fixed so that no unintended deviation from the Helmholtz geometry is possible.

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