Electricity

Cathode ray tubes

PHYSICS EXPERIMENT

Thomson tube

INVESTIGATE THE DEFLECTION OF ELECTRONS BY ELECTRIC AND MAGNETIC FIELDS

- Investigate the deflection of an electron beam by a magnetic field.
- Investigate the deflection of an electron beam by an electric field.
- Build a velocity filter using orthogonal electric and magnetic fields.
- Estimate the specific charge of an electron.

UE307050

10/08 UK

BASIC PRINCIPLES

In a Thomson tube electrons pass horizontally through a slit placed behind the anode and strike a fluorescent screen placed at an angle to the beam so that it shows the beam's path. A plate capacitor is also placed behind the slit so that the electric field between the plates can deflect the beam in a vertical plane. The addition of Helmholtz coils enables a magnetic field to be generated inside the tube in a plane perpendicular to the direction of the beam. This also deflects the beam in a vertical plane.

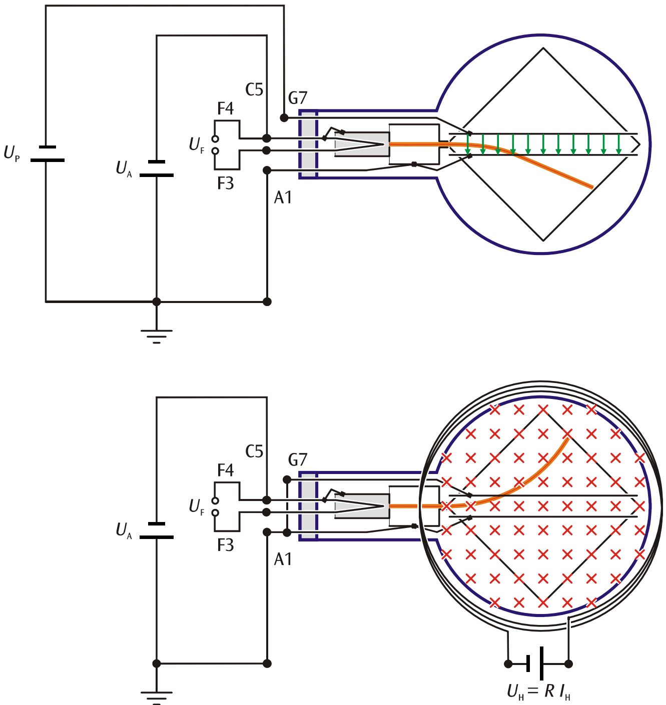

Fig. 1: Schematic diagram of a Thomson tube showing deflection by an electric field (top) and a magnetic field (bottom)

An electron moving with velocity $\boldsymbol{v}$ through a magnetic field $\boldsymbol{B}$ is subject to a Lorentz force

$$\boldsymbol{F} = -e \cdot \boldsymbol{v} \times \boldsymbol{B} \tag{1}$$

e: charge of an electron

acting perpendicular to both the direction of motion and the plane of the magnetic field. The deflection is vertical if both the motion and the field are in a horizontal plane (see bottom of Fig. 1). If the magnetic field in that plane is uniform and perpendicular to the motion, the electrons are deflected along a circular path in a vertical plane where the centripetal force is furnished by the same Lorentz force.

$$m \cdot \frac{v^2}{r} = e \cdot v \cdot B \tag{2}$$

m: mass of an electron, r: radius of circular path.

The velocity of the electrons is dependent on the anode voltage U_A according to the following relationship

$$v = \sqrt{2 \cdot \frac{e}{m} \cdot U_A} \tag{3}$$

This means that the specific charge of an electron can be determined from the radius of the circular path if the uniform magnetic field B is known as well as the anode voltage U_A. Substituting (3) into (2) results in the following equation for the specific charge of an electron:

$$\frac{e}{m} = \frac{2 \cdot U_A}{(B \cdot r)^2} \tag{4}$$

The radius of the deflection r can be deduced from the point at which the beam passes beyond the edge of screen. The magnetic field B generated by the two Helmholtz coils is calculated from the current I_H that passes through them (see Evaluation).

If a voltage U_P is applied to the capacitor plates, the electrons will be deflected by the vertical electric field $\boldsymbol{E}$ between them by a force given by the following equation:

$$\boldsymbol{F} = -e \cdot \boldsymbol{E} \quad (5)$$

e: charge of an electron

This deflection is also vertical (see top of Fig. 1). The electric field can therefore be adjusted in such a way that it precisely compensates for the deflection by the magnetic field. In this case the following is true:

$$e \cdot E + e \cdot v \cdot B = 0 \quad (6)$$

The velocity of the electrons can easily be derived from this equation as follows:

$$v = \left|\frac{E}{B}\right| \quad (7)$$

For this reason, such an arrangement of orthogonal magnetic and electric fields where the deflection by the two fields cancels out to zero is called a velocity filter.

The velocity v depends on the anode voltage U_A and can be deduced by equating the potential and the kinetic energy in the system.

$$e \cdot U_A = \frac{m}{2} v^2 \text{ bzw. } v^2 = 2 \cdot \frac{e}{m} \cdot U_A \quad (8)$$

LIST OF APPARATUS

1	Thomson tube S	U18555
1	Tube holder S	U185001
1	Helmholtz pair of coils S	U185051
1	High voltage power supply, 5 kV	U33010
1	DC power suppply, 0-500 V	U33000
1	DC Ammeter, 3 A, e.g.	U17450
1	Set of 15 safety experiment leads	U138021

Also recommended for generation of the electric field:

SAFETY INSTRUCTIONS

Heated cathode ray tubes are thin-walled evacuated glass bulbs. Handle with care: danger of implosion!

- Do not expose the Thomson tube to any mechanical stress or strain.

Danger: high voltage is applied to the Thomson tube. Avoid contact with any part of the body.

- Only use safety experiment leads for connections.
- Make the connections only when the power supply unit is switched off.
- Set up or dismantle the tubes only when the power supply unit is switched off.

SET-UP

Installation of Helmholtz coils and insertion of Thomson tube into its holder:

- Attach both Helmholtz coils in the centre of the coil attachment with their connector terminals facing outwards then push them out along the guide rails.
- Insert the Thomson tube into the tube holder. Make sure that the contact pins slot fully into the openings on the holder. The central guide pin of the tube should protrude slightly beyond the back of the holder.
- Push the Helmholtz coils in as far as the markings so that the separation of the two coils is 68 mm.

Connection of heater and accelerating voltages:

- Leave the high-voltage power supply switched off with the voltage knob turned all the way to the left.
- Connect terminals F3 and F4 on the tube holder to the heater voltage output (blue terminals) of the high-voltage power supply using safety experiment leads (see Fig. 1).
- Connect terminal C5 on the tube holder to the negative terminal (black socket) of the high-voltage power supply using safety experiment leads (terminals C5 und F4 are tied together inside the tube itself).
- Connect terminal A1 on the tube holder to the positive terminal (red socket) of the high-voltage power supply using safety experiment leads and connect also this positive terminal to the green and yellow earth socket.

Connecting the Helmholtz coils:

- Leave the DC power supply 0-500 V switched off with all voltage knobs turned all the way to the left.
- Connect terminal A on the first coil to the negative terminal and terminal Z to the positive terminal of the 12 V output.
- Connect the second coil in parallel with the first so that the terminals opposite one another are connected together.
- Connect the DC Ammeter in series to the Helmholtz pair of coils.

Connecting the deflecting voltage:

- Connect terminal G7 of the tube holder to the negative terminal of the 500 V output.
- Connect the positive terminal of the 500 V output to the green and yellow earth socket of the high-voltage supply.

Note: If either the magnetic field or the electric field deflects the beam the wrong way, simply swap over the terminals on the relevant DC supply.

Fig. 2: Experiment set-up for investigating deflection of electrons by magnetic and electric fields.

EXPERIMENT PROCEDURE

- Turn on the high-voltage power supply. The heating filament should immediately start to glow red.
- Set an accelerating voltage of U_A = 2.0 kV and observe the “horizontal” path of the beam along the screen.
- Turn on the DC power supply 0–500 V.
- Gradually increase the current through Helmholtz coils ($2\,I_H$) until the electron beam passes out through the centre of the scale (see Fig. 3).
- Apply a voltage U_P to the deflector plates that is just enough to cancel out the deflection of the beam by the magnetic field.
- Take note of the Helmholtz current $2\,I_H$ and the voltage U_P where available.
- Reset voltage U_P to zero.
- Repeat the measurement for U_A = 3.0 and 4.0 kV.

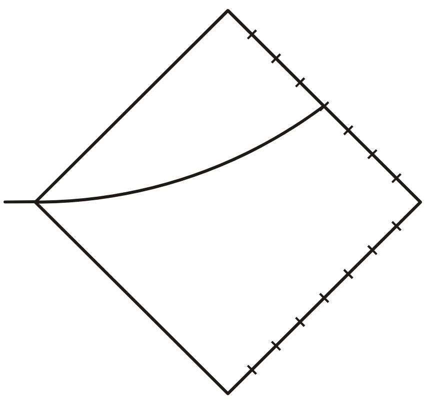

Fig. 3: Deflection of electron beam so that it passes through the centre of the scale at the edge of the screen

- Set the anode voltage to U_A = 3 kV.
- Set the coil current so that $2\,I_H$ = 0.2 A and adjust the deflector plate voltage U_P so that the deflection of the beam by both fields cancels out to zero.
- Take note of the current $2\,I_H$ and the voltage U_P.
- Repeat the process for $2\,I_H$ = 0.4 A, 0.6 A and 0.8 A.

SAMPLE MEASUREMENTS

Table 1: Current $2\,I_H$ through the Helmholtz coils sufficient to deflect the beam through the centre of the scale and voltage U_P needed to cancel this deflection to zero, depending on anode voltage U_A.

U_A / kV	$2\,I_H$ / A	U_P / V
2.0	0.53	240
3.0	0.62	330
4.0	0.74	470

Table 2: Helmholtz current $2\,I_H$ and cancelling voltage U_P for a fixed anode voltage U_A = 3.0 kV

Nr.	$2\,I_H$ / A	U_P / V
1	0.2	100
2	0.4	225
3	0.6	360
4	0.8	440

Note: here the voltage U_P is supplied by the recommended 0–450 V DC power supply.

EVALUATION

a) The magnetic field B produced by the Helmholtz coils is proportional to the current I_H that passes through each individual coil. The coefficient of proportionality k can be calculated from the coil radius R = 68 mm and the number of windings per coil N = 320:

$$B = k \cdot I_H \text{ where } k = \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot \frac{N}{R} = 4{,}2 \frac{\text{mT}}{\text{A}}$$

b) The radius of deflection r for the electron beam can be determined from the exit point B as shown in Fig. 4.

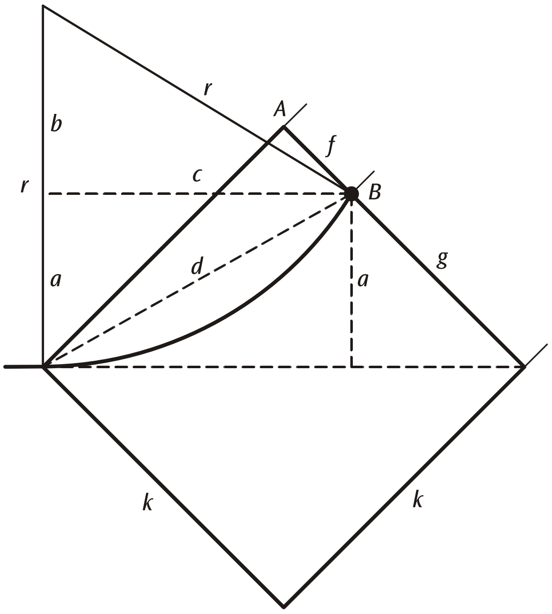

Fig. 4: Calculating radius of deflection r of electron beam exiting screen at a point B, a distance f from corner A

By Pythagoras' theorem:

$$r^2 = c^2 + b^2 = c^2 + (r-a)^2 = c^2 + r^2 - 2 \cdot r \cdot a + a^2$$

$$c^2 + a^2 = d^2 = k^2 + f^2 \text{ where } k = 80 \text{ mm}$$

$$a^2 = \frac{1}{2} \cdot g^2 = \frac{1}{2} \cdot (k-f)^2$$

Therefore $r = \frac{c^2 + a^2}{2a} = \frac{k^2 + f^2}{\sqrt{2} \cdot (k-f)}$

If B is in the centre of the scale, f = 40 mm. In this case the calculation is as follows:

r = 141 mm and $\frac{1}{2} \cdot r^2 = 0{,}1\,\text{m}^2$.

Equation (4) can be rearranged thus: $\frac{e}{m} = \frac{U_A}{0{,}1\,\text{m}^2 \cdot B^2}$

c) The electric field produced by the capacitor can be derived from the voltage U_P and the plate separation d = 8 mm:

$$E = \frac{U_P}{d}$$

d) To estimate the specific charge of an electron, calculate the magnetic field B from the values of current I_H entered in Table 1. The results should correspond to those in Table 3.

Fig. 5 shows a graph of the relationship between the anode voltage U_A and the *square* of the magnetic field B^2 for the values shown in Table 3.

The graph is a straight line through the origin with the following gradient

$$\frac{U_A}{B^2} = 1.7 \frac{\text{kV}}{\text{mT}^2}$$

This results in $\frac{e}{m} = \frac{U_A}{0.1\,\text{m}^2 \cdot B^2} = 1.7 \cdot 10^{11} \frac{\text{As}}{\text{kg}}$

(Quoted value: $\frac{e}{m} = 1.76 \cdot 10^{11} \frac{\text{As}}{\text{kg}}$)

Table 3: Values B und B^2 calculated from results for I_H given in Table 1 depending on anode voltageU_A.

U_A / kV	B / mT	B^2 / mT^2
2,0	1,11	1,24
3,0	1,30	1,70
4,0	1,55	2,41

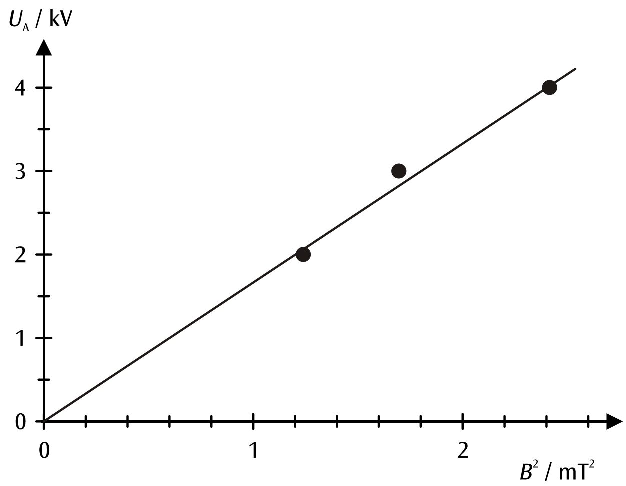

Fig. 5: Graph showing relationship between U_A and B^2 with a constant radius of deflection r = 141 mm

e) To confirm Equation (7) the values of B and E, are calculated from the results in Table 2, where the deflection by both fields cancels out to zero (see Table 4). The results are then plotted on a graph of E against B (see Fig. 6).

To within the available degree of accuracy, the results lie on a straight line through the origin, which is in agreement with Equation (7). The gradient of the line corresponds to the velocity of the electrons.

Thus: $v = 3{,}2 \cdot 10^7 \ \frac{\text{m}}{\text{s}}$ (where U_A = 3.0 kV)

Tab. 4: Magnetic field B and cancelling electric field E for a fixed anode voltage U_A = 3.0 kV

Nr.	B / mT	E / V/mm
1	0.42	12,.5
2	0.84	28.1
3	1,26	41.3
4	1,68	55.0

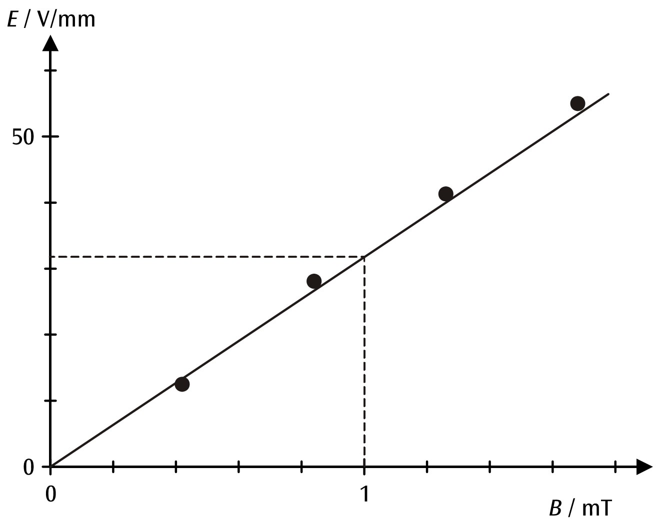

Fig. 6: Graph of results from Table 4

f) Using the results from Table 1 the electron velocity v for various anode voltages U_A can be determined. The results are shown in Table 5.

Table 5: Values of B and E derived from measurements of I_H and U_P from Table 1 plus the resulting velocity v and the square of the velocity depending on the anode voltage U_A.

U_A / kV	B / mT	E / V/mm	v / m/s	v^2 / (m/s)^2
2.0	1.11	30.0	$2{,}70 \cdot 10^7$	$7{,}3 \cdot 10^{14}$
3.0	1.30	41.3	$3{,}18 \cdot 10^7$	$10{,}1 \cdot 10^{14}$
4.0	1.55	58.8	$3{,}79 \cdot 10^7$	$14{,}4 \cdot 10^{14}$

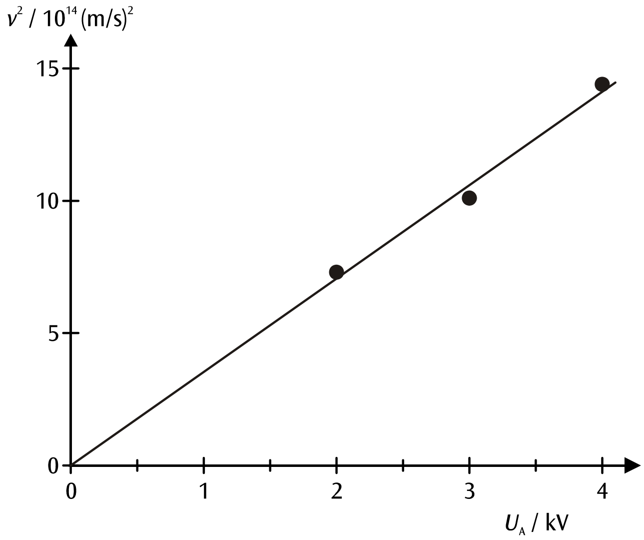

Fig. 7: Graph of v^2 against U_A

Fig. 7 is a graph of the square of the velocity against the anode voltage. The gradient of the resulting straight line through the origin also leads to a result for the specific charge of an electron according to Equation (8).

Thus: $\frac{e}{m} = \frac{U_A}{2 \cdot v^2} = 1{,}8 \cdot 10^{11} \frac{\text{As}}{\text{kg}}$

(Quoted value: $\frac{e}{m} = 1{,}76 \cdot 10^{11} \frac{\text{As}}{\text{kg}}$)