Cathode-Ray Tube

The charge of the electron was first measured by Millikan. Unfortunately, the mass of an electron is too small to measure on an ordinary balance. It is possible, however, to find the **charge-to-mass ratio**. From this ratio and the charge, the mass can be found.

The ratio of charge-to-mass was first measured in 1897 by J. J. Thomson, using a device called a cathode-ray tube. Inside the cathode-ray tube, a beam of cathode-rays (electrons) travels towards a fluorescent screen. The screen glows at the point where the electrons hit.

Electric and magnetic fields in the center of the tube exert forces on the electrons. The electric field produces a force that is directed upward, while the magnetic field produces a force that is directed downward.

The electric and magnetic fields are adjusted until the beam of electrons follows a straight, undeflected path. Then the forces due to the two fields are equal in magnitude and opposite in direction.

$$qvB = qE$$

Solving this equation for v, we obtain the expression

$$v = \frac{qE}{qB}$$

$$\boxed{v = \frac{E}{B}}$$

Thomson used the measured values of E and B to calculate the velocity of the electrons. He then removed the electric field, leaving only the force due to the magnetic field. Since the magnetic force acts perpendicular to the motion of the electrons, they move in a circular path with radius r. Thus,

$$F_c = F_B$$

$$\frac{mv^2}{r} = qvB$$

Solving for $\frac{q}{m}$ gives

$$\boxed{\frac{q}{m} = \frac{v}{Br}}$$

Thomson determined the radius of the circular path by measuring the distance between the undeflected spot and the spot when only the magnetic field acted on the electrons. Combining this value of r with the previously calculated value of v, and the known values of B and q, Thomson was able to determine the mass of a single electron.

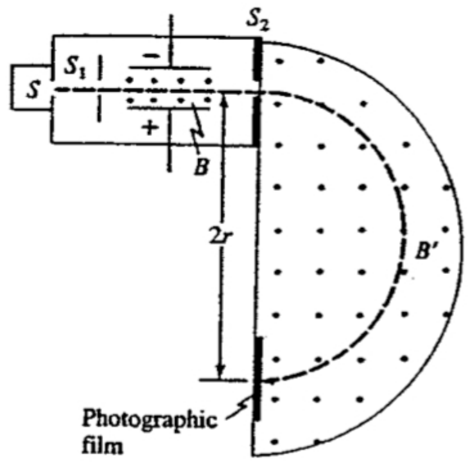
Note: The value of the **charge-to-mass ratio**, as calculated by Thomson is $1.759 \times 10^{11}\ C/kg$.

Cathode-ray tubes can be found in a number of modern devices, including televisions, oscilloscopes, and computer monitors (CRT monitors only).

Example 1
A beam of electrons travels undeflected in a cathode-ray tube. The electric field intensity is $7.0 \times 10^{3}\ N/C$. The magnetic field intensity is $3.5 \times 10^{-2}\ T$. What is the speed of the electrons as they travel through the tube?

Mass Spectrometer

Thomson's technique for determining the mass of an electron led to the development of a method for measuring the mass of any charged particle. This device, called a mass spectrometer, is shown in the diagram below (in simplified form).



Ions are produced by heating at the source, S. Those that pass through slit S_1 enter a region where there are crossed electric and magnetic fields, as in a CRT. Only ions whose speed is

$$v = \frac{E}{B}$$

will pass through undeflected and emerge through slit S_2. (This arrangement is called a **velocity selector**.)

In this second region, there is only a magnetic field B which causes the ions to follow a circular path. The radius of their path can be measured because the ions cause the photographic film to glow where they strike it. Since

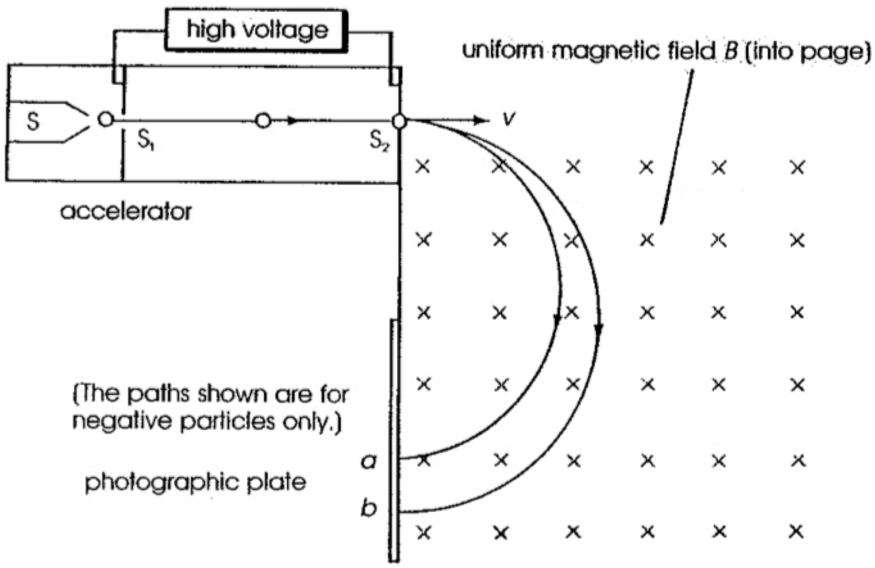
$$F_c = F_B$$
$$\frac{mv^2}{r} = qvB$$

then we have

$$m = \frac{qBr}{v}$$

All the quantities on the right can be measured, and thus *m* can be determined.

A second type of mass spectrometer is shown below:



In this device, ions are produced by heating the source S and pass through the slit S_1. The potential difference between S_1 and S_2 accelerates the ions, causing some of them to pass through the slit S_2 with a velocity v, given by

$$\Delta E_k = q\Delta V$$

$$\frac{1}{2}mv^2 = q\Delta V$$

$$v = \sqrt{\frac{2q\Delta V}{m}}$$

The second region of this mass spectrometer is identical to that of the first one we examined. Thus,

$$m = \frac{qBr}{v}$$

Example 2
The operator of a mass spectrometer produces a beam of doubly ionized ($q = +2e$) neon atoms. They are first accelerated by a potential difference of $34\ V$. In a $0.050\ T$ magnetic field, the radius of the path of the ions is $53\ mm$. Find the mass of the neon atom.

Homework
CRT and Mass Spectrometer Worksheet

CRT and Mass Spectrometer Worksheet

1. Protons passing without deflection through a magnetic field of 0.6 T are balanced by a $4.5\times10^{3}\ N/C$ electric field. What is the speed of the moving protons? ($7.5\times10^{3}\ m/s$)

2. A proton moves at a speed of $7.5\times10^{3}\ m/s$ as it passes through a 0.6 T magnetic field. Find the radius of the circular path. The charge carried by the proton is equal to that of the electron, but it is positive. ($1.3\times10^{-4}\ m$)

3. Electrons move through a $6.0\times10^{-2}\ T$ magnetic field balanced by a $3.0\times10^{3}\ N/C$ electric field. What is the speed of the electrons? ($5.0\times10^{4}\ m/s$)

4. Calculate the radius of the circular path that the electrons in problem 3 follow in the absence of the electric field. ($4.7\times10^{-6}\ m$)

5. A stream of singly ionized $\left(q=1.6\times10^{-19}\ C\right)$ lithium atoms is not deflected as it passes through a $1.5\times10^{-3}\ T$ magnetic field perpendicular to a $6.0\times10^{2}\ V/m$ electric field.
   a. What is the speed of the lithium atoms as they pass through the crossed fields? ($4.0\times10^{5}\ m/s$)
   b. The lithium atoms move into a magnetic field of 0.18 *T*. They follow a circular path of radius 0.165 *m*. What is the mass of a lithium ion? ($1.2\times10^{-26}\ kg$)

6. A mass spectrometer analyzes and gives data for a beam of doubly ionized argon atoms. The values are $q=2\left(1.6\times10^{-19}\ C\right)$, $B=5.0\times10^{-2}\ T$, $r=0.106\ m$, and $\Delta V=66.0\ V$. Find the mass of an argon atom. ($6.8\times10^{-26}\ kg$)

7. A beam of singly ionized oxygen atoms is sent through a mass spectrometer. The values are $B=7.2\times10^{-2}\ T$, $q=1.6\times10^{-19}\ C$, $r=0.085\ m$, and $\Delta V=110\ V$. Find the mass of an oxygen atom. ($2.7\times10^{-26}\ kg$)