Queen Mary
University of London

Laboratory Exercise 9 – FUNDAMENTAL and SUBATOMIC PHYSICS

The first and last parts of this exercise are concerned with two subatomic elementary particles — the **electron**, which is stable, and the **pion**, an unstable particle that lives fleetingly before it decays. Both measurements are based on the concept of momentum, so although the middle section on kinematics may seem incongruous, all three parts are linked by similar principles.

Part A: The charge-to-mass ratio of the electron, *e/m*

Introduction

A force acts on a charged particle moving in a magnetic field, tending to push the particle sideways. [The same force is responsible for the movement of a current-carrying conductor between the poles of a magnet, the basis of electric motors.] The force acting on an electron of charge e and mass m moving with velocity v in a field B is equal to Bev. Introducing the momentum $p = mv$, this becomes Bep/m. If the magnetic field is constant the electron undergoes a constant sideways acceleration. That corresponds to motion in a circle. Equating the centripetal force to the product of mass and inward acceleration v^2/r gives

$$\frac{Bep}{m} = \frac{mv^2}{r} = \frac{p^2}{mr}$$

so the momentum is

$$p = Bmr\left(\frac{e}{m}\right)$$

The kinetic energy of the electron comes from acceleration through a potential difference (voltage) V. Equating potential energy lost to kinetic energy gained gives

$$eV = \tfrac{1}{2}mv^2 = \frac{p^2}{2m}$$

Substituting for p we find

$$\left(\frac{e}{m}\right) = \frac{2V}{B^2r^2}$$

so the charge-to-mass ratio can be found by measuring the radius of the circular path, and knowing both the magnetic field and the accelerating voltage.

The apparatus comprises a spherical bulb or 'tube', with 'guns' to produce and control a narrow beam of electrons, surrounded by a pair of **Helmholtz coils** for producing the magnetic field within the bulb. There are separate power supplies for tube and coils.

Electron beam tube

The electrical features, shown in figure 1, are: a **cathode** which produces electrons, an **anode** which accelerates them through voltage V, and an additional **deflector** electrode which can steer the beam slightly. Connections are made through the base and neck of the tube. The tube is almost completely evacuated, allowing the electrons to travel freely with few collisions with gas atoms. A small quantity of helium is present; its atoms emit greenish light if ionised by collision, so making the beam visible when the ambient light level is low. Part of the glass bulb is coated with luminescent paint. There are two independent electron beams selected by a switch on the base of the tube, one directed across a diameter of the bulb, the other directed tangentially upwards. You will use the tangential beam, which can be bent into a complete circle by the magnetic field. Before switching anything on identify all the components, trace the circuit connections, and follow the instructions carefully.

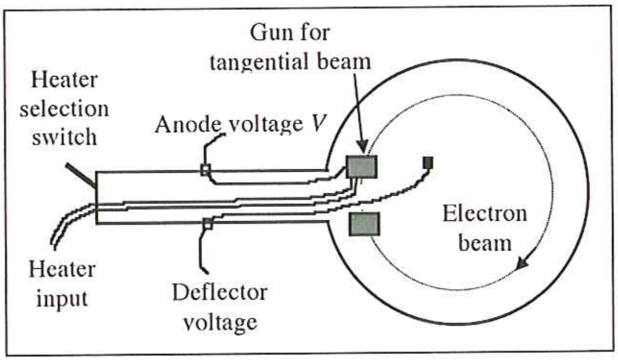

Figure 1 Electron beam tube

Each electron gun comprises an indirectly heated cathode and a conical anode with a small hole to allow the electrons to emerge; the deflector electrode nearby controls either beam. There are separate controls and meters for the anode (0–300 V) and the deflector electrode (0–50 V). When the power supply is switched on, current flows through the heater of whichever electron gun is selected. The heaters must *not* warm up while there is an accelerating voltage on the anode, so *before switching on make sure that the anode voltage is zero* by turning the control fully anticlockwise. ***Failure to do this can cause serious damage.*** Likewise, *reduce the anode and deflector voltages to zero before switching off.*

Helmholtz coils

A pair of coils arranged as in figure 2 and carrying equal currents I produce a substantially uniform magnetic field in the region between them, which is where the electron beam is produced. The essential feature of this **Helmholtz pair** geometry is that the separation of the coils is equal to their average radius R. If there are N turns of wire on each coil then the magnetic field intensity is

$$B = \frac{32\pi NI}{R\sqrt{125}} \times 10^{-7} \text{ teslas}$$

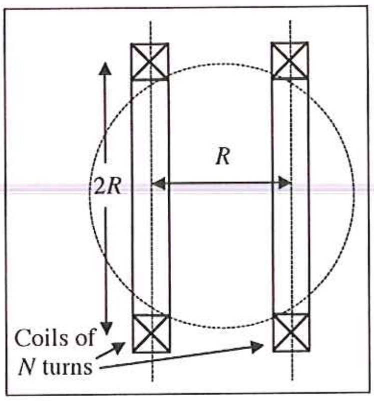

Figure 2 Helmholtz coils

These coils are wound with 320 turns of enamelled copper wire, and their mean diameter is 13.6 cm. Hence their radius is 6.8 cm. Make sure, using convenient spacers or in other ways, that the coils are parallel and that the separation between the middle of their coil windings is also 6.8 cm. Currents up to 1 A are provided from a separate power supply.

Measurements

• With the Helmholtz coil supply off and the anode voltage zero, switch on the electron tube supply. ***Wait one minute*** before applying voltage to the anode. Raise the voltage slowly. At about 50 V you will see the first sign of the beam, by 70 V it should have enough energy to cross the tube, and by 100 V it is a bright filament. Switch on the Helmholtz coil supply and increase the current. If the beam is a spiral rather than a circular arc, the coils and the tube may be slightly misaligned. This is difficult to correct (with this apparatus) but you might try turning the whole assembly around — the extra deflection may be due to the effect of a local magnetic field. A small spiral deflection doesn't matter. A voltage can be applied to the deflector plates to make sure that the electron beam leaves the anode in the right direction, but you will probably not need to use this control much.

• Measuring the diameter of the circular beam is difficult. You can hold a transparent ruler in front of the tube, or try placing a mirror behind the tube and lining up a ruler with its reflection, or even try a travelling microscope if the electron beam is narrow.

When combined, the expressions for the value of e/m and for B yield

$$\frac{1}{d} = \left(\frac{16\pi N}{5 \times 10^7 R} \sqrt{\frac{e}{10mV}} \right) I$$

where d is the diameter of the circular beam. Hence a graph of $1/d$ versus coil current I, for constant accelerating voltage V, should yield a straight line from whose slope e/m can be found. (Note that I should be plotted on the x-axis and $1/d$ on the y-axis because we know I quite precisely, while $1/d$ has substantial measurement errors.)

• Use at least two values of V, but preferably three or four, starting near 100 V and going no higher than about 270 V. For each value of V, increase I and measure d for each of about ten diameters, aiming for about 5 mm intervals. The largest value should have the beam skimming the phosphorescent screen, the smallest can be about 40 mm. The beam may be very blurred, so its centre line is uncertain. Keep a close check on V and correct it if it tends to drift.

• If you are having problems obtaining data as above because d is difficult to measure, try keeping d constant while varying V and I to give a sufficient number of data points.

Analysis

• Plot $1/d$ versus I for each value of V. From the gradient of each of your graphs deduce a value of e/m. Average these, and estimate the uncertainty of your answer. Considering the difficulty of the d measurement, this experiment can give results remarkably close to the accepted value of the electron e/m, which is 1.76×10^{11} C kg^{-1}. For example, from readings taken with anode voltages of 90 V and 180 V a Course Organiser obtained 1.78×10^{11} and 1.69×10^{11} C kg^{-1} for lines drawn through the origin.

• If all of the magnetic field comes from the Helmholtz coils, then your straight lines should pass through the origin. Consider whether or not this is the case. If it is not, then the electrons are being bent even when $I = 0$, possibly by a small and constant additional magnetic field B_0 due to the Earth's field or to iron in the lab. If I is such that it produces a field B equal and opposite to B_0 then there will be no bending, so d is infinitely large and $1/d$ is zero. This corresponds to where the straight line crosses the x-axis. To deduce B_0, use the value of this x-intercept: set B_0 equal to the value of B from the Helmholtz coils and so show that at this point

$$B_0 = -\frac{32\pi N}{\sqrt{125} \times 10^7 R} I$$

• Use this expression to deduce B_0 if your data appear to justify it.