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A Review of Determination of Charge to Mass Ratio of an Electron by Thomson's method

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ABSTRACT

The orbit of a charged particle in a uniform and constant magnetic field is a circle when the initial velocity of the particle is perpendicular to the magnetic field. The radius of the orbit depends on the charge to mass ratio of the particle, q/m, the speed of the particle v, and the strength of the magnetic field B. When the strength of the magnetic field and the initial speed of the particle are known, a measurement of a radius of the orbit determines q/m. This principle was used by J.J. Thomson to measure the charge to mass ratio of the electron, e/m, in 1897. In this experiment I have used a commercially available CRT-8SJ31J with 70mm diameter screen size to repeat the Thomson's experiment and determine e/m of the charged particles. Electronic charge to mass ratio (e/m) is determined by subjecting the electron beam to electric and magnetic fields. This experiment backs up that the measured value of charge to mass ratio is in close agreement with the standard value of this ratio.

Keywords: *Charge to mass ratio, electron, Cathode Ray Tube, Thomson's method*

INTRODUCTION

The orbit of a charged particle in a uniform and constant magnetic field is a circle when the initial velocity of the particle is perpendicular to the magnetic field. The radius of the orbit depends on the charge to mass ratio of the particle, q/m, the speed of the particle v, and the strength of the magnetic field B. When the strength of the magnetic field and the initial speed of the particle are known, a measurement of a radius of the orbit determines q/m. This principle was used by J.J. Thomson to measure the charge to mass ratio of the electron, e/m, in 1897[2,3]. The reason for a circular orbit can be understood by the fact that a charged particle experiences a force at right angles both to the instantaneous velocity and to the direction of the magnetic field. The particle therefore moves under the influence of a force whose magnitude is constant but whose direction is always at the right angles to the velocity[2,3,5]

Based on his experimental results, Thomson provided convincing evidence that the X-rays consisted of electrons. He measured the ratio of their charge to mass and estimated that the mass of the particle was about 1/1800 of that of a hydrogen atom[1,7]. Thomson investigated the nature of the emitted radiation by subjecting the radiation to an electric field and a magnetic field and found that it gets deflected by both the fields proving that the cathode rays consist of charged particles[4,7,9]. Employing a vacuum tube, the rays were collimated into a beam by two metal slits (electrodes). The first of these slits was the anode and the second was connected to the earth. The beam was then subjected to an electric field that was produced between two parallel aluminum plates connected to a battery. The end of the tube was made in the shape of a large sphere where the beam would impact on the glass, creating a glowing patch[1,6,10]. Thomson pasted a scale on to the surface of this sphere and measured the deflection of the beam. When the upper plate was connected to negative pole of the battery and the lower plate to the positive pole, the glowing patch moved downwards. When the polarity was reversed, the patch moved upwards[4,8,11].

In this experiment I have used a commercially available CRT-8SJ31J with 70mm diameter screen size to repeat the Thomson's experiment and determine e/m of the charged particles. The cathode ray tube has three parts, namely the cathode assembly consisting of a filament which on heating emits electrons, the anode which is kept at high potential accelerating the emitted electrons, and the grid which focuses the electron beam. The screen is coated with a fluorescent material which glows when the electrons impinge on it. There are two deflection anodes; the first is the X-plate and the second consists of a pair of two Y-plates, P and Q. By applying an electric- and/or a magnetic- field to this pair of plates, the direction of movement of electron beam can be altered. By using the commercially available 8SJ31J cathode ray tube (CRT), I determine electronic charge to mass ratio (e/m) by subjecting the electron beam to electric and magnetic fields. The purpose of this article is to show that the experimentally measured value is in close agreement with the standard value of this ratio.

Conceptual Description

If an electric field, E, is applied between the two plates perpendicular to the direction of electron beam passing through the space between the plates, the force acting on an electron in the upward direction of motion is given by[1,4]

$$F = eE \qquad ....1$$

where

F is the force acting on an electron,

e is the electronic charge =1.6x10-19Coulomb, and

E is the applied electric field.

Because of the applied electric field, electrons travel in a semicircular path and strike the screen at the point M1. By reversing the polarity of the voltage applied to the plate, electrons can be moved in the downward direction in a semicircular path as shown in Figure-1.

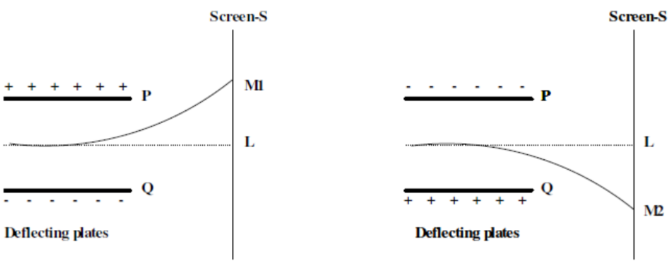

Figure-1: Deflection of electron beam by an electric field [7]

Instead of electric field if we apply a magnetic field perpendicular to the direction of electron flow, similar deflection of the beam takes place by reversing the magnetic field in which case also the direction of the beam gets reversed similar to the deflection caused by the electric field. If r is the radius of the semicircular path traversed by an electron in the magnetic field, the force acting on the electron is given by[4,7

$Bev = (mv^2)/r$ 2

where

B is the applied magnetic field, v is the velocity of the electron at the point where it enters the magnetic field, and r is the radius of the circular path traversed by the electron.

From Equation-2, e/m is given by

$\frac{e}{m} = \frac{v}{Br}$ 3

In order to determine the ratio e/m, one needs to know the value of the magnetic field applied, the velocity of the electron, and radius of semicircular path traced by the electron.

(a) Determination of electron velocity (v)

With the application of electric field, the electron beam moves to position M1 as shown in Figure-2. Now the magnetic field is applied so that the beam deflects back to its original position at O. When the magnetic force is equal to the electric force, the beam comes back to its original position. Hence one can write[1]

$$Bev = eE$$

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

$\frac{e}{m} = \frac{E}{B^2 r}$ 4

Thus the electron velocity is equal to the ratio of the two applied fields which is known. Hence v can be determined.

(b) Determination of radius (r) of the semicircular path traced by the electron beam

In order to determine the radius, r, one needs to consider the geometry of electron path as shown in Figure-2. An electron entering between the pair of plates PQ at O will trace an arc and leave the plates at R and then move in a straight line path and strike the screen at the point M2. OA is the path traced by the electron when there is no applied field. The line joining the electron path after leaving the plates is extrapolated to meet the OA line at T. Two perpendicular lines OC and RC are drawn to meet at C which forms the circle of radius r. OC and CR are two perpendicular lines drawn to meet at C. From the geometry one can write

$$\angle OCR = \angle ATM2 = \theta$$

$$\tan\theta = \frac{AM2}{AT} = \frac{OX}{OC}$$

$$r = OC = \frac{ATxOX}{AM2}$$

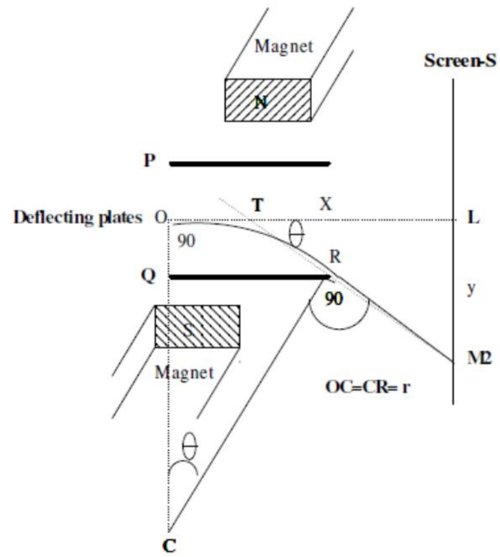

Figure-2: Geometry of the electron path[4]

If L is distance between the screen and center of the two parallel plates,

AT= L

OX is the length of the parallel plates

OX= l

LM2 = y is the distance the spot moves on the screen, which can be measured on the

graduated screen of the CRT. Hence

$$r = \frac{Ll}{y}$$

Substituting for radius and velocity, e/m is given by

$$\frac{e}{m} = \frac{yE}{LlB^2}$$

If V is the voltage applied between the two parallel plates and d is the separation between

them, then

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

Hence

$\frac{e}{m} = \frac{v_y}{dLlB^2}$................................5

(c) Measurement of magnetic field (B)

The magnetic field at the center of the two plates P and Q, cannot be measured using a gauss meter because the magnetic field produced by bar magnets is of the order of 10^{-3} Tesla which is quite low. Hence conventional methods are used for this. The magnetic field strength, B, can be calculated knowing the pole strength and dimensions of the bar magnet or by the well known method using a magnetometer which does not need information on any dimensional parameters of the magnet. In this method the bar magnets are placed perpendicular to the earth's magnetic field, as shown in the Figure-3. The CRT is aligned parallel to the earth's magnetic meridian in which case the electron beam travels parallel to the magnetic meridian.

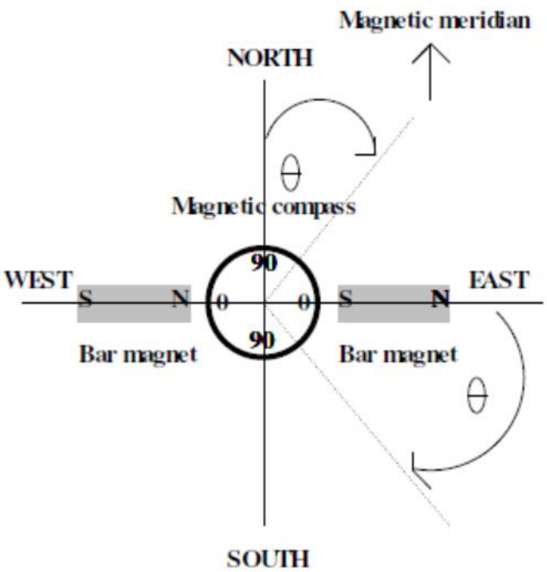

Figure-3: Magnetic compass used for measuring magnetic field[1]

The magnetic field strength at the center of the compass due to a bar magnet is given by[1]

$$B = H\,tan\theta$$

where

H is earth's magnetic field $=3.83 \times 10^{-5}\,T$ at Wolaita, and
θ is the angle of deflection of the compass needle.

The permeability of vacuum (μ_o) does not come into picture in this case, because the magnetic field produced by a moving electron or vice versa is not being considered here[1,4,7].

Hence,

$$B = H\,tan\theta$$

$$K = lLd, Hence$$

$$\frac{e}{m} = \frac{v_y}{dLlB^2} = \frac{v_y}{kB^2} = \frac{v_y}{ktan^2\theta H^2} \text{..6}$$

From this equation if one draws a straight line graph taking v_y along Y-axis and $tan^2\theta$ along X-axis, the slope of the straight line will be the average value of

$$Slope = \frac{v_y}{tan^2\theta}$$

which can be substituted in Equation-6 to obtain the value of e/m

$$\frac{e}{m} = \frac{v_y}{ktan^2\theta H^2} = \frac{Slope}{kH^2} \text{..7}$$

As indicated above, $K = lLd$ is known as CRT constant. As the data on the physical parameters of the tube is not supplied by the manufacturer, we had to cut open the tube for measuring them. The measured values of these parameters are: The length (L) distance from the center of the Y deflecting plates to the screen L =12.3cm (This can also be measured without breaking the tube, being the length of blackened portion of the CRT which is visible from outside.)

Over the years due to the change in technology, the CRT design has also changed. The Y-and X- deflecting plates are no longer parallel plates but are horn shaped. Figure-4 shows their dimensions for 8SJ31J CRT. The X-plates are connected to voltage source and there is a non-uniform electric field inside horn shaped X-plates. The electric field decreases along the horn length. The electric field is a constant wherein the electron makes entry in to the X-plates because of its uniform separation (10mm length of the X-plates are parallel). Hence there is an average electric field throughout the length of plates. Or the electric field is present along the length of the tube and hence[1,4,7]

$$Length\ of\ the\ X - plate = l = 3.1cm$$

The magnets are placed perpendicular to the Y-plates. Hence inside the two Y-plates there is non-uniform magnetic field. This field is present throughout the width and length of the Y plates. Hence width of the Y-plate is taken as plate separation d

$$Width\ of\ the\ Y - plate = d = 2.8cm$$

$$K = 12.3x3.1\ x\ 2.8 = 106.7\text{cm}^2 = 106.7\text{x}10^{-6}m^{3.}$$

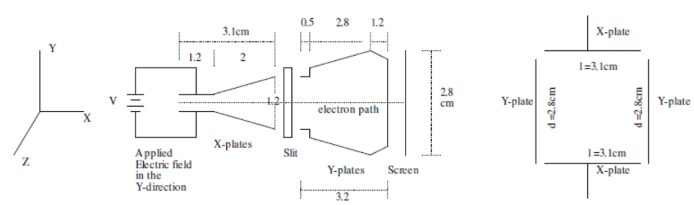

Figure-4: Structure and dimensions of CRT[7]

Materials and Methods

(a) Apparatus used

The apparatus used to determine e/m is shown in Figure-5. It consists of 1000V power supply, deflection voltage ± 25V, X-shift, focus and intensity controls. A deflection magnetometer with U-shaped stand and a set of bar magnets.

Figure-5: Experimental set-up for determination of e/m

- The magnetic meridian, giving the direction of earth's North-South magnetic field, has been marked on the center of a study table.

- The U-shaped stand has been placed on the table and its two arms have been made perpendicular to the magnetic meridian.
- The CRT has now been placed in the arms of the U-shaped stand. In this position the axis of the CRT has been parallel to the earth's magnetic field.
- The CRT has now been connected to the power supply kept away from the CRT and has been switched on. The brightness and focus knobs have been adjusted to get a bright spot on the CRT screen. With X- and Y- deflection voltage knobs turned to the minimum position, the position of the spot on the screen has been noted.
- Initial position of the spot has been reckoned as 0.0cm
- The two bar magnets have been placed on either side with opposite poles and at equal distance from the tube on the two arms of the U-shaped deflection magnetometer stand. The distance, D, has been read from the scale
- D = 3cm on the left arm and 3cm on the right arm
- The spot has moved up or down (Y-direction) depending on how the bar magnets have been placed.
- The distance moved by the spot on the screen has been noted. This is the 'y' deflection y =3.3cm
- The Y-deflection voltage has now been applied and so spot has come back to its origin position at 0.0. The deflection voltage has been read from the digital meter. This gives the value of V as V= 27.3 Volt
- This has completed the first trial. The Y-deflection voltage has now been brought back 0.0V and the magnets have been positioned at 4cm on both the arms to repeat the experiment. The distance moved by the spot
- y =2.6cm
- V=21.5V have been noted
- The trial has been repeated by keeping the two magnets at different distances on the arms and applying voltage to bring the spot back to 0.0 positions. The readings obtained have been tabulated in Table-1.
- In the second part of the experiment the position of the magnets has been reversed so that the deflection of the spot has been on the opposite side. The polarity of the deflecting voltage has also been reversed by turning the switch to the reverse position. The readings of deflection y, and deflecting voltage for different positions of the magnet have been recorded in Table-2.
- The CRT has now been removed without disturbing the arms and a compass has been placed in its place with its pointer reading 90^0-90^0 along the magnetic meridian and 0^0-0^0 perpendicular to the magnetic meridian.
- The two bar magnets have now been placed at a distance of 3cm on both the arms and deflection in the compass is noted (reading of any one of the two pointers is enough for this purpose).
- For various positions of the magnet given in Table-1, the deflection angle has been noted and recorded in Table-1. Value of the tangent of the angle has also been recorded and $tan^2\theta$ is calculated and presented in Table-1.
- The magnets have been reversed in their positions and the deflection angle, θ, of the compass needle has been noted for various positions of the magnet and recorded in Table-2. $Tan\theta$ and $Tan^2\theta$ have also been calculated and presented in the Table-2.
- A graph has been drawn with $Tan^2\theta$ on X-axis and the product 'Vy' on Y-axis, as shown in Figures-9 and 10 for the forward and reverse case respectively.

Data and Data Analysis

Table-1 Deflection of the spot and voltage applied in forward (upward) direction

Position of the magnet (D)cm	Spot deflection y(cm)	Y- deflecting voltage (V)	V_y	Deflection θ	Tanθ	$Tan^2θ$
3	3.28	27.28	90.1	80.01	5.68	32.26
4	2.70	21.51	55.90	76.50	4.16	17.30
5	2.01	17.01	33.81	73.01	3.27	10.69
6	1.63	13.61	21.77	69.02	2.61	6.80
7	1.3	11.00	14.30	65.00	2.14	4.58
8	1.11	9.21	10.12	65.50	2.20	4.84
9	0.91	7.60	6.84	55.00	1.43	2.04
10	0.71	6.52	4.56	51.01	1.23	1.51

Table-2 Deflection of the spot and voltage applied in reverse (downward) direction.

Position of the magnet (D)cm	Spot deflection y(cm)	Y- deflection voltage(V)	V_y	Deflection θ	Tanθ	$Tan^2θ$
3	3.21	-26.92	-86.08	80	5.67	32.15
4	2.40	-20.50	-49.20	76	4.01	16.08
5	2.00	-16.32	-30.98	74	3.49	12.20
6	1.50	-12.70	-19.05	70	2.75	7.56
7	1.21	-10.51	-12.61	65	2.14	4.58
8	1.00	-8.70	-8.70	61	1.80	3.24
9	0.81	-7.11	-5.69	57	1.53	2.34
10	0.69	-5.99	-4.19	51	1.23	1.51

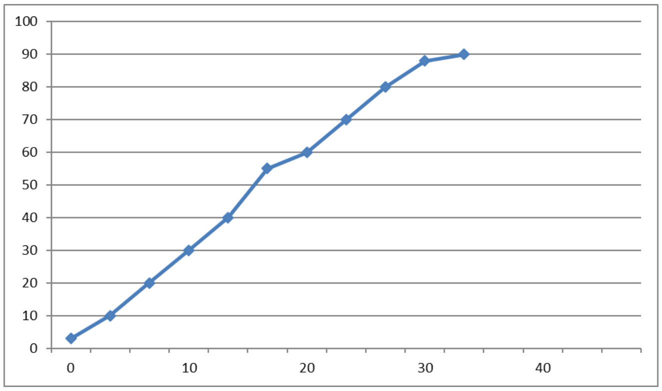

Figure-6: $Tan^2\theta$ versus Vy curve with forward voltage

The slope of the straight line is determined as

$$Slope = \frac{40 - 90}{12 - 30} = 2.788cmV = 0.02788mV$$

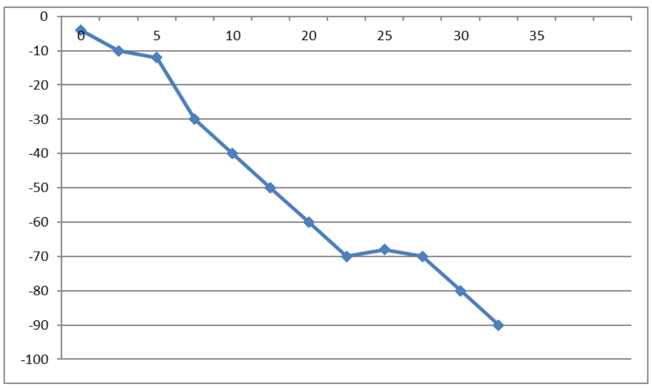

Figure-7: $Tan^2\theta$ versus Vy curve with reverse voltage

The slope of the straight line is determined as

$$Slope = \frac{-40 - -70}{10 - 21} = |-2.730cmV| = 0.02730mV$$

RESULT AND CONCLUSION

The average charge to mass ratio of an electron can be calculated by considering for both cases of voltage(forward voltage and reverse voltage):

i) For the case of forward voltage

$$\frac{e}{m} = \frac{v_y}{ktan^2\theta H^2} = \frac{slope}{kH^2}$$
$$= \frac{0.02788}{(3.83 \times 10^{-5})(3.83 \times 10^{-5})106.7 \times 10^{-6}}$$
$$= 1.78 \times 10^{11} Kg/C$$

ii) For the case of reverse voltage

$$\frac{e}{m} = \frac{v_y}{ktan^2\theta H^2} = \frac{slope}{kH^2}$$
$$= \frac{0.02730}{(3.83 \times 10^{-5})(3.83 \times 10^{-5})106.7 \times 10^{-6}}$$
$$= 1.74 \times 10^{11} Kg/C$$

Then,

Average value of charge to mass ratio of an Electron=

$$\frac{charge\ to\ mass\ ratio\ for\ the\ case\ of\ forward\ voltage + charge\ to\ mass\ ratio\ for\ the\ case\ of\ inverse\ voltage}{2}$$

Average value of $e/m = \frac{1.78\times10^{11}Kg/C + 1.74\times10^{11}Kg/C}{2} = 1.76 \times 10^{11} Kg/C$

Electron charge to mass ratio, e/m is found to be 1.76×10^{11}Kg/Coulomb, which is very close to the currently accepted value 1.758$\times$ 10^{11} Kg/Coulomb.

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