C. J. Overbeck
Professor of Physics
Northwestern University

R. R. Palmer
Professor of Physics
Beloit College

R. J. Stephenson
Professor of Physics
The College of Wooster

Marsh W. White
Professor of Physics
The Pennsylvania State University

EXP. No. ....

RATIO OF CHARGE TO MASS FOR THE ELECTRON

OBJECT: To measure the ratio of the charge of an electron to its mass.

METHOD: A stream of electrons is accelerated by having them fall through a measured potential difference. This stream is projected into a uniform magnetic field, perpendicular to the velocity vector of the electrons, that causes the electrons to bend into a circular path. The value of the ratio of charge to mass (e/m) is computed from the relationships between the measured accelerating potential difference, the magnetic flux density, and the diameter of the circular path which the electron beam describes.

THEORY: The discovery of the electron as a discrete particle of electricity is generally credited to the British physicist Sir J. J. Thomson (1856-1940). His extensive studies of cathode rays culminated in the quantitative observations of the deflection of these rays in magnetic and electric fields. These researches led to methods for the measurement of the ratio of charge to mass (e/m) for the electron. In his famous oil-drop experiments, Robert A. Millikan (1868-1953) was able to measure the charge of the electron (1.60206×10^{-19} coulomb). The currently accepted value for e/m is 1.75890×10^{11} coulombs/kg, and hence the mass of the electron could accurately be determined.

From the definition of the magnetic induction B in a magnetic field, the force F acting upon a charge e that is moving with velocity v perpendicular to the direction of the field, is given by

$$F = Bev \tag{1}$$

Since the direction of this force is always perpendicular to the velocity vector it follows that the force is a centripetal one. Such a force causes the electron to move in a circular path. The centrifugal force of reaction of the electron is equal in magnitude to the force exerted on the electron by the magnetic field. Hence

$$\frac{mv^2}{r} = Bev \tag{2}$$

where r is the radius of the circular path of the electron.

The kinetic energy acquired by an electron that falls through a potential difference V is given by

$$Ve = \frac{1}{2}\, mv^2 \tag{3}$$

From Eqs. (2) and (3)

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

The apparatus used in this experiment (Fig. 1) makes it possible to measure the values of V, B, and r and therefore to determine the ratio e/m.

The magnetic field which bends the beam is produced by a current in two Helmholtz coils. These coils are mounted vertically and, therefore, produce a field in the horizontal direction. When the distance between the coils is equal to the radius of either coil a nearly uniform field is produced at the midway point. This is because the field contributed by each coil is diminishing with a constant rate over a short distance. The diminution of the field of one coil is compensated for by the equal increase in the field produced by the other coil.

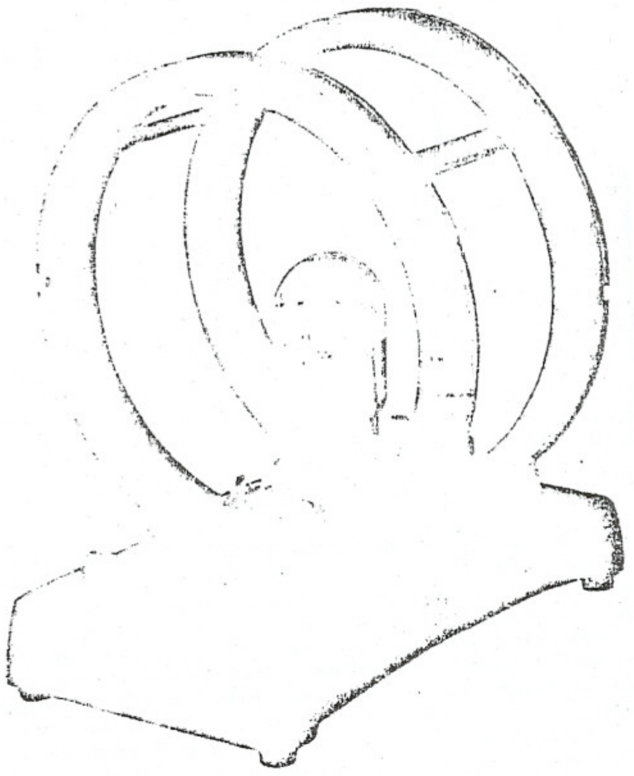

Fig. 1. Helmholtz coils.

The electron tube is held in a socket mounted between the coils, and on their common axis. The currents in the coils must be in such directions that the fields of the coils are in the same direction along their common axis. The magnitude of the flux density B at the central point is given by

$$B = \frac{8\mu_0 NI}{\sqrt{125}\, R} \tag{5}$$

where N is the number of turns per coil, I the current in the coils, R the coil radius, and μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ weber/amp-m). The flux density is given in webers/meter^2 when I is in amperes and R is in meters.

By combining Eqs. (4) and (5) an expression for e/m can be obtained that includes only constants for a given set of coils and the measurable quantities V, I, and r. When the specified mks units are used e/m is then expressed in coulombs/kilogram.

APPARATUS: The major items of the equipment consist of two parts: a specially designed Cenco three-element electron tube, and a pair of Helmholtz coils. Within the electron tube (Fig. 2) an "electron gun" is mounted, with its center line coincident with the vertical axis of the tube. The gun consists of an indirectly heated cathode which supplies the electrons; a grid, charged to a positive potential with respect to the cathode, which serves to focus the electron beam; and a circular plate, which is held at a high positive potential and thus accelerates the electrons. The electron stream is projected vertically through a small hole at the center of a disk which is mounted horizontally on the upper end of the electron gun. Four circles, with centers coincident with the hole and of radii 0.50, 1.0, 1.05, and 2.0 cm, are marked on the upper face of the disk. The bulb and disk are coated with a material which fluoresces when struck by electrons. The tube contains a trace of an inert gas that aids in focusing the electron beam as well as to cause the beam to make a visible trace.

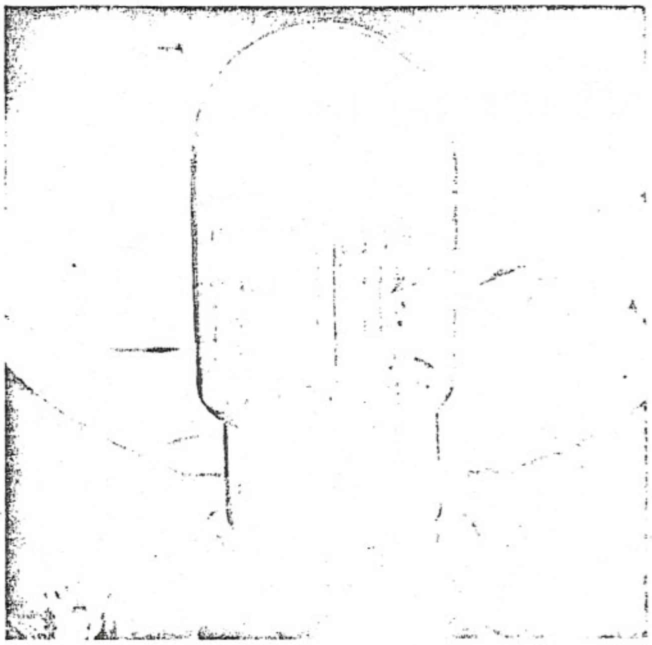

Fig. 2. Electron tube.

The Helmholtz coils of the Cenco apparatus are wound on non-magnetic aluminum rings. The rings have their rims milled away at opposite ends of a diameter to facilitate the measurement of the mean diameter. The number of turns of the coils is marked on the equipment. With a current of about 4 amp, a flux density of approximately 4×10^{-3} weber/m^2 is produced. The strength of the magnetic field can be adjusted by changing the current in the coils. Variation of either the accelerating potential difference in the tube or the strength of the magnetic field will cause the radius of the circle described by the electron beam to vary. If the beam is made to describe a semicircle above the disk and, on returning to the disk, strike one of the four circles marked on its face, the diameter of the semicircle is equal to the radius of that circle.

The following supplementary apparatus is needed for this experiment: a 1-amp dc ammeter; a 5-amp dc ammeter; a 11-ohm, 6-amp rheostat; a 44-ohm, 3-amp rheostat; a (50/250) volt dc voltmeter; a (60-220)-volt dc power supply unit (current range up to 40 ma); two 12-volt storage batteries; tap key; knife switch; reversing switch.

The electron-tube filament current should be (0.5-0.6) amp at (6.0-6.3) volts. IMPORTANT: The life of the expensive tube is limited. To ensure maximum life the tube current should always be kept at the lowest value that will produce a well-focused, visible beam. A 0.75-amp fuse should be included in the filament circuit. A plate potential of (60-135) volts gives the best operating range. If the plate or grid current is more than a few milliamperes the filament current is higher than necessary. The grid potential should be positive, less than that of the plate, and adjusted to give the beam a sharp focus. The focusing of the electron beam is accomplished by the focusing grid and also by the ionization of the gas in the tube. The positive ions that are produced in the gas will gradually destroy parts of the tube; therefore their number should be kept at a minimum. The filament current and the plate potential should be kept as low as possible to still give a well-focused, visible beam. The key in the plate circuit should be closed only when observations are being made, in order to prolong the tube life.

Precautions must be taken to see that no significant stray magnetic field affects the apparatus. The effects of the earth's magnetic field is not large, in comparison with that of the coils, but a correction can be made for this if desired. In addition to the usual instrumental errors it is instructive to consider some other sources that may limit the precision of the results of this experiment. Inability to judge accurately when the electron beam is exactly on the circle is one source of error. The errors may be minimized by taking the average of a number of readings. Since the entire tube is in the magnetic field the electrons are deflected along a path having various radii of curvature as they are accelerated from the cathode to the anode. The electrons consequently emerge from the anode at an angle to the axis of the tube. The center of curvature of the emerging beam is, therefore, below the lev. of the anode. If conditions are adjusted so that the beam strikes a circle on the anode disk, the true diameter of the beam circle is larger than the observed value. This results in a value of e/m that is larger than the standard value. Electrostatic fields in the bulb may cause errors if the tube has a different potential than the anode. Contact potentials may produce some effect in the measured values of V.

PROCEDURE: 1. Explore the area around the Helmholtz coils to see that there is no serious interference from stray magnetic fields, including the earth's field. This may be done by the use of a compass or a flip coil connected to a galvanometer. See that the meters (if not magnetically shielded) are placed well away from the Helmholtz coils and that inductively wound rheostats are not too near the electron tube. By the use of a compass make certain that the fields of the two Helmholtz coils are in the same sense.

2. Connect the apparatus as shown in Fig. 3. The electrical connections to the electron tube are shown in Fig. 4. Be sure to have the instructor check the wiring before the power sources are attached. By means of the rheostat adjust the filament current to about 0.7 amp. After allowing the cathode to heat for about 2 min reduce the filament current to the normal value of 0.5 to 0.6 amp, then apply the plate potential and notice the blue stream of electrons which rises from the hole in the center of the disk. Adjust the plate potential to (60-100) volts and vary the grid potential to bring the beam into a sharp focus with a stream having a diameter of about 2 mm.

3. With the rheostat set for high resistance close the circuit to the field coils and then vary the current to (3-5) amp until the beam bends into a complete semicircle. Adjust the plate potential to vary the accelerating potential difference and also change the field current until the beam falls on one

of the marked circles. (The grid potential must be adjusted when the plate potential is changed in order to keep the beam in focus.) Record the plate potential, the field current, and the radius of the described circle. Measure the mean radius of the Helmholtz coils and record the number of turns per coil.

4. Repeat the observations to obtain sets of data for each of the circles on the disk.

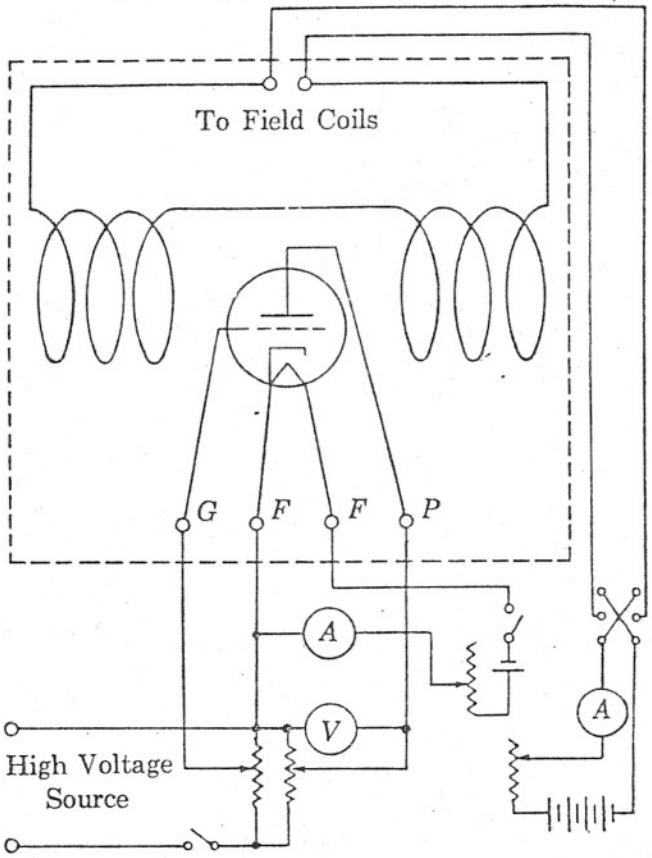

Fig. 3. Arrangement of apparatus for measurement of e/m.

INTERPRETATION OF DATA: From the recorded data and the use of the working equation calculate the values of e/m obtained from the sets of observations. Record the percentage difference between the standard value of e/m and the mean of the values calculated from the observations. Do there seem to be sources of systematic error? Try to identify some of the sources of error.

QUESTIONS: 1. From the data given in the Theory calculate the value of the "rest mass" m_0 of the electron. From

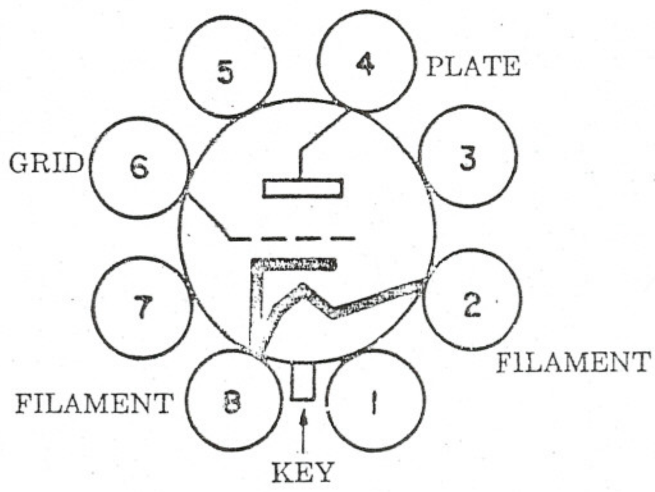

Fig. 4. Electrical connections to the electron tube.

relativity theory the mass of an electron is now known to be a function of its speed as given by the equation $m = m_0 \sqrt{1 - v^2/c^2}$. Is a mass correction appreciable for the present experiment?

2. Calculate the mass of an electron that is moving with a speed half that of light. What would the mass be for a speed 99.5% that of light?

3. The mass of a proton at rest is 1.67×10^{-27} kg. Calculate the value of e/m for a proton.

4. What potential difference would an electron have to fall through to acquire a speed of 3.00×10^{6} m/sec?

5. An electron moving with a speed of 1.50×10^{7} m/sec is projected at right angles into a uniform magnetic field of flux density 6.50×10^{-3} w/m². Calculate quantitatively the new path of the electron.

6. How would you expect the value of e/m in this experiment to vary if you changed the residual gas to one of greater atomic mass? to the same gas at a higher pressure? to an apparatus capable of measuring e/m for protons?

7. Show clearly how the effect of the earth's magnetic field in this experiment might be neutralized by the use of an auxiliary pair of Helmholtz coils. Suggest another way to do this.

8. Calculate the speed of an electron that has fallen through a potential difference of (a) 125 volts, (b) 125 megavolts.