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# Busch Tube for Determining $e/m$ for the Electron

H. V. NEHER
*Department of Physics, California Institute of Technology, Pasadena, California*

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A tube is described which is fabricated from parts readily available to most departments of physics. With the proper auxiliary equipment, it is possible to determine the ratio of charge to mass of the electron to 0.2–0.3% in a reasonable time. It is of additional interest that from the data giving the magnetic field of the solenoid, a value for the earth's magnetic field may be obtained.

## I. INTRODUCTION

IN 1922 Busch[1] described a method he used to determine the ratio of charge to mass for the electron. The value at which he arrived was considered at that time to be one of the most precise that had been obtained using the method of deflection by magnetic fields. With some care as to choice of materials, it is not difficult to fabricate a tube that can be sealed off the pumps and which has built into it the necessary geometry to achieve a high degree of accuracy.

Some laboratories have used cathode ray, oscilloscope tubes to perform the Busch experiment. Such tubes usually suffer from the following disadvantages: (1) the metal parts are nearly always made of nickel and are therefore magnetic. The stray magnetic field thus introduced will affect the paths of the electrons. (2) The beam must be deflected since it is a pencil. This is usually accomplished by applying an alternating potential to the deflecting plates. An uncertainty thus enters as to the length of the drift region. (3) There is no aperture to select out only those electrons that make certain angles with the axis of the beam, thus giving a blurred spot on the screen.

## II. PRINCIPLES OF OPERATION

The principles of operation of the tube herein described are covered in introductory physics courses. Consider a diverging beam of electrons emerging from a small hole in the final electrode $d$ of the electron gun $G$ shown schematically in Fig. 1. It enters a space that is free of electric fields and which has a uniform longitudinal magnetic field of strength $B$. The electrons emerging from $d$ have a velocity component $v\cos\theta$ along the axis of the tube and $v\sin\theta$ perpendicular to the axis. Viewed along the axis of the tube, the electrons describe circles. When they have made one revolution in going the distance $l$ to the screen $S$, they will return to the axis of the tube and an image will thus be formed of the opening in $d$. Electrons which make different angles $\theta$ with the axis come to a focus at slightly different distances along the axis. To obtain a sharp focus, it is necessary to choose out, by means of an annular aperture $A_1$, those electrons with nearly the same angle emerging from $d$. To achieve this sharp focus, which is most sensitive to a change

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[1] H. Busch, Physik. Z. **23**, 438 (1922); Ann. Physik **81**, 974 (1926).

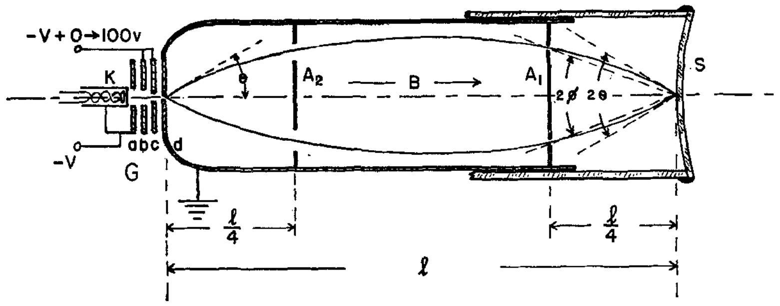

FIG. 1. The electron gun $G$ produces a controlled beam of electrons that diverge after being focused through the small hole in electrode $d$. For a given velocity, those electrons making an angle $\theta$ with the axis of the tube are brought to a focus by the magnetic field $B$, after passing through the two annular apertures. The second mode occurs when the beam first comes to a focus between the two apertures. Drawing not to scale.

of magnetic field, consideration must be given both to the diameter of the annular opening and to its width. In the tube to be described, the drift distance $l$ is about 50 cm. The annular aperture $A_1$ is a distance of $l/4$ from the screen $S$. A somewhat wider aperture $A_2$ at a distance of $l/4$ from the gun roughly defines the beam. The mean diameter of the opening in $A_1$ is 2.4 cm and its width 0.08 cm. Tests, as well as calculations, show that, with a constant beam potential, the expected error in a single setting of the current that determines the magnetic field which gives best focus of the spot on the screen is approximately 0.1%.

The time required for the electrons to travel the distance $l$ is

$$t = l/v\cos\theta.$$

If they have the cyclotron frequency $\omega$ in a plane at right angles to the axis of the tube,

$$\omega = Be/m$$

or

$$t' = \frac{2\pi}{Be/m},$$

where $t'$ is the time for one revolution. A focus will occur if $t = nt'$ where $n = 1,2,3,\cdots$ and corresponds to different modes of operation. Thus,

$$\frac{2\pi n}{Be/m} = \frac{l}{v\cos\theta}.$$

Now, for nonrelativistic velocities, $v = (2Ve/m)^{\frac{1}{2}}$; hence,

$$e/m = 2V[2\pi n\cos\theta/Bl]^2. \tag{2}$$

The value of $B$ is obtained from the dimensions of the solenoid, the current, and number of turns. The solenoid used with the tubes here described was nearly twice the length of drift space in the tube. Even so, the change in magnetic field along the axis needs to be taken into account. An integration over the length of the tube gives the effective magnetic field. To terms of second order, this is

$$B = \mu_0 ni\left[1 - \frac{d^2}{2(L^2 - l^2)}\right], \tag{3}$$

where $d$ is the mean diameter of the solenoid, $L$ its length, and $l$ the length of the drift space in the Busch tube.

The value of $\theta$ entering into Eq. (2) may be found from the geometry of the tube. The envelope of the paths of the electrons that go through the annular ring in $A_1$ is a sine curve. For the case where the ring opening in $A_1$ is $l/4$ from one end, it is readily shown that if $\varphi$ is the mean angle subtended by the opening at the screen, we find, to the desired approximation,

$\theta = (\pi/2\sqrt{2})\varphi$ for the first mode, and
$\theta = (\pi/2)\varphi$ for the second mode.

## III. DETAILS OF CONSTRUCTION

### A. Electron Gun

The source of electrons is a commercial, indirectly heated cathode which is used by the Radio Corporation of America in their television tubes. It is operated under space-charge limited conditions. With such operation, the gun must be capable of doing the following:

1. Control the current in the beam with a given over-all potential on the gun.
2. Give an electron beam that diverges on leaving electrode $d$, Fig. 1.
3. Focus most of the current through the small hole in $d$.

The gun was originally designed with the help of an electrolytic tray. The combination of electrodes $a$, $b$, and $c$, Fig. 1, forms an electron lens that focuses the electrons from the cathode $K$ through the small hole in $d$. Considerable control over this focusing may be obtained by varying the size of the holes in these electrodes as well as the spacings and thickness of the metal disks. The dimensions that have been found to give good results are as follows:

| | |
|---|---|
| Diameter of cathode | 3.2 mm |
| Thickness of $a$, $b$, $c$, and $d$ | 0.46 mm |
| Distance from end of cathode to left side of $a$ | 0.25 mm |
| Spacing $ab=bc=cd=$ | 1.00 mm |
| Size of hole in $a$ | 3.2 mm |
| Size of hole in $b$ | 2.00 mm |
| Size of hole in $c$ | 1.60 mm |
| Size of hole in $d$ | 0.50 mm. |

To hold the positions and spacings of these electrodes, two alignment holes are drilled in each piece. The electrodes are then slipped on to two close-fitting ceramic tubes. Proper thickness spacers are used and the electrodes are cemented in place with "sauereisen" cement.[2] The ceramic piece holding the cathode is also cemented to these two ceramic tubes. The gun thus becomes a unit with all parts rigidly held and aligned and may then be fastened to the leads of the glass stem. The final assembly appears as shown in Fig. 2. Note: all metal parts must be nonmagnetic. The most convenient metal to use is nonmagnetic stainless steel.

### B. Glass Envelope

Since solder glass that matches lime or lead glass is used to fasten the ends onto the tube and since lime glass is readily available, this is used. To avoid electric charges being built up on the interior glass walls, two designs have been employed. (1) A thin stainless steel sleeve is slipped inside the tube which extends the full length of the drift region. (2) The inner wall of the glass tubing is made conducting.

Glass may be made electrically conducting by procedures described in the literature.[3] The method used here was to make a furnace from a 5-ft long stainless steel tube 2 in. in diameter. The steel tube was wound with resistance wire and covered with mineral wool. A baking temperature of about 410°C is required. The furnace was placed horizontally and, with the glass tube to be coated inside, a stream of air was blown through after passing over hot $SnCl_2$. It is desirable to protect a length of several inches of the glass tubing from being coated near the end where the electron gun is to be mounted. This can be done with a thin metal sleeve. With some

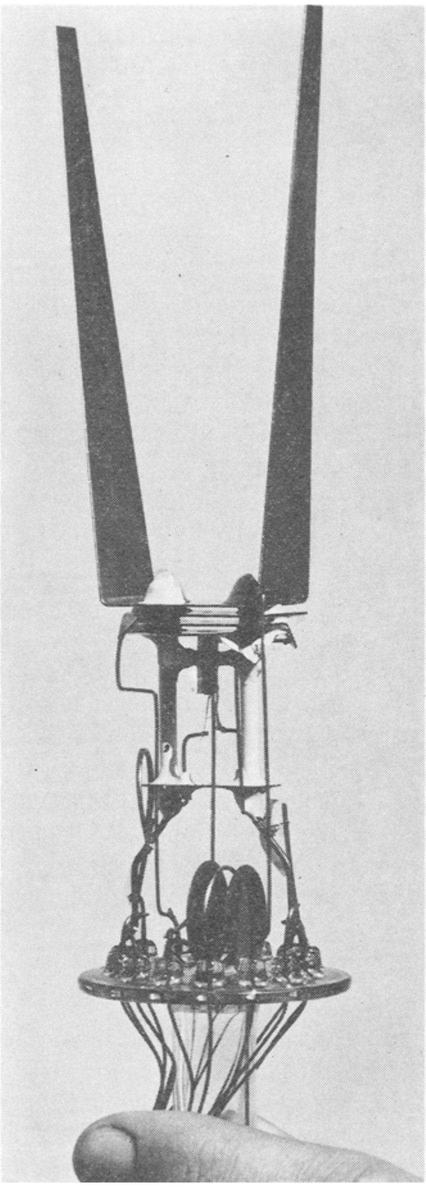

FIG. 2. The electrodes and cathode of the gun are held rigidly in alignment by cementing the parts to ceramic supports while they are being held in proper position.

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[2] Sauereisen Cements Company, Pittsburgh, Pennsylvania.

[3] Robert Gomer, Rev. Sci. Instr. **24**, 993 (1953).

care, a coating will be formed which has a resistance as low as 5000 ohms between the ends and the light transmission will not be reduced appreciably. The advantage of such a coating is that the inside of the tube is not hidden from the view of the student.

The electron beam comes to a focus at the screen *S* when adjustments are correct. To make possible a precise determination of the distance *l*, the screen is made of a "watch glass" with the convex side toward the gun. Before sealing onto the end of the glass tubing, the watch glass (obtainable from chemical supply houses) is given a conducting coating with $SnCl_2$. After sealing on with solder glass, the conductivity of the coatings, in all cases so far encountered, extends under the solder glass to the outside.

### C. Fluorescent Coatings

The screen and annular rings are given a thin coating of fluorescent material.[4] The coating is easily applied by precipitating a fine suspension of the material in water and syphoning off the liquid. The coating should be sufficiently thin as to be partially transparent.

### D. Assembly

The tube is assembled using the techniques described by Harries.[5] On a 1.6-in. diameter 14 conductor glass stem are mounted the gun, two getters, and a Penning gauge. The two annular apertures are held at the proper spacing inside the tube by two long stainless steel strips. These strips are fastened to the electrode *d* (Fig. 1) of the gun. Although electrical contact with the inner wall of the glass tubing may be made by these strips, thin, springy pieces of metal fastened to the strips at each end will insure good contact.

### E. Baking and Sealing Off

It is found desirable to neck down the glass tubulation on the glass stems before evacuating, otherwise difficulty with the glass caving in may later be experienced in the process of sealing off. The tube is baked for 6–8 hours at 380°C with a good vacuum inside. On cooling, the cathode is activated. This is done by gradually raising the potential applied to the heater of the cathode, passing through the working voltage and until the power input is from 2 to 3 times the rated operating value. When the cathode reaches a dull red heat, considerable gas will be given off. If a potential of 0–200 v is applied to electrodes *b* and *c* (Fig. 1) while 2 to 3 times operating power is being fed to the heater, the cathode emission will gradually build up until one should obtain 5–10 ma of current. The two getters are then fired sufficiently to evaporate a small amount of metal. This ensures that the gases in the getters come off and are pumped out. The tube is then sealed off. As described by Harries,[5] the BaAl getter is fired first, then the titanium getter. Further pumping may be done with the Penning gauge.[5]

For protection, the Busch tube is mounted inside a lucite tube, using rubber or felt spacers.

## IV. AUXILIARY PIECES OF EQUIPMENT

The solenoid used consists of 1622 turns of No. 18B- and S-gauge Formvar covered wire wound in two layers. It is wound on a form that is mounted in a framework so that the axis of the solenoid may be tipped to any angle with the vertical.

To measure the length of the drift region *l* (Fig. 1), a trough is used, at the bottom of which is a long glass mirror mounted beside a calibrated meter scale. By aligning the eye with the screen or electrode *d* and its image in the mirror, parallax may be eliminated and the distance determined to a small part of a millimeter.

The power supply should have its potential regulated and the positive side grounded. The potential of the supply built for the tubes here described is adjustable from 900–1100 v. Two precision resistors across the output allow a potentiometer to be used, thus permitting an accurate determination of voltage. To determine the beam current, a 0–100-$\mu$a meter is used. To control the beam current, the power supply is also provided with a variable potential of 0–+100 v with respect to the cathode. This is applied to electrodes *b* and *c*, Fig. 1. Only a few microamperes of current flow to these electrodes.

To take advantage of the precision of the rest

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[4] Calcium tungstate gives a bluish color. It is obtainable from E. I. DuPont de Nemours and Company, Patterson Screen Division, Towanda, Pennsylvania.

[5] J. H. Owen Harries, Am. J. Phys. 28, 698 (1960).

of the equipment, the solenoid current should be determined with a standard resistor and potentiometer.

### V. EXPERIMENTAL DATA

The following data were obtained on tube No. 4. This tube had a metal sleeve surrounding the drift space.

To eliminate the effect of the earth's magnetic field, the axis of the solenoid was lined up with the earth's field as indicated by centering of the spot on the screen. The average of the solenoid current when the two fields were parallel and antiparallel was taken. (Table I.)

TABLE I. Values of solenoid current in amperes at a beam current of 5 $\mu$a.

| | First mode | Second mode |
|---|---|---|
| Parallel | 0.5682<br>0.5679<br>0.5692 | 1.1499<br>1.1514<br>1.1491 |
| | 0.5684 | 1.1502 |
| Antiparallel | 0.6061<br>0.6082<br>0.6060 | 1.1885<br>1.1885<br>1.1885 |
| | 0.6071 | 1.1885 |
| Av | 0.5877 | 1.1693 |

From Eqs. (2) and (3), the two values found for $e/m$ were

$$e/m = 1.760 \times 10^{11} \text{ coul/kg.}$$

$$e/m = 1.761 \times 10^{11} \text{ coul/kg.}$$

Taking an error of 0.1% in $V$, $B$, and $l$, the expected probable error in $e/m$ should be $\pm 0.2\%$. The value of $e/m$ given by Cohen *et al.*[6] is $(1.75890 \pm 0.00002) \times 10^{11}$ coul/kg.

### VI. DISCUSSION OF ERRORS

By referring to Eq. (2) for the value of $e/m$, some estimate may be made of the errors entering into its determination. On using precision resistors and a potentiometer, $V$ may be determined with an error of considerably less than 0.1%. Cos$\theta$ is a geometrical quantity and can certainly be determined to the necessary accuracy. If the length of the drift space is measured to 0.2 mm, the error in $l$ will be less than 0.05%. The determination of the magnetic flux $B$ is more involved. It is found that the solenoid current, for best focus of the beam, with beam potential constant, is a function of beam current. We may plot the solenoid current vs beam current and extrapolate to zero beam current. On doing this, it is found that a negligible change in solenoid current occurs below 5-$\mu$ beam current. A run of ten values of current for best focus, at a given value of beam current and beam voltage, indicates that the probable error in the average is approximately 0.05%. Even so, the uncertainty in $B$ is probably the largest statistical error in the determination of $e/m$ with this apparatus.

There are possible sources of systematic error with these Busch tubes, such as space charge effects and gas focusing of the beam. Such effects would be expected to become less important as the beam current is decreased, and the procedure described above for determining the solenoid current should give the correct value.

### VII. VALUE OF THE EARTH'S MAGNETIC FIELD

From the above data given in V, an accurate value of the total earth's magnetic field may be found. The difference in the magnetic field of the solenoid, when adjusted for best focus of the beam and when it is parallel and antiparallel to the earth's field, gives twice the strength of the earth's field. This is found to be:

| | First mode | Second mode |
|---|---|---|
| $\Delta B$ | 0.887 | $0.879 \times 10^{-4}$ wm$^{-2}$. |

This gives for the total earth's magnetic field, where this experiment was performed, an average value of $0.441 \times 10^{-4}$ wm$^{-2}$ or 0.441 gauss.

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[6] E. R. Cohen, K. M. Crowe, and J. W. M. DuMond, *Fundamental Constants of Physics*, Interscience Monographs in Physics and Astronomy (Interscience Publishers, Inc., New York, 1957), p. 267.