THE ANGULAR DISTRIBUTION OF ELECTRONS SCATTERED BY MERCURY VAPOR

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Abstract

Instead of using pressures of the order of 10^{-2} mm the apparatus described is designed for pressures in the range 10^{-3} to 10^{-4} mm. Heavy primary current densities are used to afford measurable scattered currents, and high angle scattering is found to be more easily measurable. It is found that the angular distribution curves for electrons scattered by mercury are not monotonic functions of the angle of scattering. For a given energy of incident electrons the curve passes through a minimum, the angular position of which depends upon the energy.

I. Scheme of Experiment

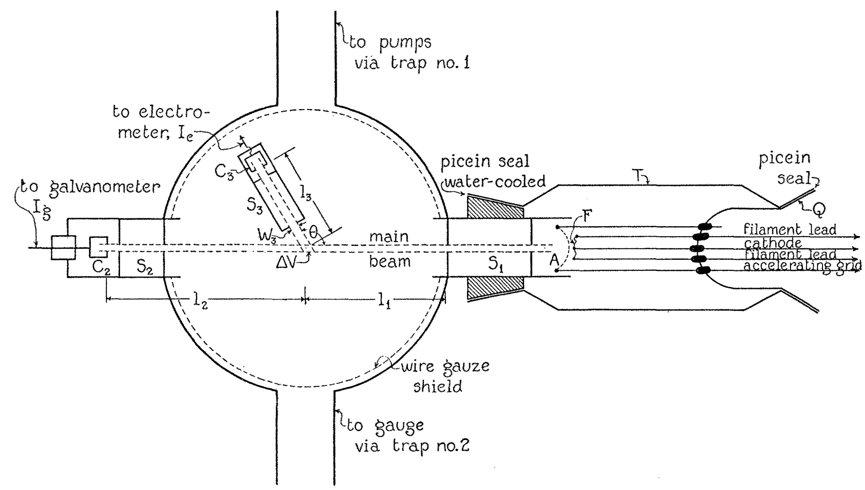


Fig. 1. Diagram of tube.

The principles of design of this type of apparatus are well enough known so that it will be necessary here to point out only the salient features.

The tube is constructed of brass. It is 15 cm in diameter, and shaped as in Fig. 1. Electrons are accelerated from the tungsten filament F (supplied at the center-tap), through the grid A, and retarded between the grid A and the first of the collimating slits S_1.

The circuits are so arranged that the entire enclosure is maintained at ground potential. The electron beam passes diametrically across the chamber to the slits S_2, and through these to the Faraday cage C_2.

The axis of the main beam is oriented to be parallel to the horizontal component of the earth's field, which is carefully neutralized by one set of large Helmholtz coils. A magnetic pendulum was used to determine the necessary current.

Slits S_1 and S_2 are optically aligned, and by means of another pair of large Helmholtz coils the vertical component of the magnetic field in the apparatus is adjusted until the main beam is received on C_2. By changing the current in the latter coils the beam can be moved back and forth across the slits S_2. This affords a means of measurement of the divergence of the beam.

Electrons scattered from the main beam are collected principally by the walls of the chamber, which are made more absorbing by the use of the copper gauze as shown.

A portion of the electrons scattered at an angle θ in the center of the apparatus, pass through the slits S_3 and reach C_3. The axis of collimation of slits S_3 passes always through the center of the apparatus as θ is varied. See Fig. 2 for a vertical section.

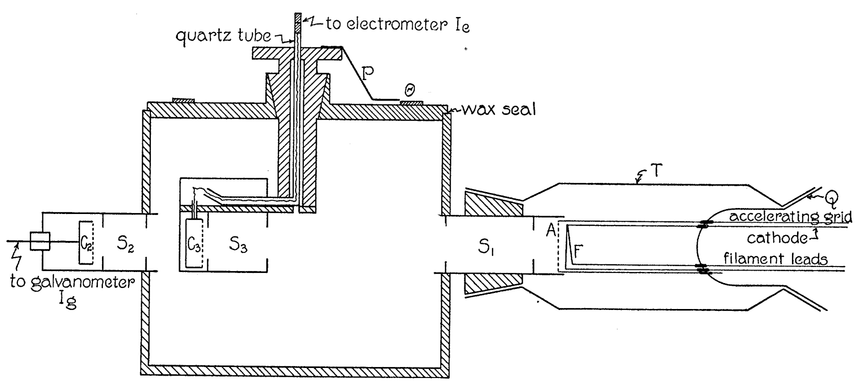


Fig. 2. Vertical section of tube.

Slits S_3 and cage C_3 are mounted in the lid on a movable, central, stem with a tapered joint as shown. A pointer P reads the angle θ, on a scale engraved on the lid.

Slits S_1 and S_2 are 10 mm long. Slits S_3 are 8 mm long. The spacings and widths are so adjusted that, with length considered, 90 percent of the electrons passing any pair of slits is contained within an angle of $\pm 1.5°$ of the central axis of that pair.

Other details such as accessibility of the filament or of the chamber, are explained by the figures.

The electric circuits are shown in Fig. 3.

II. Theory of Apparatus

Let ΔV be the volume of the intersection of the paths of collimation of S_1 and S_3. Let p be the gas pressure in mm Hg; α the coefficient of scattering in the expression,

$$I = I_0 \exp(-\alpha p x).$$

Let I be the current in amperes, at the point "x" measured along the main beam from ΔV; I_0 the main beam current entering ΔV; l_2 the distance from C_2 to ΔV; l_3 the distance from C_3 to ΔV (constant). Let $f(\theta)d\theta$ be the probability under given conditions that a scattered electron will be deflected between the angles θ and $\theta+d\theta$.

At any point x in the beam passing ΔV we have the current

$$I = I_0 \exp(-\alpha p x). \tag{1}$$

So in the distance dx

$$dI = -\alpha p I_0 \exp(-\alpha p x)dx. \tag{2}$$

$-dI$, is therefore the scattered current in the distance dx.

Let us consider now the current we can hope to receive on C_3 at the angle θ. Let I_s be the current scattered in ΔV; w_3 the width of slits S_3. Then

$$I_s = -dI = \alpha p I_0 \exp(-\alpha p x)dx = \alpha p I_0 w_3/\sin\theta.$$

since $x=0$ at ΔV and $dx=w_3/\sin\theta$. Hence the fraction of I_s that is scattered between θ and $\theta+d\theta$ is given by

$$I_s f(\theta)d\theta = \frac{\alpha p I_0 w_3 f(\theta)}{\sin\theta}\, d\theta. \tag{3}$$

Of this current only a fraction, K_3, will reach C_3 because of slits S_3. The current is also attenuated by scattering along the path of length l_3 from ΔV to C_3. So the current, I_e, received on C_3 is

$$I_e = \frac{\alpha p I_0 w_3 f(\theta) K_3}{\sin\theta}\, d\theta \exp(-\alpha p l_3). \tag{4}$$

Consider next the current received on C_2: because of the slits S_2 only a fraction, K_2, of the incident main beam will reach C_2. The beam is also attenuated by scattering along the path of length l_2. Hence the current, I_g, received on C_2 is

$$I_g = I_0 K_2 \exp(-\alpha p l_2). \tag{5}$$

If we divide (4) by (5) we eliminate I_0:

$$\frac{I_e}{I_g} = \frac{\alpha p K_3}{K_2} w_3 \frac{f(\theta)}{\sin\theta}\, d\theta \exp(\alpha p[l_2 - l_3]).$$

so that

$$f(\theta) = \frac{K_2 \exp(-\alpha p[l_2 - l_3])}{K_3 \alpha p d\theta w_3} \frac{I_e}{I_g} \sin\theta.$$

$$f(\theta) = K\frac{I_e}{I_g}\sin\theta \tag{6}$$

where

$$K = \frac{K_2 \exp(-\alpha p[l_2 - l_3])}{K_3 \alpha p d\theta w_3}.$$

The value of K is constant so long as one set of conditions is constant, since $d\theta$, K_2, K_3, l_2, and l_3, are all functions of a fixed geometry. The K's seem to depend upon the electron speed, and upon the condition of equilibrium of the apparatus. This is probably because the condition of the slit surfaces depends upon the bombardment they receive. During a given run, if the apparatus has previously been brought to equilibrium, K will remain quite constant. However, when the apparatus has been out of equilibrium between runs, K will vary by as much as a factor of 5.

It follows that by measuring I_e, I_g, and θ, the value of $f(\theta)/K$ can be calculated as a function of θ.

It is noted that the current I_e received by C_3,

$$I_e = \frac{\alpha p I_0 w_3 K_3 f(\theta) d\theta}{\sin \theta} \exp(-\alpha p l_3)$$

goes to zero for high pressures because of the exponent, and to zero for low pressures because of the factor p. However it goes to zero much more slowly

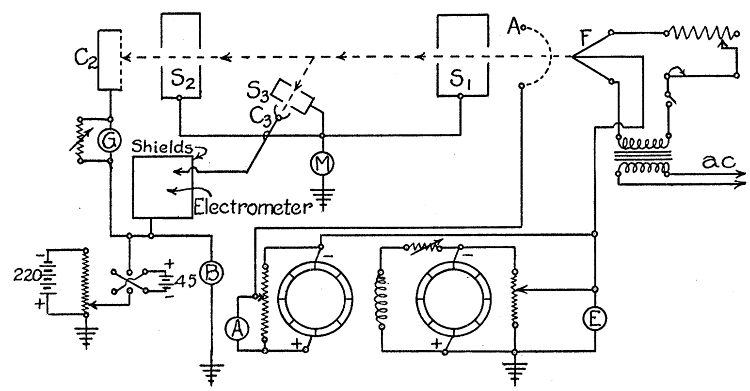


Fig. 3. Diagram of electrical arrangement.

on the low pressure than on the high pressure side of its maximum. This is fortunate since the maximum lies at such a high pressure that the condition of "single" scattering is not satisfied in an apparatus of practical dimensions.

In using lower pressures if the product pI_0 is kept constant, I_e can be maintained at a readable value.

I_e was measured by a "null" circuit using a modified Dolezalek electrometer.[1]

From the experimental values of α, and the dimensions of this apparatus, the mean free path of an electron is about the diameter of the apparatus at $p=10^{-3}$ mm Hg. Thus at the pressure used ($1.8\cdot 10^{-4}$mm) the condition for single collision scattering is well satisfied.

[1] J. M. Pearson, Journ. Op. Soc. 19, 6, p. 371.

In order to obtain the intensities of main beam desired some concessions had to be made in the voltage distribution of the electrons. Coated, equipotential, low temperature cathodes were tried, but were short lived owing to the heavy positive ion bombardment. Heavy tungsten was finally used, with a center-tap through which to supply the space current.

Studies were made of the voltage distribution of the electrons received on the Faraday cages. Two things were discovered, namely: (1) that the electrons were distributed over a range of 3 volts at E; and (2) that the cages were inefficient electron collectors. This was made evident by the fact that the electron current was cut off by a bias as much as 20 volts less than E, in vacuum, when the bias was applied to the cage. If however, the bias was applied to a grid somewhat ahead of C_2 (not shown), the cut-off bias was the same as E. This indicated that a deeper cage was necessary, or at least that an assisting gradient towards the cage was necessary.

Because of this low resolving power both at the collectors and at the filament, inelastic electrons were not resolved from the elastic electrons.

The currents received on C_2 are of the order of microamperes, and are measured by a suitably shunted wall galvanometer "G" (Fig. 3).

III. Manipulation

The apparatus is manipulated as follows:

(1). After several hours of pumping the filament is lit and the slits are bombarded. Liquid air is maintained on both traps. (see Fig. 4.) From two to five hours generally suffices to reach a state of equilibrium.

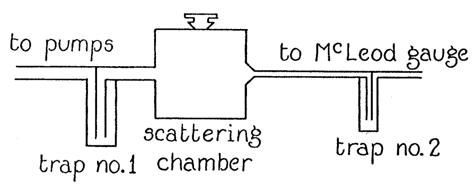


Fig. 4. Scattering chamber and connecting traps.

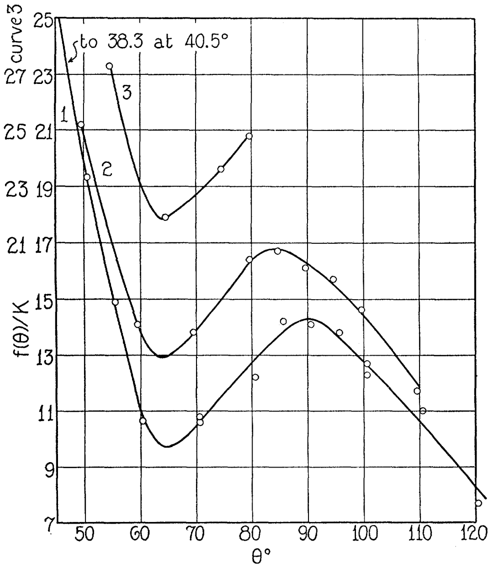
(2). When equilibrium is reached, an ice bath, vigorously agitated, is substituted for the liquid air on trap No. 1. Liquid air is maintained on trap No. 2, on the other side, connected to the chamber through a long tube. Thus after another lapse of hours the mercury vapor pressure inside the chamber becomes stable at very close to $1.8 \cdot 10^{-4}$ mm Hg.

(3). With the magnetic field neutralized and the values of the accelerating and retarding potentials adjusted, two sets of simultaneous readings of I_e and I_g are made at each setting of θ. When these pairs of readings check to ± 5 percent at each point, the run is accepted. Otherwise the apparatus is considered to be out of equilibrium.

In order to eliminate the effects of the positive ions that are collected due to the negative bias on the cages, readings are first taken with a low bias and then with a high bias so that the difference of the readings gives the electron current. The positives are usually of the order of one-tenth the strength of the electrons. The biases used are marked on the curves.

IV. Results

The curves of Figs. 5 to 9 give a graphic summary of the results obtained. Of special interest is the fact that the curves are not monotonic, but behave as though the scattering were negligible at a certain angle for each electron energy. That these phenomena are associated with the mercury is attested by the fact that other gases (air, for instance, in thise case) gave monotonic scattering curves. In a vacuum (as in (1), manipulations,) no scattering is found at all.



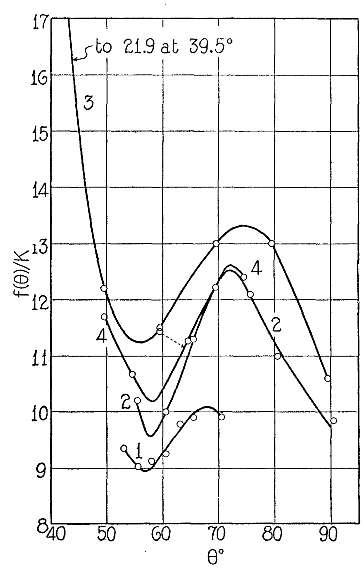


Fig. 5. Scattering curves. Energy, 100 volts. *A*, 95 volts; *E*, 100 volts; *M*, 0.007 amp.; *B*, −75, −102 volts. Curve 1, positive angles; Curve 2, negative angles taken several hours later; Curve 3, negative angles taken several days later.

Fig. 6. Scattering curves, Energy 125 volts. *A*, 165 volts; *E*, 125 volts; *M*, 0.0058 amp.; *B*, −100, −126 volts. Curve 1, positive angles; Curve 2, positive angles taken later; Curve 3, negative angles taken next day; Curve 4, negative angles taken two hours later.

An interesting relationship is presented by the last curve, where the cotangents of the positions of the minima are plotted with the energies. However, lacking a theoretical interpretation this relation may be fortuitous.

For energies less than 100 electron-volts the main beam currents become unmanageably small, while above 200 electron-volts the minima are concealed in the steep part of the curve.

That these minima have not been reported before is perhaps due to the high angles at which they occur. In this case the use of high primary currents makes measurements at the higher angles comparatively easy.

The apparatus can also be used to check the scattering at low angles, and the results fit Langmuir's[2] empirical equation very well:

$$f(\theta) = f(\theta)_{\theta=0} \exp\,(-\,\theta^2/\theta_0^2).$$

The experimental points found fit best when $\theta_0 = 12.7°$ at 150 electron-volts energy.

Langmuir finds that for Arnot's[3] curve for 82 volt electrons, $\theta_0 = 11.3°$ is the best value.

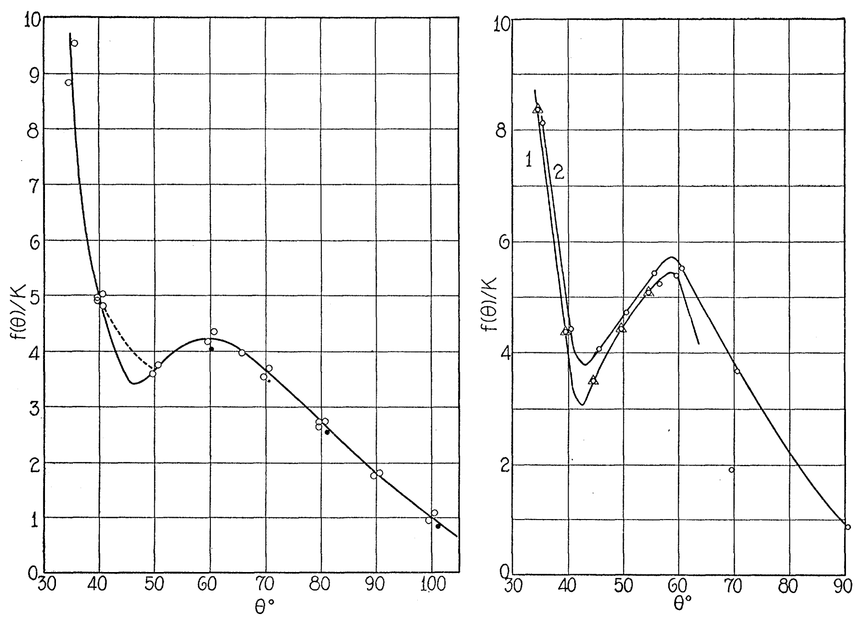


Fig. 7. Scattering curves. Energy 150 volts. A, 190 volts; E, 150 volts; M, 0.006 amp.; B, -120, -150 volts. Positive and negative angles read in succession. The solid dots are check points taken later.

Fig. 8. Scattering curves. Energy 175 volts. A, 210 volts; E, 175 volts; M, 0.007 amp.; B, -140, -180 volts. Curve 1, negative angles; Curve 2 positive angles taken later. The triangles are check points on negative angles taken two days later.

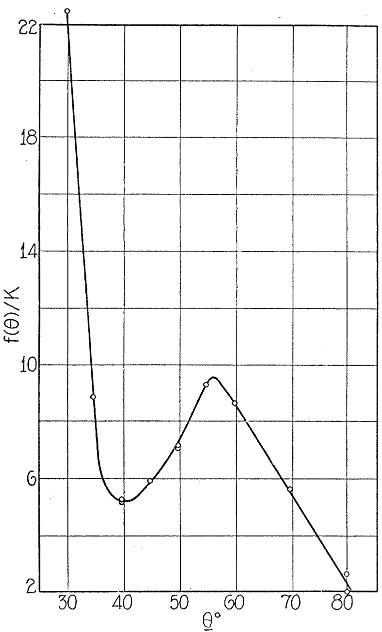
Some objections to measurements made at small angles can be offered in that the resolving power is somewhat diminished at small angles because of the slit length. Further investigations may justify a correction for this effect.

It is the authors' intention to present these data as being more of a preliminary than of a final nature. Improvements and simplifications which will follow from further work with this type of apparatus, will undoubtedly make for greater precision. At present, the loci of the minima are probably not determined better than $\pm 1.5°$.

[2] K. T. Compton, Irving Langmuir, Revs. Mod. Phys. **2,** 123 (1930).

[3] F. L. Arnot, Proc. Roy. Soc. **A125,** 660 (1929).

In conclusion the authors wish to express their appreciation and indebtedness to Dr. R A. Millikan for his continued interest and advice in this work. We should like to thank also the members of the laboratory shops for their care and skill in constructing the apparatus.



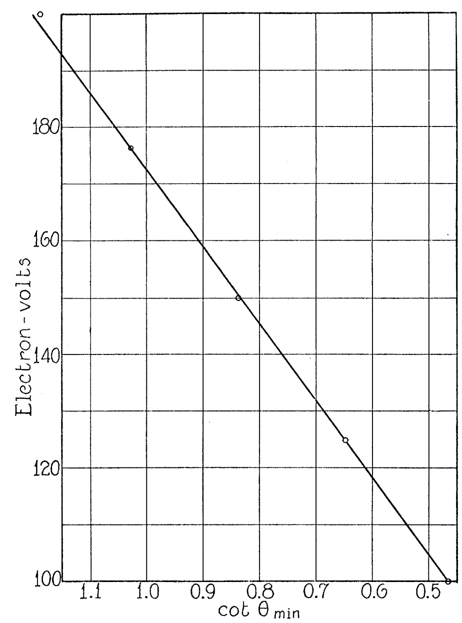


Fig. 9. Scattering curves. Energy 200 volts. *A*, 258 volts; *E*, 200 volts; *M*, 0.006 amp.; *B*, −160, −200 volts. Readings made at different times with apparatus out of equilibrium in meantime.

Fig. 10. Variation of the cotangent of the angle of minimum scattering with electron energy.

Energy	θ_{min}	Weight
100 volts	65	3
125	57	3
150	50	7
175	44	3
200	40	1