The Angular Distribution of Electrons Scattered Elastically and Inelastically in Mercury Vapor

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A long electron gun was mounted to rotate about a well-shielded scattering region from which electrons scattered by gas molecules through a definite angle from a beam of small cross-section were collected, and their velocities determined, by a stationary collector containing an efficient Faraday cage, 6.0 cm in length. Angular distribution curves for electrons scattered elastically, for electrons scattered due to excitation of the atom (mainly 6.7 volt energy loss), and for electrons resulting from ionizing impacts are presented for 80, 120, 230, 490, and 700-volt electrons. In general, for a particular group, the curves are steeper the higher the velocity of the incident electron. The elastic group shows a diffraction pattern at large angles and the positions of the peaks agree well with those found by Arnot. The curves for the excitation group are much steeper than are those for the elastic group, and fall to very small values at large angles. The curves for the ionization group are also steeper but not so steep as the excitation group; at large angles the scattering is due mainly to slow electrons of this group. The ionization group is divided into sections and further characteristics are observed. Numerical integration of these curves gives the cross-sectional area for collision, the efficiency of ionization, and the efficiency of excitation.

INTRODUCTION

OF THE many methods devised to study the structure of the molecule and its accompanying field of force, those involving the measurement of the scattering of electrons in gases are yielding information of much value. Early experiments contented themselves with measuring the total number of electrons scattered from an electron beam due to interaction with gas molecules resulting in a deflection or energy loss sufficient to remove the electron from the beam. Among the important results of such experiments to determine the cross-section for interception of electrons have been those of Ramsauer who found that the inert gases show a special transparency to electrons of a few volts velocity, a result which Townsend simultaneously and independently discovered by an indirect method. Other investigators have studied the energy losses suffered by electrons which continue nearly undeviated after impact, and have identified these losses with certain critical potentials for excitation of the molecule. These experiments yielded early significant verifications of the quantum theory.

In the last few years a new type of experiment has developed, that of studying the angle of deflection of electrons which have interacted with gas molecules. Such experiments were inspired partially by the hope that diffraction phenomena would be observed. The now classical experiments of Davisson and Germer, which exhibited the wave nature of the electron, had

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just been performed. Also there was the hope that the new wave mechanics would be able to make calculations on such problems and checks could be made with theory. The fulfillment of the first hope was denied to those who first worked in this field[1–4]—they observed merely that the number of electrons scattered decreased rapidly with increase in angle of deflection—and it has been but recently that such diffraction phenomena have been observed. Mark and Wierl[5] first obtained diffraction rings by using high speed electrons in complex molecular gases, and others[6–10] have subsequently observed similar effects with lower velocities in various gases. As for the second hope, wave mechanics has probably lent itself more satisfactorily to the calculation of collision problems than any previous theory. A general summary of the methods used in the application of wave mechnaics has been given by Condon.[11] Mott,[12] using Born's approximation method, has succeeded in calculating the angular distribution of electrons scattered elastically by the atoms of a gas. He has neglected such factors as polarization of the atom due to the incident electron, possibility of exchange between the incident electron and an orbital electron, and distortion of the incident electron wave due to the atomic field. Supposedly these factors would be of small importance for high velocity electrons, and indeed Mott found fair agreement with the results of Dymond and Watson for 210-volt electrons in helium. Other observers[6,7,9] have also found fair agreement with experiment in the region of small angle scattering of moderately fast electrons in a few other gases. Attempts to incorporate the neglected factors into theory have resulted in further, qualitative at least, agreement with experiment.[6,7,13,14] However, it seems that the factor to be taken into consideration in a particular case, depends on which one gives the best agreement with experiment. There remains much to be done along this line.

The experimental work on angular scattering has also been often open to criticism. In general the scattering region has not been as free from stray

[1] E. G. Dymond and E. E. Watson, Proc. Roy. Soc. **A122,** 571 (1929). Dymond had earlier reported maxima and minima in scattering curves but he later found these effects were spurious.

[2] G. P. Harnwell, Phys. Rev. **33,** 559 (1929); **34,** 661 (1929).

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

[4] J. H. McMillen, Phys. Rev. **36,** 1034 (1930).

[5] H. Mark and R. Wierl, Naturwiss. **18,** 205 (1930).

[6] F. L. Arnot, Proc. Roy. Soc. **A130,** 655 (1931); **A133,** 615 (1931).

[7] E. C. Bullard and H. S. W. Massey, Proc. Roy. Soc. **A130,** 579 (1931); **A133,** 637(1931).

[8] J. M. Pearson and W. N. Arnquist, Phys. Rev. **37,** 970 (1931).

[9] A. L. Hughes and J. H. McMillen, Phys. Rev. **39,** 585 (1932).

[10] C. Ramsauer and R. Kollath, Phys. Zeits. **32,** 867 (1931).

[11] E. U. Condon, Rev. Mod. Phys. **3,** 43 (1931).

[12] N. F. Mott, Proc. Camb. Phil. Soc. **25,** 304 (1928).

[13] H. Faxen and J. Holtzmark, Zeits. f. Physik **45,** 307 (1927), take into account the distortion of the incident electron wave due to the atomic field. Using this method Holtzmark, Zeits. f. Physik **55,** 437 (1929); **66,** 49 (1930), has calculated the total cross-sectional area of argon and krypton for slow electrons and has obtained good agreement with the Ramsauer-Townsend effect.

[14] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. **A132,** 605 (1931) by further refine ments have calculated the probabilities of a number of collision problems.

electric fields and secondary electrons as it should have been; also the means of collecting the scattered electrons has not always been satisfactory. It was partially for these reasons that the present research was undertaken. The immediate cause was the disagreement between the results of Arnot[3] for the scattering of 82-volt electrons in mercury vapor and those of one of us.[15] Indirect evidence bearing on the angular distribution of scattered electrons indicated that the scattering curves should not be so steep as those obtained by Arnot.

Apparatus

The apparatus used for this work is sketched in Fig. 1a. It was constructed entirely of copper. The electron gun, G, was mounted in such a way that it could be rotated about axis $a-a$, and electrons scattered by gas molecules through a definite angle, θ(Fig. 1 (b)), were collected in the Faraday cage, FC. The electron gun was made sufficiently long and the defining slits of

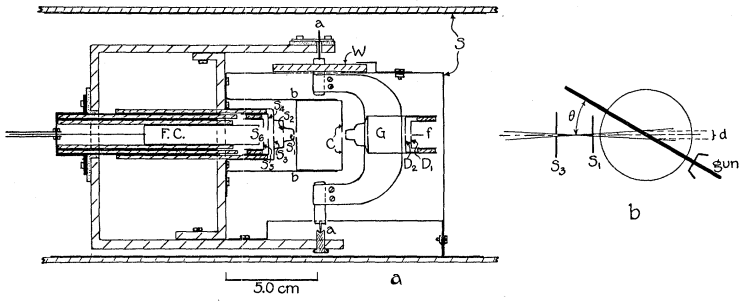

Fig. 1. Diagram of apparatus.

such a size (about 0.7 mm in diameter) that the electron beam was of small cross-section in the scattering region. The filament was mounted on a small cylinder which could be clamped in position behind the first diaphragm, D_1. A difference of potential between diaphragms D_1 and D_2 defined the velocity of the electrons. Flexible filament leads were brought out through the shield near the lower pivot. Two coaxial cylinders, C, separated by about 3 mm, were mounted as indicated, and the electron beam passed between them, being absorbed by the outer cylindrical shield and end-plates, S. These cylinders served the double purpose of shielding the scattering region from both stray electric fields and secondary electrons. The slits S_1, S_2, and S_3, spaced 5.0 mm apart, were about 0.35 mm in width and 1.4, 10, and 3.0 mm in height, respectively. S_4, S_5 and S_6 increased in size to 6.2×10.5 mm for S_6, and were spaced about 3.0 mm apart. The length of the beam from which scattered electrons could be collected is $d/\sin\theta$ (where $d=1.3$ mm) as defined by slits S_1 and S_3. As these slits are at the same potential this length is independent of the velocity of the electrons. Different potentials could be

[15] R. R. Palmer, Phys. Rev. **37**, 70 (1931) measured the absorption coefficient (cross-section for interception) of electrons with a Mayer type of apparatus, with a diaphragm of variable aperture mounted at the end of the scattering chamber.

applied to the diaphragms S_4, S_5 and S_6, for the purpose of analyzing the velocities of the scattered electrons. To insure its being a good collector of electrons the Faraday cage was over 6.0 cm in length. The metal parts for the gun and collector were spun cylinders and were all separated with Pyrex tubing excepting for the quartz tubing used as insulation between the Faraday cage and its shield. The ends of the gun and collector were tapered, the slits were bevelled, and important surfaces were sooted to reduce further errors due to secondary electrons. The gun could be rotated by means of the grooved wheel, W. A cable of fine copper wires making one turn about this wheel was connected to a long rod mounted to slide on the main frame of the apparatus. This rod extended into a side tube and could be moved by means of a special magnetic device so constructed that all magnetic material could be removed at each reading. The angular setting could be read from a scale on the wheel, W.

The apparatus was housed in a large Pyrex tube one end of which was closed by means of a copper plate sealed to the tube with low vapor pressure wax. The tube was long enough that it was possible to heat the apparatus up to about 300°C without softening the wax. The metal parts had previously been outgassed in a quartz furnace at about 600°C. Vacuum conditions were such that a pressure of less than 10^{-5} mm would build up in the system in 24 hours. A pair of Helmholtz coils was used to neutralize the earth's magnetic field.

Tests on the Apparatus

An electrometer was used to measure the current to the Faraday cage and a galvanometer connected to the outer cylinder measured the main beam current. For a particular angular setting, electron velocity and gas pressure, it is of course necessary that the ratio of these two should remain constant as one varies the filament emission. This was found to be the case, but not until the Pyrex tubing which was first used as insulation between the Faraday cage and its shield was finally replaced by a quartz tube. The intensity of the electron beam was varied by as much as a factor of 60, and no sensible change in this ratio was observed. This, of course, signifies that the electrometer system is well insulated and well shielded. It also indicates that neither the filament current nor the electron beam influence appreciably the electron scattering.[16]

[16] F. L. Arnot, Proc. Roy. Soc. **A129,** 361 (1930), has studied the effect of the passage of an electron beam through an otherwise field-free enclosure. He used beam currents of from 5 to 25 microamperes intensity passing through mercury vapor at a pressure of about 0.001 mm, and observed that a difference of potential of as much as 2.0 volts was set up between the interior of the beam and the outer electrodes. This is due to the relative slowness with which the positive ions diffuse out of the beam in comparison with the scattered electrons. Since the work we are reporting has been done with lower beam currents (in all cases less than 0.3 microampere) and since the electron velocities (excepting for those electrons scattered with loss in energy) were greater than 80 volts, it would seem unnecessary to take this into account. Indeed the linear relationship observed between the beam current and the scattered current indicates that this is the case.

In Fig. 2a are plotted three typical velocity distribution curves for the scattered electrons. The scattered current to the Faraday cage is plotted as a function of the retarding potential between slits S_4 and S_5. Curve A is for 80-volt incident electrons at an angular setting of 7°; curves B and C are for 120-volt electrons at angular settings of 10° and 43° respectively. Since the difference between the ordinates for two values of the retarding potential, V_1 and V_2, is a measure of the number of electrons with energies between V_1 and V_2, one can obtain from such curves the number of electrons scattered in any particular energy range. For instance, for curve A the value of the

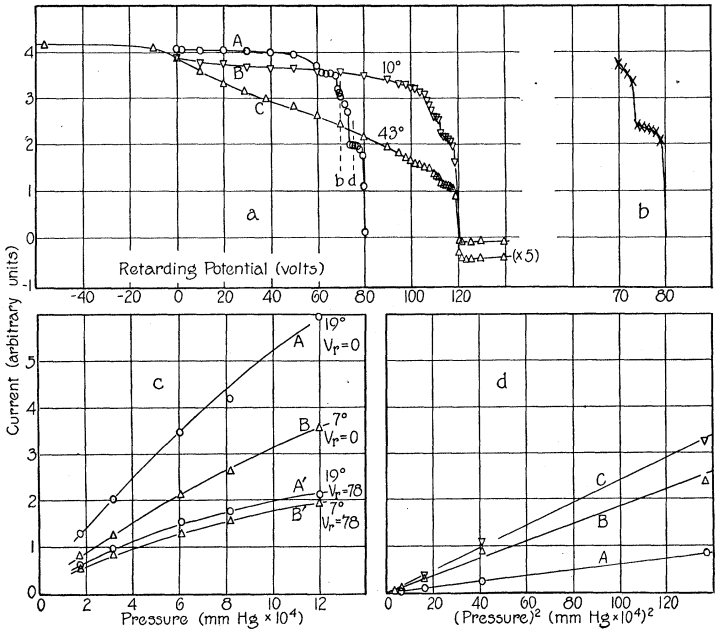

Fig. 2*a*, Typical velocity distribution curves. Curve A, 80-volt electrons ($\theta = 7°$). Curves B and C, 120-volt electrons. *b*. To show penetration of fields through slits. *c*, Scattered current as a function of gas pressure. *d*, Positive ion current as a function of the square of the pressure. (80-volt electrons, 86 volts retarding potential).

ordinate at d indicates the number of electrons scattered with their original velocity (elastically scattered electrons). The difference between this and the value of the ordinate at b (for a retarding potential of 80 − 10.4 volts— the velocity of the incident electrons less the ionization potential of mercury) represents the number of electrons which have excited the mercury atom to various energy levels. The abrupt rise at about 73 volts indicates that most of these electrons have excited the 6.7 volt energy level. The difference between the value of the ordinate at b and that for zero retarding potential is a measure of those electrons which have resulted from collisions in which the energy loss is greater than the ionization potential. Such collisions may result in direct ionization with the removal of one or more electrons from the atom or in the excitation of the atom to an energy state greater than the ionization

potential. In the latter case the atom may return to the normal state either by radiation alone or by radiation accompanied by the emission of one or more electrons. The curves for 120-volt electrons show these same features. It is to be noted that relatively more of the electrons scattered through large angles are slow electrons than is the case for small angles. Most curves show a more or less flat section in the region from 12 to 18 volts less than the incident electron velocity—this shows up distinctly in curve A. This must mean that when an electron loses more than the ionizing energy to a mercury atom the process is such that it is not likely to lose from 2 to 8 volts in addition to the energy of ionization. This point has not been studied systematically, but it has been observed in most velocity distribution curves which have been taken. It may be linked with the so-called "ultra-ionization" potentials which have been observed in mercury.

When the retarding potential is greater than that necessary to stop all of the scattered electrons a negative current is obtained. This is shown for curve C. When the potential is further increased this current goes through a maximum and then slowly decreases. This effect might be due to secondary electrons emitted from the Faraday cage or to positive ions entering the Faraday cage. However, neither of these would be expected to show the maximum and decline with increase in retarding potential, unless, in the case of its being a positive ion current, the positive ions were formed in the neighborhood of slits S_4 and S_5 by the scattered electrons themselves. If this were true this current would be proportional to the square of the gas pressure. Fig. 1d shows this to be the case.[17] Curves A, B, and C are for a retarding potential of 86 volts (80-volts incident electrons) between slits S_3 and S_4, S_4 and S_5, S_5 and S_6, respectively. It is evident from this linearity that the positive ions from the main scattering region are not appreciably represented in the scattered current, though this might not be true for intense beam currents at angles near 90°.

When an accelerating potential is applied at the collector there is in general a small increase in the electron current. This is due to a retarding effect on the positive ions just mentioned, and perhaps also to a certain amount of penetration of the field into the scattering chamber to bring in low velocity electrons which would otherwise miss the collector. An accelerating field of 100 volts does not in general increase the measured current by more than a few percent. This effect has been reduced by the insertion of slit S_2.

If, instead of applying the field between slits S_4 and S_5, it is applied between S_5 and S_6, the same curves, within a few percent, as those in Fig. 1a are obtained. This is also true if the difference of potential is applied between S_3 and S_4, excepting in the case of high velocity electrons (say, 700 volts) when large fields cause a greater discrepancy due to penetration into the main scattering region.

[17] S. Werner, Proc. Roy. Soc. **A134,** 220 (1931), in studying the scattering at 90° in helium, also observed this negative current and found it proportional to the square of the pressure, but he attributed it as due to ionization near the collector slits by "long wave radiation" from the scattering region.

Likewise the same curves are duplicated by a constant factor, within a few percent, when the gas pressure is changed. This relation between the scattered current and pressure for 80-volt electrons is shown in Fig. 2c, for two angular settings and two retarding potentials. It is noted that these curves bend over slightly, as a result of the interception of the scattered electrons by gas molecules, and of the fact that the galvanometer current is a measure of the total electron current from the gun and not a measure of the

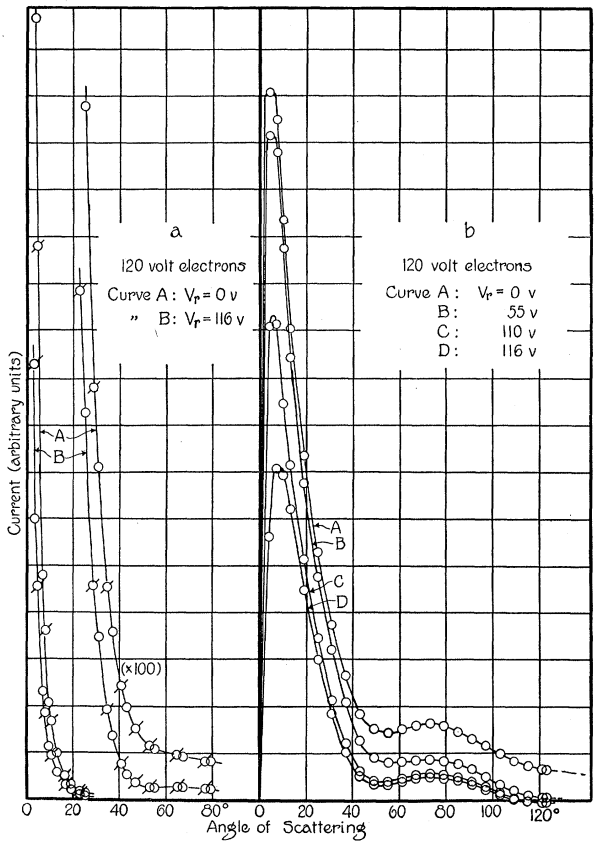

Fig. 3*a*, Current collected as a function of angular setting. To show symmetry of scattering (circles, scattering on one side of beam; circles with lines through them, scattering on the other side). *b*, Scattered current per unit angle (between θ and $\theta+d\theta$) as a function of angle.

beam current at the point of scattering. The curves taken with a retarding potential deviate more from a straight line than do the others which is probably due to the positive ion current discussed above.

The Faraday cage was made long to insure its being a good collector of electrons. It was at first thought that an accelerating field between S_5 and S_6 would increase its efficiency by retarding any slow secondary electrons which attempted to escape. But this was found to be unnecessary, and indeed quite inadvisable. In Fig. 2b is drawn the end of a velocity distribution curve for

80-volt incident electrons, with the retarding potential applied between slits S_4 and S_5. With this potential fixed at 80 volts, an accelerating potential was applied in one-volt steps between S_5 and S_6, giving the crosses from right to left. It is noticed that they practically retrace the first curve. Evidently there is a distinct penetration of this field into the region between S_4 and S_5. A similar result was obtained when the retarding potential was applied between S_3 and S_4 and the accelerating potential between S_5 and S_6, though in this case the new curve fell slightly below the original one. It is obvious that it is inadvisable to use this method to increase the efficiency of a collector.[18]

The symmetry of scattering to the right and left of the electron beam is shown for 120-volt electrons in Fig. 3a. The number of electrons collected by the Faraday cage is plotted as a function of the angular position of the electron gun. Curve A is for no retarding potential and curve B for a retarding potential of 117 volts. The circles are the experimental points for scattering say to the left of the beam and the circles with the lines through them to the right of the beam. It is seen that the criterion of symmetry is met very nicely.

As the ionization potential of mercury is 10.4 volts, when a 120-volt electron directly ionizes a mercury atom there remains about 110 electron-volts of energy to be divided between the incident and the ejected electrons. For every electron going off with an energy less than 110/2 volts there must be an electron with an energy between this value and 110 volts. Hence the total number of electrons scattered with energies between 0 and 55 volts should equal the number with energies between 55 and 110 volts. (This would be strictly true only if there were no multiple ionization and no inelastic impacts with energy loss greater than 10.4 volts which do not result in ionization in which case it would be impossible to say anything about the division of energy. Bleakney[19] has studied the formation of multiply charged ions in mercury vapor, and has found that approximately 15 percent of the ions formed by 120-volt electrons are double charged.) In Fig. 3b are given curves for the number of electrons scattered with different energies in a cone between θ and $\theta+d\theta$ from a definite length of the beam for 120-volt incident electrons. To obtain these curves the experimental curves are multiplied twice by sin θ, first to correct for the variation in the effective length of the beam with angular setting (Fig. 1) and second to change from scattering in units of "electrons scattered per unit solid angle" to "electrons scattered per unit angle." The area under curve A is a measure of the total number of

[18] Arnot, reference 6, in studying the angular distribution of elastically scattered electrons, has applied such additional accelerating potentials "to prevent any secondary emission of electrons from the Faraday cylinder." His collector was short and secondary emission might otherwise have been large. He has used from 12 to 21 volts, and as his slit system was similar in dimensions to ours it would seem that his measurements are subject to this error. When, for 80-volt electrons, a retarding potential of 77 volts is used to eliminate all but those electrons which are scattered elastically, and then a subsequent 12 volts accelerating potential is applied, the increased current is not due alone to increased collector efficiency but also to the addition of a number of *inelastically* scattered electrons which can now pass through the slit system.

[19] W. Bleakney, Phys. Rev. **35**, 139 (1930).

electrons scattered and the areas under curves B, C and D, the number of electrons scattered with energies in excess of 55, 110 and 116 volts, respectively. By numerical integration it is found that the number of electrons with energies between 0 and 55 volts is to the number with energies between 55 and 110 volts as 1.0 is to 1.1. Perhaps not quite all of the low velocity electrons are collected, probably because the readings could not be carried beyond 123°. The extrapolation to 0° is quite definite, as a bending over of the curves is discernible for small angles of deflection. On the whole, these tests indicate that the apparatus is quite satisfactory.

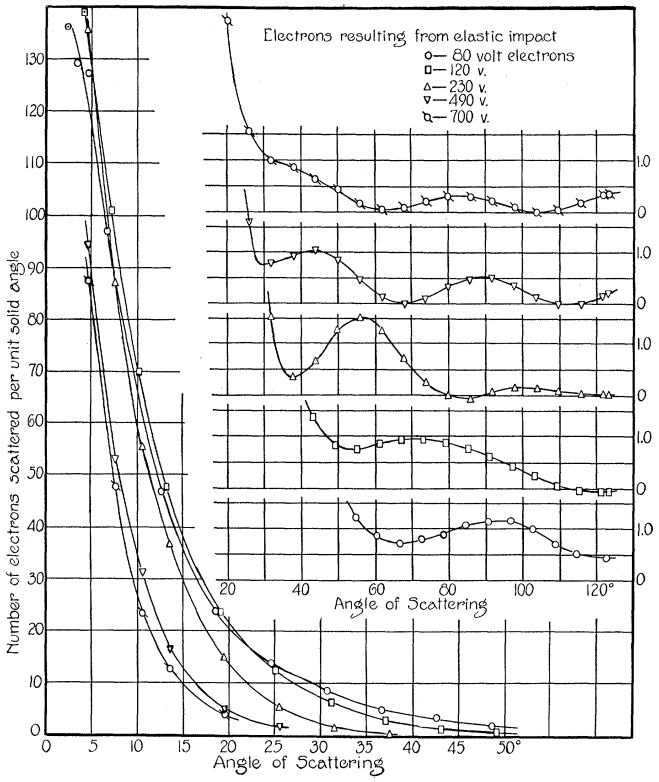

Fig. 4. Number of electrons elastically scattered (per primary electron, per unit solid angle, per cm path, per mm pressure at 0°C) as a function of angle.

The results to be presented are for the scattering of 80, 120, 230, 490 and 700-volt electrons in mercury vapor at a pressure of 1.17×10^{-3} mm. With the mercury frozen out with liquid air the scattered current at all angles was less than 2 percent of that at this pressure. This was the case up to within about 3° of the direction of the electron beam. In analyzing the velocities of the scattered electrons retarding potentials were applied between slits S_4 and S_5.

Elastic Scattering

The curves in Fig. 4 show the angular distribution of electrons scattered

elastically for the five velocities indicated. The ordinates are given in units of the number of electrons scattered per primary electron, per unit solid angle, per cm path, per mm pressure at 0°C. The method of converting scattering as experimentally measured in arbitrary units into the units given will be discussed later. The number of electrons scattered is seen to decrease very rapidly in the region of small-angle scattering with increase in the angle of deflection. This steepness of the curves is in general greater the higher the velocity of the incident electrons. Similar curves have been obtained by Arnot[6] for scattering in mercury vapor.

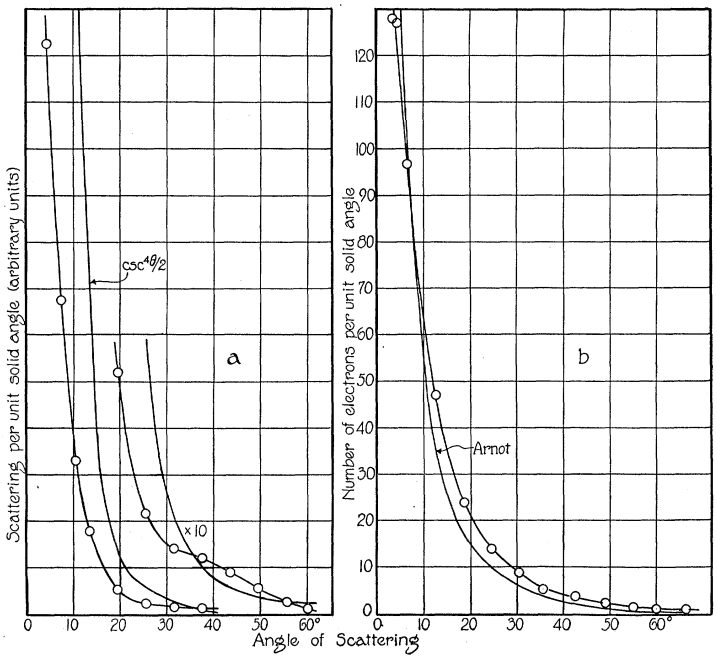

Fig. 5*a*, Comparison of elastic scattering of 700-volt electrons with cosec⁴ $\theta/2$ (Mott's theory). *b*, Comparison of elastic scattering of 80-volt electrons with Arnot's results for 82-volt electrons.

When the elastic scattering is studied at large angles a series of peaks is observed in the scattering curves. These are plotted to a different scale in the inset to Fig. 4. (It will be noted that some of the curves fall below the zero-axis at certain angles. This is due to the fact that no correction was made for the secondary positive ion current previously mentioned. Excepting for the scattering at large angles in the neighborhood of the minima this correction would have been inappreciable.) A single peak is observed in the 80-volt curve at about 95°. As the velocity increases this is seen to move in to smaller angles, finally merging with the main peak, and new maxima appear. There is also an indication of a "merged maximum" in the 80-volt curve at about 28°, which would show up as another order of diffraction for lower electron velocities. The angles at which these peaks occur agree well

with those obtained by Arnot.[6] There is no satisfactory theory of this effect, though in view of the many current experiments which confer the property of a wave upon a moving electron such diffraction phenomena are not entirely surprising. Bullard and Massey[7] have succeeded in a rough way in duplicating diffraction peaks for a limited range of velocities in argon, following a method due to Faxen and Holtzmark.[13] Arnot[6] has similarly fitted this theory to the scattering of 54-volt electrons in krypton, reproducing the 70° peak.

Mott[12] gives for the number of electrons elastically scattered per primary electron, per cm path, per unit solid angle, per atom in a unit volume, as a

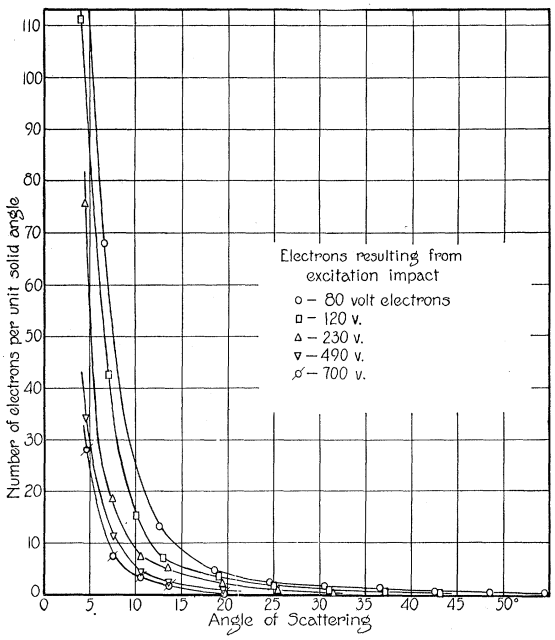

Fig. 6. Number of electrons scattered inelastically at excitation impact (per primary electron, per unit solid angle, per cm path, per mm pressure at 0°C) as a function of angle.

function of the angle of deflection, θ, and the velocity of the incident electron, v,

$$I(\theta, v) = \left(\frac{e^2}{2mv^2}[N - F]\,\mathrm{cosec}^2\frac{\theta}{2}\right)^2,$$

where N is the atomic number and F the atomic structure factor. The equation is supposedly good for high velocity electrons. For a particular gas and electron velocity the scattering should then be proportional to $\mathrm{cosec}^4\,\theta/2$. In Fig. 5a the experimental results for 700-volts electrons are compared with a curve of $\mathrm{cosec}^4\,\theta/2$, both in arbitrary units. It is seen that the theoretical curve is much steeper than the experimental curve out to 40°. Evidently Mott's theory is not applicable to the elastic scattering of electrons in mercury vapor for electrons with even as much as 700 volts velocity.

In Fig. 5b our curve for the elastic scattering of 80-volt electrons is compared with that of Arnot (for 82-volt electrons). The units are again the number of electrons scattered per primary electron, per unit solid angle, per cm path, per mm pressure at 0°C. It is to be noted that Arnot's curve is much steeper than ours. Due to the system of potentials used in his collector is is believed that Arnot collected not only electrons scattered elastically but also a large number of inelastically scattered electrons.[18] As electrons scattered inelastically exhibit a more decided preference for small angle scattering than do electrons scattered elastically (as will be seen in the next section), curves including them would of course be steeper.[20]

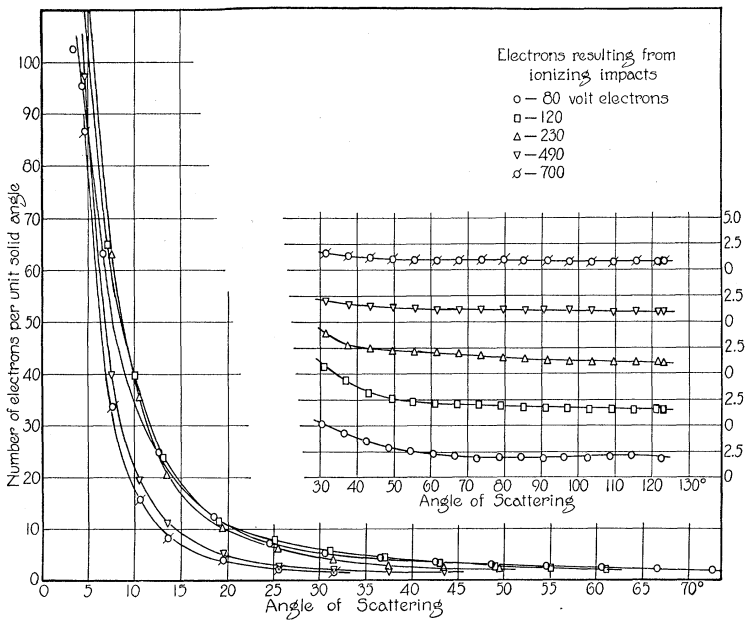

Fig. 7. Number of electrons scattered inelastically at ionizing impact (per primary electron, per unit solid angle, per cm path, per mm pressure at 0°C) as a function of angle.

Inelastic Scattering

In Fig. 6 are plotted the curves for the number of electrons scattered inelastically from a collision in which the mercury atom is excited. The ordinate is again in the conventional units given above. As was seen from the velocity distribution curves of Fig. 2, the energy loss suffered by electrons in this group was mainly 6.7 volts. Here it is again seen that forward scat-

[20] Though the curves are given in the same units the difference between the numerical magnitudes has no significance since it is difficult to transcribe the experimentally measured quantities into the conventional units. In particular, the effective length of the electron beam from which scattered electrons are collected and the effective solid angle for collection are difficult to ascertain,—in Arnot's case fields applied between the diaphragms which define these quantities enhance this difficulty. Arnot believes that he has "an estimate of the absolute scattering which is probably correct to within 50 percent."

tering is highly favored. The curves are much steeper in fact than are those for the elastically scattered electrons. In general they are also steeper the higher the velocity of the impinging electrons. These curves decrease to very small values of the ordinate for large angles, and do not show any pattern within the experimental error of the measurements.

Curves for the angular distribution of electrons scattered inelastically after impacts which have resulted in energy losses greater than the ionizing potential are also steeper than are those for elastic scattering but not so steep as those for the excitation group. Such curves are presented, in the usual units, in Fig. 7. These curves include all electrons scattered with en-

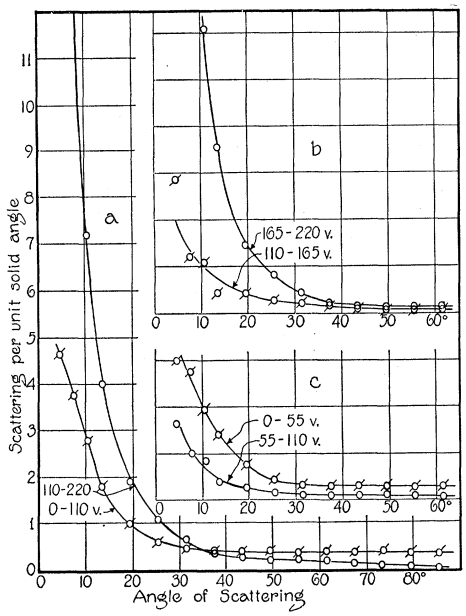

Fig. 8. Angular distribution of colliding and ejected electrons resulting from a 230-volt collision. (Energy range of scattered electrons is indicated.)

ergies between 0 and $(V_a - 10.4)$ volts, where V_a is the velocity of the incident electrons. They include both the scattered incident electrons and the ejected electrons. In general here again we have an increase in steepness with increase in velocity of the incident electrons. For large angles of scattering this group is relatively more prominent than either of the other two groups. In the inset these curves, plotted to a different scale, are carried to an angle of 123°. It is interesting to note the wide range at large angles over which the scattering is nearly constant.

After a 230-volt electron ionizes a mercury atom there remains approximately 220-electron volts of energy to be divided between the colliding and the ejected electrons. Following the procedure of Hughes and McMillen[9] we will label the slower of these two electrons the ejected electron, and the faster, the colliding electron. This is done as a matter of convenience, inasmuch as

there is supposedly no physical difference between any two electrons. In Fig. 8 we have divided the electrons resulting from a 230-volt ionizing collision into groups according to their energies. It is seen from *a* that the colliding electrons are greatly in excess of the ejected electrons at small angles, and that the reverse is the case at large angles. The two groups show decidedly different types of angular distributions. A numerical integration of these curves gives for the ratio between the number of ejected electrons and the number of colliding electrons: 1.0 to 1.1. In the insets of Fig. 8 these groups

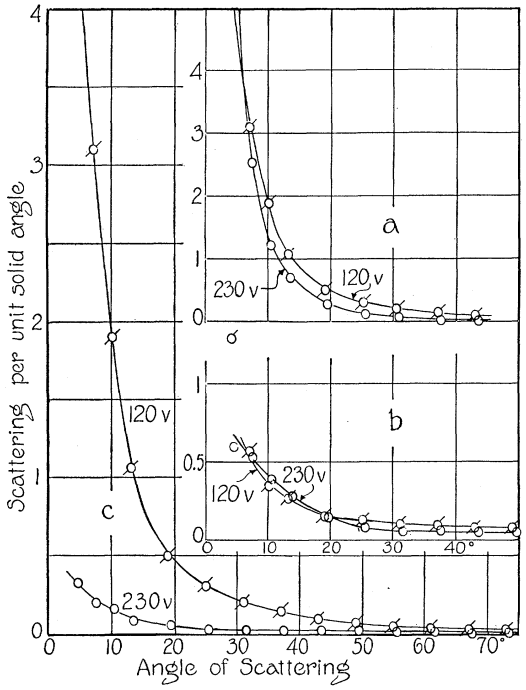

Fig. 9. Angular distribution of groups of electrons resulting from 120- and 230-volt collisions. *a*, Electrons which have lost from 0 to 55 volts in addition to the ionization potential. *b*, Electrons which emerge with from 0 to 55 volts velocity. *c*, Electrons which emerge from 55 to 110 volts velocity.

are further subdivided. It is to be noted that both groups of the faster electrons, *b*, have similar angular distributions, and that both groups of the slower electrons, *c*, also have similar distributions. Further, of the two subgroups in *b*, the faster group is much in excess of the other at all angles; of the subgroups in *c*, the slower is in excess at all angles. This indicates that the division of energy remaining after ionization takes place in such a way that one of the electrons emerges with most of the energy, and the other one with very little. There is thus not much probability that the energy will be shared approximately equally.

In Fig. 9a are plotted the angular distributions for electrons which have lost up to 55 volts in addition to the energy necessary to ionize the

mercury atom. Thus, for a particular range of energy loss, the higher the velocity of the incident electron the steeper the angular distribution curve, as was also observed by Hughes and McMillen[9] for a narrow range of energy loss.

It is interesting to examine the angular distribution curves for electrons emerging with a particular velocity as a function of the velocity of the incident electron. In Fig. 9b are curves for electrons scattered with energies from 0 to 55 volts. Evidently it is of little consequence to electrons in this range of energies as to whether they result from 120 or 230-volt impacts. On the other hand, for the same two incident velocities, when we consider the angular distributions for electrons emerging with velocities between 55 and 110 volts, the effect of the velocity of the incident electron is quite apparent,—the

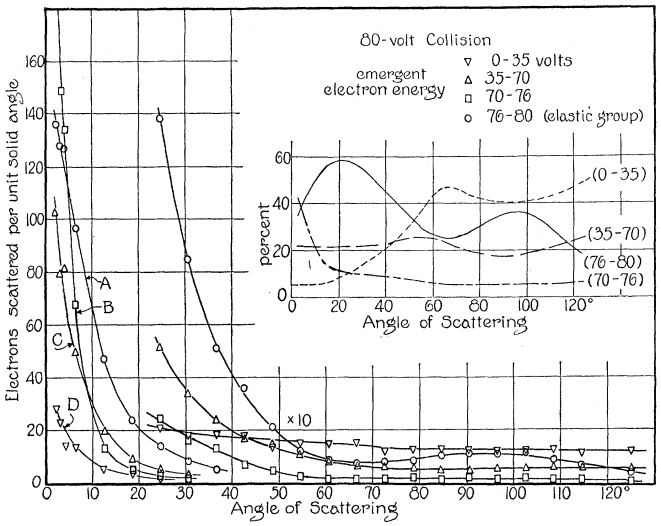

Fig. 10. Angular distribution of various groups of electrons resulting from an 80-volt collision in units of number of electrons per primary electron, per unit solid angle, per cm path, per mm pressure at 0°C. Inset: percent of total scattering due to these various groups.

curves of Fig. 9c are decidedly different. We note that these electrons (emerging with from 55 to 110 volts velocity) are what we have chosen to call colliding electrons for 120-volt collisions, and ejected electrons for 230-volt collisions, whereas the electrons of *b* (emerging with from 0 to 55 volts velocity) are in both cases ejected electrons. These results, and those of Fig. 8, indicate that when we are dealing with scattered electrons which are ejected electrons we get a different type of angular distribution than when these electrons are the colliding electrons. Such results tempt one to go farther than merely to label these two groups as colliding and ejected electrons—one is tempted actually to identify them as such.

For purposes of comparison, the angular distribution curves for the four groups of electrons resulting from 80-volt collisions are plotted in Fig. 10. These curves are given in the conventional system of units. In the region of

small angle scattering it is seen that the electrons scattered at excitation impacts exhibit the most decided tendency to persist in the forward direction. In general, for the three inelastic groups, the smaller the energy loss the steeper the distribution curve. These curves are extended out to 123°, drawn to a larger scale, as is indicated. It is to be noted that at large angles the slower group of electrons, the ejected electrons, predominate, whereas there are very few which have resulted from excitation impacts. These relations between the four groups are further exhibited in the inset of Fig. 10. Here the percentage of the total scattering at a particular angle which is due to a particular group is plotted as a function of the angle.

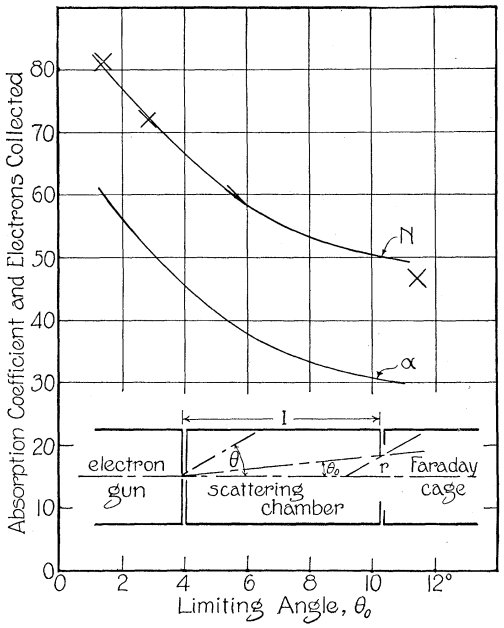

Fig. 11. Absorption coefficient, α, as a function of limiting angle of collection, θ_0, for 80-volt electrons, using apparatus of inset. (Results of Palmer, reference 15.) Total number of electrons collected N, as a function of θ_0.

Absolute Scattering

The scattering curves have been presented in units of the number of electrons scattered per primary electron, per unit solid angle, per cm path, per mm pressure at 0°C. The current ratios measured experimentally were of course in arbitrary units, and to obtain the absolute scattering the following method was used.

In Fig. 11 are presented some of the results of a series of measurements by one of us[15] on the effect of resolving power on measurements of the absorption coefficient α, of electrons in gases. The radius r, of the exit-diaphragm of a scattering chamber in a conventional Mayer type of apparatus (see inset to Fig. 11) could be changed, giving a limiting angle θ_0, below which if electrons were deflected by gas molecules they would not be counted

as having collided. The value of α thus determined for 80-volt electrons is plotted as a function of θ_0. By taking into consideration the ions formed which drift to the walls of the scattering chamber (and neutralize the effect of a certain number of electrons) it is possible to calculate the total number of electrons actually collected. This gives the curve N,[21] in units of number of electrons scattered per primary electron, per cm length of scattering chamber, per mm pressure at 0°C. This may be obtained for any value of r by a numerical integration of the experimentally determined angular scattering curve for the total scattering of 80-volt electrons, $K \cdot F(\theta)$. The number of electrons collected by the scattering chamber in the above units will then be

$$N = \int_{\theta_0}^{\pi} (1 - r/l \tan \theta) \cdot 2\pi \sin \theta \cdot K \cdot F(\theta) \cdot d\theta$$

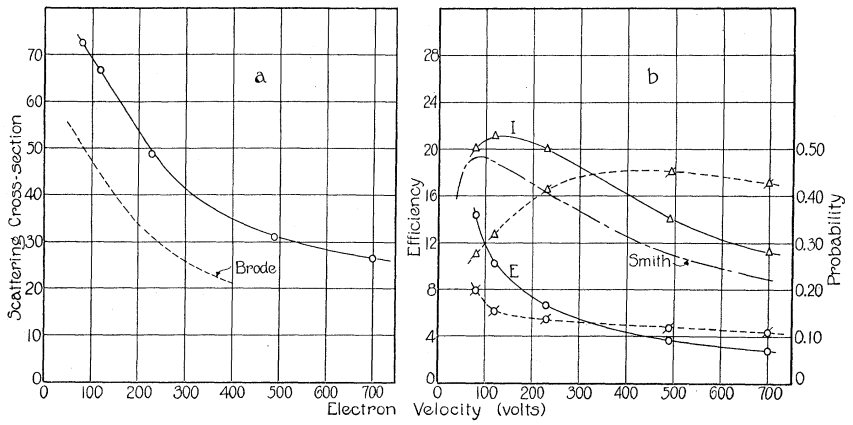

Fig. 12. *a*, Scattering cross-section (absorption coefficient) as a function of primary electron velocity, in cm^2/cm^3 per mm pressure at 0°C, obtained by numerical integration. *b*, Efficiency of ionization I, in number of units of positive charge formed per primary electron, per cm path, per mm pressure at 0°C, obtained by numerical integration. Efficiency of excitation, E, in number of molecules excited per primary electron, per cm path, per mm pressure at 0°C, obtained by numerical integration.

where θ_0 is $\tan^{-1} r/l$. Such a numerical integration was performed for four different diaphragm openings, and with an appropriate constant, K, the four crosses in Fig. 11 were obtained. This constant was then applied to the experimentally measured ratio to give the angular scattering curves in the conventional units. It should be emphasized that the good agreement between the crosses and the curve of Fig. 11 serves as an additional check on the validity of the angular scattering curves.

Cross-section for Interception, Excitation, and Ionization

By a numerical integration of our angular distribution curves it is possible to obtain curves for the cross-section area for the interception of electrons,

[21] We have used the efficiency of ionization data of P. T. Smith, Phys. Rev. **37**, 808 (1931) in this calculation, partially for reasons of internal consistency. The original curve for N was obtained from the data of Bleakney.[19]

and for the efficiencies of excitation, and ionization by electron impact. From Bleakney's work[19] one can calculate the fraction of the electrons resulting from ionizing impacts which are ejected electrons. This fraction of the number of electrons obtained by a numerical integration of the curves of Fig. 7 represents the number of ejected electrons and is hence a measure of the efficiency of ionization. This assumes that all impacts which result in energy losses greater than the ionization potential actually ionize the atom. An integration of the curves of Fig. 6 gives the number of electrons scattered due to excitation collisions. An integration of the curves for the total scattering less the ejected electrons gives the number of primary electrons scattered, or, which is numerically the same, the cross-sectional area for interception. This latter is plotted in Fig. 12a for the five electron velocities studied. The units are cm^2/cm^3 blocked off by gas molecules per mm pressure at 0°C, or the number of collisions per electron, per cm path, per mm pressure at 0°C. The curve obtained by Brode[22] with a Ramsauer type of apparatus is also presented. His values are lower than ours because his absorption coefficient is defined by an apparatus with finite slits such that electrons which are deflected through a small angle are not counted as having collided. It should be noted that our value for 80-volt electrons agrees quite well with the value of α which would be obtained from Fig. 11 by an extrapolation back to $\theta_0 = 0°$.

The curve I of Fig. 12b gives the efficiency of ionization in terms of the number of units of positive charge formed per electron, per cm path, per mm pressure at 0°C, obtained as outlined above. The curve obtained by Smith[21] in a straight-forward manner is presented for comparison. Probably the agreement is as good as could be expected because of the uncertainty in the extrapolation to 180°—there is an appreciable number of slow electrons scattered at large angles. The curve E represents the number of excited molecules formed per primary electron, per cm path, per mm pressure at 0°C, also obtained as outlined above.

From these curves and the absorption coefficient curve one can calculate the actual probability that a collision will result in an excited atom or a unit of positive charge. These probabilities are given by the two dashed curves. As the energy loss due to excitation is mainly 6.7 volts, it is interesting that the probability should be so high. Brattain[23] has measured the probability of excitation of the 6.67-volt energy level in the mercury atom for electron velocities in the neighborhood of this value. He finds that the probability reaches a maximum and begins to fall at about 7.0 volts, having a peak value of about 0.06 (in the same units as we have used). Evidently the probability rises again for higher velocity electrons. The probability for ionization shows a maximum of about 0.45 at about 400 volts.

Further work is in progress which will enable a study of the scattering of lower velocity electrons, and larger angles of deflection.

[22] R. B. Brode, Proc. Roy. Soc. **A125,** 134 (1930).
[23] W. H. Brattain, Phys. Rev. **34,** 474 (1929).