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Electron Scattering in Helium

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An electron scattering apparatus has been used to investigate the scattering of 100 volt incident electrons in helium gas. The angular distribution curves for total scattering and for elastic scattering are compared with the theory as given by Morse and by Mott and Massey and are found to give greater relative scattering at angles near both 0° and 180° than is predicted by the theory. In absolute magnitude the experimental curves generally fall somewhat below the theoretical curves. The angular distributions of electrons scattered with various energy losses equal to or greater than the ionization loss were determined. The curves show that in general, the greater the energy loss the more uniform is the distribution in angle of the scattered electrons. There is a pronounced preference for forward scattering when the energy loss over that required for ionization is small. Integration over the entire solid angle gives the probability for scattering with different energy losses. Curves so obtained for this probability as a function of the energy loss are in qualitative agreement with Wetzel's theoretical calculations except for electrons which have lost nearly all their energy or just slightly more than the ionization energy.

INTRODUCTION

When a gas atom is ionized by the impact of a colliding electron, the electron must give up kinetic energy equal to the ionization energy of the atom and may also transfer any amount of its remaining energy to the ejected electron. If V_c is the collision energy and V_i the ionization energy, then both the incident and the ejected electrons will have energies lying between 0 and $V_c - V_i$. Furthermore, since other processes in which the electron loses as much energy as V_i are relatively unlikely, it is possible to investigate the electrons involved in an ionization by studying those electrons scattered with energies between 0 and $V_c - V_i$.

Studies on the electrons scattered with energies in this region have been made by several experimenters.[1–3] Their results have indicated that, for such electrons, the smaller the loss in energy of the electron, the more likely it is to be scattered in the forward direction. It appears, further, that when an electron ionizes an atom, the remaining energy tends to be divided unequally between the incident and the ejected electron.

The theory has been investigated by Wetzel,[4] who calculated, with the Born approximation, the angular distribution of electrons deflected in ionizing collisions with the helium atom. From the results he was able to arrive at the probability that an electron of incident energy V_c shall retain, after ionizing a helium atom, an energy V,

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[1] C. B. O. Mohr and F. H. Nicoll, Proc. Roy. Soc. **A144**, 596 (1934).
[2] A. L. Hughes and J. H. McMillen, Phys. Rev. **39**, 585 (1932); **41**, 39 (1932)..
[3] J. T. Tate and R. R. Palmer, Phys. Rev. **40**, 731 (1932).
[4] W. W. Wetzel, Phys. Rev. **44**, 25 (1933).

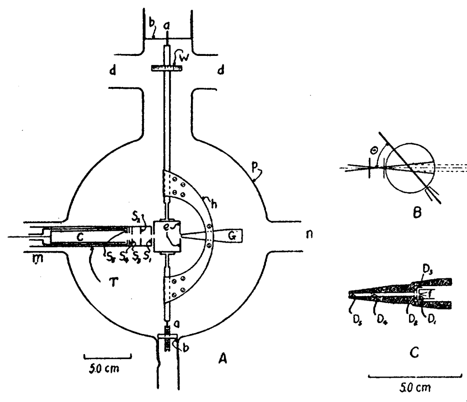

FIG. 1. Diagram of apparatus.

as a function of V. The curves show the general characteristics mentioned as appearing in the experimental results. Wetzel also found the probability for ionization as a function of the incident energy. This last calculation was compared with the efficiency of ionization as measured by Smith[5] and found to predict reasonably well both the absolute magnitude and the shape of the curve.

A more intimate test of the theory can be obtained by comparing with experiment, either the angular distributions of these electrons or the curve giving the probability for an electron to retain a given energy. The present experiment was therefore undertaken to determine, with 100 volt incident electrons in helium, the angular distributions of electrons scattered with various energy losses from 25 to 100 volts over as wide an angular range as possible.

APPARATUS

The apparatus, Fig. 1, was constructed of copper and housed in a 5-liter Pyrex flask sealed without ground glass or wax joints so that it could be thoroughly outgassed by baking. The inside of the flask was coated with a thin layer of evaporated platinum which both shielded the scattering region from stray electrostatic fields and collected the initial beam of electrons passed through the tube. A pair of Helmholtz coils around the tube neutralized the earth's magnetic field. The apparatus was baked out at bright red heat before, and at 300°C for 30 hours after, it was assembled in the tube.

The electron gun G, is shown in cross section in Fig. 1C. Preliminary tests with electron guns had shown that good focusing with good velocity distribution could be attained by dividing the accelerating potential into two parts with diaphragms quite close together. For 100 volt electrons, 20 volts were placed between D_1 and D_2 and 80 placed between D_2 and D_3. The spread in velocity was such that at 100 volts, about 90 percent were within 0.3 volt of the mean. The gun was mounted so that it could be rotated about the axis a–a by means of a cable of copper wires making one turn about the wheel W and extending into the sidearms d–d. This was actuated by an electromagnetic device such that all magnetic material could be removed after a setting was made. The angular setting was read on a scale at W with a vernier attachment. The cups e–e, separated by about 4 mm to permit the electron beam to pass between them, served further to shield the scattering region from both stray electrostatic fields and secondary electrons. All leads were shielded and carried out through the lower bearing.

The collector system T, consisted of a long rectangular box with collimating slits in the diaphragms as shown, a "guard ring" box with opening S_5 and the Faraday cage C. The slit dimensions were 0.5×2.6 mm, 0.65×3.8 mm, 0.5×4.2 mm, 0.8×6.0 mm, and 2.0×10.0 mm in the order of S_1 to S_5. The slits S_1 and S_3 determined the solid angle for collection of electrons as seen from a point in the scattering region. Since slits S_1 to S_4 were all at the same potential, that of the scattering region, potentials applied between S_4 and S_5 could penetrate S_3 very little. Consequently, the effective solid angle of collection was assumed to be equal to that calculated from the geometry of the slits. If a and b are, respectively, the widths of S_1 and S_3, A and B the respective distances of S_1 and S_3 from the scattering center and h the height of S_3, then

$$\Delta\Omega = abh/B(Ab+aB),$$

where $\Delta\Omega$ is the average solid angle for collection. This calculation is similar to one given by Brode[6] and assumes that in the vertical plane of the collector slits, most of the electron beam lies in the umbra of slits S_1 and S_3. In our

[5] P. T. Smith, Phys. Rev. **36**, 1293 (1930).

[6] R. B. Brode, Rev. Mod. Phys. **5**, 273 (1933).

apparatus A and B were respectively 18.0 and 38.0 mm and the beam was not more than 1 mm in cross section at the scattering center. A simple calculation with these values shows that the above condition was satisfied. The formula gives $\Delta\Omega = 0.98 \times 10^{-3}$. The length of electron beam path from which the scattered electrons were taken was $d/\sin\theta$ where $d = 1.4$ mm and θ is the angle of scattering. The scattered currents were measured with one of the d.c. amplifiers built by Distad and Williams[7] having a sensitivity of 125,000 mm/volt. A balancing-out arrangement was used such that in the region of small angles, the total current received by the Faraday cage would equal 15,000 divisions on the scale. It was then possible, when conditions were good, to measure differences of the order of 1 percent with an accuracy of a few percent.

Tests on the Apparatus

To determine the angular scale reading for electrons directed straight into the collector, that is, the zero angle, the scattering was measured over a considerable range on each side of the approximately known zero angle. In Fig. 2a we have shown such a measurement for 100 volt impacts in helium. The ordinates represent the total number of electrons, both elastic and inelastic, received by the collector.

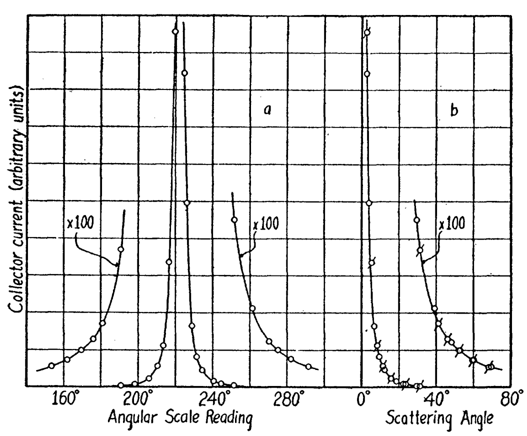

FIG. 2. a, Determination of zero angle. b, Test for symmetry about the zero angle. Circles are for one side of the beam and circles with lines through are for the other side. Curves are for 100 volt impacts and for total scattering uncorrected for change of scattering volume with angle.

[7] M. Distad and J. H. Williams, Rev. Sci. Inst. 5, 289 (1934).

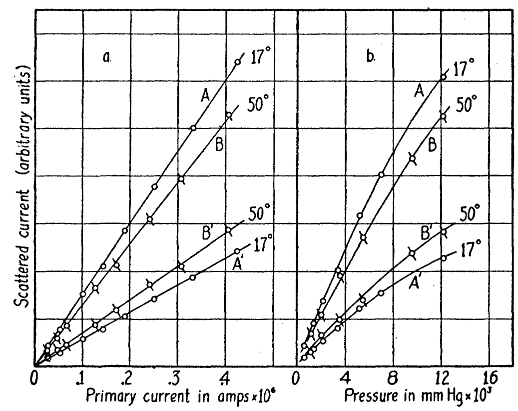

FIG. 3. Curves A and B for total scattered current with 100 volt primaries. Curves A' and B' for elastically scattered current with 100 volt primaries.

If the position of zero angle is taken as 222°, the data from the two sides of the zero angle can be plotted together as is done in Fig. 2b. The circles are for one side of the beam and the circles with lines through them are for the other side. The symmetry is seen to be excellent down to angles as small as about 3°. This indicates that the alignment of the apparatus is good and that the electron beam is itself quite symmetrical.

That the effect of secondary electrons in the apparatus was negligible was demonstrated by measuring the collector current when no gas was present in the tube. This current was too small to be measured at the large angles and at the small angles was never more than a few percent of that obtained with gas in the tube at the pressures ordinarily used.

Figure 3 shows the relation of the scattered current to the primary current and to the gas pressure. The first of these shows very good linearity as indeed it should but the second shows a slight bending. A number of factors may contribute to such a lack of linearity, most important of which is multiple scattering. This enters in two ways, (1) electrons may be scattered through angles whose sum is equal to the measured angle of deflection and thus be added to the proper scattered current and (2) electrons scattered through the measured angle may subsequently collide with another atom and thereby fail to reach the collector. An additional factor which, in our case, added to the apparent nonlinearity was an uncertainty in the measurement

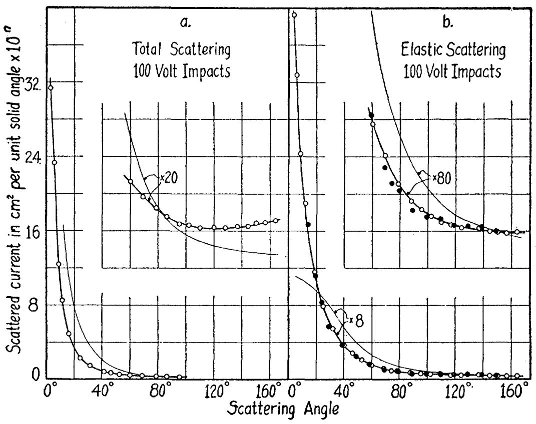

FIG. 4. Circles with heavy lines are experimental curves. Light lines are theoretical curves. Solid curves are from the data of Hughes, McMillen and Webb.

of the gas pressure. The pressure was measured with a McLeod gauge which was later found to be nonuniform. As the data which we shall report were all taken at the same pressure, the relative values of the scattering coefficients should not be greatly affected. However, since the curve in Fig. 3b bends over as it does, we should expect the absolute values to be too low.

In the region of 90° scattering, Arnot[8] observed a considerable number of positive ions entering the collector and came to the conclusion that they were due to a radial field about the electron beam caused by the slowly moving heavy ions. Although the same effect was observed in our apparatus with mercury vapor, it was not found with helium. This was attributed to two causes, (1) the number of ions formed was smaller because of the lower probability of ionization of helium and (2) as the mass of the helium ion is only 1/50 that of the mercury ion, the former has a temperature velocity $(50)^{\frac{1}{2}}$ times that of the latter and therefore the helium ions built up a smaller space charge. A very small positive current was attributed to ions formed in the collector slits and pulled into the collector by the retarding potential for electrons. This effect was observed by Tate and Palmer.[3]

TOTAL SCATTERING AND ELASTIC SCATTERING

The scattering coefficient $P_t(\theta)$ (the total current scattered through an angle θ per atom per unit primary current per unit solid angle) for 100 volt incidence in helium has been plotted as a function of θ in Fig. 4a. Morse[9] has given an expression calculated from the wave mechanics for such scattering. It is,

$$P_t(\mu)=(m^2e^4/4h^4)[(Z-F)^2+(Z^2-F^2)/Z]\mu^{-4},$$

where Z is the atomic number of the scattering atom, $F(\mu)$ its atom form factor and $\mu=(\sin\theta/2)/\lambda$. θ is the angle of scattering and λ is the de Broglie wave-length of the electron, given by $\lambda=h/mv$, where m and v are, respectively, the mass and velocity of the incident electron. With values of the atom form factor given by James and Brindley,[10] this expression was evaluated and is shown as the light solid line in the Fig. 4a. At the small angles the theoretical scattering curve is not steep enough and at the large angles it is too steep. This is in accord with the results of Hughes and Harris[11] who measured the total scattering in helium for impacts of from 200 volts upwards. They did not obtain absolute values but by "matching" the curves at one point, found agreement in shape of the curves for 700 volt incidence and higher. According to our results, the absolute magnitude predicted by the theory would appear to be correct at about 80°. However, it must be remembered that our values are undoubtedly too low.

Figure 4b shows the scattering coefficient $P_e(\theta)$ for elastically scattered electrons only. The heavy line with the circles represents our experimental values while the light line represents the theoretical curve. The latter, excepting for the small angle values, was calculated from Morse's expression,

$$P_e(\mu)=(m^2e^4/4h^4)(Z-F^2)\mu^{-4},$$

using James and Brindley's F values. Of these F values the one for $\mu=0.1\times10^8$ cm is apparently unreliable as it gives a maximum in $P_e(\theta)$ at about 20°. Mott and Massey[12] have given a table of values for $P_e(\theta)$ calculated by the use of

[8] F. L. Arnot, Proc. Roy. Soc. **A129**, 361 (1930).

[9] P. M. Morse, Rev. Mod. Phys. **4**, 609 (1932).

[10] R. W. James and G. W. Brindley, Phil. Mag. **12**, 81 (1931).

[11] A. L. Hughes and W. Harris, Phys. Rev. **48**, 408 (1935).

[12] N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions*, p. 120.

the Hylleraas[13] ψ function for helium. These values decrease monotonically as θ increases and agree with the values from Morse's expression for angles of above 30°. For angles of less than 30° we have used Mott and Massey's table in making up the theoretical curve. As in the case of the total scattering the theoretical curve is too steep at the large angles and not steep enough at the small angles. Hughes, McMillen and Webb[14] have determined the relative values of the elastic scattering coefficients in helium

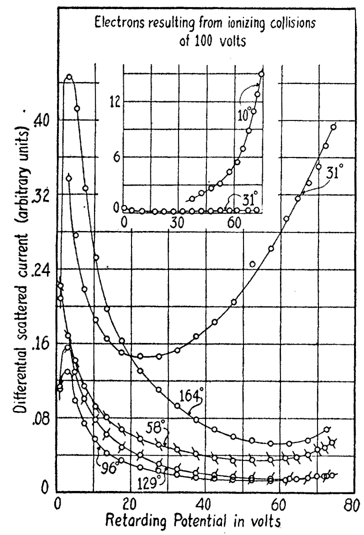

FIG. 5. Energy distribution of scattered electrons at the various indicated angles.

for a number of incident voltages and have found, for impacts of 500 volts and upwards, agreement with the theory in the shapes of the curves. That their results agree with ours can be seen in the figure where we have plotted their values as the solid circles. Their results have been adjusted to agree with ours at $\theta=50°$

SCATTERING FROM IONIZING COLLISIONS

The curves in Fig. 5 illustrate the method of taking the data for the electrons from ionizing collisions. At each angular setting, the distribution in energy of the electrons received by the collector was taken by recording the changes in the collector current when the retarding potential was changed by definite amounts. The data have all been reduced to correspond to uniform increments of one volt so that the ordinates are proportional to the number of electrons received by the collector with energies between $V_r-\frac{1}{2}$ and $V_r+\frac{1}{2}$ volts when the collector is set at the various indicated angles.

Since energy losses of less than 24.5 volts (the ionization energy) were not investigated, the curves do not extend to electron energies above V_c-V_i or 75.5 volts. The curves show that the higher energy electrons, that is, those which have lost small amounts in addition to the ionization energy, predominate at the small angles whereas the low energy electrons or those which have lost most of their energy, predominate at the larger angles. It is interesting to note that for angles of above 90° there is a peak in the curves at about 3 volts, showing that the probability for an electron to come off at these angles with V volts energy approaches zero as V approaches zero, for V less than about 3 volts.

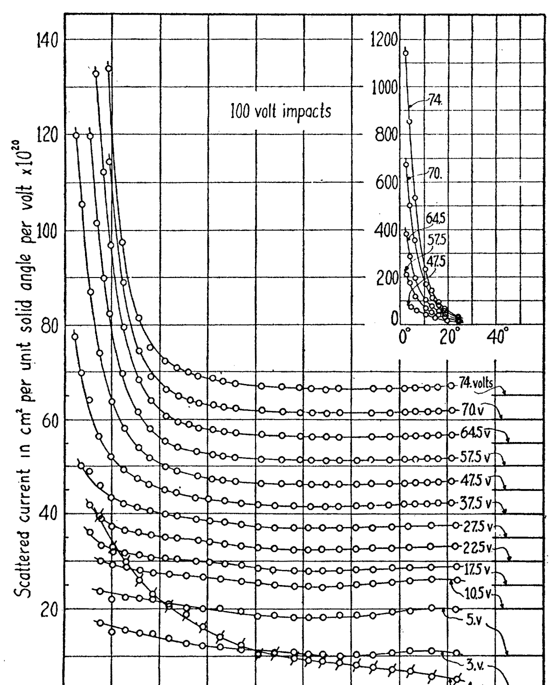

FIG. 6. Angular distribution curves for electrons scattered with the indicated energies when the incident electron energy is 100 volts. The zeros of the curves are shifted upwards as shown.

[13] E. Hylleraas, Zeits. f. Physik **54**, 347 (1929).
[14] A. L. Hughes, J. H. McMillen and G. M. Webb, Phys. Rev. **41**, 154 (1932).

On account of the inherent difficulties in measuring the number of such low velocity electrons, the exact shape of the curves in this region cannot carry much importance. However, the peak is quite definite at the large angles.

In order to compare the scattering of electrons of a given energy loss at the different angles it is necessary to divide the ordinates of Fig. 5 by the length of primary beam path from which the electrons are taken. This, as previously stated, is $0.14/\sin\theta$ cm where θ is the angle of scattering. When this is done one gets the curves shown in Fig. 6. Here we have also multiplied by a constant $K/(3.56\times10^{16}\times P\times\Delta\Omega)$ where P is the gas pressure ($=0.012$ mm Hg), $\Delta\Omega$ is the average solid angle of collection ($=0.98\times10^{-3}$) and K is a factor depending on the sensitivity of the amplifier and that of the galvanometer which measures the total gun current. The ordinates then represent the number of electrons scattered through the angle θ in the given energy range, per primary electron per unit solid angle when there is one atom per cubic centimeter at the scattering center.

The curves in Fig. 6 show that the electrons which have lost most of their energy, that is, those which have very little remaining energy, are scattered rather uniformly over all angles with a slight preference for the forward direction. Those which have retained a greater amount of their energy are scattered more in the forward direction. In fact, the greater the energy retained by the electrons, the steeper the angular distribution curve is. This is in accord with the observations of Tate and Palmer[3] in mercury vapor and with those of Mohr and Nicoll[1] in helium. The one volt electrons, that is, those which come away with energies between 0 and 2 volts, form an apparent exception. It is quite likely that this is a spurious effect. While our scattering region appeared to be quite free from electrostatic and magnetic fields, it is easily possible that there may have been fields present great enough to affect electrons of a few tenths of a volt velocity.

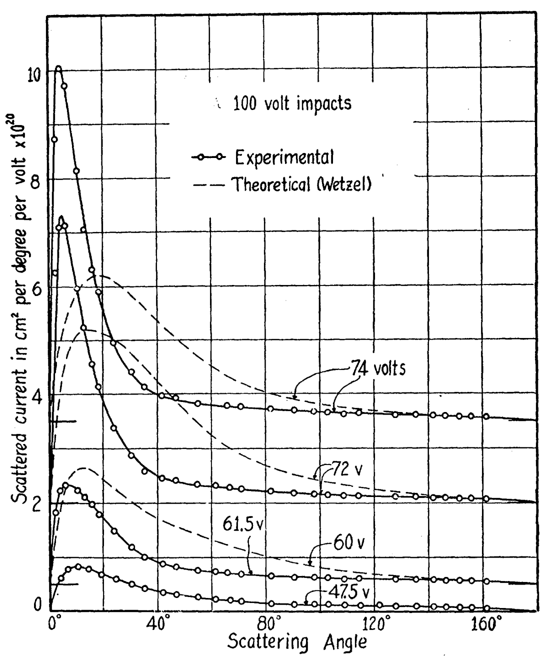

FIG. 7. Scattering per degree of electrons of the indicated energies when the incident electron energy is 100 volts. The zeros are shifted upwards as shown.

In Figs. 7 and 8, the experimentally determined scattering per unit angle curves are shown as the circles with the solid lines drawn through them. The zeros of the various curves are shifted upwards as indicated to avoid congestion of the lines. The ordinates here represent the effective cross section of a helium atom for scattering electrons of the indicated energy into the region between the cones θ and $\theta+\Delta\theta$ when the impinging electron has an energy of 100 volts. As before, each curve includes the electrons having energy within $\frac{1}{2}$ volt of that indicated. Since $\Delta\theta$ was made equal to one degree of arc, the ordinates are expressed in cm^2 per volt per degree. To obtain these curves, the scattering per unit solid angle must be integrated over the azimuthal angle which is accomplished by multiplying by $2\pi\sin\theta\cdot\Delta\theta$. The solid angle between the cones θ and $\theta+\Delta\theta$ obviously approaches zero as θ approaches both 0° and 180°. Therefore, if the scattering per unit solid angle is to remain finite, it is necessary that the scattering per unit angle approach zero at these two angles. This makes it possible to extrapolate the curves if they can be determined to a point where they appear to be past any maxima. In all cases it was possible to get at least one point far enough beyond the maximum so that the extrapolation could be be made. To do this it was necessary to measure the scattering for the higher energy electrons at

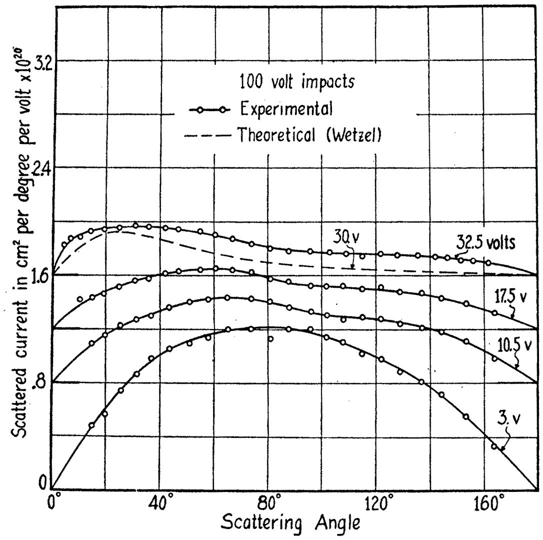

FIG. 8. Scattering per degree of electrons of the indicated energies when the incident electron energy is 100 volts. The zeros are shifted upwards as shown.

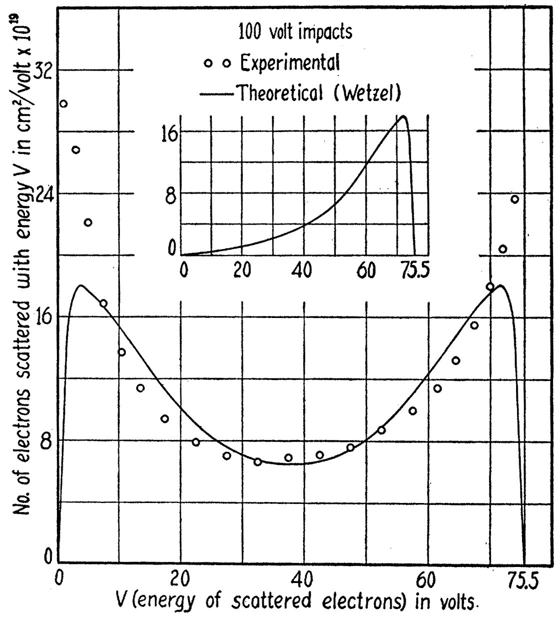

FIG. 9. Distribution in energy of the sum of incident and ejected electrons scattered over the entire solid angle. Inset: theoretical distribution for incident electrons only.

very small angles. The curves obtained are reasonably regular in spite of the fact that any errors in the reading of the angle are extremely important here since the experimental data have to be multiplied by $\sin^2 \theta$. The extrapolation of the lower energy curves is much less evident both because the maxima are flatter and because small angle data for these energies were harder to get. The latter is due to the fact that at small angles these currents are very small relative to the total scattered current.

Since the angular distribution curves calculated by Wetzel[4] are for the incident electrons only and the experiment curves include both incident and ejected electrons, the two are not strictly comparable. However, the higher energy electrons may be supposed to be made up largely of incident electrons so that here the theory might be expected to predict the experimental curves. In Fig. 7 we have shown Wetzel's results in the case of 100 volt impacts for 74, 72 and 60 volt scattered electrons along with our results for 74, 72 and 61.5 volt electrons. The theoretical curves are the dashed lines. In each of these cases the experimental data show a greater concentration of scattered electrons in the forward direction than is predicted by the theory. The maxima in the theoretical curves fall considerably below the experimental maxima in the cases of the 74 and 72 volt electrons whereas the maximum in the 60 volt theoretical is somewhat higher than that in the 61.5 volt experimental curve. The absolute magnitude predicted by the theory appears to become more accurate at the larger angles in all three of these cases. In Fig. 8, the theoretical curve for 30 volt electrons is compared to the experimental curve for 32.5 volt electrons. Since the number of ejected electrons of this energy is presumably greater than the number of incident electrons, we expect the theoretical curve to be low, which it is found to be. For the larger losses in helium and in hydrogen, Mohr and Nicoll[1] have compared the theoretical angular distribution of the incident electrons with that of the ejected electrons and found the two to be quite similar. Therefore, we might expect Wetzel's 30 volt curve to predict the shape of the experimental curve. This is seen to be only very roughly true, the relative scattering at the large angles being much larger than predicted.

By integrating numerically, theoretical curves of the type shown in Figs. 7 and 8, Wetzel obtained the number of incident electrons scattered with a given energy over the whole solid angle as a function of this energy. This curve for 100 volt impacts is shown in the inset of Fig. 9. An accurate, though less detailed comparison with the theory can be made at this point. Since, for every electron scattered with a loss of V volts in addition to the ionization loss (V_i) there is an ejected electron coming away with V volts energy, we can find the theoretical curve for the sum of the incident and ejected electrons by adding to the curve in the inset of Fig. 9, its mirror image. The result, which obviously must be symmetrical about the energy $(V_c - V_i)/2$ or 37.75 volts, is given by the solid line in Fig. 9. We see that the theory predicts a minimum probability for an ionization which leaves the incident and the ejected electrons with equal energies. Furthermore, the most probable process is one in which one electron carries all but about 3.5 volts of the available energy. The experimental results which we have determined by numerical integration of the curves in Figs. 7 and 8 are given by the circles in Fig. 9. The absolute values have been multiplied by the factor 1.9 to effect a better comparison. They confirm the minimum at $(V_c - V_i)/2$ volts but show no evidence of maxima at 72 and 3.5 volts. In order to determine more accurately the shape of the curve in the regions of the predicted maxima, retarding potential increments smaller than the 2 volts used, are necessary. Intensity limitations prevented us from making the increments smaller excepting for the high energy electrons in the region of small angles. Fig. 7 shows that the small angles contribute most of the scattered electrons of high energy. Therefore one would expect to observe the higher energy maxima of Fig. 9 as a peak near 75 volts in the velocity distribution of electrons scattered at small angles. Although retarding potential increments as small as 0.2 volt were used, no such peak was found. It must be remembered that the accuracy of the theory should be better at higher incident electron energies. Consequently, it is necessary to get further experimental data before making any certain evaluation of the theory on this point.

In conclusion, the writer wishes to express his gratitude to Professor John T. Tate under whose direction the work was done. Thanks are due also to Professor E. L. Hill for helpful discussions on the theory of electron scattering.

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Disintegration of Aluminum by Polonium Alpha-Particles

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In order to investigate the discrepancies existing in the experiments of Pose and of Chadwick and Constable regarding the protons emitted by aluminum under alpha-particle bombardment, the thick target absorption curve for the protons has been repeated. The radioactive source was polonium, and an FP-54 vacuum tube electrometer was used to detect the protons. The structure of the groups observed in the present experiment agrees with the work of Chadwick and Constable, and confirms their interpretation of the results. The ranges of the principal groups are in better accord with those found by Pose. It is suggested that Pose's discrepancies were due to sources which predominantly emitted particles of shortened range, and to an insufficient number of accurate points. An increase in proton yield with the height of the resonance levels has been observed. The relative intensity of the short and long range groups is 4.0, and the difference in energy of any two corresponding groups is 2.4 Mev.

Introduction

In many respects aluminum makes an ideal target for nuclear investigations. For this reason the reaction

$$_{13}Al^{27} + {_2He^4} = {_{15}P^{*31}} = {_{14}Si^{30}} + {_1H^1} + Q,$$

where Q represents the energy balance, is today the most thoroughly studied of its type. In aluminum only the $_{13}Al^{27}$ nucleus is stable, so there is no confusion as to which of several isotopes might be involved in the reaction. The