ANGLE AND ENERGY DISTRIBUTION OF ELECTRONS SCATTERED BY HELIUM, ARGON AND HYDROGEN

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Abstract

The distribution of electrons rebounding at definite angles from gaseous molecules was investigated. An electrostatic re-focussing arrangement was used to analyse the energies of the electrons. In helium, it was possible to identify the following energy losses at several angles, 21.12, 22.97, and 23.62 volts for a primary electron beam of 50 volts, but not the 19.77 and 20.55 volt losses.

The number of electrons, rebounding without loss of energy, was measured for different angles of rebound (7° to 60°) from argon, helium, and molecular hydrogen molecules, and for various energies (50 to 150 volts). A scattering curve was also obtained in helium for 100 volt electrons that had lost 21.12 volts energy. In almost all cases, the number scattered decreased rapidly as the angle increased. The higher the energy of the electrons, the more rapidly did the number fall off with increasing angle. The steepness of the curves increases as we go from argon to helium to hydrogen for the slower electrons. For the faster electrons their curves are practically superposable.

The results were compared with those of other observers and with the theoretical predictions of Mott, Mitchell and Sommerfeld.

Introduction

An investigation of single scattering of electrons by gaseous molecules has become a subject of particular interest, in that it enables one to appraise certain theoretical predictions of the new quantum mechanics and to verify the choice of external atomic fields used in the application of the general scattering theory.

The general theory of scattering was first investigated, from the point of view of wave mechanics, by Born.[1] Sommerfeld[2] and Mitchell,[3] using Born's general theory, have calculated the angular distribution of elastically scattered electrons in argon. Mott[4] has done the same for helium and Born[5] for atomic hydrogen. Few experimental measurements, however, have been made on the scattering of electrons by gaseous molecules. Dymond and Watson[6] have measured the distribution of inelastically and elastically scattered electrons in helium, using 210 volt electrons. Their results agreed well with the calculations of Mott. Harnwell,[7] with 120 and 180 volt electrons, has measured the scattering in atomic and molecular hydrogen. Arnot[8]

[1] M. Born, Zeits. f. Physik **38,** 803 (1926).
[2] Atombau und Spektrallinien Wellenmechanischer Ergänzungsband, p. 226.
[3] A. C. G. Mitchell, Nat. Acad. Sci. Proc. **15,** 520 (1929).
[4] N. F. Mott, Proc. Cam. Phil. Soc., **25,** 304 (1929).
[5] M. Born, Gottingen, Nachr. p. 146 (1929).
[6] Dymond and Watson, Proc. Roy. Soc. **125A,** 660 (1929).
[7] G. P. Harnwell, Phys. Rev. **34,** 661 (1929).
[8] F. L. Arnot, Proc. Roy. Soc. **125A,** 660 (1929).

obtained scattering curves for 80 volt electrons in mercury vapor. Little work has been done, however, using a large range of velocities in conjunction with several scattering gases.

It was the purpose of this investigation to measure and compare the angular distribution of electrons elastically scattered by the three gases, helium, argon and molecular hydrogen, when colliding electrons of several energies are used. The energies used were 50, 75, 100 and 150 volts. The angles investigated ranged from 7° to 60°. The distribution of inelastically scattered electrons in helium was likewise determined for 100 volt electrons. This investigation also includes a measurement of the energy losses in helium at various angles.

Description of Apparatus

The apparatus used in this investigation may be briefly described as consisting of an electron projector A, a collision chamber B and an analysing chamber C. A diagram is given in Fig. 1. Electrons leaving the projector A were scattered by the gas molecules in chamber B. After single collisions in B the electrons passed through the slit s_4 into the analyser C. The two cylindrical plates, M and N in C, when set at the correct potentials, deflected the electrons into the Faraday cylinder F.

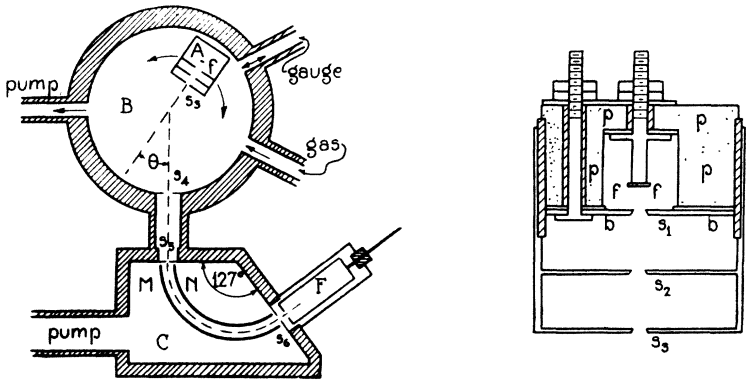

Fig. 1. Diagram of apparatus.

The projector, as shown in Fig. 1, consisted of an oxide coated filament f, a grid b with slit s_1, a final grid with the two slits, s_2 and s_3, and a back plate p. All parts were made of brass, with the exception of the plate p, which was constructed of aluminum alloy. A glass cylinder and mica sheets were used as insulators. The potential on the final double slits, s_2 and s_3, determined the energy of the electrons projected through the slit. The potentials on b and p were fixed so as to give the maximum emission from the projector, or gun, as it is sometimes called. The slits of the gun play an important part, since they are the chief source of slow electrons. Their lips were sharply bevelled and sooted to eliminate slit-scattering. The dimensions of the slits were $s_1 = 1$ mm $\times$ 15 mm, $s_2 = 0.8$ mm $\times$ 14 mm, $s_3 = 0.4$mm $\times$ 14 mm.

The projector could be rotated about the axis of the cylindrical chamber B. In B the electrons collided with the gaseous molecules and were reflected

at various angles. Only those electrons which were reflected at an angle θ entered the analysing chamber. This angle was determined by the gun-setting. The gun was fastened to a brass tube which fitted into a ground glass joint. The ground glass joint was waxed into the back end of the brass chamber B. On to the front end was fastened a thick glass plate. A copper screen placed on the inside surface of the glass plate insured the equipotentiality of chamber B.

The analysing chamber was connected to the collision chamber B by a short brass tube. The two chambers were separated by two slits; s_4, 2mm $\times$14mm and s_5, 0.3mm$\times$10mm. The angle subtended at s_5 by s_4 measured one and a half degrees. The cylindrical plates M and N were bolted to the wall of the chamber and insulated from it by sheets of mica. The radii of curvature of the plates were 50 mm and 60 mm respectively. The plates formed an arc which subtended an angle of 127° 17′. It has been shown, and predicted by theory, that the potential difference between the plates necessary to deflect electrons from s_5 to s_6 is proportional to the energy of the electrons The particular chamber and the properties of the electrostatic analysing method have been described by Hughes and Rojansky[9] and Hughes and McMillen.[10] The Faraday cylinder was connected to a Compton electrometer.

The gas to be investigated flowed into chamber B through a small capillary and was pumped out by a mercury diffusion pump. This arrangement maintained a steady pressure and a fresh supply of pure gas in the collision chamber B. The pressure was read on a McLeod gauge. To secure high pumping speeds, a glass tube of large diameter connected the analysing chamber with a Gaede two stage steel diffusion pump. The gases used in this experiment were helium, hydrogen and argon. Helium was purified by slow passage over charcoal at liquid air temperature. The hydrogen was obtained by heating a palladium tube. A discharge in the presence of calcium vapor was employed to purify the argon. To freeze out the mercury liquid air traps were inserted. The following pressures in mm of Hg were used with the following gases: helium, 0.008 mm; hydrogen, 0.006 mm; argon, 0.004 mm.

Energy Losses in Helium

To measure the energy losses, the projector was set at some fixed angle and the electron current to the Faraday cylinder noted for each set of potentials on the deflecting plates. The energy of the deflected electron is readily obtained from the potential on the deflecting plates when the ratio of the energy of the deflected electron to the deflecting potential is known. This ratio was established when no gas was in the apparatus. One can then obtain a set of curves plotting the number of electrons against their energy. Unfortunately, because of excess scattering of the slits and other unaccounted for defects in the apparatus, the original curves had to be modified by subtracting from them spurious peaks and background scattering which were also present in the absence of any gas.

[9] Hughes and Rojansky, Phys. Rev. **34**, 284 (1929).
[10] Hughes and McMillen, Phys. Rev. **34**, 291 (1929).

In Fig. 2 can be seen an energy loss curve for helium. This curve was taken with electrons of 50 volts energy and indicates the energy losses for those deflected at 10°. The abscissa measures the energy of the electrons after collision, while the ordinate measures the number of electrons having that particular energy. The energy loss is also indicated in the diagram. The main peak at 50 volts, comprised of electrons making elastic impacts, is many times higher than the remaining peaks and extends off the figure. A group of peaks is seen near 30 volts energy region, indicating losses of the order of 20 volts. In this group there are three distinguishable peaks. The obvious lack of symmetry of the main energy-loss peak suggests a smaller peak, or peaks, overlapped by the main peak. One notes, too, on the low

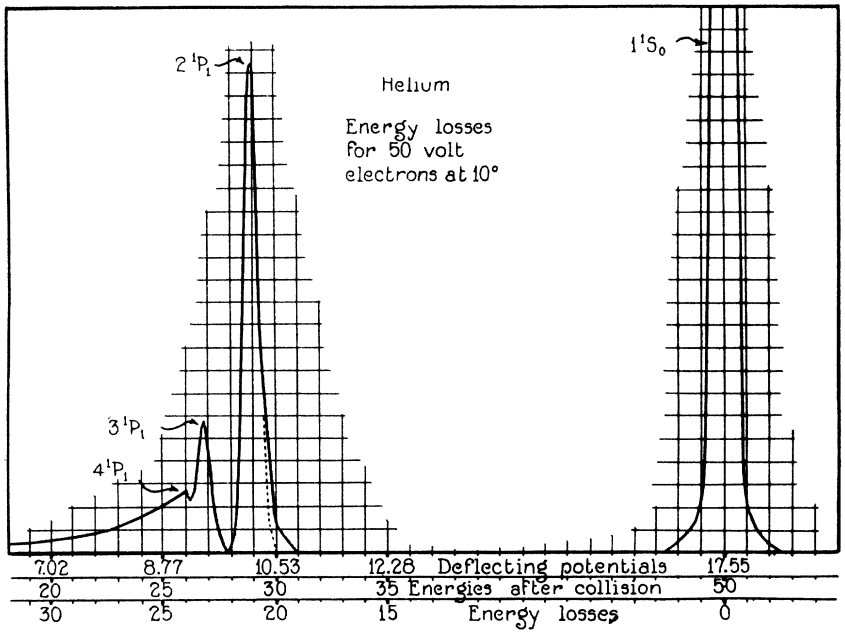

Fig. 2. Energy losses in helium for 50 volt electrons simultaneously deflected at 10°.

energy side of the last peak, that there is a gradual shading off in intensity. Fig. 3 shows the main energy-loss peak and the composite subsidiary peak for 100 volt electrons. For the case of electrons of 100 volts energy the lesser peaks have become indistinguishable because of the poor resolving power at higher voltages. These curves are similar to those obtained by Dymond,[11] who used the magnetic deflection method.

In identifying these energy-loss peaks great care was taken in measuring the magnitude of the energy loss of the main energy-loss peak, and the remaining peaks were then referred to it. The procedure was carried out in the following way: the main beam of electrons was directed into the gas at a definite energy, as read on the accelerating voltmeter. With the deflecting potential set at the value to give the main energy-loss peak, the energy of the

[11] E. G. Dymond, Phys. Rev., **29**, 433 (1927).

original beam was lowered until the main beam reached an energy value such as to be directed into the Faraday cylinder. The reading of the voltmeter under those conditions subtracted from the original setting read directly the energy loss in volts. This method of measurement demanded only two readings and both readings were taken on the same voltmeter, thus giving greater accuracy. Also the difference read in this manner was three times the corresponding unconverted reading on the deflecting potential voltmeters.

A set of 15 readings over a range of 50 to 150 volts gave for the main energy-loss peak an average energy loss value of 21.50 with the probable

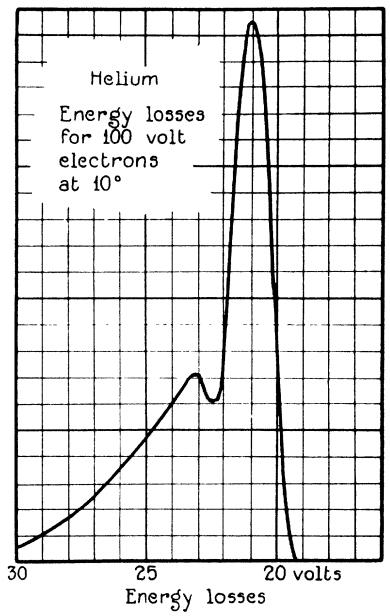

Fig. 3. Energy losses in helium for 100 volt electrons simultaneously deflected at 10°.

error of 0.15 volts. One has from spectroscopic data the following possible energy losses: 19.77, 20.55, 21.12, 22.98, 23.63, etc., corresponding to the transitions $1^1S_0-2^3S_1$, $1^1S_0-2^1S_0$, $1^1S_0-2^1P_1$, $1^1S_0-3^1P_1$ and $1^1S_0-4^1P_1$ respectively. The above measured-loss 21.5 lies closer to the spectroscopic value 21.12 than to any of the others, which indicates that the main energy loss peak corresponds to the 21.12 loss or to the first transition in the principal series, $1^1S_0-2^1P_1$. This choice is further supported by a series of measurements taken on the other two peaks. These measurements were taken directly from the energy-loss curves and measured as separations of the two small peaks from the main energy-loss peak. These measured separations of the two small peaks from the main energy-loss peaks showed that in matching experimental separations of energy losses with the various combinations of possible separations taken from spectroscopic data a good match was obtained by assigning to the main energy-loss peak the transition

$1^1S_0-2^1P_1$, as was done above, and to the next two peaks the transitions $1^1S_0-3^1P_1$ and $1^1S_0-4^1P_1$ respectively. The averaged separation between the first main peak and the next was 2.13, while the spectroscopic difference between 2^1P_1 and 3^1P_1 is 1.85. The averaged experimental separation between the two lesser peaks is 0.82, and the spectroscopic difference between 3^1P_1 and 4^1P_1 is 0.65. This is fairly good agreement, in view of the uncertainty of measurement for the low intensity peaks. Dymond, in his paper on electron scattering, attributed the main energy-loss peak to the 20.55 loss, which, in view of the above results, seems to be untenable. Further support for the identification of this main energy-loss peak as the 21.12 loss peak is obtained from probability considerations. Attributing the main energy-loss peak to the transition associated with the 21.12 loss indicates, in view of the prominence of this peak, that this loss is by far the most probable in the 50 volt energy range. This is in accord with the work of Glockler,[12] who measured double impact losses in helium by the partial current method. Glockler's most prominent double impact peak, 40.86, was assigned to the transitions 21.12 and 19.77, the 21.12 loss occurring when the colliding electron had 40.86 volts energy. Dymond,[13] also using the double impact method, found that the most probable loss in this energy range was 20.9 ± 0.2, which, in view of the present work, should be assigned to the 21.12 loss. However, Dymond assigned this energy difference to the 20.55 transition.

The indication of one or more peaks on the high energy side of the $1^1S_0-2^1P_0$ peak is in such a position as to be due to either a 19.77 loss, a 20.55 loss, or both. The gradual tapering off in intensity evident after peak C can be explained, as was done by Dymond and Watson, as the composite of the peaks of decreasing intensity corresponding to the remaining lines in the principal series. It is interesting to note that no peak appears corresponding to the energy lost in ionization, i.e. at 24.5 volts. In the first place, the efficiency of ionization is low for 50 volt electrons and, in the second place, there are now two electrons after collision, and conceivably, they may share the excess energy in all possible combinations.

The energy-loss values showed no variation when measurements were made for various angles The angles used ranged from 0° to 20°. It was also observed that there were no variations in the energy-loss values outside of the experimental errors of the apparatus when colliding electrons of energies ranging from 40 to 150 volts were used.

Angular Distribution of Rebounding Electrons

The angular distribution curves for electrons making elastic impact were determined for the two monatomic gases, helium and argon, and the diatomic gas hydrogen. The energies of the colliding electrons ranged from 50 volts to 150 volts, while the angles investigated extended from 7° to 60°. An inelastic scattering curve was also obtained for helium with electrons of

[12] G. Glockler, Phys. Rev. **27**, 423 (1926).
[13] E. G. Dymond, Proc. Roy. Soc. **107A**, 291 (1925).

100 volts. These curves have been plotted so as to indicate the proportionate number of electrons scattered per unit solid angle at the angle indicated. The abscissa is calibrated in degrees, while the ordinate is graduated in

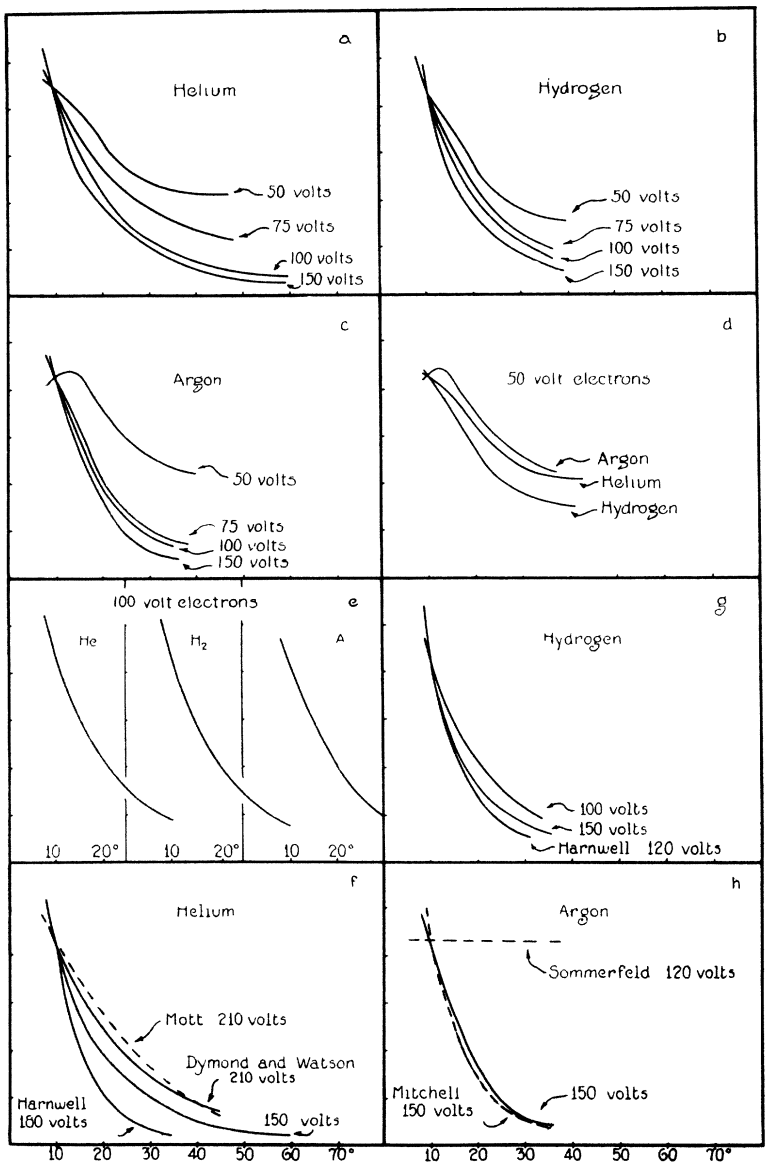

Fig. 4. Distribution per unit solid angle of elastically scattered electrons.

arbitrary numbers. All curves given in the accompanying figures were so arranged as to coincide at 10°. This was a necessary procedure because of the difficulty one encounters in attempting to measure the absolute value of the intensity of the scattered electrons.

A scattering curve was obtained by setting the potentials on the deflecting plates in the analyser to correspond to one of the peaks of the energy-loss curve and by measuring the electron current to the Faraday cylinder for various settings of the projector. The total number scattered upon a collision with an energy-transfer or upon elastic collision at any angle is proportional to the area under the corresponding peak of the energy-loss curve taken at that angle. A separate investigation showed that the area under the peak was proportional to its height, which justifies the procedure of taking the height of the peak as a measure of the number scattered at that angle. There were always present in the scattering curves some spurious electrons. In order to correct for these, their magnitude was determined by a separate set of readings with no gas in the apparatus and subtracted from the original curve. The magnitude of this spurious curve was much greater, however, than its effective magnitude when the gas was present. This was due to the fact that the electrons causing the spurious peaks were partially absorbed or scattered by the gas molecules as they pass from the gun slit to the analysing chamber slit. Hence the spurious curve obtained with no gas in the apparatus was reduced before being subtracted from the original curve. A further correction had to be applied to the original scattering curve in order to correct for the variation of scattering volume with changes in the angle of the projector. It is apparent that the collision volume, the volume common to the emission wedge from the projector and the reception wedge of the slit s_3, varies as $1/\sin\theta$. To reduce, then, one's readings to the same volume of collision, one multiplies the results by the $\sin\theta$.

The angle θ was measured accurately by a protractor and pointer arranged outside the apparatus. Because of the fact that the gun emitted a wedge-shaped beam of electrons, some electrons were measured after having been deflected at an angle other than that of θ. This discrepancy in the value of θ became appreciable only for small values of θ The co-latitude angle measured in the plane perpendicular to the paper in Fig. 1 remains the same for all settings of the projector. Its magnitude is approximately equal to the length of the slit-entrance of the Faraday cylinder divided by the path from the gun to the Faraday cylinder. It is about 2°.

The elastic scattering curves, i.e., curves indicating the angular distribution of electrons rebounding from elastic collisions, can be advantageously studied, by comparing curves for one gas with electrons of various energies and then by comparing the curves for the various gases with colliding electrons of the same energy. The three sets of curves taken with the three gases, helium, argon and hydrogen, are shown in the accompanying figure; helium, Fig. 4(a); hydrogen, Fig. 4(b); argon, Fig. 4(c). An inspection of these curves shows the following characteristics:

(a) First, one observes that the curves for electrons of lower energy are much less steep than those of higher energy. That is to say, the higher the energy of the electrons, the less the deviation from the undeflected path. This is true for all three of the gases used.

(b) It can also be seen that the change in slope of these curves is more

evident in the comparison of the 100 volt and 50 volt curves than in the comparison of the 100 volt and 150 volt curves. Thus, the change in slope with energy of the colliding electron is more marked at low velocities.

(c) One further notes a change in shape of the low energy curves. These curves flatten out at small angles, indicating a smooth hump in this small angle region. The higher energy curves, on the other hand, rise steeply with no suggestion of becoming horizontal. The argon curve for 50 volts, Fig. 4(b), has a definite hump at 12°.

(d) In Fig. 4(d) are superimposed the 50 volt curves of the three gases, helium, hydrogen and argon. The curves are very different, argon showing a much greater degree of scattering than helium and helium a greater degree than hydrogen.

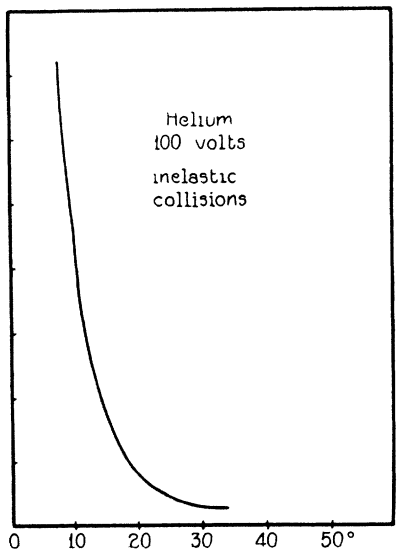

Fig. 5. Distribution per unit solid angle of electrons scattered from helium molecules with a loss of energy corresponding to the transition $1^1S_0-2^1P_1$.

(e) For electrons of greater energy, energies of 100 or 150 volts, the curves for the three gases do not differ much. An inspection of Fig. 4(e) shows that there is very little difference between the three curves when the 100 volt electrons were used. The change in slope, then, for various gases is only evident with electrons of low energy.

It was also possible to obtain an angular distribution curve for electrons having lost energy upon collision. In Fig. 5 is shown the distribution for electrons having lost energies corresponding to the $1^1S_0-2^1P_1$ transition in helium. The curve drops off rapidly, showing that electrons losing energy are only slightly deflected by the collision. Dymond and Watson's inelastic curve is in agreement with the one obtained in this investigation.

Discussion of Scattering Measurements

Although these scattering curves allow certain definite observations to be made concerning the behavior of scattered electrons when the scattering

gas is varied and when the energy of the colliding electrons is varied, no simple collision process, such as that used most successfully by Rutherford in his theory of α-ray scattering, based on classical methods, is forthcoming. A collision theory based upon the new mechanics, however, has been developed by Born. All collision theories make this one observation; namely, the decrease in the degree of scattering for electrons of higher energy, an observation in accord with the results obtained in this investigation.

For helium Mott has applied this general theory to elastic collisions, assuming an atomic force field given by Hartree's selfconsistent fields. The result, however, applies to relatively fast electrons and has only been worked out for 210 volt electrons. An experimental curve for scattering in helium has been obtained by Dymond and Watson for 210 volt electrons which agrees well with Mott's theoretical curve, but which is less steep than our 150 volt curve, as can be seen in Fig. 4(f). This difference between the results of Dymond and Watson for 210 volt electrons and our results for 150 volt electrons is of too great a magnitude and in the wrong direction to be explained as a difference caused by the use of two different electron velocities. Harnwell, in a qualitative investigation of helium,observed very little difference in the degree of scattering by helium and by hydrogen (an observation verified in this investigation for high velocity electrons). If this is so, Harnwell's hydrogen curve may be used as an estimate of his helium scattering curve. Investigation of Fig. 4(f) shows that this curve is much steeper than either Dymond and Watson's or the author's. These three measurements of elastic scattering in helium, although at variance with each other, are all much closer to the prediction of Mott, based on the new mechanics, than to the results obtained when one assumes the Coulomb field.

In Fig. 4(g) can be seen Harnwell's 120 volt hydrogen curve and the 100 and 150 volt hydrogen curve as obtained in this investigation. (Harnwell's curve has been replotted from the original data to indicate the number scattered per unit solid angle at the angle θ. The original data was given as the number scattered in the total solid angle subtended between θ and $\theta+\Delta\theta$). Harnwell's curve is much steeper than either our 100 or 150 volt curve. It is difficult to explain this discrepancy. No theoretical results have been given for molecular hydrogen.

Both Mitchell and Sommerfeld have calculated the degree of scattering for argon. Sommerfeld has applied Born's general collision theory and obtained an atomic force field by assuming that all the electrons were situated in the K shell. For 120 volt electrons Sommerfeld finds practically no change in the number of electrons scattered as the angle is increased from 0° to 90°. This does not agree with the results obtained above. Mitchell has adopted an atomic field force given by Fermi and calculated the degree of scattering in argon for electrons of various velocities. Fig. 4(h) shows good agreement for the 150 volt electrons. The figure also gives Sommerfeld's results approximately. Mitchell's curves for the lower velocities did not agree well with our experimental values. (Dr. Mitchell very kindly contributed the data, as yet unpublished, used in drawing the above curve.)

In conclusion I wish to thank Professor A. L. Hughes, under whose direction this work was carried out.