ON ELECTRON SCATTERING IN HELIUM

By E. G. Dymond

Abstract

Velocity and angular distribution of electrons scattered by single collisions in helium.—An apparatus is described in which both the velocity and the angular distribution of electrons which have suffered single collisions in a gas are examined. It is found in helium that, for initial velocities of 100 volts and over, the principal energy loss is due to the excitation of the 2^1S state, corresponding to 20.5 volts. No loss corresponding to 19.7 volts is found for these velocities. For still higher velocities it seems probable that the energy interchange ceases to be quantized, and that the atom is capable of absorbing temporarily more energy than is required for excitation. The angular distribution of electrons which have lost 20.5 volts energy in colliding shows very marked maxima, the predominant one being in the forward direction. The bearing of the Schrödinger wave mechanics on this point is discussed.

THE problems of electron collisions have been in the past attacked from only two sides; that is by the determination of critical potentials and of the efficiency of excitation and ionization. The information which we may obtain from these sources, useful as it has been, is, especially in the case of efficiency of inelastic impact, very incomplete, and also is insufficient in itself to provide us with an idea of the mechanism of excitation or ionization. We need in addition to the energetic relations of collisions, those of momenta also. We must consequently trace the paths of the colliding bodies as well as determine the interchange of energy between them.

Because of the disparity in the masses of the atom and the electron it is only necessary to follow the latter. Little work has been done in this field. Davisson and Kunsman[1] have investigated the scattering of electrons by thin metal films and Langmuir[2] has found some surprising features in the scattering on excitation in a gas.

In view of the unexpected results obtained by these workers and of the great theoretical interest recently attached to these phenomena the work to be described here was undertaken in order to determine with some exactness the angular distribution of the electron paths about the initial direction after a collision has taken place, and also to investigate the energy losses in a region of velocity which has hitherto been difficult of access. A brief report on the scattering has already been published.[3]

[1] Davisson and Kunsman, Phys. Rev. **22**, 242 (1923).
[2] Langmuir, Phys. Rev. **27**, 806 (1926).
[3] Dymond, Nature, p. 336, September 4, 1926.

Experimental Arrangements

A magnetic deflection method was used to determine the velocity distribution. The apparatus is shown in side and end elevations in Fig. 1. The source of electrons was a short tungsten filament surrounded by a copper cylinder A, whose end was closed by two discs pierced with two slits S_1. On the application of a field between cylinder and filament, this portion of the apparatus acted as a electron "gun." shooting out a narrow beam of electrons into the surrounding space. A glass tube supported the gun and received the leads from the filament and cylinder. This tube could be rotated about an axis BB, a ground sleeve C lubricated with rubber grease maintaining the airtightness of the whole. Immediately below the axis BB were two slits S_2 and S_3.

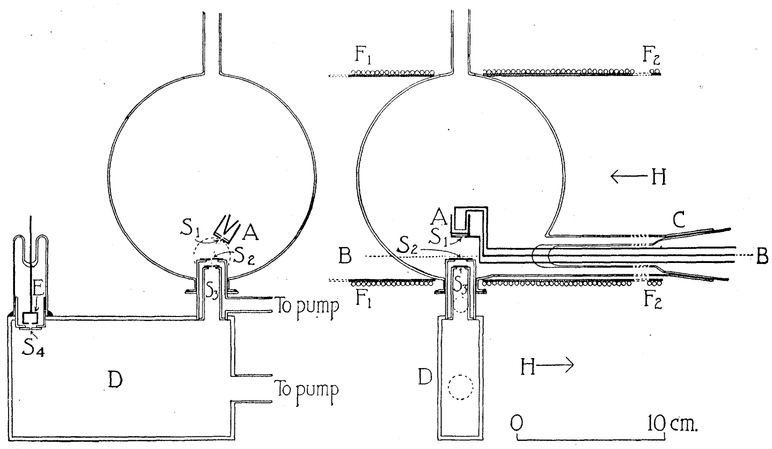

Fig. 1. Side and end elevations of apparatus.

It will be seen that these slits could select a group of electrons which had been scattered out of the main beam by collision with the gas anywhere along the line BB. By rotating the tube on which the gun is mounted the angle of scattering could be varied from 0° to 90°. By a suitable choice of gas pressures it was assured that electrons could pass through the slits S_2 and S_3 only after having made one collision.

After passing through S_3 the electrons were bent round in a magnetic field and received by the Faraday cylinder E through the slit S_4. By a device not shown, the width of S_4 could be adjusted while the apparatus was evacuated, a thin copper diaphragm being employed to take up the motion of the slit and to maintain gas tightness. A wide slit enabled feeble effects to be observed, while a narrow slit was required to separate groups of electrons of small velocity difference. Differences of velocity of 1 in 1000 could readily be detected. The slits S_1 were 0.5 mm broad and 0.5 mm deep; S_2 was 0.1 mm broad and 0.9 mm deep; S_3 was 0.1 mm broad and V-shaped. S_4 was also V-shaped and could be varied from 2 mm to zero. All slits were 5 mm long. Two independent diffusion pumps of large capacity pumped off the gas leaking through S_2 and S_3 and maintained a low pressure in the interior of the brass velocity analyzing chamber D. This was necessary to prevent further scattering in this region. The error in the angle of scattering, due to electrons which do not travel in the plane of the paper (Fig. 1, side elevation), was not more than 1°, given by the ratio of the length of the slits to the length of path within the chamber D.

It will be noted that the magnetic field producing the deflection must not extend into the part of the apparatus where the collisions under consideration take place. As the determination of the velocity was made by varying the magnetic field and thus bringing electrons of different speeds on to the slit S_4, any field in the neighborhood of S_2 would by bending the primary electron stream vary the angle of scattering. A pair of coils in the Helmholtz arrangement (not shown) were used. They were sufficiently large to produce a sensibly uniform field over the whole of the apparatus; this field was compensated in the region comprising the gun A and slit S_2, by a pair of solenoids F_1 and F_2, carrying a fraction of the current through the main coils. The exact compensation was best effected by turning the gun to the vertical position, that is, corresponding to zero scattering angle, when there was no gas in the apparatus. The ratio of the currents through the two sets of coils was varied, until electrons were found to pass through the slit system and be received on E. The setting was found to be critical but did not require to be altered for different electron velocities, that is to say, for different magnetic fields. This method of compensation rendered the electron paths beneath the slits S_2 and S_3 far from circular, but as only comparative results for the velocities were required, this can raise no objection.

The helium, which was used throughout the research, was initially purified in a circulatory system by passing over heated copper oxide and charcoal cooled in liquid air. From the storage reservoir it could be passed into the apparatus through a fine capillary, passing again over cooled charcoal. Leaking through the slits S_2 and S_3, it was pumped off into another reservoir, and after repurification could be used again. The continual flow of gas made for purity, and in spite of the presence of a wax joint, joining the brass chamber to the glass part of the apparatus, and of the lubricated sleeve C, no trace of impurity was evident in the gas, as tested by the method later to be described. The current arriving at the Faraday cylinder E was measured by a Compton electrometer. It was frequently necessary to use the instrument at a sensitivity of 25,000 mm per volt. Except for a steady drift of zero no difficulty was experienced in working at this sensitivity, until the onset of hot weather. The climate of New Jersey was then found unsuitable for further work on such small effects.

Discussion of Results

Due to the presence of three variables, the initial velocity of the primary beam, the velocity of the secondary scattered beam and the angle of scattering, the complete investigation is very lengthy and has not yet been made. It is felt however that the results already obtained may have sufficient interest to be reported now.

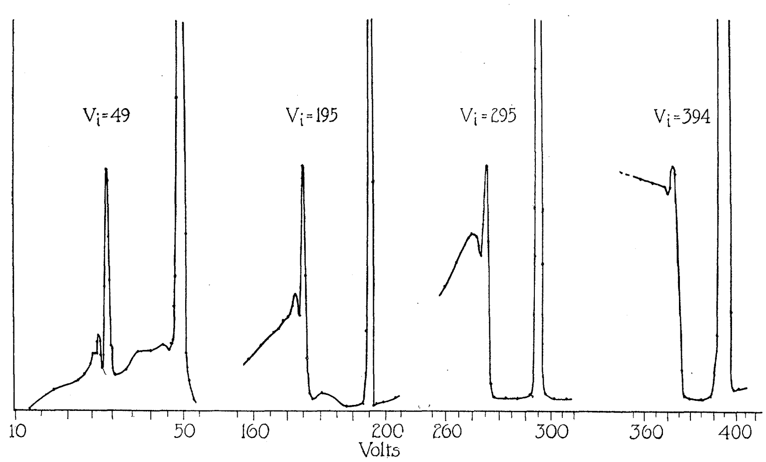

Fig. 2. Showing the relation of the number of electrons scattered by 5°, with their velocity for various initial velocities V_i.

We will first consider the velocity relations when the scattering angle is held constant. In the instances to be discussed, with one exception, this angle was 5°.

The results for a number of velocities, V_i, of the primary beam are collected in Fig. 2, where the ordinates represent the number of electrons scattered, and the abscissas are proportional to the magnetic field and consequently to the square root of the energy. The pressure of gas in all cases was 0.03 mm of mercury, except in those for which $V_i = 400$ volts, where it was 0.09 mm. Doubtless the broadening of the principal peak for those initial velocities was due to the higher gas pressure in the analyzing chamber D.

We notice in all cases two principal features, the presence of two peaks, one at a velocity equal to that of the primary beam, due to elastic reflection, and one some 20 volts lower, due to inelastic collisions which lead to excitation of the atom. The absence of any intermediate peak speaks for the purity of the gas, if we except the run for $V_i = 50$, in which the liquid air surrounding the charcoal was low. There is also a smaller peak corresponding to large energy loss, constantly associated with the main one. The energy losses, calculated from the separation of the peaks is shown in Table I.

TABLE I.

Energy losses of electrons in helium for various initial velocities V_i.

V_i	Energy losses (volts)		
49	19.7	20.7	22.6
97.6	——	20.8	23.2
196.	——	20.4	23.1
297.	——	20.4	24.2
395.	——	21.5	——
572.	——	22.0	——

For an initial velocity of 49 volts a slight hesitancy in the rise of the 20.7 volt peak may be interpreted as a loss of 19.7 volts energy. It is however very indistinct. It should correspond to the transfer $1^1S \rightarrow 2^3S$. The main peak is plainly due to the transfer $1^1S \rightarrow 2^1S$, which requires 20.55 volts. The mean value, determined from the first four rows is 20.58 volts. Lesser accuracy is to be expected for the higher initial velocities, as the loss of energy bears a smaller ratio to the initial energy.

The smaller peak is due to a complex of the higher states of helium, which are too close together to be resolved. Its behaviour is remarkable. With increase of initial velocity it gains in importance with respect to the 20.55 volt peak, and simultaneously broadens. By 400 volts initial velocity it forms a continuum which decreases very slowly with increasing energy loss and is perceptible to 200 volts.

It is possible that this continuum is due to ionization. As the electron ejected from the atom may have any velocity we should expect no sharp rise in the velocity distribution curve corresponding to a loss of 24.5 volts, a rise which in fact is never found. But if an electron loses say 200 volts in ionization, there should appear an electron of 175 volts energy, which has been ejected from the atom.

It seems that in fact there may be such an electron, if we look for it at scattering angles greater than 5°. Fig. 3 shows the scattering for an initial velocity of 340 volts and scattering angle 15°. A pronounced maximum at 50 volts has made its appearance, while the continuum afore mentioned rises to a maximum at about 290 volts. If we accept the view here given, there is a discrepancy of 25 volts in the expected positions of the two peaks. We can however form no complete picture of the processes involved without full knowledge of the behaviour of the curve shown in Fig. 3 for all angles. From the data already obtained it appears that the maximum at 50 volts persists to large angles of scattering, while that in the neighborhood of 200 volts declines; the measurements are not yet sufficiently complete to show any periodic variation in intensity, as is the case with the peak due to excitation, to be discussed later.

It is difficult however to ascribe this continuum to ionization when we consider the relative intensities, for $V_i=50$ and $V_i=400$. For the lower velocity there is little or no evidence of any effect due to ionization, indicating that it is spread over a wide range of velocities. Now Compton and Van Voorhis[4] have shown that the efficiency of ionization

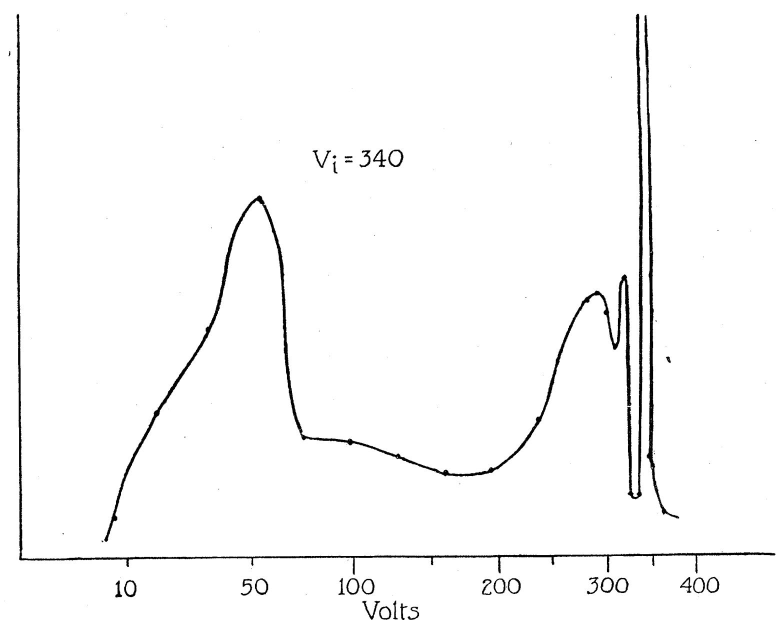

Fig. 3. Showing the number of electrons scattered by 15° for an initial velocity $V_i=340$.

in helium at 400 volts is only about twice its value at 50 volts. Further the continuum at the higher velocity does not begin at a point corresponding to an energy loss of 24.5 volts, but in the neighborhood of 22 volts.

Now for an electron whose speed is great compared with that of one of the orbital electrons of helium, the time of collision is short compared with the period of rotation in the orbit, or compared with the time required for quantization, if we speak in terms of the old quantum theory. No exact formulation of what this means when expressed in the new mechanics has been made, but a clue has been provided by

[4] Compton and Van Voorhis, Phys. Rev. **27**, 724 (1926).

Heisenberg,[5] who has reintroduced the idea of atomic frequencies. It is not unreasonable to expect therefore that when the time of collision is short compared with these frequencies (Resonanz-schwebungen) the normal laws of energy transfer break down, and that we may here admit the possibility that an electron may lose more energy to the atom than is necessary to cause transfer from one stationary state to another. A stable state would quickly be assumed by radiating the excess of energy, presumably in continuous radiation.

The continuum extending for energy losses greater than 22 volts is precisely what we should expect on this view.

It will be seen that when the series of curves shown in Fig. 2 is complete for all angles, the determination of the excitation probabilities will be an easy matter. The ratio of the heights of the subsidiary peaks to that due to elastic collisions, when integrated over all angles will give the excitation probabilities of the respective states. Except to note the absence of excitation to the first orthohelium state, requiring 19.7 volts, at the higher velocities, we can as yet make no certain statement on this point.

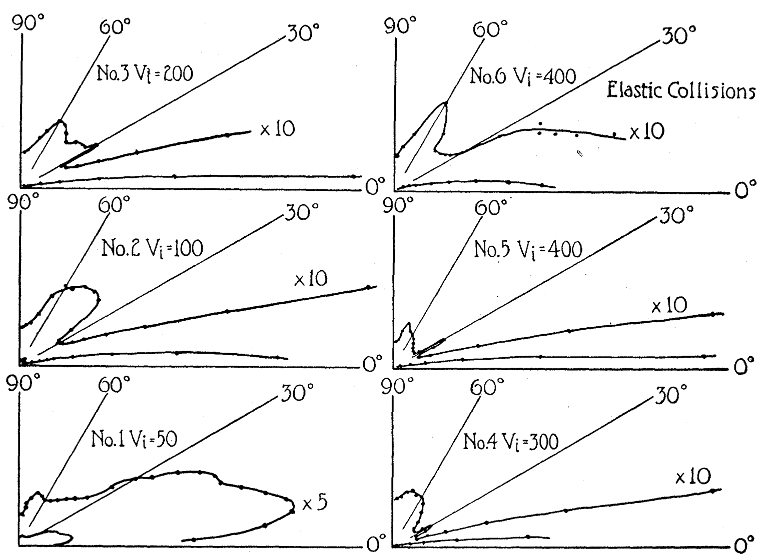

Fig. 4. Showing the number of electrons scattered at different angles for various initial velocities V_i. Nos. 1, 2, 3, 4 and 5 are for electrons which have lost 20.5 volts energy. No. 6 is for electrons which have lost no energy.

The Variation of Scattering with Angle

To determine the angular relations of the various types of collision it is only necessary to set the magnetic field to allow electrons with the

[5] Heisenberg. Zeits. f. Physik **38,** 411 (1926).

required energy loss to enter the Faraday cylinder and to rotate the electron gun A (Fig. 1).

A thorough investigation so far has only been undertaken for electrons losing 20.5 volts energy, that is to say, for those giving rise to the $1^1S \rightarrow 2^1S$ transition, for which $\Delta j = 0$. Fig. 4 shows the mean results of several runs at each angle. The radius vectors are proportional to the number of electrons scattered per unit solid angle at the various angles. The curves shown in my letter to Nature[3] are drawn from the same data, but represent the number scattered between two cones of semi-angles θ and $\theta + d\theta$. They differ from the curves here shown by a factor sin θ, which profoundly changes the relative intensities of the various maxima. It should be noted that Fig. 4 represents the original determinations, as of course the solid angle subtended by the slit S_2 at the point of impact is constant for all scattering angles.[6] The curves are reduced to have a common area, except where a multiplying factor indicates otherwise.

The principal maximum is found to move to smaller angles with increasing initial velocity. Above 100 volts it is too near zero to measure, but the rise increases in steepness at the higher velocities. The concentration of nearly all the electrons, which have excited at high velocities, in the forward direction is the effect already noted by Langmuir.[2] It should be noticed that as in the transition of the helium atom considered there is no change in the angular momentum ($\Delta j = 0$), the electron cannot pursue identical paths before and after collision, but one must be displaced parallel to the other (assuming that there is no deflection). For a collision in which $\Delta j = 1$, there is a unique striking radius for which the electron may pursue a straight path, but in general the path after collision will also be displaced laterally.

In addition to the maximum considered, in which all but a small fraction of the electrons lie, another maximum is found at larger angles, which moves with increasing initial velocity of the electron in the opposite direction, that is to say to greater angles.

Further, for velocities greater than 200 volts, there appears a peak, remarkable for its sharpness, which does not alter its position but increases in intensity with increasing velocity. The positions of these various maxima are shown in Table II.

The last row of the table, and the top right hand curve of Fig. 4 (No. 6), show the data for a run where the scattering was due to elastic

[6] *Note added to proof.* A correction must be applied to all the curves shown in Fig. 4, because of the fact that the small volume, in which the collisions considered take place, varies with the angle of scattering. The radius vectors must be multiplied by sin Θ, and consequently the curves shown in the letter to Nature represent the true scattering per unit solid angle. Table II, showing the positions of the maxima, has had this correction included.

impact. The points are somewhat scattered owing to the difficulty of finding the top of an exceedingly sharp peak in the velocity distribution curve.

The scattering is of completely different character from that due to inelastic impacts. The principal maximum lies further out and is not so intense relative to the rest of the curve. The fixed peak at 30° does not appear.

TABLE II

Positions of maxima in the angular scattering of electrons of various initial velocities V_i which have lost 20.5 volts energy.[6]

V_i	Positions of maxima		
48.9	24°	—	45° ? 70°
72.3	8	—	
97.5	5	—	50°
195.	<2.5	30°	59
294.	<2.5	30°	69
400.	<2.5	30°	70
400.	7	—	62

Any discussion of these results on the basis of the old quantum theory must inevitably lead to the same difficulties as appear in the explanation of the work of Davisson and Kunsman,[1] on the scattering of electrons in metal films. However Elsasser[7] has shown that this class of phenomenon may be treated as a diffraction effect of the phase waves of De Broglie. More recently Born,[8] on the basis of the Schrödinger wave mechanics, has shown that inelastic collisions should give rise to a periodic variation of scattering with angle, similar to a diffraction pattern. The theoretical side of the problem is however not yet sufficiently advanced to give detailed information on the phenomena to be expected, so that the results above reported cannot be said to substantiate the wave mechanics except in the most general way.

In conclusion I must express my deepest gratitude to Professor Karl T. Compton for extending to me the privilege of working in the Palmer Laboratory and for his constant interest and help, and also to the International Education Board for their support during my stay in Princeton.

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* Received December 24, 1926.

[7] Elsasser, Die Naturwissenschaften **13,** 711 (1925).

[8] Born, Zeits. für Physik, **38,** 803 (1926).