The ionization of helium by neutral helium atoms

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A method is described for investigating the ionization produced in helium by collisions between quasi-stationary atoms—that is, atoms possessing only thermal velocities—and a beam of neutral helium atoms with kinetic energy less than 100 eV. Ionization is shown to begin when the kinetic energy of the bombarding atoms is twice as great as the minimum kinetic energy which electrons must possess in order to ionize helium.

INTRODUCTION

The excitation and ionization produced when electrons make collisions with the atoms of a gas have been extensively investigated over a number of years, and a certain amount of work has also been done with positive ions as bombarding particles; but there is little information concerning the effects produced when the bombarding particles are neutral atoms. The possibility of producing reasonably intense beams of atoms with kinetic energy greater than that which could be obtained from thermal sources was first indicated by the work of Kallmann & Rosen (1929, 1930). They showed that when positive ions passed through the gas from which they had been formed, an ion might capture an electron from a ‘stationary’ atom or molecule, and go on its way as a neutral particle, with its speed and direction of motion unchanged. If, therefore, a beam of ions produced from a gas traverses a chamber containing that gas, and if, on emerging from this chamber, the remaining ions are deflected out of their original path, we obtain a beam of neutral particles, whose interaction with ‘stationary’ atoms may be investigated. The kinetic energy of the particles in the neutral beam can be controlled by adjusting the potential difference accelerating the original positive ions, and the homogeneity in velocity of the neutral particles is simply that of the ion beam.

Several attempts have been made to measure the minimum kinetic energy which such neutral atoms must possess in order to excite or to ionize gases through which they pass; but the earlier results were vitiated by ignorance of the nature and relative magnitudes of secondary effects, such as the release of electrons from metal surfaces by atomic impact, which masked or simulated the onset of gaseous ionization. These secondary effects have now been investigated, chiefly by Rostagni (1934a, b), and the precautions necessary to avoid confusing them with the ionization resulting from atomic collisions are fairly well established. Rostagni (1934c) also showed that the efficiency of neutral atoms in producing ionization in a gas is very small. Thus in order to determine the minimum kinetic energy which such an atom requires in order to ionize by collision, the experimental arrangements must ensure that the largest possible number of atoms enters the ionization chamber, where the pressure must be such that as great a fraction as possible makes collisions with
'stationary' atoms. A very sensitive detecting instrument is also necessary. In the present investigation the point of setting in of ionization of helium by neutral helium atoms was examined.

DESCRIPTION OF APPARATUS AND EXPERIMENTS

A diagrammatic view of the experimental tube is shown in figure 1. The tube was made of pyrex glass, the main part of it being 5½ cm. in diameter. The electrodes shown were made of gas-free nickel sheet and gauze, and the nickel wires leading to them were welded on to tungsten for sealing through the glass. The filament $F$ was of pure tungsten, and was used as a source of electrons for ionizing the helium in the apparatus and thus producing positive helium ions. It is shown as a straight line but is actually zigzagged in a horizontal plane. The apparatus was connected by a tube 1·5 cm. wide to a pumping system, through a tap of wide bore, a bulb containing phosphorus pentoxide and a liquid oxygen trap. The connecting tube leaves the apparatus at right angles to the plane of figure 1, and is indicated by the dotted circle. Two other tubes were sealed on to the apparatus to serve as inlets for the
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helium; these are shown at \( X \) and \( Y \). Of these, \( X \) leads to the upper part of the apparatus, at right angles to the plane of figure 1, and is on the opposite side of the experimental tube to the exit to the pumping system. \( Y \), which is in the plane of figure 1, leads to the lower end of the experimental tube. The helium, which was spectroscopically pure, entered the apparatus from a reservoir fitted with stopcocks, through a capillary tube for restricting and regulating the flow, and a tube containing activated carbon, immersed in liquid oxygen.

Before admitting helium to the apparatus, the latter was subjected to the usual heat treatment, in order to remove residual gas from glass and metal as completely as possible, and an investigation was made which showed that any impurities which might be emitted after this treatment were present in quantities too small to vitiate the measurements made with helium in the apparatus.

The arrangement of the electrodes is shown in figure 1. The wide cross-tube above the exit to the pumping arrangements will be referred to as the ionization chamber, for it is in the central portion of this tube that the atomic collisions occur which are the subject of this investigation. The cylindrical nickel electrode \( K_3 \) has its lower side extended at \( H \) so as to cover completely the cross-section of the vertical tube, except for a small slit cut over the axis of this tube; the middle of the slit is in alignment with the centres of the series of holes in electrodes \( E, D, B \) and \( A \). The electrode \( K_3 \) is similar to \( K_2 \) except that it lacks the extension over the vertical tube. Each of these electrodes has a vertical end of fine nickel gauze as shown \( (G_2, G_3) \) and encloses a plate electrode \( (P_3, P_3) \). Either of these plates, and also the plate \( P_1 \) enclosed by the cylinder \( K_1 \), could be connected to the measuring electrometer. Leakage to the electrometer system along the surface of the glass was prevented on the inside by tightly fitting earth-connected spirals of wire, and on the outside by sealing wax.

The capacity of the Dolezalek electrometer and its connexions, used for detecting positive ions or electrons produced by atomic impacts, was 200 cm. and its sensitivity 200 cm./V. An electrometer was used in preference to a ‘space-charge detector’, for, although the latter instrument has the advantage of responding only to the arrival of positive ions and not to secondary electrons, the experiments of Wayland (1937) have shown that its sensitivity may be considerably lower than that of an electrometer.

In investigating the effects of the collisions of fast neutral helium atoms with ‘stationary’ helium atoms, electrons from the filament \( F \) were accelerated to the electrode \( A \) and passed through the gauze into the region above it. When \( A \) and \( B \) were connected together outside the apparatus, a field-free region was enclosed between these electrodes in which positive ions were formed by collision between electrons and helium atoms. Some of these positive ions diffused through the hole in \( B \) into the space between \( B \) and \( D \) where they were accelerated across the gap into electrode \( D \) which formed the neutralization chamber. The beam which emerged from the top of \( D \) thus consisted of fast neutral atoms formed by charge exchange between the ions and atoms in \( D \), some positive ions which had not suffered such charge exchange and some electrons from the filament which had been slowed down,
but not completely stopped by the opposing potential difference between $B$ and $D$. Some of the slow ions formed when the original ions capture an electron from an atom in the neutralization chamber may also diffuse out of the hole in the top of electrode $D$. The charged components of this composite beam were removed by maintaining the plate $E$ at a suitable potential, and by a transverse field applied between the vertical plates $C_1$ and $C_2$. Thus only neutral particles entered the ionization chamber through the slit in electrode $H$. Measurements of the effects occurring in the ionization chamber were usually made at the plates $P_1$ and $P_2$, either of which could be maintained at any convenient difference of potential from the gauze $G_1$ or $G_2$ respectively. In making determinations of the minimum kinetic energy of neutral helium atoms for the production of ionization, a quantity which for brevity we shall call the activation energy*, the positive ions resulting from this ionization were used when measurements were made at $P_1$ and the electrons when measurements were made at $P_2$.

The most reliable estimate of this minimum energy hitherto recorded is probably that of Rostagni (1934c), who found that the ionization began when the kinetic energy of the impinging particles was in the region of 60 eV. The purpose of Rostagni’s investigation was, however, to determine how the cross-section for ionization of ‘stationary’ helium atoms by fast atoms of the same kind varied with the kinetic energy of the latter, rather than to ascertain the minimum energy at which the effect occurred at all. He makes no claim to high accuracy for his estimate. From the curve which Rostagni gives, it is clear that the attainment of greater precision must depend on increasing considerably the number of ionizing impacts made by helium atoms having the necessary minimum energy. In the present apparatus this was achieved by using a larger thermionic emission from the filament, a higher pressure of helium and a greater potential difference accelerating the electrons into the region where positive ions were to be formed, each of which factors caused the number of ions entering the neutralization chamber to be larger than in Rostagni’s arrangement. Conditions in the neutralization chamber were such that a larger proportion of the incoming positive ions passed out as fast neutral atoms and through the slit in electrode $H$ into the ionization chamber, where the greater gas pressure used in these experiments caused a relatively greater number of collisions to occur. It is estimated that the cumulative effect of all these advantages is to give a 300-fold increase in the number of ionizing collisions made by fast neutral atoms in the ionization chamber as compared with the number occurring in Rostagni’s arrangement.

With a pressure of helium of $1.5 \times 10^{-2}$ mm. of mercury (which preliminary experiments had shown to be suitable), and with the general arrangement of electric fields already indicated, a composite beam of positive ions, electrons and neutral atoms passed through the hole in the top of electrode $D$ into the region above. The kinetic

* This quantity should, in the terminology used by Massey & Smith (1933, p. 159), be referred to as ‘the activation energy for ionization of helium by helium atoms’. In its abbreviated form the term is admittedly ambiguous, but it is thought that no confusion can arise in this particular case.
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Energy of the neutral atoms in the beam was controlled by the potential difference between the electrodes B and D. The charged components of the beam were removed by the transverse field between electrodes C₁ and C₂, and secondary electrons, if any, were emitted from the negative plate C₂ as a result of its bombardment by positive ions, were prevented from reaching the electrode H by making this electrode 20 V negative with respect to C₂. This arrangement ensured also that no secondary electrons liberated from the positive plate C₁ by electrons from the filament would enter the ionization chamber. The beam of uncharged helium atoms which entered the ionization chamber was detected by the emission of secondary electrons from P₁ under the impact of the beam, when the gauze G₁ was at a positive potential.

The results given in table 1 illustrate the efficiency of the transverse field in removing charged particles from the beam. They show that as the potential difference Vᶜ between the plates C₁ and C₂ was gradually increased, the current measured by the electrometer connected to P₁ decreased until Vᶜ had reached a value of about 18 V, after which there was little further decrease of the current with increase of Vᶜ. The residual current then measured must be attributed to the action of the neutral helium atoms which had entered the ionization chamber. Vᶜ was therefore fixed at a value greater than 18 V, and the current to the plate P₁ was measured as a function of Vᵖ, the potential of this plate above that of the gauze. The graph in figure 2 represents a typical set of results of such measurements taken with Vᶜ equal to 40 V, the maximum kinetic energy of the neutral atoms entering the ionization chamber being 62 eV.

The positive current indicated in the graph when the plate P₁ is negative, or only slightly positive with respect to G₁, is due to the loss of electrons from P₁ under bombardment by fast neutral helium atoms, together with the arrival at P₁ of positive ions produced from the gas by atomic impacts in the ionization chamber. The negative current detected when P₁ is more than 3 V positive with respect to G₁ is due to the arrival at P₁ of electrons released in the same way from G₁. It does not saturate as completely as does the positive current, a result which is compatible with the view that some of the electrons emitted from the lower side of the gauze G₁ travel towards H; thus an increase in the field between G₁ and P₁ slightly augments the fraction of the total emission which is directed towards P₁. When measurements of the current to P₁ were made, the electrodes K₂ and K₃ (that is, G₂, G₃ and H) were connected together and a potential difference to direct positive ions towards G₁ was maintained between these electrodes and K₁.

In investigating the activation energy, the quantity which is determined experimentally is the kinetic energy (in electron volts) which each positive ion of helium acquires in being accelerated across the gap between electrodes B and D, and which it maintains through the field-free space within the neutralization chamber D until it makes a collision. It is assumed, in accordance with the theory of Kallman & Rosen (1930), that a neutral atom which enters the ionization chamber without making a collision on its journey up the tube has the kinetic energy of the ion from which it was formed, immediately prior to neutralization. The maximum kinetic energy
TABLE 1

Maximum kinetic energy of neutral helium atoms = 60 eV. \( V_0 \) = potential difference between \( C_1 \) and \( C_2 \).

<table>
<thead>
<tr>
<th>( V_0 ) ( \text{volts} )</th>
<th>measured current in arbitrary units</th>
<th>( V_0 ) ( \text{volts} )</th>
<th>measured current in arbitrary units</th>
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</thead>
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<td>9.35</td>
</tr>
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<td>36.4</td>
<td>9.35</td>
</tr>
<tr>
<td>6.0</td>
<td>15.7</td>
<td>48.6</td>
<td>9.38</td>
</tr>
<tr>
<td>9.0</td>
<td>11.2</td>
<td>60.0</td>
<td>9.36</td>
</tr>
</tbody>
</table>

Figure 2. Current measured at electrode \( P_1 \), due mainly to the emission of secondary electrons from \( P_1 \) and \( C_1 \) under bombardment by neutral helium atoms.

possessed by any of the neutral atoms is thus determined by the potential difference between \( B \) and \( L \). That most of the neutral atoms which enter the ionization chamber and whose effects are detected do, in fact, enter with this energy follows from the consideration that those neutral atoms which make collisions below the ionization chamber and suffer an appreciable loss of energy are likely to be deflected from the path of the beam and prevented from passing through the slit in \( H \) into the chamber above. Similarly, those ions which make collisions resulting in loss of energy before being neutralized will not, after neutralization, be able to pass through the series of apertures along the axis of the tube and enter the ionization chamber. The small proportion of neutral atoms which collide just below \( H \) and lose energy and yet succeed in entering the ionization chamber will be so directed as to be unlikely to contribute appreciably to the measured current.

The curve in figure 2 has been explained on the view that neutral helium atoms can release electrons from metal surfaces on which they impinge, when these surfaces
are charged negatively with respect to neighbouring electrodes. Suppose that the total emission from \( P_1 \) is \( I \); then the number of neutral particles arriving per second at \( P_1 \) is \( I/k \), \( k \) being the coefficient of liberation of electrons from nickel by helium atoms, which increases with the kinetic energy of the atoms. The number of neutral atoms in the beam reaching \( P_1 \) depends on the number of positive ions diffusing out of \( B \) and entering \( D \); this also increases as the potential difference between \( B \) and \( D \), which controls the energy of the neutral beam, increases. The current detected by the electrometer connected to \( P_1 \) will increase therefore with the kinetic energy of the neutral particles, even while this is too small for ionization of the gas to take place. The small additional increase due to the collection of positive ions at \( P_1 \) when the kinetic energy of the bombarding atoms was raised above about 60 eV—Rostagni’s value of the activation energy—proved to be very difficult to distinguish. The precise determination of the energy at which it first began was not possible.

Various attempts were made to eliminate the background current due to the emission of secondary electrons from \( P_1 \), and one of these enabled an approximate estimate of the activation energy to be obtained. A beam of neutral particles entered the ionization chamber, charged particles having been deflected away from the axis of the tube by the transverse field between \( C_1 \) and \( C_2 \). The gauze \( G_1 \) was made negative with respect to \( H \) so that most of the electrons emitted from the former by impacts of swift atoms were pulled towards \( H \). The electron emission from \( P_1 \) was suppressed by making this electrode positive with respect to \( G_1 \). Thus the resultant negative current to \( P_1 \) before ionization of the gas began was very small. When the kinetic energy of the atoms was increased sufficiently to produce ionization, a positive current was detected at \( P_1 \), due to the collection of the positive ions formed by atomic collisions between \( H \) and \( G_1 \). This method gave a value of 56 eV for the activation energy.

The advantage of this method is that it enables ionization to be detected in a fairly direct way. It shows that helium atoms can produce ionization in helium when their kinetic energy is less than the values reported in previous work; but it is not well adapted for a precise determination of the activation energy. Some of the positive ions formed between \( H \) and \( G_1 \) will not have enough kinetic energy to reach \( P_1 \) against the opposing field between \( G_1 \) and \( P_1 \); some may be neutralized before reaching \( P_1 \); others may be captured on the wires of \( G_1 \); and the positive current resulting from the collection of the ions which escape any of these fates will be superimposed on the negative current due to the arrival of electrons from \( G_1 \), and those produced by ionization of the gas between \( G_1 \) and \( P_1 \). Thus the value obtained by this method sets an upper limit to the magnitude of the activation energy, and the results of this preliminary work in general showed that a different technique must be evolved in order to obtain a more accurate value.

The method finally adopted was based on the following considerations. Let \( i_o \) denote the current corresponding to the positive ions entering electrode \( D \) (figure 1), where neutralization is to take place. Let the axis of the tube be taken as the \( x \)-axis,
the origin being at the point where the ion beam enters $D$. After travelling a distance $x_1$, which, to a first approximation, may be taken as the distance to the middle of the space between the condenser plates (see figure 1), the positive ions which have not been neutralized are removed by the transverse field between $C_1$ and $C_2$. The neutral atoms go on alone and enter the ionization chamber at $x = x_2$. The positive ions which these form by collision with helium atoms between $x_2$ and $(x_2 + h)$ are collected at $P_1$, $h$ being the distance between the slit in electrode $H$ and the plate $P_1$.

Let $p$ = the pressure of helium, expressed in mm. of mercury,

$$Q_n = \frac{\text{the cross-section of helium ions for neutralization, expressed in cm}^2/\text{c.c.}}{1\text{ mm. of mercury}},$$

$$Q_d = \frac{\text{the cross-section of helium atoms and ions for elastic collision with stationary helium atoms.*}}{1\text{ mm. of mercury}}.$$ 

Reasons for assuming that the cross-section of helium atoms for elastic collision is, at least to a first approximation, equal to the corresponding quantity for helium ions have been given by Rostagni (19346).

Assuming that each ion and atom which makes an elastic or ionizing collision is lost from the beam, and ignoring for the present the limiting action of the apertures on the beam, it can be shown that the number of neutral atoms in the beam entering the ionization chamber is given by

$$n_2 = \frac{i_0}{E}e^{-Q_d p x_2}[1 - e^{-Q_n p x_1}],$$

where $E$, the charge carried by each ion, is numerically equal to the electronic charge. Now the beam of positive ions entering the neutralization chamber is slightly divergent, so not all the neutral atoms formed by charge exchange will travel along the axis of the tube and enter $H$, even in the absence of collisions. Also, if an atom makes a collision close to $H$ resulting in a deflexion through a fairly small angle, it may still be able to pass through the slit in $H$ and enter the ionization chamber. The actual number of neutral atoms entering the ionization chamber is not therefore given by equation (1) but by

$$n_2 = m_1\frac{i_0}{E}e^{-Q_d p x_2}[1 - e^{-Q_n p x_1}],$$

where the reduction factor $m_1$ depends on the geometry of the apparatus, and on the potential difference between $B$ and $D$, since this last factor affects the divergence of the ion beam in the neutralization chamber.

Consider now what happens to the beam of neutral atoms between $H$ and $P_1$. Unless the effect of a collision near $H$ is to deflect the impinging atom through an angle greater than about 30°, this atom will be able to reach $P_1$. The nearer to $G_1$ the collision takes place, the greater is the angle through which the atom may be

* For helium atoms with kinetic energy 50 eV, $Q_d = 22.2\text{ cm}^2/\text{c.c.}$, while the cross-section of helium atoms for ionization by collision with atoms of the same gas, possessing kinetic energy 50 eV, is less than 0.05 cm$^2$/c.c., and can therefore be neglected in comparison (Rostagni 1934c, 1938).
deflected and still be able to reach $P_1$. The neutral atoms reaching $P_1$ are therefore much less homogeneous in energy than when they entered the ionization chamber. If $P_1$ is sufficiently negative with respect to $G_1$ to saturate the current due to secondary electron emission from the former, the current measured by the electrometer will be

$$I = k_v m_i i_0 e^{-Q_{d+q_0}x_1}[1 - e^{-Q_{n+q_1}x_1}],$$  \hspace{1cm} (2)

where $k_v$ is the effective value of the coefficient of liberation of electrons from nickel for this beam. It increases as the kinetic energy of the neutral atoms comprising the beam increases. If the kinetic energy of the neutral atoms is increased until they can ionize the gas, and if the positive ions then formed are accelerated to $P_1$, the positive current to this electrode will become

$$I = k_v m_i i_0 e^{-Q_{d+q_0}x_1}[1 - e^{-Q_{n+q_1}x_1}] + i_s[1 - k_v + k_+],$$  \hspace{1cm} (3)

where $i_s$ is the current carried by the positive ions and $k_+$ is the coefficient of liberation of electrons from nickel by these ions.

Now suppose that the plates $C_1$ and $C_2$ are connected together, so that no positive ions are withdrawn from the beam, but all those in the direct line enter the ionization chamber. Let the emission of secondary electrons from $P_1$ be completely suppressed by making this electrode positive with respect to $G_1$. Then the current reaching the slit in $H$, due to those ions which have not been neutralized, and which have not made elastic collisions is

$$i_2 = m i_0 e^{-(Q_{d+q_0}+q_1)x_1},$$  \hspace{1cm} (4)

where the factor $m$ is introduced to allow for the geometry of the apparatus and the limiting action of the apertures on the positive ion beam.

Elastic collisions and neutralization between $H$ and $G_1$ will not appreciably alter the number of positive ions in the beam, for the electric field will tend to pull back to the axis of the tube those ions which have been deflected through small angles, and the new, slow ions resulting from the neutralization of the original ions will be accelerated towards $G_1$. Between $G_1$ and $P_1$ neutralization will result in a reduction of the number of ions in the beam, since in this region the new ions travel away from $P_1$. The current actually measured by the electrometer connected to $P_1$ is

$$i_+ = m_2 i_0 e^{-(Q_{d+q_0}+q_1)x_1} e^{-Q_npl},$$  \hspace{1cm} (5)

where $l$ is the distance from $G_1$ to $P_1$, and the change of the numerical factor from $m$ to $m_2$ is introduced to allow for the fact that some of the positive ions formed by the neutralization of the original ions between $H$ and $G_1$ will be unable to reach $P_1$ against the opposing field. If the cross-section of the ions for neutralization be taken as independent of their velocity over the small range used, this effect can be taken

* When positive ions entered the ionization chamber, and the electrodes $K_1$, $K_2$ and $K_3$ were at the same potential, no positive current could be detected at $P_2$. Thus the number of ions deflected through large angles as a result of collisions with atoms is negligibly small. The same is probably true of collisions between the atoms in the beam and the atoms of the gas in the ionization chamber.
as constant in any one series of observations, where the only variable quantity is
the velocity of the ions.

When the kinetic energy of each bombarding atom is too small for ionization of
the gas to take place, we have from equations (2) and (5)

\[
\frac{I}{i_+} = k_e \frac{m_1}{m_2} [e^{Q_n p a} - e^{Q_n p b}],
\]

(6)

where

\[ a = (x_2 + l) \quad \text{and} \quad b = (x_2 - x_1) + l. \]

By plotting \( I/i_+ \) against the potential difference \( V \) which accelerates the ions from
\( B \) to \( D \) a smooth curve should be obtained so long as no ionization of the gas is
produced by neutral atoms. As soon as such ionization does begin we shall have from
equations (3) and (5)

\[
\frac{I}{i_+} = k_e \frac{m_1}{m_2} [e^{Q_n p a} - e^{Q_n p b}] + \frac{i_0}{i_+} [1 - k_0 + k_+].
\]

(7)

Hence at the activation energy the slope of the curve should suddenly change.

This method of obtaining the activation energy will be practicable only if the
pre-ionization ratio given by equation (6) increases less rapidly with \( V \) than does
the value of \( I \) given by equation (2). There are three reasons for believing that this
will be the case. In the first place it is probable that \( i_0 \), the initial intensity of the
positive-ion beam, is affected by the potential difference between \( B \) and \( D \). An
increase in this potential difference increases the rate at which the ions diffuse out
of the space enclosed by electrode \( B \) on account of the greater potential gradient
just outside \( B \), and any penetration of the field between \( B \) and \( D \) to the space inside
\( B \) would accentuate this increased rate of diffusion. Thus the pre-ionization current
given by equation (2) owes part of its increase to the increase of \( i_0 \) with \( V \). This
increase does not appear in the graph of \( I/i_+ \) against \( V \) since the expression for the
pre-ionization ratio \( I/i_+ \) does not involve \( i_0 \). Secondly, the term
 appearing in equation (5) increases as \( V \) increases. Taking Rostagni’s values for
\( Q_n \) and \( Q_d \) at the appropriate voltages, and substituting the numerical values for
\( x_2 \) and \( l \), it can be shown that for a pressure of \( 1.5 \times 10^{-2} \) mm. of mercury, the value
at 50 V is about 1.5 times as large as the value at 38 V. Further, \( m_2 \) probably increases
slightly as \( V \) increases. The slope of the curve showing \( I/i_+ \) as a function of \( V \) will
therefore be smaller before ionization begins than the slope of the corresponding
portion of the curve showing \( I \) as a function of \( V \). The onset of ionization should
therefore be more easily detectable by means of the former curve than was possible
by inspection of the \( I \) against \( V \) curve. That this belief was justified is seen by com-
paring the curve of figures 3 and 5.

In taking measurements of \( I \), the electric fields below electrode \( H \) were arranged
as already described in connexion with the results given in figure 2. The secondary
electron emission from \( P_1 \) was saturated by making this plate 15 V negative with
respect to \( G_1 \). Any positive ions formed in the ionization chamber as a result of
collisions between the neutral atoms in the beam and ‘stationary’ helium atoms
were accelerated to $G_1$ through a potential difference of 18 V established between this electrode and $H$. The accelerating potential was limited to this rather small value in order that electrons leaving $G_1$ should not be able to make inelastic collisions with helium atoms. The presence of any excited atoms produced in this way would give rise to more secondary emission from $P_1$ and make the rate of increase of the pre-ionization current larger. The results obtained for three different pressures are shown in figure 3.

![Figure 3](image-url)

**Figure 3.** Graph showing the current $I$ to electrode $P_1$, as a function of $V$.

$i_+$ was very much larger than $I$, and in order to measure it a condenser of known capacity was placed in parallel with the electrometer. To admit the beam of ions to the ionization chamber the plates $C_1$ and $C_2$ were connected together, their common potential being 27 V below that of the plate $E$. Throughout the measurements of $I$ and $i_+$, this plate was 6 V positive with respect to $D$, so that in the latter series of measurements the slow ions formed when the original ions were neutralized in $D$ could not reach the electrode $E$ and were therefore lost to the beam which passed on to the slit in electrode $H$.

Electrons from the filament which had not made inelastic collisions with gas atoms were turned back before reaching electrode $H$. The emission of secondary electrons from $P_1$ owing to its bombardment by positive ions and neutral atoms was prevented by making the potential of $P_1$ 15 V above that of $G_1$. Figure 4 shows the three curves, corresponding to those in figure 3, of $i_+$ plotted against the appropriate values of $V$.

In the curves of figure 5, which show the ratio $I/i_+$ as a function of $V$ for three different pressures, the ordinates are obtained by dividing the ordinates of the curves in figure 3 by those at the same voltages on the corresponding curves in figure 4. This ratio is seen, as the theory has suggested, to increase with $V$ less rapidly than $I$ increases. For values of $V$ less than about 50 V, it is a linear function of $V$, but at higher voltages it increases more rapidly. The value of $V$ at which the more
rapid increase begins defines the minimum energy which the neutral atoms of helium must possess in order to ionize the quasi-stationary atoms of the same gas on collision with them, i.e. what we have termed the activation energy. Taking the mean of the values obtained from the curves in figure 5 this critical energy is 49.5 eV.

Figure 4. Graph showing the current $i_+$ to electrode $P_1$, as a function of $V$.

Figure 5. The onset of ionization of helium by neutral atoms of the same gas, having kinetic energy of about 49.5 eV.

In deriving expressions for $I$ and $i_+$ the photo-ionization of the gas and the liberation of electrons from $P_1$ by photo-electric action have been neglected. To show that the currents resulting from these effects are very much smaller than those due to the action of ions and atoms of helium, electrons from the filament were accelerated to electrode $E$ and then removed by the transverse field between $C_1$ and $C_2$. The pressure of helium was $2 \times 10^{-2}$ mm. of mercury, and the potentials of the
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electrodes in the tube above $C_1$ and $C_2$ were the same as in the measurement of $I$. In these circumstances positive ions could be formed by electron impact over the whole path from $A$ to $C_1C_2$, instead of being limited to the distance from $A$ to the top of $B$ as was the case in the previous measurements. Hence it would be expected that the amount of radiation entering the ionization chamber, due to the recombination of ions with free electrons would be greater than it was in the experiments in which $I$ and $i_+$ were measured. The current detected at $P_1$ was, however, less than one-fifth of the smallest measured value of $I$. It is therefore clear that no serious error is introduced into the measurement of $I$ and $i_+$ by the effects of radiation.

The apparatus was designed with electrodes $P_2$ and $P_3$ in the cross-tube as shown in figure 1 in order that the products of ionization might be investigated at an electrode which was not in the direct path of the neutral atom beam, for it was to be expected that the effect of the neutral atoms in liberating secondary electrons, and thus giving rise to a background current, would be very much less serious with such an arrangement and the onset of ionization of the gas thus more easily detected. In making this investigation the electrometer was therefore connected to $P_2$ and the electrodes $K_1$, $K_2$, $P_1$ and $P_3$ were connected together and maintained at a potential $V_G$ lower than that of the gauze $G_2$, so that electrons produced in the ionization chamber would be directed towards $G_2$, and those which passed through the interstices of that gauze would be collected by the plate $P_2$ and the electrometer. The potentials of the electrodes below $H$ were maintained as in the experiments already described. A negative current was detected, and the velocity distribution of the electrons composing this current was investigated by measuring the current to $P_2$ as a function of the potential difference between $P_2$ and $G_2$ with a view to ascertaining where the secondary electrons had originated. The results of such investigations, using helium at a pressure of $1.5 \times 10^{-2}$ mm. of mercury, are shown in the three curves of figure 6, each curve corresponding to a different value of $V_G$.

These curves show that there are two distinct groups of electrons present. The majority constitute a low energy group having a maximum kinetic energy corresponding to about 6 V, and there is also a second, smaller group, in which the maximum kinetic energy in each experiment corresponds to that which would be acquired by an electron in travelling to $G_2$ from either of the other electrodes bounding the ionization chamber. The number of electrons in this group remains constant while $V_G$ increases from 15.5 to 28 V, whereas the number of low-energy electrons increases during this change. When all the electrons were prevented from reaching $P_2$ a small positive current was detected, the magnitude of which was independent of $V_G$. It seems probable that this positive current is to be attributed to the photo-electric liberation of electrons from $P_2$ by radiation resulting from recombination in the ionization chamber.

From the results in figure 6 it appears that the high-energy group of electrons is liberated with very small velocity from one or more of the electrodes in the ionization chamber. Experiments carried out with these electrodes at different relative potentials showed that the gauze $G_1$ contributed about half of the effect and the gauze
and the electrode \( H \) the remaining half. The observed order of magnitude of the current can only be accounted for by supposing that the electrons were liberated from the edges of the slit in \( H \) and from the wires of \( G_1 \) by grazing impacts of the atomic beam.

\[
\begin{align*}
V_G & = 22 \text{ volts} \\
V_G & = 15.5 \text{ volts}
\end{align*}
\]

**Figure 6.** The energy distribution of the electrons reaching electrode \( P_2 \).

The small kinetic energy of the electrons in the larger group shows that these cannot originate from any of the electrodes, with the possible exception of \( G_2 \); but the magnitude of the current due to them is difficult to reconcile with such an origin, as is also the increase in the number which reach \( P_2 \) as \( V_G \) is increased. It therefore seems clear that these electrons originate from the gas atoms by ionization. In order to be quite certain that these electrons originate from the ionization of helium by fast neutral atoms of helium and not from photo-ionization, an experiment was made in which no neutral atoms or positive ions could pass up the tube, but in which it would be expected that much more radiation would originate in such a position as to influence the gas in the ionization chamber than in the conditions in which the curves in figure 6 were obtained. The current measured was found to be much too small to account for the low-energy group of electrons. Moreover, the current due to photo-ionization, measured as a function of the gas pressure, was found to decrease continuously over the range \( 3 \times 10^{-2} \) to \( 10^{-5} \) mm. of mercury, whereas the number of low-energy electrons reaching \( P_2 \) in the circumstances of figure 6 varied with the pressure in a very different way, increasing at first as the pressure of helium was increased, but attaining a maximum value at a pressure of \( 1.5 \times 10^{-2} \) mm. of
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mercury, after which it decreased with further increase of pressure. This pressure of maximum current is the pressure of helium employed in the main experiments.

Considerations of the distribution of electric intensity in the ionization chamber due to the configuration of the electrodes shows that this is capable of accounting for various features of figure 6 which, at first sight, seem puzzling; namely, (a) the fact that the current due to the ionization of the gas increases as \( V_G \) increases, while the current due to the secondary electrons emitted from the electrodes does not, (b) the rather small value of the potential difference between \( P_2 \) and \( G_2 \) required to stop the collection of all the ionization electrons, and (c) the fact that this potential difference does not alter much as that between \( G_2 \) and \( G_3 \) increases.

Having established that when the kinetic energy of the neutral atom beam corresponds to about 80 V the negative current measured when electrons are driven to \( P_2 \) is predominantly due to ionization of the gas produced by the fast neutral atoms, measurements were made to determine the minimum energy of these atoms at which this ionization takes place. The pressure of the helium in the tube was adjusted to 1.5 \times 10^{-2} \text{ mm of mercury}, so as to obtain the maximum ionization current, and the voltage between electrodes \( B \) and \( D \), which controls the kinetic energy of the neutral atoms, was increased step by step. The electrodes \( G_1 \) and \( H \) were maintained 24 V negative with respect to electrode \( G_2 \) which in turn was 25 V negative with respect to \( P_2 \). The arrangement of the fields for preventing the original beam of positive ions or any secondary electrons liberated from the electrodes \( C_1 \) or \( C_2 \) from entering the ionization chamber were the same as in the earlier experiments. The results of such an investigation are shown in curves \( L, M \) and \( N \) of figure 7. In obtaining curves \( L \) and \( M \) the potential difference \( V_F \) accelerating electrons from the filament into electrode \( A \) was 83 V. The conditions for the two curves were, however, different, in that for the curve \( L \) the plate electrode \( E \) was 33 V negative to electrode \( D \), while for curve \( M \) it was 6 V positive to that electrode. The arrangement of electric fields secures that the number and energy of the neutral atoms in the beam proceeding from the neutralization chamber \( D \) are the same in the two cases, but those positive ions which escape neutralization and pass through the hole in electrode \( E \) will have more energy in the circumstances of curve \( L \) than in those of curve \( M \). Also, the new, slow ions resulting from charge exchange in the neutralization chamber can reach the region above plate \( E \) in the former case, but are prevented from doing so in the latter.

In the curve \( N \) the potential difference \( V_F \) was reduced to 51 V, the fields otherwise being the same as for curve \( M \). The effect of this reduction in \( V_F \) would be to reduce the number of neutral atoms formed, but not the kinetic energy which each has. All these curves show a current which increases with the kinetic energy of the neutral atoms entering the ionization chamber and which begins to increase at a more rapid rate when this energy reaches 49.4 eV, thus indicating that this is the point at which ionization by neutral atoms sets in. The current measured for lower values of the variable voltage corresponds to the high-energy group of electrons indicated by the curves of figure 6 and already explained as originating largely from grazing impacts of neutral atoms with the sides of the slit in electrode \( H \) and the wires of the gauze \( G_1 \).
If in curves $L$ and $M$ we compare the increase in current above the background current for any value of $V$ after ionization has set in, by subtracting the extrapolated value of the background current from the total measured current, we find that the increase (i.e. the ionization current) is the same in the two cases. This is to be expected, since the number and energy of the fast neutral atoms entering the ionization chamber were the same in both instances. Moreover, the ionization current is definitely smaller in curve $N$ than in curves $L$ and $M$, as might have been predicted from the smaller number of neutral atoms employed. The difference of the background currents in curves $M$ and $N$ is also due to the smaller number of neutral atoms in the case of curve $N$. There is a difference of background current also in the case of curves $L$ and $M$. This may be explained on the view that some positive ions are produced in $D$ by those electrons which have not made an inelastic collision in the space enclosed by electrodes $A$ and $B$ and which, although slowed down by the potential difference $V$ between $B$ and $D$, yet retain enough energy to ionize helium atoms by collision in the neutralization chamber. Some of these positive ions diffuse out of the hole in the top of electrode $D$, and, in the circumstances of curve $L$, reach the region above the plate $E$ with kinetic energy 33 eV. Those ions, which are neutralized by charge exchange before striking the negative condenser plate, may enter the ionization chamber, either directly, or after reflexion from the condenser plate. Since their kinetic energy cannot exceed 33 eV, these neutral atoms cannot ionize the gas in the ionization chamber, but they will be able to contribute to the background current by liberating electrons from the edges of the slit in $H$ and from the wires of the gauze $G_2$. In curve $M$, on the other hand, positive ions formed in $D$ and diffusing out at the top would never reach electrode $E$.

The values deduced for the activation energy from all the curves obtained in the

\[ \text{Figure 7. The onset of ionization of helium by neutral atoms of the same gas, having kinetic energy of about 49·5 eV.} \]
two methods of experimenting described above ranged from 49.0 to 50.0 eV, and there was no significant difference between the results obtained by the two different procedures. The mean value obtained for the activation energy was 49.4 eV.

**Discussion of results**

The value obtained for the activation energy in the present experiments is considerably smaller than those obtained from previous investigations, the results of which are summarized in table 2.

<table>
<thead>
<tr>
<th>Authority</th>
<th>Activation energy</th>
</tr>
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<tbody>
<tr>
<td>Varney, R. N. (1936). <em>Phys. Rev.</em> (2), 50, 159–161</td>
<td>more than 400 eV</td>
</tr>
</tbody>
</table>

The apparatus used by Brasefield was designed with the intention of eliminating complications due to the emission of electrons from metal surfaces—an effect whose presence had led him to reject the results of his earlier experiments (Brasefield 1932). In these later experiments a small residual current was detected in the chamber in which ionization by atomic impact was to take place, even when this was in direct communication with the pumping system. Brasefield suggests that this residual current, which bore approximately the same ratio to that obtained when gas was present in the ionization chamber, in the case of argon, neon and helium, may have been due to the secondary electrons which the swift atoms liberated from the edges of a narrow gap between the electrodes in the ionization chamber. This relationship between the residual current and that detected with gas in the ionization chamber would not be expected if the latter were due to a genuine ionization of the gas by swift neutral atoms; for the coefficient of liberation of electrons from metals is greater for helium atoms than for either of the other two gases, and the cross-section for ionization of helium by its own neutral atoms is smaller than the corresponding quantity for argon or neon. The result can, however, be explained on the view that the gas admitted to the ionization chamber scatters the swift atoms, thus increasing the number which collide with the electrodes, and enhancing the emission of secondary electrons. The cross-section of helium atoms for elastic scattering in helium is smaller than the corresponding quantity for neon and argon atoms in their own gases, but helium atoms are more effective in liberating secondary electrons from metal surfaces than are atoms of neon and argon. The fact that no increase in the current above the residual value could be detected until the kinetic energy of the swift atoms exceeded about 100 eV may be attributed to the fact that collisions with stationary atoms would result in a diminution of the kinetic energy of the bombarding atoms. Thus, although the number of atoms striking the electrodes increases on the admission of gas to the ionization chamber, the number of secondary electrons emitted from the electrodes would not necessarily be greater when the atoms in the beam have only small kinetic energies.
The reasons for regarding Rostagni's value as an upper limit, rather than a precise determination of the activation energy, have already been discussed. The failure to detect ionization even when the kinetic energy of the bombarding atoms was increased to 400 eV, in Varney's experiments, is probably due to his use of a space-charge detector to reveal the presence of positive ions. Experiments on the detection of fast alkali ions by this device (Kienzle 1937) have indicated that in Varney's apparatus the ions produced by atomic impact did not pass sufficiently close to the hot filament from which the space-charge limited current was produced. Their effect in neutralizing the space-charge, and consequently in augmenting the emission of electrons, may therefore have been too small to detect. Further, it has been shown (Wayland 1937) that an ionization current large enough to be measured by an electrometer failed to be detected by the space-charge method as used by Varney. With the present arrangements, currents of the order of $10^{-15}$ amp. could be detected, and the electrons produced by the impacts of neutral atoms with metal surfaces were clearly distinguishable from those resulting from gaseous ionization. It is therefore to be expected that the onset of ionization by atomic impact should be determined with less ambiguity than was possible in the other researches referred to here.

The results of this investigation have shown that when a collision occurs between a 'stationary' and a moving helium atom, ionization begins when the translational kinetic energy of the bombarding atom is just twice as great as the internal energy which a helium atom must acquire in order that one of its orbital electrons may escape. Now it follows from the laws of conservation of energy and momentum that when a collision occurs between a moving particle and a stationary one of equal mass, the maximum loss of translational kinetic energy which can take place is one-half that of the moving particle before impact. The value obtained for the activation energy of helium suggests, therefore, that it is possible for the whole of the kinetic energy lost at a collision between two atoms of this gas to be transformed into internal energy of one of the atoms involved. Thus a collision between a rapidly moving helium atom and a 'stationary' one is in this respect similar to a collision between a fast electron and a stationary atom. The experimental results suggest also that in the collision of two helium atoms, there is no source, other than translational kinetic energy, from which the energy necessary for ionization can be drawn.

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