Ionization and Scattering Accompanying Positive Ion Impact in Gases*

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(Received November 19, 1932)

The ionization produced by K^+ ion impact in A, Ne, He, N_2, CO, H_2, and Hg was studied for voltages ranging from 0 to 4000 volts. These results check with the results of previous investigators wherever it was possible to make comparisons. The A curve saturates (i.e., the ionization in A approaches a constant maximum value as the voltage is increased) at 4000 volts. The Ne curve shows a tendency to saturate at 4000 volts. The ionization in He and H_2 was very weak. N_2 and CO ionize equally well and their curves fall just a little above the neon curve. The minimum potentials at which ionization sets in vary from 100 volts for A to 1600 for H_2. Accurate measurement of these potentials was not attempted. It is shown that when the results are plotted against the kinetic energy of the impinging ion-molecule system (relative to its center of mass) that the various ionization potentials show a comparatively small range. The scattering experiments show that at low voltage a few of the K^+ ions make direct impact in mercury and are reflected with 4/9 of their original energy which is the value expected from conservation of momentum and energy. Small angle scattering was also observed in this case and for K^+ and Na^+ in argon. No ions are here observed with appreciable velocity in the reverse direction. The evidence indicates that the gases which ionize most readily are also most effective as a scattering agent. It is suggested that ionizing collisions are glancing collisions.

1. INTRODUCTION

THE ionization of noble gases by the impact of the various alkali ions has been investigated for acceleration voltages up to 750 volts.[1] The purpose of this investigation was first to extend the ionization measurements to higher potentials and to include a greater number of gases, and second to investigate the nature of a non-ionizing collision.

Part I of this paper will deal with the ionization of argon, neon, helium, hydrogen, nitrogen, carbon monoxide and mercury by potassium ion impact. Part II will deal with the scattering of K^+ and Na^+ ions in mercury vapor and argon.

2. APPARATUS AND METHOD

The experimental tube is shown in Fig. 1. It resembles that of Sutton[1] except for the following modifications: (1) a system of differential pumping was employed; (2) an earthed wire gauge was placed around the filament chamber; (3) a Faraday cylinder was used to

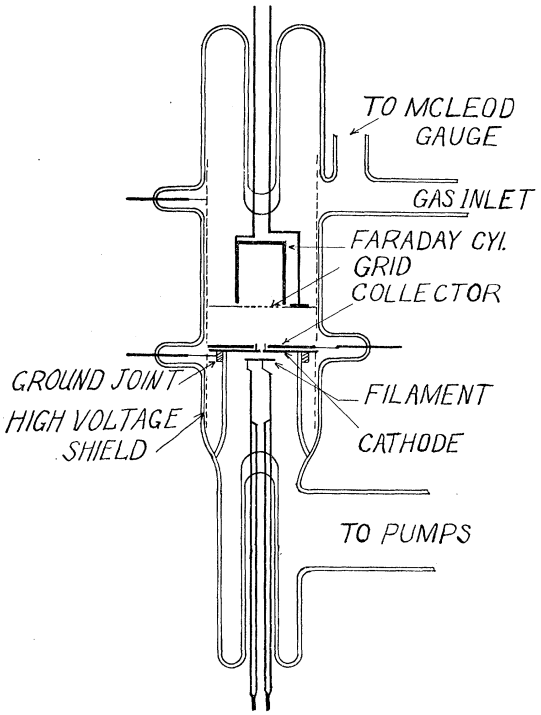

FIG. 1. Diagram of experimental tube.

* Presented at Washington Meeting, American Physical Society, April, 1932.

[1] Sutton, Phys. Rev. **33**, 363 (1929); Beeck, Ann. d. Physik **6**, 8, 1001 (1930); Sutton and Mouzon, Phys. Rev. **35**, 694 (1930); Beeck and Mouzon, Ann. d. Physik **11**, 858 (1931); Ann. d. Physik **11**, 737 (1931); Zwicky, Proc. Nat. Acad. **18**, 314 (1932). Mouzon has published a paper (Phys. Rev. **41**, 605 (1932)) in which he extends the voltage to 2000 volts, since this paper was prepared for publication.

catch the primary ion beam. It was imperative that the filament chamber be evacuated to such an extent that the residual gas would not support a discharge at the high voltages used. Thus it was necessary to employ a system of differential pumping. High-speed mercury vapor pumps were used and a 1000-fold pressure difference could be maintained across the cathode with 0.01 mm pressure in the ionization chamber. A Faraday cylinder covered with a wide mesh grid was employed to catch the primary ion beam and to reduce the effect of the secondary electron emission to a minimum.

The tube is divided into two compartments by the cathode. One compartment contains the filament and the other the electrodes used for the ionization measurements. The cathode was fitted to the re-entrant glass tube containing the filament by a closely fitting, dry, ground joint. The positive ions were liberated from a closely wound, tungsten spiral filament coated with Kunsman[2] catalyst. These ions were then accelerated to the iron cathode and in part projected into the upper chamber through a 0.5 mm hole in the cathode. This chamber contained gas at pressures which were varied from 0.03 mm to 0.09 mm for various runs. Here the ionizing collisions were made. The electrons formed by ionization were drawn to the collector which was placed immediately over the cathode. The collector was protected from the incident ion beam by a small projection or "snout" integral with the cathode.

The grid served to bound the region for which ionization was measured and the distance between it and the collector was 2 cm. This grid was made of 1 mil tungsten wire and the spacings were about 2 mm. Thus very little area of metal was exposed to the positive ion beam.

The main tube voltage was supplied by a bank of four d.c. motor generators connected in series. The voltage applied to the tube could be varied continuously from 0 to 4000 volts by a high-resistance potentiometer.

The gas technique varied for the different gases used. The hydrogen, nitrogen and carbon monoxide gases were manufactured as they were used, and admitted into the ionization chamber by a fine capillary of suitable size; the gas which diffused through the cathode was pumped out into the room. The noble gases were admitted into the system after it had been pumped out and shut off from the fore pump. Instead of pumping these gases out into the room they were shunted back into the ionization chamber so that the same gas was used over and over.

The hydrogen was prepared by the electrolysis of phosphoric acid and the nitrogen and carbon monoxide were prepared according to a method described by Warren.[3]

Since these gases (H_2, N_2 and CO) were supposedly prepared in a pure state no method of purification was attempted. The noble gases were purified by either a misch-metal glow discharge or charcoal tube placed in the circulatory system between the two-stage diffusion pump and the ionization chamber. The results in helium and hydrogen were found to be extremely sensitive to traces of impurity as has been reported by Sutton[1] (for helium).

Mercury vapor was admitted into the tube from a bulb sealed to the side of the tube at the point marked "gas inlet" in Fig. 1. The bulb containing the mercury was placed in a heated oil bath to give the desired temperature, while the tube as a whole was slightly superheated to prevent condensation. The tube was protected from water and grease vapor by liquid air traps. The glass line to the McLeod gauge, which passed through liquid air was about 1 meter in length (10 mm tubing) and a constriction was added near the tube so that Hg pressure in the tube was very nearly equal to that in the Hg bulb.

A diagram of the electrical circuit is shown in Fig. 2. Both the collector current and primary current were measured on a galvanometer G_1 which had a sensitivity of 10^{-11} amp./scale div. This was made possible by a highly insulated 4-pole double-throw switch. Galvanometer G_2 (sensitivity of 4×10^{-11} amp./scale div.) was connected in the primary circuit at all times and used to check the steadiness of the primary current.

The grid was made negative with respect to the collector so that the ionization electrons

[2] Kunsman, Rev. Sci. Inst. **1**, 654 (1930).

[3] Warren, Phil. Mag. **42**, 246 (1921).

formed between the grid and the collector would go to the collector. This potential difference did not exceed the electron ionization potential of the gas. The secondary electron emission from the walls of the Faraday cylinder reaching the collector was reduced to a minimum when the Faraday cylinder was made six or seven volts positive with respect to the grid. Below 1000 volts accelerating potential the secondary electron current to the collector (with $<10^{-5}$ pressure in tube) was less than 1 percent of the primary ion current, at 4000 volts this increased to about 4 percent. This secondary electron current was undoubtedly due to emission from the grid. In all cases except for argon (where the correction

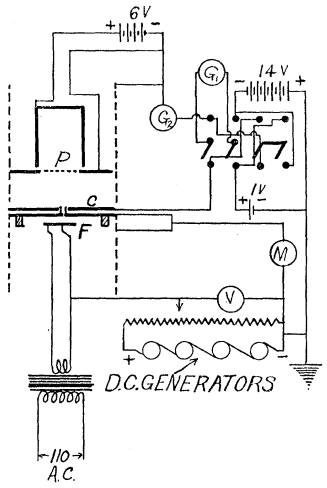

FIG. 2. Diagram of electrical circuit.

was only slight) the ionization curves were corrected for this secondary emission.

The number of ions returning to the cathode snout had to be investigated before any degree of confidence could be placed in the results. The collector current and primary current were studied as a function of the voltage for various gas pressures. It was discovered that the snout played a rather important rôle when the gas pressures were high enough to stop an appreciable number of positive ions close to it. This was not very important, however, for the pressures used in this experiment. The collector was made 1 volt positive with respect to the cathode so that any electrons formed near the snout would be drawn to the collector.

3. Experimental Results and Discussion

Part I. Ionization in A, He, H_2, N_2, CO and Hg

(*a*) *Experimental curves on ionization.* The experimental curves showing the number of ions formed per ion, per cm path, at 1 mm gas pressure, by K^+ ion impact as a function of the tube voltage are shown in Fig. 3.

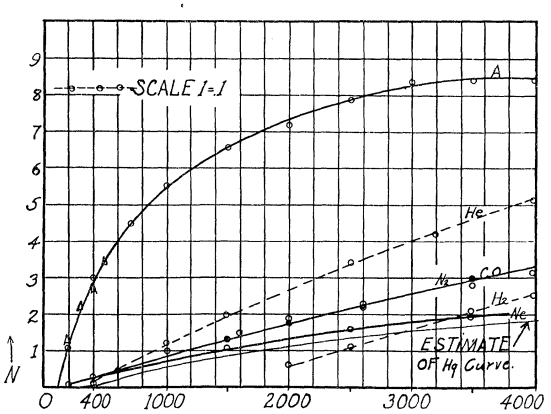

FIG. 3. Number of ionization electrons formed per K^+ ion per cm path through gas at 1 mm pressure as a function of the K^+ ion energy in volts. The ordinate scale for H_2 and He is to be reduced by a factor of ten.

These curves are each the result of the averaging of several runs. In test runs the gas pressure was varied from 0.03 mm to 0.09 mm yet for A, Ne, N_2 and CO the different series of observations checked (when reduced to same standard pressure of 1 mm) within 10 or 15

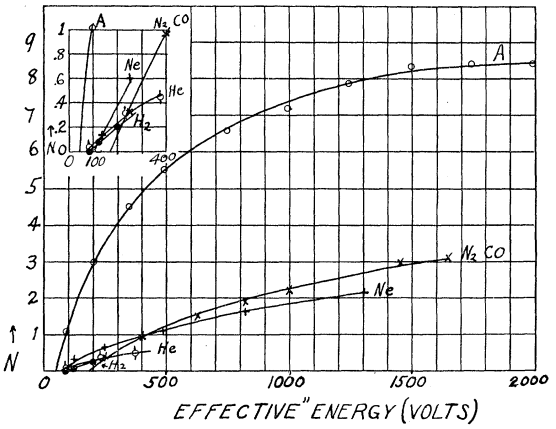

FIG. 4. Number of ionization electrons formed per K^+ ion per cm path through gas at 1 mm pressure as a function of the "effective" energy ($MV/M+m$ where V is the voltage of Fig. 3) of the K^+ ion.

percent (which is as close as the McLeod gauge can be read with certainty). This shows that the observed effect was proportional to the gas pressure. However, final data were taken in the pressure range of 0.03 mm to 0.05 mm. The results for A agree well with those of Beeck whose results are indicated by the triangles on the curve; Sutton's values are somewhat higher. The precision in the case of helium and especially hydrogen is somewhat less than this since the effect is very small and the question of gas purity is important. The ionization efficiency of mercury has also been computed (from Fig. 5). The presence of reflected ions introduces a complexity here and the results are subject to a rather larger error than for other cases.

The ionization in argon is remarkably higher than in the other gases. The argon curve saturates at about 4000 volts while the other curves (except for neon) show only a very slight bending. The neon curve shows some sign of approaching saturation.

From the results of Beeck and Mouzon,[4] which are limited to the noble gases, one should expect the degree of ionization to go up with the mass of the target particle until the masses are equal. If this relation between mass and ionization efficiency holds for all gases, one would expect hydrogen to be the lowest, and it is the lowest. The curves for N_2 and CO come in just above neon which seems to be about the place one would expect to find them, if one uses the mass of the molecule rather than that of the atom.

Not much can be said concerning the expected variation of ionization with mass of target particle when the mass of the target particle exceeds the mass of the impinging particle. It is seen that the curve showing ionization in mercury (a very massive atom) is among the lowest in Fig. 3.

The maximum ionization efficiency for K^+ ion impact in argon and neon is of the same order of magnitude as that found for ionization by electron impact. In argon the number of ions formed by electrons per cm path length at 1 mm gas pressure is about 10.3 at 150 volts[5] (the voltage of maximum efficiency) at 4000 volts which is approximately the voltage of maximum efficiency for K^+ ions the corresponding number of ions formed by a K^+ ion is 8.5. In neon the number formed by electrons is about 3.2 as compared to 2.1 for K^+ ions. The neon curve has not, however, reached its maximum at 4000 volts. The curves for the other gases do not lend themselves to such a comparison since they have not yet reached their maxima.[6]

The minimum potentials which were found to be necessary for ionization range from about 100 volts for argon, to about 1600 for hydrogen. These values agree quite well with the earlier results of Beeck, although in a later paper he gives a considerably higher value for neon.[7]

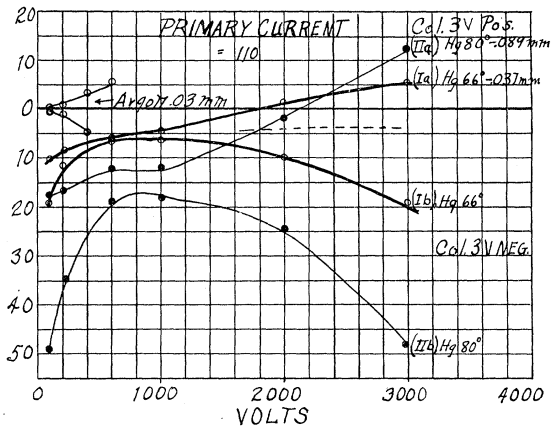

FIG. 5. Collector current as a function of the main tube voltage when the grid is made ±3 volts with respect to the collector. Curves I(a) and I(b) are for 0.37 mm Hg pressure and II(a) and II(b) are for 0.089 mm. Similar curves for argon are included for comparison. These curves show reflections of positive ions by Hg vapor at the lower tube voltage. The dotted line represents the assumed reflected current at high voltage.

Previous investigators have failed to detect ionization in hydrogen—in most cases because the voltages used were too low. Gurney[8] used potentials as high as 7000 volts but was forced to work with low pressures and low primary

[4] Beeck and Mouzon, Ann. d. Physik **11**, 737 (1931).

[5] Compton and Van Voorhis, Phys. Rev. **26**, 436 (1925).

[6] Compton and Van Voorhis, reference 5, values of maximum efficiencies for electron ionization are as follows: Hg, 19.5; A, 10.3; N_2, 10; H_2, 3.5; Ne, 3.1; He, 1.75.

[7] Beeck, reference 4. (Some of the later results of Beeck differ considerably from his earlier results. In view of the fact that no specific explanation of this lack of agreement is given in his later paper one is inclined to compare with the most favorable results.

[8] Gurney, Phys. Rev. **32**, 795 (1928).

currents. This fact may perhaps account for the uncertainty of his results.

(*b*) *Ionization as function of energy available for ionization.* When two particles of comparable masses collide, only a portion of the kinetic energy can be lost in the impact. If one of the particles (mass M) is at rest and the other moving with kinetic energy $\frac{1}{2}mv^2$, the maximum energy which may be lost is $\frac{1}{2}[mM/(M+m)]v^2$. In Fig. 4 the observed ionization currents are plotted against this available energy. One no longer observes the large differences of ionization potentials. Except for N_2 and CO the "reduced" ionization potentials are all less than 100 volts. Even on the reduced scale there is no correlation of ionization potentials with ionization potentials for electron impact.

Part II. Scattering of alkali ions by gases

(*a*) *K^+ ions in mercury at low vapor pressure.* When K^+ ions strike atoms of mercury vapor at voltages too low to permit ionization some of the ions are reflected backward from the heavier atoms and give a positive current to the collector. This offers a means of studying the nature of the collision between ion and atom.[9]

The K^+ ions were projected into the Hg vapor as described for the other gases mentioned above. Fig. 5 represents the current to the collector as a function of the tube voltage. In these curves the potential difference between the grid and collector was 3 volts. In I(a) and II(a) the field was in such a direction as to attract positive ions to the grid and send electrons to the collector. In curves I(b) and II(b) this field was reversed so that the grid attracted electrons and repelled positive ions to the collector.

These curves of Fig. 5 show a current to the collector at low tube potentials which is due to the reflection of ions on impact; this has not been observed in any of the other gases. At higher tube voltage the characteristic ionization is shown (evidenced by the separation of curves I(a) and I(b)). In curves I(a) the collector collects positive ions at low voltage and this in spite of the 3 volt *retarding* potential. This must be due to reflection of K^+ ions by the mercury molecules. The curve deflects upward at 600 volts, due to ionization setting in, and crosses the axis when this ionization current becomes greater than the reflected ion current. In curve I(b) this 3 volt field is reversed, now *attracting* positive ions to the collector instead of *repelling* them. Slow speed ions are attracted to the collector and electrons are repelled to the grid. Thus curve I(a) is a measure of the high-speed reflected positive ions plus slow speed *negative* ions (electrons—products of ionization) and curve II(b) is the sum of the high-speed positive ions plus slow-speed *positive* ions. The separation of the curves I(a) and I(b) at low voltage is due to slow K^+ ions which have either lost most of their energy by second collisions or to those which approach the collector so obliquely as to have but a small component velocity normal to it. The number of these "small velocity component" ions naturally decrease with increasing voltage. Above 900 volts the slow speed ions are largely due to ionization.

The curves I(a) and I(b) were taken with the mercury at 66°C (pressure of 0.037 mm). They show a reflection of about 15 percent at 100 volts. According to the simple kinetic theory the mean free path (mercury in mercury) at this pressure would be 0.37 mm. The dimensions of the apparatus were such that only those ions making collisions angles greater than approximately 130° would reach the collector. Since this angle is about one-fourth of the total solid angle and if all angles of scattering were equally probable the whole scattered current would be about sixty percent. This corresponds to an experimental mean free path of about 4 cm.[10] This is, obviously, very much larger than the kinetic theory value and it is quite probable that these high-speed ions scatter through smaller angles. These curves show that the m.f.p. is decreasing as the velocity is lowered. At higher voltage the scattering decreases to 5 percent (at 800 volts) and the separation between the curves (corresponding to reflected ions with small velocity) decreases.

[9] Cox, (Phys. Rev. **34**, 1426 (1929)) and Thompson, (Phys. Rev. **35**, 1196 (1930)) have studied the motion of slow Li^+ and Cs^+ ions in Hg, H_2 and He.

[10] Durbin, Phys. Rev. **30**, 844 (1927), has measured the m.f.p. for K^+ ions having velocities corresponding to 0 to 250 volts in several gases but not in Hg. This value is, however, very much larger than his value.

Above 800 volts the reflection is partly masked by the ionization current. The reflection accounts in part for the dissymmetry in the positive and negative currents. The number of reflected ions probably stays nearly constant or perhaps decreases somewhat at higher voltage as shown by the hypothetical (dotted) line.

From other experiments it was found that ionization sets in at about 300 volts. It does not become an important factor for several hundred volts further, as is seen by the fact that curves I(a) and I(b) do not diverge below 600 volts. If the "hypothetical" reflected current (shown by dotted line) is approximately correct, the positive ion current is almost twice as large as the negative current at 3000 volts. Such a dissymmetry is to be expected. The Faraday cylinder was always positive with respect to the grid (to eliminate the effect of secondary electrons). Hence, all negative ions produced between grid and cylinder are drawn to the cylinder. Curve I(a) is a measure only of the ions formed between the grid and collector. Curve I(b) on the other hand, measures also the positive ions forced out of the cylinder. In other words, curve I(b) is a measure of the ions formed for a path about twice as long as the path for curve I(a).

It is not possible to estimate this ionization current with the precision of the other ionization curves but taking the negative current as equal to 10 divisions (at 3000 volts) one obtains about 1.4 for the number of ions formed per cm path at 1 mm mercury vapor pressure.

Curves II(a) and II(b) were taken with a higher vapor pressure in the tube. The pressure has been something more than doubled and one observes a little more than twice the ionization and something more than twice the reflected current and a great many more slow-speed reflected ions. (The separation between the curves has increased.) This large increase in slow-speed reflected ions is due to multiple collisions since the chance of two collisions is quadrupled as the pressure is doubled.

Curves similar to these are shown for argon for a small range of voltage at a pressure nearly equal to that for I(a) and I(b). The same dissymmetry is shown but there is no evidence at any voltage of reflected ions. Ionization begins at 100 volts.

(*b*) *"Directed energies" of reflected ions.* The argon molecules are equal in mass to the K^+ ions and direct reflection of K^+ ions from argon is not to be expected. In a direct impact the energy is handed over from the K^+ to the argon molecule. The energy retained after an elastic collision at any angle is, of course, derivable from the simplest application of conservation of energy and momentum.[11] One may reasonably assume that the collisions of K^+ ions in mercury at low voltage are elastic. Limiting the consideration to "head on" collisions the K^+ ion should be reflected back with about 2/3 of its original velocity, i.e., 4/9 of its original kinetic energy.

The energy distributions curves for 50, 100 and 200 volt K^+ ions impinging in Hg vapor are shown in Fig. 6. Here the potential difference between grid and collector (which was held constant in Fig. 5) was varied and these curves of Fig. 6 are obtained by plotting the collector current as a function of the difference of potential. To the left of the zero ordinate axis the curve represents positive ions moving forward, to the right it represents positive ions reflected backwards. The abscissas give the stopping (or accelerating potential between grid and collector. The ability to overcome a stopping potential depends not upon the total kinetic energy of the ion, but upon what one may call the "directed kinetic energy." By this is meant $\frac{1}{2}mv_x^2$ when v_x is the component of velocity in the direction of the field. It is this directed kinetic energy which is given (in terms of electron volts) by the abscissas.

Curves A and B were taken for different pressures, as indicated in the figure. In each case two sets of curves are shown. The one set with the solid circles represents the energy distribution of the K^+ ions in a vacuum. The hollow circles represent the energy distribution with Hg vapor in the tube at 74°C and 58°C.

In the case of the vacuum curves the positive ions are seen to have a rather small range of velocities. A current is received by the collector when the retarding potential on the grid (*col.*

[11] Joos and Kulenkampf, Phys. Zeits. **25**, 257 (1924).

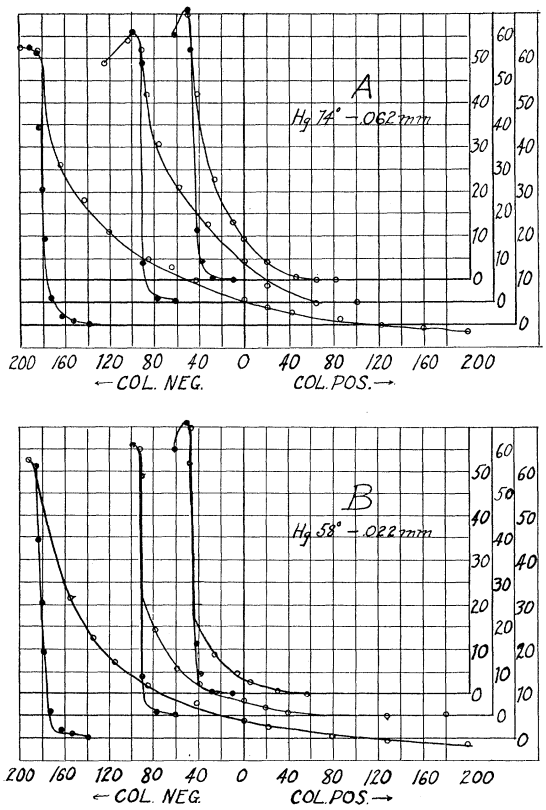

FIG. 6. Collector current as a function of the potential difference between grid and collector for 50, 100 and 200 volt K^+ ions projected into Hg vapor. Solid points represent results with vacuum in tube. These curves give substantially the "normal component" of the energy distribution among the positive K^+ ions after impact.

neg.) is almost as great as the tube voltage,[12] which is to be expected. When the Hg vapor was in the tube the total ion current is 60 divisions as in the vacuum case, but now the current is received with *smaller* or even *reversed* voltages on the grid.

When the grid is made negative so that the field repels ions from the collector the current decreases and reaches zero at about 45 volts (for 50 volt ions). This 45 volts gives a measure, presumably, of the fastest *reflected* ions. This is in general agreement with expectations. If it be assumed that the collision takes place in the neighborhood of the grid the ions involved will have an energy of 100 volts at this point on impact. (The field which is indicated as (*col. pos.*) was applied by making the grid more negative with respect to filament and snout rather than by changing the potential of the collector). According to the theory, an ion making a direct collision should be reflected back with 4/9 of this energy, i.e., be able to overcome a retarding potential of about 40 volts which is made nearer to the collector than this, a larger stopping potential on the collector should be applied. However, there are other factors (multiple collisions, etc.) which are very important and all of which tend to operate in the opposite direction.

In general, if V is the cathode potential (with respect to the filament) and R the grid potential, the energy of the ion as it reaches the grid is $V+R$; after direct impact it is 4/9 of this. Hence the maximum *retarding* potential is given by $(4/9)(V+R)=R$ or $R=(4/5)V$. In other words, when the potential R is equal to $(4/5)V$ the elastically reflected K^+ ions from Hg will just be prevented from reaching the collector. The 50 volt ions should be stopped by 40 volts, the 100 volt ones by 80 volts, and the 200 volt ions by 160 volts. Actually, the curves shown for 100 volt positive ions indicate only a slightly greater stopping potential than the 50 volt curve. In the case of the 200 volt ions ionization begins to play a rôle. The grid potential added to the tube voltage of these ions gives these ions at the extreme right of the curve some 400 volts which is able to produce ionization and cause the curve to cross the axis. This makes the interpretation difficult but it is clear that the stopping potential is not less than 120 volts. In view of the neglected factors these results may be considered as in rather good agreement with the theory.

Collisions of a more glancing type are certainly quite prominent. This can be seen from the difference between the vacuum curves and the Hg curves to the left of the zero axis of ordinates. It is clear that for a mercury pressure of 0.062 mm there are practically no ions which entirely miss making mercury collisions in any of these curves. In each case the vapor curve starts to break away from the vacuum curve rather quickly. There seem to be a great many ions

[12] As the retarding voltage is made still larger the collector current drops off slightly because the ion beam is turned back sooner and more of it reaches the snout and less to the collector.

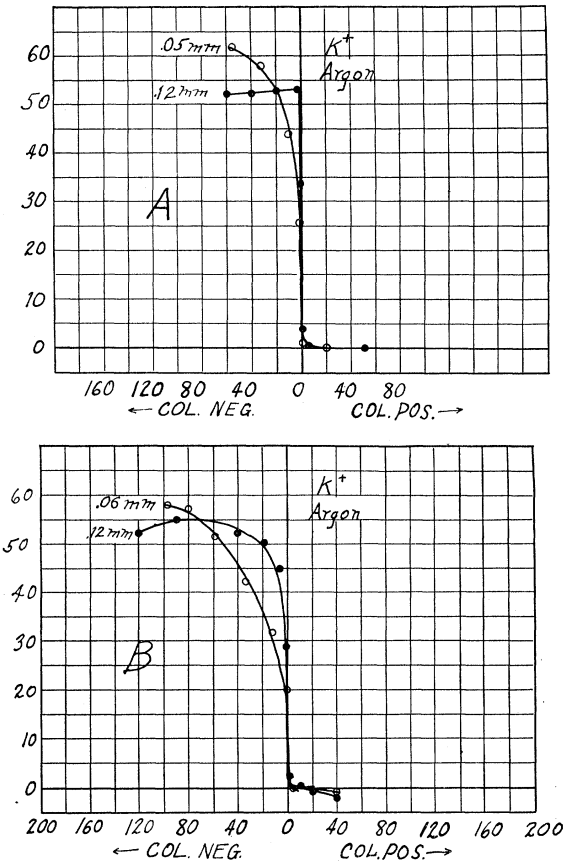

FIG. 7. Collector current as a function of the potential difference between grid and collector for 50 and 100 volt K^+ ions projected into argon. Similar to curves of Fig. 6 for Hg.

which have retained 50 or 75 percent of their original energy (i.e., stopped by a retarding voltage on the grid of 50 to 75 percent of the tube voltage) but very few indeed with the full energy. Fig. 6B shows similar curves for much lower vapor pressure. The maximum reflected velocities (the intercept "*col. pos.*") are about the same as before.

The curves for 50 volt and 100 volt ions quite clearly intersect the vacuum curves (Fig. 6B) showing that in these cases something like 50 percent of the ions suffer no energy losses. In case of the 100 volt curve the number which have escaped collision seems rather higher than for the 50 volt curve; for the 200 volt curve all of the ions seem to have lost energy. It is not clear whether small energy losses are indeed more probable with higher velocity particles or whether the difference is due to some experimental difficulty. This point would deserve further investigation.

(*c*) *K^+ ions in argon.* Curves showing the velocity distribution for 50 and 100 volt K^+ ions projected into argon are shown in Figs. (7A and B) respectively. In general, the argon curves are of an altogether different type from the mercury curves. They indicate that the mean free path of K^+ ions in argon is shorter than in mercury. At 0.12 mm pressure multiple collisions produce complete energy losses. The curves show that K^+ ions are not reflected backward by the argon atoms; no such reflection can occur because the K^+ ions and argon atoms are of equal mass.

(*d*) *Na^+ in argon.* A distribution curve for 100 volt Na^+ ions in argon is shown in Fig. 8.[13] The reflected current (if it existed at all) is very small as is evidenced by the fact that the curve goes to zero very soon on the right side of the zero axis of ordinates. This is to be

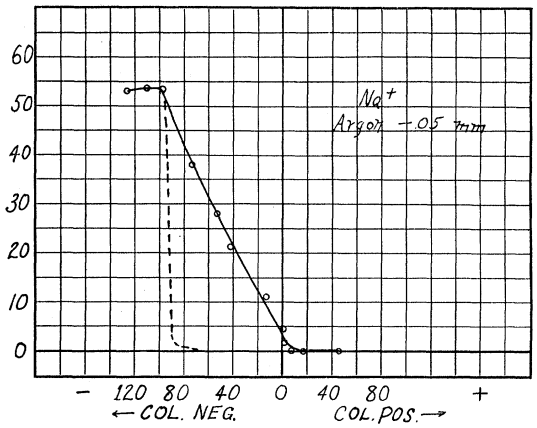

FIG. 8. Curve for Na^+ ions impinging in argon, similar to Figs. 6 and 7 for K^+ ions in Hg and argon. The dotted line shows the assumed distribution of the energy of the Na^+ ions in a vacuum.

expected from a consideration of the relative masses of sodium and argon. Na^+ reflects from Hg much the same way as K^+, but a detailed study of this was not made.

(*e*) *Probable nature of ionizing collisions.* One last observation in this study of the nature of ionic impact should be recorded. It pertains to

[13] The dotted curve represents the assumed distribution curve for Na^+ in a vacuum.

the ionizing collision. The secondary electrons and positive ions resulting from ionization are collected by a small potential difference. I(a) and (b) of Fig. 5 were taken with a collector voltage of ± 3 volts. A larger voltage adds little to the separation of the curves. This would seem to indicate that the Hg ion is propelled forward at the moment of formation with negligible speed. This means that the collisions which produce ionization are of a "glancing" type, the K^+ ion suffering little change in momentum. If this interpretation is correct, it is, to say the least, a remarkable state of affairs. It does not agree with Zwicky's[1] fundamental hypothesis that the probability of ionization depends on the momentum transfer.

The author takes this opportunity to express his appreciation of the advice and suggestions given by Professor J. A. Eldridge under whose direction this work was done.