Large Angle Scattering and Energy Loss of Potassium Ions Scattered by Heavy Monatomic Gases

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A beam of potassium ions with energies in the range between 90 and 360 volts was scattered by collision with the heavy monatomic gases argon, krypton, xenon, and mercury vapor and the angular distribution was observed. For slower particles the scattering per unit solid angle relative to the center of mass of the colliding particles decreases with angle. At higher voltages the scattering increases at larger angles with a minimum about 60. The scattering at the larger angles increases with voltage. The results are not compatible with a rigid sphere model of the atom. The large deviations may be associated with exciting or ionizing collisions.

INTRODUCTION

WHEN an ionic beam is sent into a gas at low pressure the ions are scattered by collision. For collisions between rigid spheres the classical kinetic theory predicts equal scattering in all directions (if the angles are measured relative to the center of mass of the colliding particles rather than to the apparatus). Wave mechanics give substantially the same result for rigid spheres excepting for a great increase in very small angle scattering. For models with less abrupt force fields the large angle scattering should decrease more or less with angle; the Rutherford scattering in a Coulomb field is an extreme case. For rigid spheres the scattering should be independent of the speed of the ions; for other laws of force one should expect, so long as ionization and excitation play no role, the scattering to decrease with increasing energy of the beam.

It is not easy to obtain unambiguous experimental results in this field. Along with the scattered primary ions there may be electrons produced by ionization or ejected from the walls of the apparatus. There may be, at least at smaller deviations, ions of the scattering gas. The deviated particle may suffer multiple collisions or may lose its charge. To a certain extent these effects may be controlled by proper experimental conditions. Nevertheless the phenomena in the tube remain complicated. In an exploratory investigation in the field probably the best evidence that the data are reliable is to measure the energies of the scattered particles and show that energy and momentum are conserved in the impact.

The small angle scattering of low velocity neutral atoms has been studied by Zabel,[1] Broadway,[2] and others. It was found that the results were in accord with the scattering expected by wave mechanics applied to a rigid sphere. Frische[3] has reported that alkali ions are scattered from mercury vapor through large angles (in the neighborhood of 180°) and that these ions loose approximately the amount of energy expected in a single elastic collision. This paper is a report on an investigation of the angular distribution of potassium ions (in the range from 90–360 volts) scattered through large angles by heavy monatomic gases.

DESCRIPTION OF THE APPARATUS

In this experiment a beam of ions of known velocity was sent into a gas and the scattered ions were collected in a collector which could be set at various angles with the incident beam. The current to this collector was then measured with an electrometer.

A cross-sectional view of the apparatus is shown in Fig. 1. The apparatus is divided into two chambers by a plate which holds in place the collimator for the incident beam. Above the collimator is the potassium ion source, a flat tungsten filament coated with Kunsman catalyst. The filament was adjusted to its position above the collimator by means of a sylphon arrangement not shown in the figure. Below the dividing

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[1] Roland Zabel, Phys. Rev. **96**, 411 (1934).
[2] L. F. Broadway, Proc. Roy. Soc. **A141**, 634 (1933).
[3] Carl A. Frische, Phys. Rev. **43**, 160 (1933).

plate is the scattering chamber which contains the collector. By means of a ground glass joint the collector could be rotated through an angle of 135° with the beam. This angle was read by a pointer attached to the ground glass joint.

The scattering gases were admitted to the scattering chamber through the inlet shown. Argon was pumped through and out the system, its pressure being controlled by a needle leak valve. Mercury vapor pressure was controlled by a mercury well at a fixed temperature, the remainder of the apparatus being maintained at a higher temperature. The technique for krypton and xenon was somewhat different. Small quantities of spectroscopically pure gas were admitted to the system and used until slightly contaminated as shown by a change in pressure. The gas was kept in circulation while in use, thus maintaining a low pressure in the upper chamber and the desired pressure in the scattering chamber. The pressure was measured with a McLeod gauge connected directly to the scattering chamber.

Figure 2 is a more detailed picture of the collector and collimator both drawn to scale. The collector proper was a plate enclosed in a metal shielding box with a double top. The collecting plate was connected to the electrometer by a lead which passed through a shielding metal tube and out through the ground joint. Slits in the double top 4×0.5 mm and 3 mm apart provided resolution for the scattered beam.

The axis of rotation of the collector was adjusted to intersect the incident beam just below the collimator. Under these conditions the scattered beam was symmetrical. When the axis of rotation was raised about 2 mm above the end of the collimator it was observed that no ions reached the collector at large angles. If the collector was pointed to one side of the beam no ions reached the collector. This indicated that the collector admitted ions only from the direction defined by its slits.

The shape of the incident beam as defined by the collimator is indicated in Fig. 3. The graph shows the logarithm of the current to the collector for ions with 360 volts energy in a vacuum. From the dimensions of the collimator and collector slits, the geometrical edge (i.e., shadow) of the beam should be at about 15° and the graph shows that at this angle the intensity has dropped to one thousandth of its maximum value. Thus most of the ions of the incident beam move practically parallel with the axis of the collimator. A small spurious background at 90° (in a vacuum) was negligible in comparison with the scattered current from the heavier gases. However, for argon which scattered practically nothing through 90°, this background was important.

In measuring scattering the gas pressure in the scattering chamber was kept low to avoid the possibility that the scattered current observed could be due to multiple collisions. The pressure of the scattering gas was maintained at 0.01 mm of Hg or less and the observed scattering, at a particular angle, was actually found to be proportional to the pressure within experimental error. Further, Frische,[3] and Durbin[4] have shown that positives have as a rule longer mean free paths, for appreciable angle deflections, than neutral atoms. Mean free paths of neutrals at the

[4] F. M. Durbin, Phys. Rev. **30**, 844 (1927).

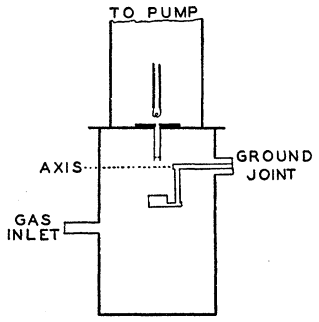

FIG. 1. Arrangement of ion source and collector.

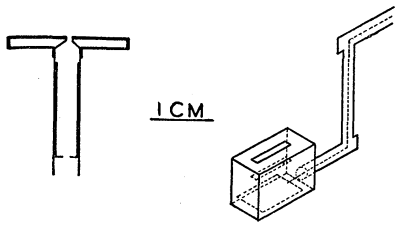

FIG. 2. Detail of ion source and collector.

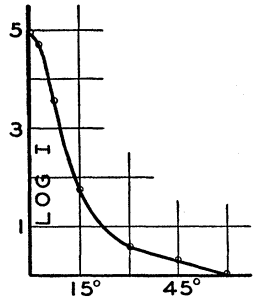

FIG. 3. Distribution of current in incident beam.

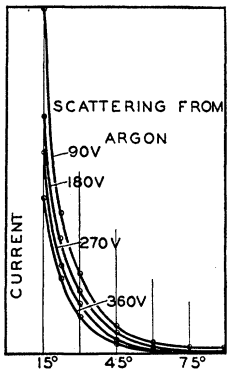

FIG. 4. Scattering of potassium ions in argon.

pressure mentioned are somewhat greater than the dimensions of the apparatus.

Energy momentum considerations show that in a single collision potassium ions cannot be deviated more than 30° by neon nor more than 90° by argon in the laboratory system of reference. This agrees with the experimental results. Also the measured energies of the scattered particles agree with the values expected for single elastic collisions.

The possibility of double collisions is very greatly reduced by the collimating effect of the collector slits. The double slits insured that only ions moving in a particular direction could enter. Hence only two collisions which both occurred within a very small volume just below the collimator could produce ions which could reach the collector. The collector allowed some control over charges which entered it by means of a potential applied between the collecting plate and its shielding container. This potential was made to repel electrons and attract positives. The space outside the collector was not affected by this potential so that the scattering took place in a field free region.

ANGULAR DISTRIBUTION

To obtain the angular distribution of the scattered ions the current to the collector was measured at various angles both with and without a scattering gas, the difference of the two currents being taken as the scattering due to the gas. The filament current controlled the intensity of the beam and a voltage applied between the filament and the collimator gave the incident ions their initial energy. A potential of from 22 to 67 volts was applied between the collecting plate and its shielding container so that positives which entered the slits reached the collector and the negatives were repelled. This potential was found particularly necessary at the higher voltages which produced ionization.

The scattering volume from which ions can enter the collector is approximately the volume cut out by two intersecting cylinders, one along the incident beam and the other along the scattered beam. This volume evidently varies with the angle between the axes of these two cylinders.

The data, reduced to a standard scattering gas pressure and incident beam intensity and corrected for scattering volume, were plotted in arbitrary units against the scattering angle in Figs. 4, 5, 6, and 7. The scattering angle plotted was measured with respect to the apparatus. This sort of a graph gives an idea of the actual space distribution of the scattered ions.

The classical theory for rigid spheres predicts equal scattering in all unit solid angles when measured in a system of coordinates at rest with respect to the center of mass of the two colliding particles (the so-called relative system of coordinates). For the case of particles of equal mass, this uniform scattering becomes a cosine curve when observed in a system of coordinates fixed in the apparatus. Argon and potassium have masses of 40 and 39 respectively and so almost satisfy the condition of equal masses. The scattering curve for argon does become zero at 90° as it must from energy momentum considerations but otherwise does not resemble the cosine curve. Neglecting the part of the scattering curve above 75° where the scattering is too small to draw definite conclusions, one must say that the curve falls off more rapidly than the cosine curve and therefore more rapidly than predicted classically for rigid spheres. Fig. 4 also shows that the scattering at any angle decreases with voltage.

Figures 5, 6, and 7 show the scattering from gases heavier than argon and therefore heavy enough to scatter the potassium ions through more than 90°. At lower voltages the curves more or less resemble those of argon, decreasing with angle. Confining attention to some particular angle, the scattering may increase or decrease with voltage, although always at the large angles the scattering is greatest at 360 volts.

For purposes of comparison it is better to have

the scattering function plotted against the relative scattering angle. A simple transformation will accomplish this. Two changes are brought about in transforming the scattering curve from fixed coordinates to relative coordinates; first the angle of scattering is changed, thereby altering the abscissa, second the scattering per unit solid angle is changed, thereby altering the ordinate. The changes are less important for target atoms much heavier than the incident ions but in every case the scattering at large angles is increased.

Figure 8 shows the transformed data for the three heavier gases. Curves A, B, C, and D are the voltages 90, 180, 270, and 360, respectively. The remarkable things about these scattering curves for the heavier gases are the maxima have now disappeared, at sufficiently high voltages there is an increase in scattering with angle, and at large angles there is an increase in scattering at the higher voltages. No simple theory predicts these phenomena. The curves would suggest that a new interaction is occurring at higher voltages which increases the probability of collision especially for large angle deflections. This new interaction may be some sort of an inelastic collision or a resonance or interference phenomenon. But in any case the scattering curves are unusual and unexpected and for that reason very interesting.

Energy Loss

In order to establish the validity of these results and to show that the ions scattered to the collector were indeed, as was assumed, those scattered by single collisions, the residual energy of the ions was measured by applying a retarding potential between the collector and its shielding container. Fig. 9 shows two curves obtained in this manner. Curve A is for 90 volt ions scattered through 30° by krypton and curve B is for 180 volt ions scattered through 45° by krypton. The ion current is reduced to zero by retarding potentials of 74 and 140 volts respectively in the two cases; that is, the fastest ions had lost $90-74=16$ volts and $180-140=40$ volts in the collision. The curves cut the axis at 16 and 40 volts, respectively. The kinetic energy lost by the ion in an elastic collision can of course be computed from simple energy momentum considerations and for these particular cases, it is 12 and 45 volts, respectively. The agreement is within the experimental error.

It would be supposed that the scattered ions (at a given angle) would all have the same velocity; under ideal conditions the drop in these curves should occur suddenly at the theoretical voltage. Actually it does not do so; the curves for these voltages are always of the general type shown. However this is not to be interpreted as casting doubt upon the hypothesis of single elastic collisions. When similar retarding potential curves are taken on the incident beam (with no gas in the chamber) the same shape of the curves results. Fig. 10 is such a curve for a beam of 90 volt ions. The absence of a sharp break may be inherent in this method of measuring the

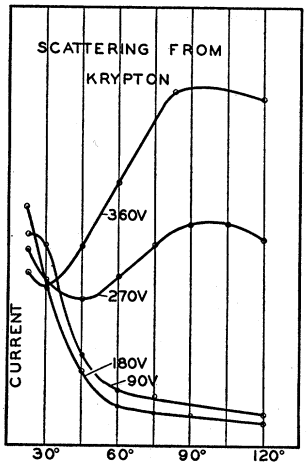

FIG. 5. Scattering of potassium ions in krypton.

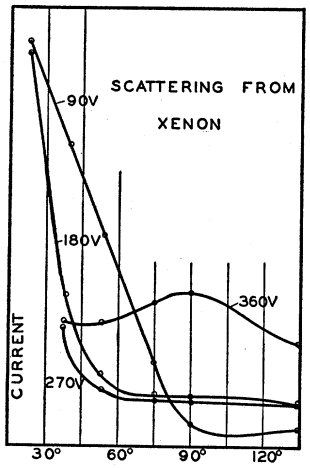

FIG. 6. Scattering of potassium ions in xenon.

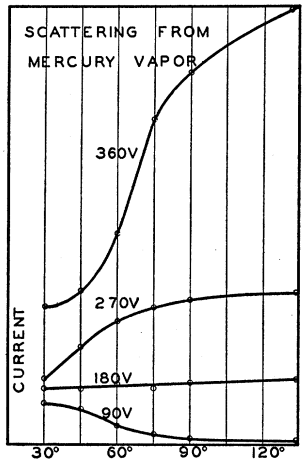

FIG. 7. Scattering of potassium ions in mercury vapor.

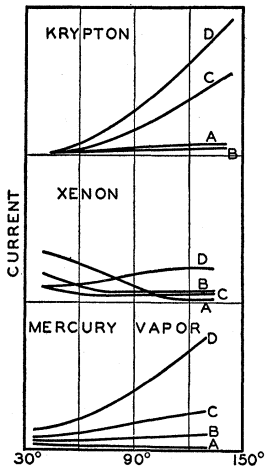

FIG. 8. Scattering of potassium ions in krypton, xenon, and mercury vapor. The angles are in the system moving with the center of mass of the colliding particles. Curves *A*, *B*, *C*, and *D* are for 90, 180, 270, and 360 volt ions, respectively.

energy of positive ions or it may be due to a spread in the energy of the primary beam. Since the curve for the incident beam becomes zero at zero potential there is this justification for taking the intersection of the curve with the axis as a measure of the energy lost.

A summary of several retarding curves is presented in Table I. The angle of scattering and the initial energy of the ion are given in the column at the left while the target atom is indicated above. In each case two numbers are given, the first is the calculated energy loss for a single elastic collision and the second is the observed loss. The last three lines (for higher voltage ions and larger angles) are data not obtained on this apparatus and will be explained later.

IONIZATION

In the retarding curves just presented the ion current dropped to zero and remained zero even at very large retarding potentials. However, above 180 volts, there was considerable ionization in the tube and the retarding curve, as shown in Fig. 11, became negative; more electrons than positives reached the collector. This naturally made it impossible to make a reliable determination of the potential at which the positives ceased to reach the collector. The curve also indicates that an attracting potential of approximately 45 volts was necessary for saturation of the positives and, as was mentioned previously, this potential was used in obtaining the scattering curves in Figs. 4–7. Fig. 11 is a retarding curve for 225 volt ions scattered through 90° by krypton. The increased positive current of the collector at an attracting voltage was observed only when there was a scattering gas in the chamber which proved that the ions were scattered from the target atoms.

It seemed advisable to design another apparatus in which the negative and positive currents could be separated and the speed of either measured. Also, in view of the surprising results of the earlier scattering curves it seemed possible that the increase in total scattering at high voltages might be associated with the inset of ionization and confirmation of these scattering curves was sought in an apparatus of radically different design.

Figure 12 shows an apparatus the scattering chamber of which contains four co-axial insulated brass cylinders. The outer one serves as a collector while the inner three define the scattered beam and can be used as grids for control and observation of the scattered beam. A slot which nearly encircled the cylinder was made in each of the inner three only enough of the metal being left for support. By properly adjusting the voltages on the several grids, it is possible to separate the positive and negative scattered particles; also, of course, this apparatus collects all ions scattered through 90° and therefore from a larger solid angle than did the other apparatus which consequently allows the use of a lower scattering gas pressure.

One function of this second apparatus was to measure the energy of the electrons (products of ionization) because the obvious interpretation of Fig. 11 is that the electrons have a surprisingly large amount of energy. Fig. 13 shows the electron current to the collector as a function of the potential of the middle cylinder. The scattering gas was xenon, the incident ions had 360 volts energy, and the collector was at such a potential that no positive could reach it. The sharp break in the curve is characteristic of a retarding curve for electrons all of which have approximately the same energy. The maximum energy of the scattered electrons as shown by this curve is 1 or 2 volts.

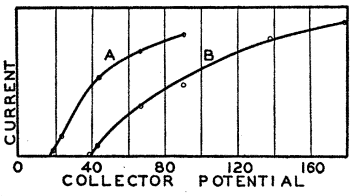

FIG. 9. Current *vs.* retarding potentials. Curve *A*, 90 volt ions scattered through 30°; curve *B*, 180 volt ions scattered through 45°, both in krypton.

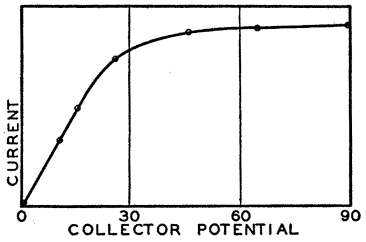

FIG. 10. Current *vs.* retarding potential for 90 volt ions in vacuum.

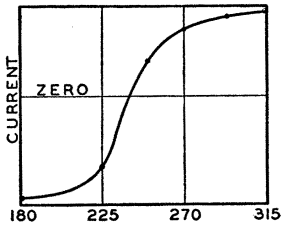

FIG. 11. Current *vs.* retarding potentials for 225 volt ions scattered through 90° in krypton.

Retarding curves for determining the energy of the positives as measured with this apparatus are shown in Fig. 14. The target atom was krypton and the incident ions had 270 volts energy for curve *C*, and 360 volts for curve *D*. At these voltages electrons were numerous enough to cause complications with the first apparatus, but with this apparatus they were eliminated by a few volts on the middle cylinder as was shown possible in Fig. 13. The calculated energy loss again agreed with that measured and the results of these retarding curves for positives are summed up in the last three lines of Table I.

It might be supposed that inelastic collisions could be observed by careful analysis of the retarding curves for the higher voltage positives. An attempt was made to do this but no definite conclusions could be drawn from the data obtained.

A final check on the data was obtained by observing with this apparatus the scattering at 90° as a function of voltage. Although differing markedly in construction from the first apparatus the results obtained were in general agreement. In Table II columns *A* and *B* give the scattering under the conditions indicated with the first and second apparatus, respectively. The scattering is given in arbitrary units, the size of the unit being adjusted so that the numbers in the two columns are somewhat the same size. It is readily seen that the increase of scattering with voltage is comparable in both cases.

Column *E* in this same table is a rather rough measure of the number of electrons which were observed at these various voltages. This number was secured by putting the collecting cylinder in the second apparatus at such a potential that no positives could reach it. Although there is no one to one correspondence between the increase of scattering at 90° and the number of electrons observed the results seem to indicate a possible relation between them.

TABLE I. *Calculated (first column) and observed (second column) energy losses.*

	ARGON		KRYPTON		XENON		MERCURY	
30° 90 V	23	20	12	16	7	5	5	8
30° 180 V	45	45	23	24	14	18	9	
45° 90 V	45	46	23	20	15	18	10	10
45° 180 V	90	95	45	40	31	30	20	
90° 180 V			120	115	83	85		
90° 270 V			180	180	110	120		
90° 360 V			240	247	165	175		

DISCUSSION OF RESULTS

Data have been presented on the energy lost by a potassium ion when it undergoes a single elastic collision with a heavy atom. This energy loss depended upon the initial energy of the impining ion, the mass of the target atom, and the angle through which the ion was deflected and was found to be in agreement with that loss calculated assuming energy and momentum were conserved.

The angular distribution of the ions scattered by the various gases presents some very interesting possibilities. The marked increase of scattering with increasing angle is entirely unexpected and cannot be explained on the basis of any simple classical theory. Since there is also an increase in the scattering at the higher voltages the data suggest the possibility of an interaction which becomes effective at these voltages and increases the probability of large angle collisions.

The electrons formed by ionizing the scattering gas have been found to have a maximum energy of 1 or 2 volts.

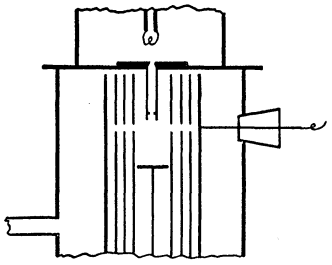

FIG. 12. Apparatus for measuring scattering at 90°.

In an attempt to correlate the increased scattering at high voltages with the phenomenon of ionization a comparison of the scattering with the ionization was made. No definite conclusion could be drawn from this comparison but a possible relationship was in evidence.

TABLE II. *Scattering at 90° in the first (column A) and the second (column B) apparatus. Column E gives the number of electrons.*

	KRYPTON			XENON			HG	
V	*A*	*B*	*E*	*A*	*B*	*E*	*A*	*E*
90	2.0	2.5	0.0	1.0	1.6	0.0	0.3	0.0
180	1.4	2.2	4.0	2.6	3.2	1.4	3.0	5.0
270	12.3	9.0	6.0	2.6	5.6	4.5	7.4	10.0
360	19.4	11.5	11.0	8.5	9.0	6.0	20.2	20.0

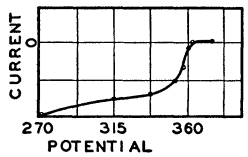

FIG. 13. Current (electron) to the outer cylinder *vs.* potential of the middle cylinder.

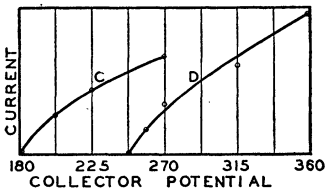

FIG. 14. Positive ion current in second apparatus *vs.* retarding potentials for 270 volt ions (curve *C*) and 360 volt ions (curve *D*) in krypton.

Further work on the scattering curves should lead ultimately to an understanding of the interaction forces between the two particles and a determination of the collision cross sections for the types of collisions which occur.

The author wishes to acknowledge his indebtedness and gratitude to Professor John A. Eldridge for his guidance in this investigation.

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Paramagnetic Measurements at Low Fields with the Rankine Balance

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The Rankine magnetic balance previously reported has been adapted for making paramagnetic measurements at low fields. An analysis of the stability of the balance under these conditions is given. The volume magnetic susceptibilities of gaseous O_2 and of aqueous $NiCl_2$ solutions relative to water are reported, and from these values the relative mass susceptibilities of O_2 and $NiCl_2$ are deduced. The mass susceptibility of H_2O is assumed to be -0.7200×10^{-6}, in terms of which, that of O_2 is 104.4×10^{-6} and of $NiCl_2$ is 33.97×10^{-6}.

IN a previous paper[1] details for the construction of a Rankine balance for measuring magnetic susceptibilities were given. The results of measurements of diamagnetic susceptibilities on mixtures of heavy and light water were reported.

The adaptibility of the Rankine balance for making low field paramagnetic measurements is demonstrated herein, and the results on aqueous nickel chloride solutions and on gaseous oxygen are given.

The equilibrium condition for the Rankine balance is:[1]

$$T+T_0+\frac{\pi m^2 b\kappa \sin\theta}{2x^2}+\tau(\theta+\theta_0)=0, \qquad (1)$$

in which the symbols have the same significance as in the previous paper.[1] For small angular

[1] H. P. Iskenderian, Phys. Rev. **51**, 1092 (1937).