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THE MOTION OF SLOW POSITIVE IONS IN GASES

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ABSTRACT

Positive caesium ions with velocities of 3.5 to 600 equivalent volts have been studied in hydrogen and helium. No absorption of the ions in the apparatus used is found for pressures below 0.01 mm of mercury. For the higher velocities this absence of absorption persisted for pressures as high as 0.05 mm of mercury. In all cases the ions were retarded in passing through the gas and there is an approximate probability distribution of ion energies about an average retarded value. The retardation in all cases is found to be proportional to the pressure. For Cs^+ ions in helium the percent loss of initial energy varies from 11.5 for 400 volt ions to 55 for ions of 3.5 volts initial energy. Similar results are found for hydrogen. Values of the constant, h, of the error curve which are characteristic of a particular distribution are given for various velocities and pressures. An interpretation of the absence of scattering and the retardation of the ions is given on the basis of elastic collisions between ion and gas molecule. It is found that no absorption of the Cs^+ ions would be expected until the pressures are high enough to give rise to multiple scattering. The data on retardation give values of the radius of the Cs^+ ion as: 1.78A in helium and 3.09A in hydrogen. The slowing up of the ions offers an explanation of the large absorption of Cs^+ in helium found by Ramsauer and Beeck. Probability considerations show that for increasing velocities the energy loss per collision found in the present experiments is less than that to be expected on the basis of elastic collisions.

The absorption of Li^+ ions has been studied by three methods for velocities of 20 to 900 equivalent volts. The coefficients of absorption, C, representing the effective absorbing cross section have been determined by two methods. The general dependence of C on the ion velocity is the same for the two types of apparatus used, but the values of C are found to depend on the dimensions of the absorbing chamber. The results have led to the interpretation of scattering in which forces other than those due to elastic collisions are effective. No general retardation of the Li^+ ions was found. Values of C found by Ramsauer and Beeck are interpreted in terms of the dimensions of their apparatus. It is concluded that no absolute significance may be attached to values of atomic radii determined from measurements of this kind.

WHEN a beam of positive ions moves through a column of gas there is in general a weakening of the bundle which may be due to a number of different processes of interaction between ion and gas molecule. Neutralization of the ions, either from the capture of a free electron or an ionization of the gas molecule, scattering or a combination of these effects will contribute to a decrease in intensity. In addition, any retardation of the ions may show itself as an absorption unless precautions are taken in the experimental method of measurement. It is customary to express any absorption of the ion bundle in the relation:

$$N = N_0 e^{-xp/760L} \tag{1}$$

where N is the intensity of the beam after passing through a distance, x, of the gas at pressure p; N_0 the intensity of the incident ions, and L the absorption coefficient, also referred to as the mean free path under standard conditions. Writing L in terms of the radii of the ion and gas molecule,

$$\begin{aligned} L &= 1/\pi n(R_{ion} + R_{mol})^2, \text{ or} \\ C &= \pi(R_1 + R_2)^2 = 1/Ln \end{aligned} \tag{2}$$

where C may be termed the effective absorbing cross section. Most of the experiments on absorption of positive ions have yielded in effect values for L and C.

A study of the motion of hydrogen and helium ions in helium has been made by Dempster using his positive ray apparatus.[1] He found that protons with velocities corresponding to potential differences of 14 to 900 volts passed through many helium atoms without neutralization and with slight changes of velocity and direction; while 900 volt helium ions in helium were absorbed much more readily and showed a mean free path but little greater than the kinetic theory value. These were the first experiments of this kind with low velocity positive ions.

Durbin[2] and Ramsauer and Beeck[3] have studied the slow alkali metal ions in various gases and found in most cases abnormally long free paths varying up to ten times the kinetic theory value. Their experimental methods would not distinguish the three causes of absorption mentioned above.

Kennard[4] modified the method used by Durbin and Ramsauer and Beeck, and by measuring the ions of various velocities which passed through the gas column was able to detect a change in velocity as well as any weakening due to other causes. He found that for 90 volt Cs^+ ions in hydrogen there was a decrease in speed equivalent to 1.3 volts per collision, but no evidence of scattering or neutralization, for pressures up to 0.008 mm of mercury. Slowing up was also observed for 35 and 90 volt Cs^+ ions in both hydrogen and helium with only a slight weakening of the bundle due to other causes. For Cs^+ in argon no slowing up was observed but there was a rapid absorption of the bundle with pressure, which Kennard interpreted as due to neutralization.

Recently, Cox[5] has shown from experiments with Li^+ ions in mercury vapor that for gas-ion combinations which show no definite change in speed of the ion, the chief cause of absorption is scattering. The velocities were from 18 to 300 equivalent volts. For the ions of higher velocity range—10,000 to 50,000 equivalent volts—there is evidence of some scattering but the velocity losses are less than one-half of one percent.[6,7]

[1] Dempster, Phil. Mag. **7**, Series *13*, 115, (1926).

[2] Durbin, Phys. Rev. **30**, 844 (1927).

[3] Ramsauer and Beeck, Ann. d. Physik **87**, 1 (1928).

[4] Kennard, Phys. Rev. **31**, 423 (1928).

[5] Cox, Phys. Rev. **34**, 1426 (1929).

[6] G. P. Thomson, Proc. Roy. Soc. **102**, 197 (1922).

[7] Koenigsberg and Kutschewski, Ann. d. Physik **161**, 37 (1912).

Thus it appears that the entire problem of positive ion absorption is quite complex and depends not only on the gas-ion combinations, but on the velocity, gas pressure, apparatus and method used and other experimental variables. For heavy ions passing through light gases at moderate velocities the predominant effect seems to be a slowing up of the ion bundle, whereas for a light ion in a heavy gas the chief cause of absorption is due to scattering. Intermediate cases may show a combination of both effects; for example, Kennard found that for Na^+ ions with a velocity of 455 volts in hydrogen, there was a small but definite slowing up, together with an absorption probably due to scattering. As pointed out by Cox, it seems evident that the importance of any absorption process due to scattering, and, in some cases, of that due to retardation is dependent on the dimensions of the apparatus used and the method of measurement. Thus, the absorption constants usually calculated from such measurements have no absolute significance and cannot be interpreted in terms of any atomic process.

The purpose of the experiments to be described was: first, to make a more complete study of the motion of Cs^+ ions in hydrogen and helium, particularly in the region of low velocities, and, secondly, to investigate the process of absorption of a light ion in a light gas as typified by Li^+ ions in helium; and to study any dependence of this absorption on velocity.

Caesium in Hydrogen and Helium

The results obtained by Kennard for 35 and 90 volt Cs^+ ions have been obtained for 100 and 200 volt ions in helium. The apparatus used is based on Dempster's method of positive ray analysis and is shown in Fig. 1.[8] The cylinder C was removed in some experiments and a single collector mounted above the slit, S_2. The ion source contained in the furnace, A, is made positive with respect to the slit S_1, the emission current being held constant and measured with the galvanometer G. The ion beam enters the magnetic field and by varying the magnet current, is swept across the slit S_2, after traversing the gas-path S_1MMS_2. The dimensions of the path through the armature were, $3.0\times10\times112$ millimeters. The resultant intensity through S_2 is then measured by balancing the current to the collector against the ionization current from the RaE tubes shown at R. A Compton electrometer, E, adjusted to a sensitivity of 2500 divisions per volt was used as a null indicator. Helium was introduced into a reservoir by allowing it to pass slowly through a charcoal trap immersed in liquid air; after this preliminary purification the gas was admitted to the apparatus through a drying tube, a fine capillary and a second charcoal trap which was also kept at liquid air temperature. The gas was tested by observing the spectrum with a hand spectroscope, the lines showing distinctly on a dark background.

The gas enters the tube at D and is kept in circulation through the apparatus. Various pressures are established by adjusting the rate of pumping of the mercury diffusion pumps connected at O. An ionization gauge was

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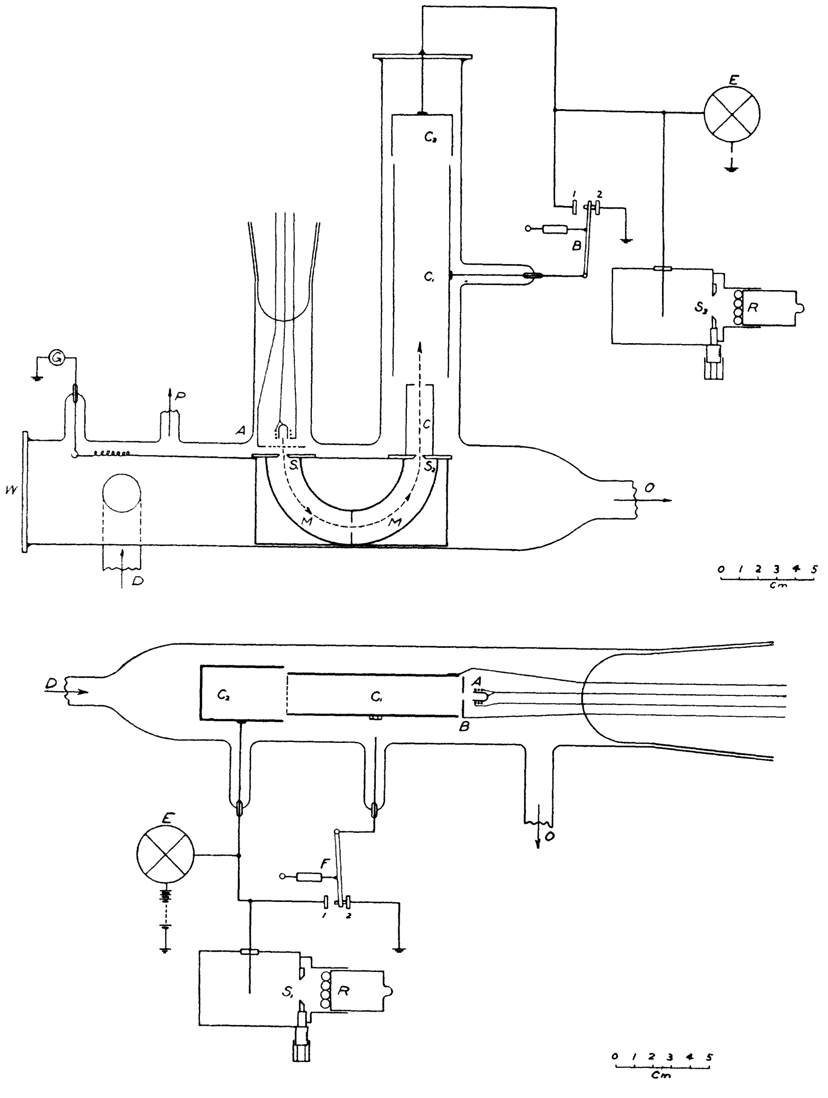
[8] Dempster, Phys. Rev. **11**, 316 (1918).

used in some experiments to show when steady gas pressures were attained, all final measurements being made with McLeod gauge attached at *P*. For a definite pressure and emission current the current through S_2 is measured as a function of the magnet current, four or five such curves being taken for a single accelerating potential.



Figs. 1 and 2. Diagram of apparatus.

The type of curves obtained are the same as those of Kennard and are shown in Fig. 2. For increasing pressures the peaks of the curves are seen to be shifted in the direction of lower ion velocities, the general symmetry of the curves being retained about the shifted peak. Within the limits of experimental variation, the areas under these curves remain constant, showing that in traversing the gas-path S_1MMS_2 all the ions of various velocities reach the collector. Kennard observed this behavior for Cs^+ ions in hydrogen and helium for 35 and 90 volts velocities. He concluded that there was a general slowing up of the Cs^+ ions, and for pressures up to 80×10^{-4} mm of mercury, due to the constancy of the areas, that there was no neutralization or scattering of the bundle.

This behavior of Cs^+ ions for the velocities used in the above method indicated the possibility of isolating a single process of interaction between ion and gas molecule and of studying this process over a range of conditions in which it was operative.

In the procedure outlined above it is essential that the emission of ions through S_1 be held constant over a considerable period of time in order that the complete curves of Fig. 3 may be obtained for several gas pressures. This difficulty together with that of obtaining sufficient intensity with low velocity ions limited the range of the method. Also in establishing the equality of the areas under the curves shown, it is difficult to determine the exact range of the base line.

Experiments were tried with the two-cylinder method shown drawn to scale in Fig. 1 and used by Cox in experiments on Li^+ ions in mercury vapor.[5] Here the ion bundle is accelerated to S_1 as before and bent through 180° in the magnetic field. The collimating slit C directs the beam up the axis of the cylinders C_1 and C_2. Measurements to detect any absorption were made by first connecting C_1 and C_2 together with the switch B in position (1); then C_1 was grounded and those ions which had travelled over the extra gas-path of length C_1 were collected and measured in C_2. Both values are determined with the balance method described. No absorption in C_1 for Cs^+ ions in helium was observed for velocities of 25 to 600 volts and pressures up to 0.013 mm of mercury. Here again the difficulty of obtaining sufficient intensity limited the range.

In order to study the behavior of Cs^+ more directly and over a range of velocities not possible with the magnetic methods described, a third tube was constructed and shown drawn to scale in Fig. 2. Tubes of similar construction have been used by Mayer,[9] Akesson[10] and Eldridge[11] in experiments on electron velocity distribution.

The source of ions was contained in the small electric furnace shown at A. The ions were accelerated to the slit B, passed through a field-free space within the nickel cylinder, C_1, 9.2 cm long and were collected in the Faraday cylinder C_2. The gas entered at D and was kept in circulation through the tube, various pressures being established by adjusting the rate of pumping of the mercury diffusion pumps connected at O. Pressures were measured with a McLeod gauge connected first at O and later, in order

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[9] Mayer, Ann. d. Physik **64,** 451 (1921). Also P. Lenard; Wien's "Handbuch der Experimental Physik" XIV, 170, (1927).

[10] Akesson, Lund's Arsskrift **12,** 11 (1916).

[11] Eldridge, Phys. Rev. **20,** 456 (1922).

to insure that no pressure gradient affected the measurements, to the central tube which supports the electrode above *F*. Helium was purified as in the experiments outlined above; hydrogen was admitted through a heated platinum tube sealed into the glass line and about which was circulated commercial hydrogen at atmospheric pressure.

In experiments with a tube of this type a particularly pure source of ions was essential as no magnetic separation was possible. This source was found in the mineral pollucite which is essentially a caesium aluminum silicate containing 27 percent caesium ($H_2O.Cs_2O.\ Al_2O_3.9SiO_2$). The mineral is powdered and packed into the small resistance-wound furnace made of steel tubing 5 mm long and about 2.5 mm inside diameter. In some instances the mineral was mixed with powdered iron to make it conducting and allow it to fuse more readily. It was found that the substance could not be fused on a platinum strip as is the case with the lithium source, spodumene. This source was prepared and always placed in the magnetic analyzing apparatus before use and examined for other ions. No emission other than Cs^+ was detected for temperatures considerably above those normally used. At a dull red heat a very strong and steady emission of Cs^+ ions was obtained. The experimental tube and source were baked out thoroughly for several hours before use.

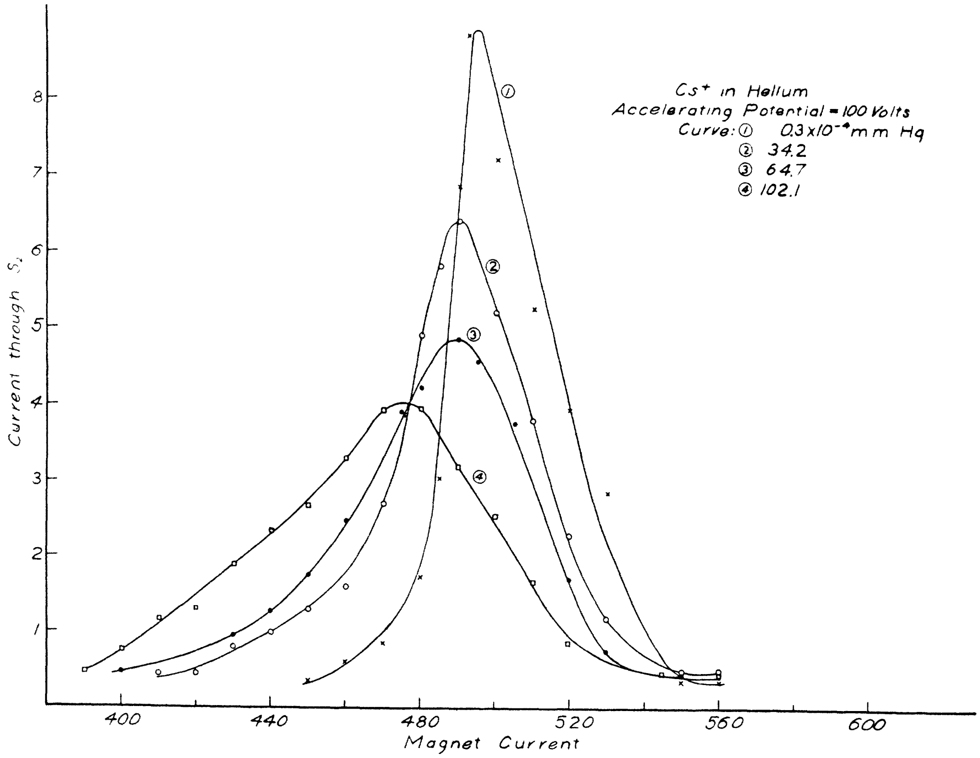

Fig. 3

It was thought that the process of interaction of Cs^+ ion with hydrogen and helium was one of pure retardation, but to make certain of this, experiments were first tried to detect any weakening or absorption of the ion bundle due to causes other than slowing up. For this purpose the gauze shown on the end of C_1 in Fig. 2 was removed. The central electrode supported C_1 at the center, the ground connection through the stem being removed. By connecting the switch F in position 1, the total ion current to (C_1+C_2) was observed. Then with C_1 grounded, by moving F to position 2, the ions which reached C_2 after traversing the gas-path through C_1 were measured. As in the first type of tube both currents were measured by the balanced electrometer arrangement, intensities being proportional to the slit widths, S_1. Measurements of the ratio, $C_2/(C_1+C_2)$ were taken for increasing pressures in the tube so that any weakening of the beam was detectable in a decrease in this ratio. For very low velocity ions this ratio was not equal to unity for low pressures because of the divergence of the bundle caused by the field between A and B so that some of the ions hit the wall of C_1. However, in all cases, values of the ratio were obtained for several pressures so that any real absorption could be observed.

In this way it was found that for pressures less than 0.01 mm of mercury, no appreciable absorption of the Cs^+ ions in hydrogen and helium took place for velocities of 3.5 to 600 equivalent volts. For velocities above 10 volts this absence of absorption persisted for pressures even higher than 0.03 mm of mercury. Below 10 volts and for pressures above 0.01 mm of mercury a definite weakening of the bundle set in and increased rapidly with the pressure. This absorption is probably due to the effects of multiple scattering as the number of collisions with the slow moving ions is increased, and is discussed later.

Thus for a considerable range of velocity and pressure the Cs^+ ions are not deviated appreciably from their path, making it possible to study the slowing up effect as an individual process over this range.

The arrangement used for observing the retardation of the ions is shown also in Fig. 2. The ions are accelerated as before, by applying a positive potential to A; B and C_1 are grounded as shown; the ions pass through the field-free space C_1, and are collected in the Faraday cylinder, C_2. In some experiments a grounded shield was placed around the two cylinders but this was not used in general as the ion path is well shielded as shown and the grounded cylinder provided an extra leakage path. Any retardation takes place over the gas-path, AC_2, measured from the ion source to the far end of the collector C_2 or 14.2 cm. With a constant pressure in the tube, increasing retarding potentials are placed on C_2 through the electrometer as shown. This potential is applied with respect to the gauze on C_1, which gives a more uniform distribution of the field. The current to C_2 is then observed as a function of the retarding voltage. Hence, only those ions with velocities greater than or equal to the retarding potentials will be recorded in C_2. In this way the velocity or energy distribution of the retarded ions was measured for various pressures. Curves of this type are shown in Fig. 4, which shows the distribution for 6.4 volt Cs^+ ions in helium at the pressures given. Another set for 100 volt Cs^+ ions in hydrogen is shown in Fig. 5. In both these sets except for the lowest pressure the actual curve drawn represents the theoretical energy distribution fitted to the experimental data as explained below. The points shown were determined experimentally as described. Similar sets were taken for velocities ranging from 3.5 to 600 volts in both hydrogen and helium. Any point on these curves is proportional to the number of ions retaining energies equal to or greater than the corresponding voltages. In all such curves the distribution at low pressure was always taken as

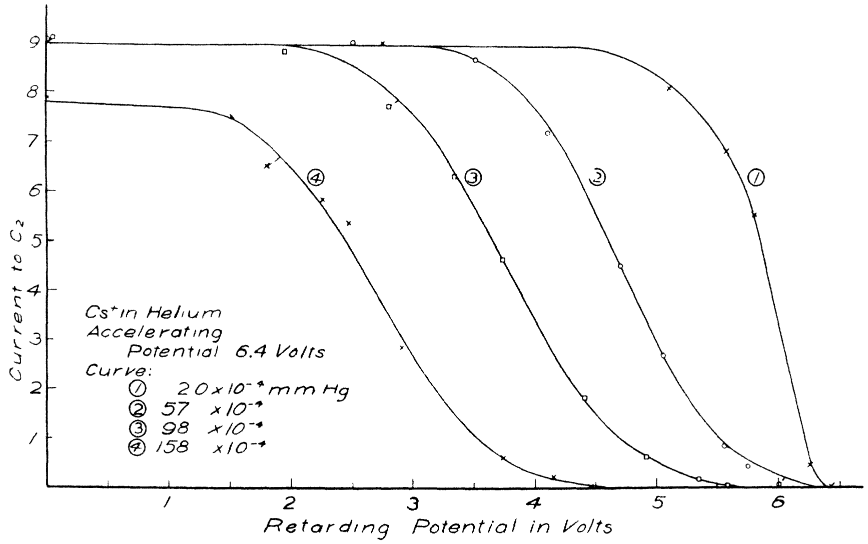

Fig. 4

a control, since here the distribution of energies should be approximately homogeneous. The points shown in the curves of Figs. 4 and 5 were not corrected for small changes in the emission current at the various pressures so that no significance is to be attached to the absolute values of the ordinates shown. As explained above, separate experiments were made to determine any change in the current to C_2 with pressure.

By integration of curves of the form

$$y = ke^{-h^2 x} \tag{3}$$

it was found that the resulting curve could be fitted to the experimental points, indicating that when the ions reached the collector there was an approximate probability distribution of energies about the average retarded value. This distribution is what would be expected from probability considerations, due to some ions making more collisions, and some less than the average number in completing the path, L. Each point on the curves of Figs. 4 and 5 represents the number of ions found to retain energies equal to or greater than the corresponding voltage. For a value of the retarding voltage,

V_R, the number of ions retaining energies greater than V_R would be expected to be given by

$$I = k \int_{V_R}^{\infty} e^{-h^2 V^2} dV$$

the constant, h, depending on the particular distribution. In order to obtain the value of h, which is characteristic of a particular energy distribution, we may consider the expression:

$$P = \frac{h}{\pi^{1/2}} \int_0^{V-V_0} e^{-h^2(V-V_0)^2} d(V - V_0) \tag{4}$$

for the probability that an ion will retain an energy between V_0 and V. Here V_0 is the average retarded velocity, represented in the experimental curves (Figs. 4 and 5) by the half ordinate, and corresponding to the peak value of the error curve. The constant, h, may be conveniently found by observing the energy, V_1, at which the probability is one-fourth as indicated in Figs. 6 and 7. Setting:

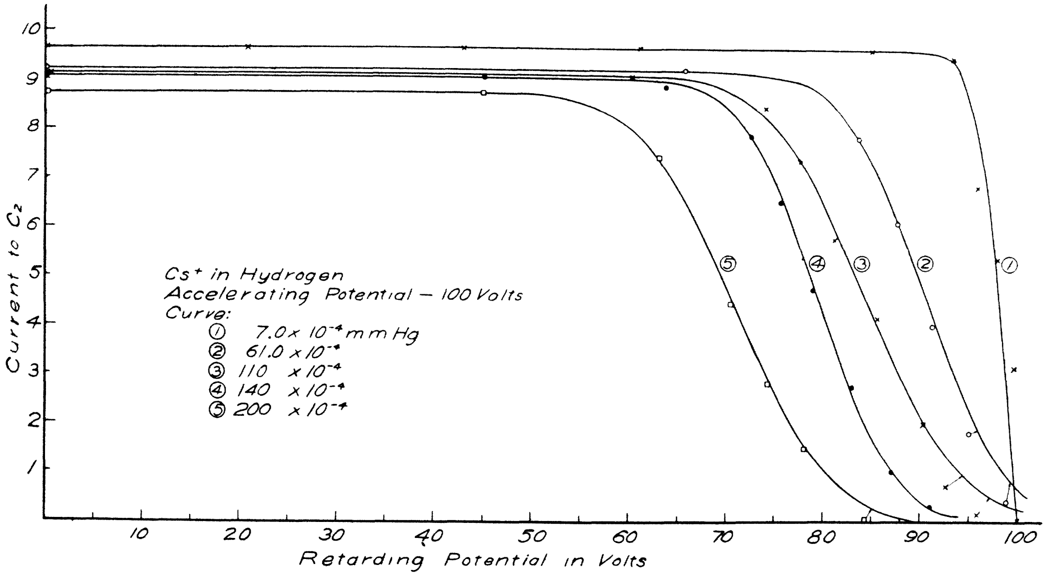

Fig. 5

$$h(V - V_0) = z$$

we then have that:

$$P = \frac{1}{\pi^{1/2}} \int_0^{z} e^{-z^2} dz = \tfrac{1}{4}$$

for $z = z_1 = h(V_1 - V_0)$. As, $z_1 = 0.477$, $h = 0.477/(V_1 - V_0)$.

If n is the average number of collisions, the probability of an ion making a number greater than n but less than, $n+z(2n)^{1/2}$ is:

$$\frac{1}{\pi^{1/2}}\int_0^z e^{-z^2}dz.$$

If the energy loss per collision were constant, $z(2n)^{1/2}$ would be proportional to $(V-V_0)$, or z/h. That is, we should expect h^2 to be inversely proportional to the number of collisions, the pressure, or the average energy lost by the ions, which is (V_i-V_0), V_i being the initial velocity. Thus for a constant energy loss per collision, $h(V_i-V_0)^{1/2}$ would be constant. If $h(V_i-V_0)^{1/2}$ is less with ions of high velocity, it signifies that the energy loss per collision is less in this case.

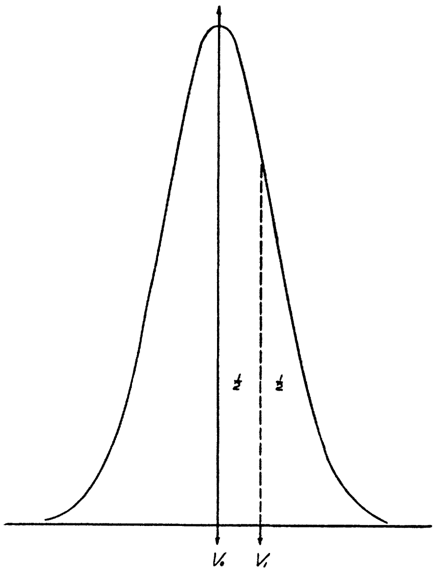

Fig. 6

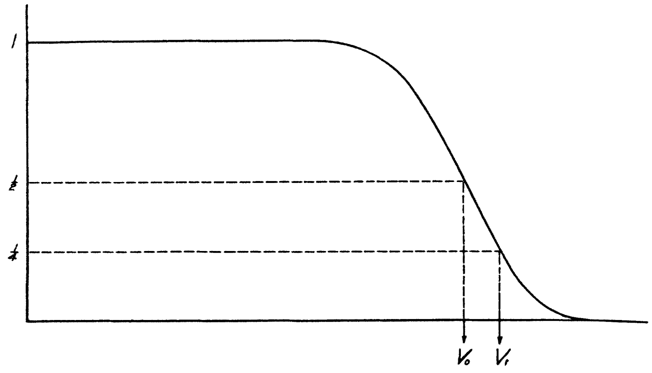

Fig. 7

In the case of the 6.4 volt Cs^+ ions in helium at a pressure of 98×10^{-4} mm of mercury, the dispersion, (V_1-V_0) was 0.55 and $h=0.87$; $h(V_i-V_0)^{1/2}=1.41$. Values of h calculated from the experimental data, together with the quantity, $hV_i-V_0)^{1/2}$ are shown for various velocities and pressures in the Table I. From the values of h given in the table, the expected energy distribution may be calculated and compared with the experimental results. The theoretical curve is obtained for any particular distribution by the use of the proper h in the integral of Eq. (4). The resulting curves are shown for two initial velocities in Figs. 4 and 5 together with the experimental points. It is seen that the agreement is in general better for the low velocity ions and for the higher

TABLE I. *Cs^+ in helium.*

Initial velocity V_i	Pressure $\times 10^4$ mm mercury	V_0	(V_1-V_0)	h	$h\ (V_i-V_0)^{\frac{1}{2}}$
3.5	57.0	2.24	0.31	1.54	1.73
	83.0	1.97	0.33	1.45	1.79
	110.0	1.45	0.32	1.49	2.14
6.4	57.0	4.70	0.45	1.06	1.38
	72.5	4.35	0.53	0.90	1.29
	98.0	3.75	0.55	0.87	1.41
	126.0	3.20	0.55	0.87	1.55
	158.0	2.78	0.49	0.97	1.84
9.3	52.0	6.57	0.95	0.50	0.826
	110.0	5.15	0.99	0.48	0.976
30.0	60.0	24.40	3.05	0.157	0.372
	97.0	21.80	3.00	0.159	0.455
	163.0	19.70	2.40	0.199	0.64
60.0	60.0	51.50	4.00	0.119	0.347
	116.0	45.60	4.90	0.097	0.368
	167.0	41.30	3.90	0.122	0.528
100.0	50.0	88.00	5.70	0.084	0.291
	85.0	80.50	6.60	0.072	0.318
	150.0	70.80	7.00	0.068	0.368
200.0	88.0	170.00	13.50	0.035	0.192
	168.0	151.00	14.00	0.034	0.238
	242.0	132.00	15.00	0.032	0.264
400.0	52.0	370.00	15.00	0.032	0.175
	90.0	343.00	21.00	0.023	0.174
	160.0	333.00	22.00	0.022	0.180
	220.0	293.00	27.00	0.018	0.186
590.0	76.0	570.00	16.00	0.030	0.134
	242.0	487.00	33.00	0.014	0.142
		Cs^+ in hydrogen			
3.5	46.0	2.36	0.31	1.54	1.65
	65.0	1.90	0.35	1.36	1.72
	108.0	1.17	0.33	1.45	2.21
13.5	40.0	11.40	0.60	0.79	1.14
	96.0	9.20	1.00	0.48	1.00

TABLE I. *Cs$^+$ in hydrogen (Continued).*

Initial velocity V_i	Pressure $\times 10^4$ mm mercury	V_0	(V_1-V_0)	h	$h\,(V_i-V_0)^{1/2}$
	40.0	27.7	1.00	0.48	0.728
30.0	65.0	26.1	1.60	0.30	0.592
	100.0	23.7	2.00	0.24	0.603
	215.0	18.5	2.20	0.22	0.746
	270.0	15.5	1.70	0.28	1.060
	57.0	55.0	2.00	0.24	0.537
60.0	75.0	52.5	2.80	0.17	0.466
	160.0	44.4	3.60	0.13	0.514
	290.0	35.0	3.50	0.14	0.700
	61.0	90.5	4.50	0.11	0.340
100.0	110.0	84.4	5.34	0.089	0.352
	140.0	79.5	4.20	0.113	0.520
	220.0	71.0	5.30	0.090	0.485
	61.0	183.2	7.30	0.065	0.266
200.0	90.0	177.2	8.80	0.054	0.258
	131.0	170.0	7.50	0.064	0.350
	216.0	151.0	9.40	0.051	0.357

pressures. On the high velocity side of the curves the points were obtained with much less precision.

The values of h given in the table are seen to decrease with increasing voltage and the values of $h(V_i-V_0)^{1/2}$ are not constant as would be expected if the energy loss per collision were the same for ions of all velocities. As explained above the decrease is what would be expected if the energy loss per collision decreases with the high velocity ions. In hydrogen, the consistently

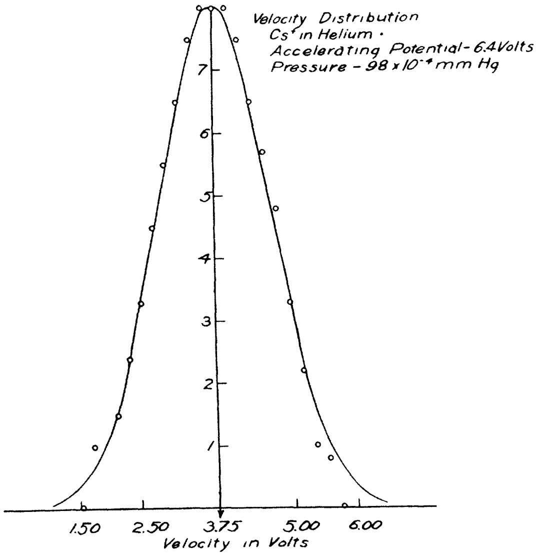

Fig. 8

larger values of h than in helium for corresponding voltages indicate that in this gas there is less loss of energy per collision.

The actual error curve distribution for the case of 6.4 volt Cs^+ ions in helium for a pressure of 98×10^{-4} mm of mercury is shown in Fig. 8. The full line represents the theoretical distribution of the velocities for curve (3) of Fig. 4. Here V_0 is 3.75 volts and V_1 is 4.30 volts; the points shown are obtained by graphical differentiation of the experimental curve.

Each of the curves in Figs. 4 and 5 represents a new distribution of energies about a most probable energy V_0 which is that corresponding to the half ordinate. The difference then between the applied potential and this half ordinate energy gives the retardation of the ions for the pressure shown. For each applied potential this retardation has been plotted as a function of the pressure and is found to be linear over a wide range. This slowing up took place over the gas-path AC_2 measured from the furnace source to the far end of the collector, C_2, or 14.2 cm. From the curves the retardation for 0.01 mm of mercury was obtained since for this pressure no absorption was found. Fig. 9 shows this retardation, expressed as a percent loss of initial energy, as a function of the initial velocity in volts. Points for 600 volt ions, not shown on the curves, would fall on the lower linear portion if extended. The loss in helium is seen to be greater over most of the range as might be expected for the gas molecule of greater mass, especially if the interpretation is that of mechanical collisions. In both cases the loss decreases with increasing velocity. This is in agreement with the data cited for canal rays of 10,000 volts and more which show less than one-half of one percent loss of energy.[6,7] Below forty volts the curves rise rather rapidly and tend to merge; extending them to the axis of ordinates indicates that the maximum loss for this pressure would be about 66 percent.

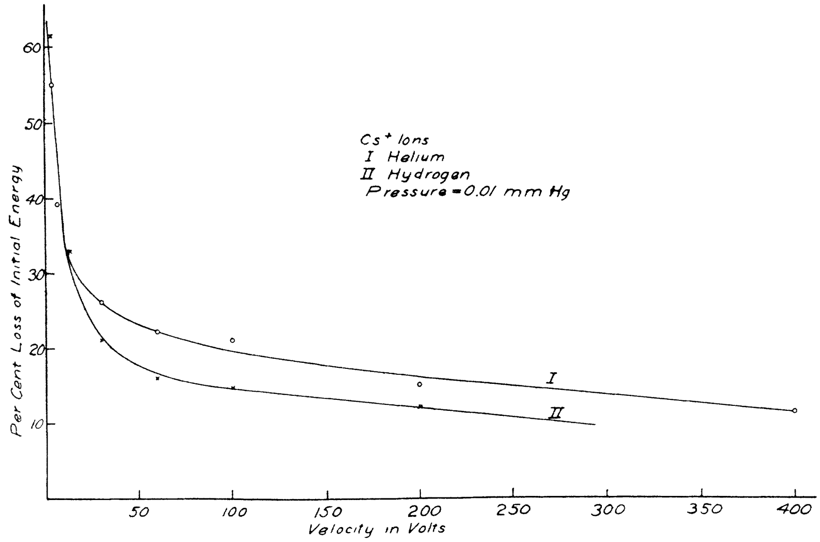

Fig. 9

These results suggest an interpretation of the results of Ramsauer and Beeck[3] for Cs^+ ions in helium that differs from their conclusions. In their experiments the apparatus used was similar to that described in connection with Fig. 1, except that the dimensions were much smaller. The method of observations was to hold the magnetic field constant and observe the weakening of the bundle for several gas pressures. Referring to Fig. 3, this is seen to be equivalent to observing the intensities along a vertical line drawn through the peak value of the lowest pressure curve used. It is evident that this method of observation would show an apparent absorption for the retarded ions. From their results, Ramsauer and Beeck calculate what is designated as the "Wirkungsquerschnitt," which is the value $1/L$ from Eq. (1), reduced to 1 mm of mercury. For Cs^+ ions in helium, they find a considerable absorption of the ions for velocities of 1 to 10 volts; for instance, reducing their values in terms of the effective cross section, C, gives a value of 11.3×10^{-1} cm^2 for ions of 9 volts velocity; or in terms of the mean free path, $L=33\times10^{-6}$ cm under standard conditions. These values show a large opposing cross section of ion against molecule, whereas for the pressures used by Ramsauer and Beeck,[3] no real absorption at all was observed in the present experiments. Fig. 9 shows that 9 volt Cs^+ ions suffer a loss in velocity of about 35 percent, which, as explained above, would account for the large value of C found by Ramsauer and Beeck.[3] No relation to atomic constants can be attached to the values of C and to the various values of atomic radii calculated therefrom as they are at once seen to depend on the dimensions of the apparatus and the experimental method used. Thus the mechanism of absorption is of primary importance in the interpretation of these measurements.

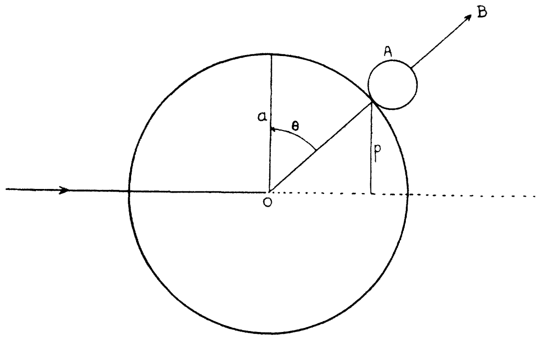

Fig. 10

It is of interest to compare the results for caesium ions with what would be expected on the basis of elastic collisions between ion and gas molecule. In Fig. 10 consider a Cs^+ ion moving forward with a velocity V among helium atoms at rest. If an elastic collision occurs with the helium atom at A, this atom is projected along OAB with a velocity, $2V\sin\theta$, provided the mass of the Cs^+ ion is very large compared to that of helium. Since the ratio is 133/4 we may take this velocity as a first approximation. The equality of momenta in a transverse direction shows that the Cs^+ ion then receives a velocity at right angles to its direction equal to:

$$V' = 2V \sin\theta \cdot \cos\theta \cdot 4/133.$$

The angle made by the ion with its original direction is then,

$$\phi = V'/V = 8/133 \cdot \sin\theta \cos\theta$$

since V is only slightly altered. Now the number of collisions in the range, p to $p+\Delta p$ as shown in the figure is proportional to the area presented in the direction, V, i.e., to $2\pi p \Delta p$. Since the total number of collisions is proportional to, πa^2, where a is the radius of the Cs^+ ion, we may write for the average angle of scattering,

$$\Phi = \frac{1}{\pi a^2}\,\frac{8}{133}\cdot \int_0^a \frac{p}{a}\left(1 - \frac{p^2}{a^2}\right)^{1/2} \cdot 2\pi p \cdot dp$$

where, from Fig. 10 $\cos\theta = p/a$ and $\sin\theta = (1 - p^2/a^2)^{1/2}$. This upon integration gives,

$$\Phi = \pi/133 = 0.023 \text{ radians}.$$

The maximum angle of scattering, for $\theta = 45°$, gives

$$\phi_{max} = 0.030 \text{ radians}.$$

In the apparatus used, an ion would always reach the collector unless deflected by more than 10/92 or 0.11 radians. Thus single scattering is unable to produce a weakening of the bundle. Experimentally, no weakening was observed until the pressure was made high enough to give rise to multiple scattering.

We may also calculate the energy loss to be expected on the basis of elastic collisions. In the Fig. 10 let m equal the mass of the helium atom and M the mass of the Cs^+ ion. On the basis of elastic collisions, the energy lost by the Cs^+ ion is equal to the amount gained by the helium atom, or,

$$\Delta E_0 = \tfrac{1}{2}m(2V \sin\theta)^2$$

for the loss due to a collision at angle, θ. The ratio of this loss to the initial kinetic energy of the Cs^+ ion is then,

$$\frac{\Delta E_0}{E_0} = \frac{\tfrac{1}{2}m(2V\sin\theta)^2}{\tfrac{1}{2}MV^2} = \frac{16}{133}\sin^2\theta.$$

In travelling a distance, L, the average fractional loss per collision may be written, referring to Fig. 11 as:

$$\frac{\Delta E}{E} = \frac{1}{\pi a^2 L_n}\int_0^{\pi/2} \left\{(2\pi a \cos\theta)(a \sin\theta d\theta)Ln\right\}\left(\frac{16}{133}\sin^2\theta\right) = \frac{8}{133}$$

where, $a = r_1 + r_2$, the sum of the ion and atom radii; and, $n =$ the number of helium atoms per cc for the pressure considered.

The energy remaining after, $\pi a^2 Ln$ collisions may then be written as,

$$\left\{1-\frac{\Delta E}{E}\right\}=\left\{1-\frac{8}{133}\right\}^{\pi a^2 Ln}. \tag{6}$$

From Fig. 9 we may obtain a value of the percent loss of initial energy of the Cs^+ ion for the smallest velocity observed. The value for helium is 55 percent for 3.5 volt ions. In Eq. (6),

$$L = 14.2 \text{ cm}$$

$$n = 3.48 \times 10^{14} \cdots (p = 0.01 \text{ mm of mercury})$$

so that,

$$a = r_{Cs} + r_{He} = 2.88\text{A}.$$

Viscosity measurements give for the radius of the helium atom, $r_{He} = 1.10$A, so that we should expect a value for the radius of the Cs^+ ion,

$$r_{Cs} = 1.78A.$$

Herzfeld[12] gives values of r_{Cs^+} which vary from 0.83 to 2.36A depending on the method of measurement. The radius of the xenon atom obtained from viscosity measurements is 2.44A. Similar calculations for hydrogen, where $\Delta E/E = 4/133$ and the percent loss was 61.5, gave a value,

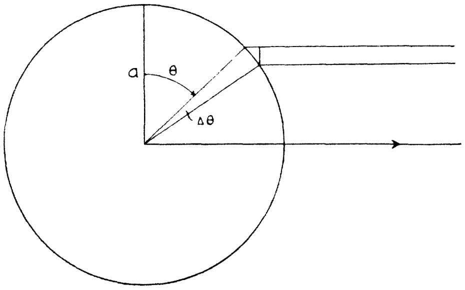

Fig. 11

$$a = r_{Cs} + r_{H_2} = 4.55\text{A}.$$

A value for r_{H_2} from viscosity measurements quoted by Jeans as 1.36A leaves for the radius of the Cs^+ ion,

$$r_{Cs} = 3.19\text{A}.$$

For ions of greater initial energy the percent loss decreases. This disagrees with the elastic collision interpretation which would make the percent loss a constant. We must conclude that at higher velocities the interaction at a collision of a Cs^+ ion with a helium or hydrogen molecule is different from

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[12] Geiger Scheel, "Handbuch der Physik," Band XXII, 386, 1926.

that considered in the kinetic theory of gases and that less energy is lost than would be the case, were the collisions elastic.

LITHIUM IONS IN HELIUM.

With low velocity Li^+ ions in helium the change in the curves produced by increasing pressure was entirely different from that found in Cs^+ ions. We shall find that with the light ion, small angle scattering is the predominant phenomenon, whereas with the heavy Cs^+ ions, scattering was inappreciable in comparison with process of retardation. By using several different experimental arrangements it has been possible to establish the type of absorption that occurs over the range of velocities studied, namely 20 to 930 equivalent volts.

METHOD I

The apparatus used has been described in connection with the experiments with caesium and is shown drawn to scale in Figs. 1 and 2. In this method the cylinders C_1 and C_2 were replaced as before with a single Faraday cylinder, mounted above S_2. The slit S_1 varied between 1 and 2 mm and in several instances runs were taken with this slit entirely removed.

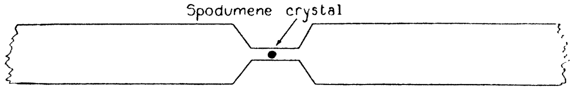

Fig. 12

In Kennard's experiments the ion sources used were the positive ion iron catalysts supplied by Kunsman. These catalysts usually emit Na^+ and K^+ to an appreciable extent together with an ion possibly arising from the insulating cement of the furnace. This necessitates the assumption that the total emission current held constant and measured with the galvanometer G, is also constant in its composition throughout the series of observations. In order to obviate this difficulty the mineral spodumene (used by Hundley[13]) was investigated for purity in emission. A small crystal, less than 0.2 mm in diameter, was melted down on the center of a constricted platinum filament as shown in Fig. 12. This strip is mounted horizontally over the slit S_1 and replaced the furnace source at A (Fig. 1). At low temperatures in vacuum this source showed a large emission of Na^+ and K^+ but continued heating at a yellow heat removed these ions to less than one-half of one percent. By treating the substance in this way a very pure source of Li_7^+ was obtained, which in many cases could be used for 100 hours or more, with good intensity and constant emission. Due to the small value of the emission current to S_1, an electrometer shunted with a high resistance replaced the galvanometer G in most of the experiments in an attempt to attain greater accuracy of observation. Since the method used depends on Eq. (1), the emission current N_0

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[13] Hundley, Phys. Rev. **30**, 864 (1927).

must be constant and proportional to the actual ion current passing through S_1. The current actually recorded represents the total ion current through S_1 as well as to neighboring metal parts connected to the magnet armature. It was not possible, with this arrangement, to determine whether the actual current through the slit remained constant, but it was assumed that a constant fraction of the total emission current entered S_1. This assumption is not entirely justified as spreading of the beam may occur due to the admission of gas, or the actual character of the emission from the source may change, giving a bundle of varying divergence. This indefiniteness accounts partially for the variation of the absorption coefficients obtained by this method, although no difficulty was found in getting reasonable checks.

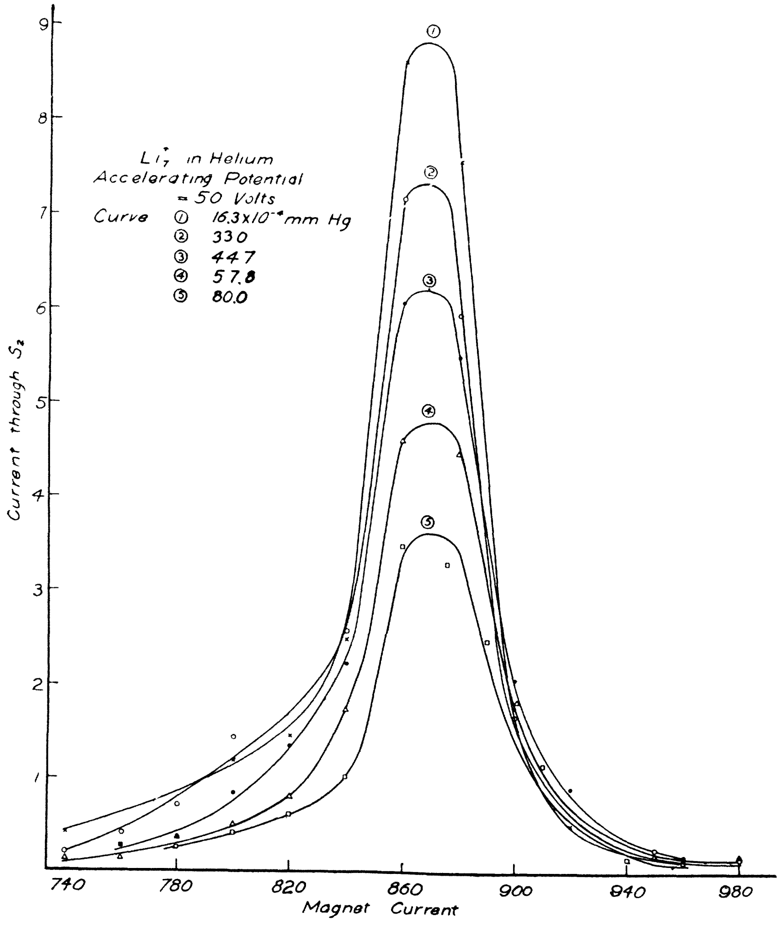

Fig. 13

The method of procedure is the same as that of Kennard and has been outlined above. The type of curves obtained for five different pressures with a constant accelerating potential is shown in Fig. 13 for Li^+ ions of 50 equivalent volts. Sets of curves of this type were taken for velocities varying from 20 to 931 volts and for each velocity at least three such sets were obtained. From each pair of pressures of each set of curves, the value of the mean free path, L, was determined, making use of Eq. (1). The gas path was 11.2 cm in length, so that L was given by:

$$L = 11.2 \times (p_2 - p_1)/760 \times 2.30 \times \log\frac{N_1}{N_2}.$$

From Eq. (2), C is then obtained, where,

$$C = \pi(R_{Li} + R_{He})^2 = 1/Ln$$

and

$$n = 2.70 \times 10^{19}.$$

Values of C are shown as curve I, Fig. 14 for ion velocities ranging from 20 to 500 equivalent volts; a value of C for 931 volts is not shown on the curve, but has a value of 9.5×10^{-17} cm^2, and would fall on the lower linear portion if extended. Using kinetic theory values of the atomic radii as,

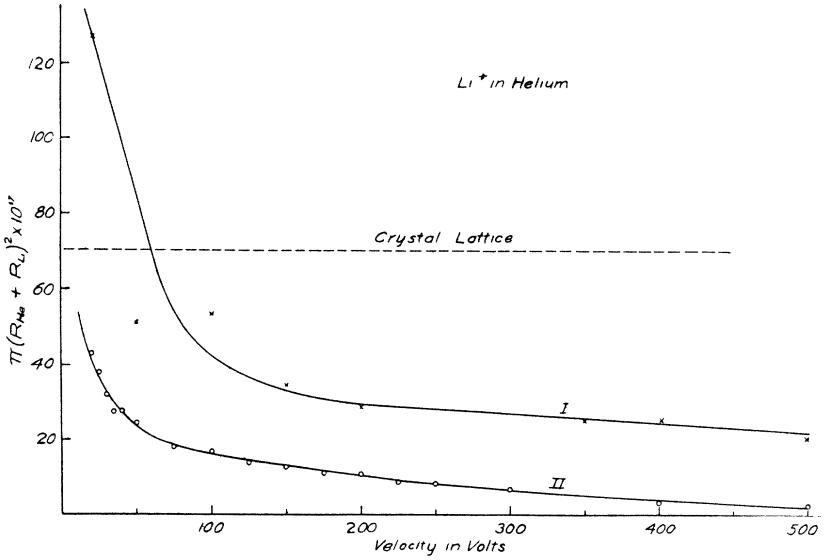

Fig. 14

$$R_{He} = 1.10 \times 10^{-8} \text{ cm—viscosity measurements}$$

and, $R_{Li} = 0.41 \times 10^{-8}$ cm—crystal lattice data we find for C, $C = 70.1 \times 10^{-17}$ cm^2 and this value is shown as a dotted line in Fig. 14. In terms of the mean free path, the values of L found vary from about one-half the kinetic theory value at 20 volts to almost eight times this at 931 volts. Reducing Ramsauer and Beeck's values of the "Wirkungsquerschnitt" for Li$^+$ and helium in terms of C we find for 16 volt ions,

$$C = 42 \times 10^{-17} \text{ cm}^2.$$

This value is about one-third of that found in the present experiments which, from the curve, would give 130×10^{-17}. The difference is accounted for by the dimensions of their apparatus, which had several times the angular aperture used in the present experiments. It has been found that the rate of absorption of the lithium ions depends strongly on the dimensions of the measuring chamber, which indicates that the process is one of scattering. On this basis a considerably smaller value of C would be expected for the wider apertures used by Ramsauer and Beeck.[3] As in the experiments of Cox, the interpretation of the behavior of Li^+ in helium as due to scattering is strengthened from the results obtained with a second type of apparatus.

METHOD II

This method has been used by Cox and described by him in detail for the case of lithium ions in mercury vapor.[5] The experimental tube is shown in Fig. 1, where the dimensions of the various parts are drawn to scale. Measurements of C and L are based on Eqs. (1) and (2), where the length of the absorbing gas path is equal to 11.3 cm. For a given pressure, the total ion current (N_0), to C_1 and C_2 is measured by connecting these two cylinders together with the switch B in position (1). Then with B in position (2), C_1 is grounded and the value of N is measured as the ion current to C_2. This method allows a more rapid determination of N and N_0 and eliminates the problem of measuring the emission current to S_1. Values of C and L were determined from observations at three different gas pressures. In all cases the currents to C_1+C_2 and to C_2 were equal for the lowest pressures attainable (10^{-5} mm of mercury). This equality was attained by means of the collimating slit, C, placed over the emergent slit S_2, which directed the ions up the axes of the cylinders; in this way none of the ions struck the cylinder C_1 at low pressures.

The values of C determined in this way are shown plotted against the ion velocity in Fig. 14, curve II. It is seen that the general shape of this curve is identical with that obtained with Method I, but that in all cases the values of C are smaller. In both cases the values of C rise sharply for velocities below 40 volts, in the one case rising to a value over twice that calculated from kinetic theory values and in the second case approaching the crystal lattice value for low velocities. The dimensions of the absorbing paths for the two methods correspond to those used by Cox and while the actual values of C are smaller, as might be expected with the lighter gas, the same change in these values is found for the two types of apparatus. These results show that the most reasonable interpretation of the process is that of scattering in which forces other than those of elastic collisions come into play. For the large scattering apertures of Method II, a much larger cone of rays may pass over the absorbing path than for Method I, where the angular opening was several times smaller and many more of the ions were lost through deflections to the walls of the chamber. It has been shown by Dempster[6] that the rate of absorption may show a strong dependence on the dimensions of the apertures, provided some law of force other than that of elastic collisions is effective.

Experiments on the scattering of the Li+ ions were also tried, using the apparatus shown in Fig. 2. Results obtained for several velocities confirm the conclusions reached above,—that the absorption of the ions is due to scattering and depends on the dimensions of the absorbing chamber and of the collector. Velocity distribution curves were also obtained for Li+ in helium by the method of retarded potentials, used with Cs+ ions. This distribution for 50 volt Li ions is shown in Fig. 15. It is seen that the shapes of these curves are quite different from those obtained with Cs+; they do not shift to the left as a whole and some of the ions appear to retain approximately their full initial velocity. The decrease in the number of ions of any particular velocity with pressure is probably due to a decrease in the forward component as a result of scattering, so that we have an "absorption" process which involves only a scattering of the ion bundle as distinct from retardation.

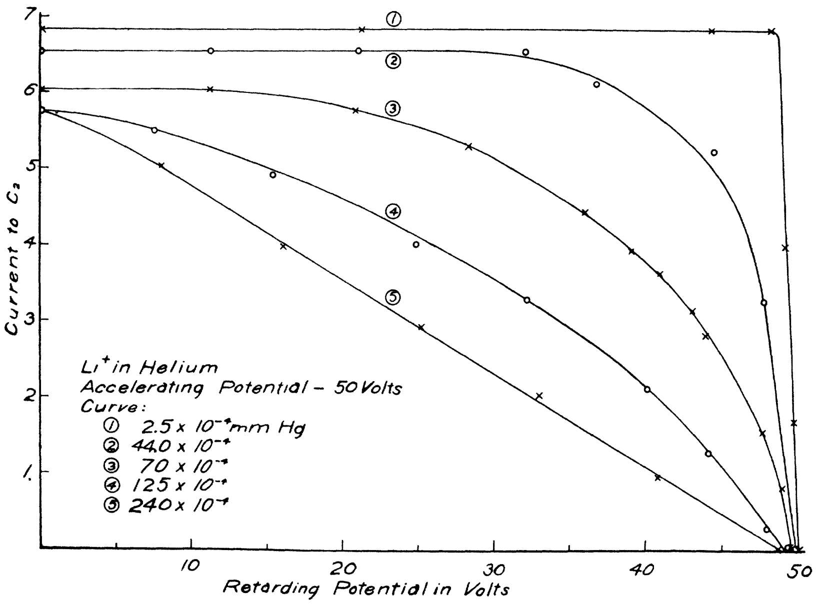

Fig. 15

Professor A. J. Dempster suggested the experiments reported on in this paper. The writer is indebted to him for the theory of retardation of the Cs+ ions as well as for invaluable suggestions and advice regarding experimental procedure and interpretation of results.