THE CAPTURE AND LOSS OF ELECTRONS BY HELIUM IONS IN HELIUM

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Abstract

Mean free paths for capture (L_1) and loss (L_0) of electrons by helium ions in helium have been measured by a method whose chief novelty is the use of an ion source which gives quite strictly homogeneous velocities. In the range of velocities 0.6×10^8 cm/sec. to 1.0×10^8 cm/sec. L_0, reduced to 760 mm, is found to decrease from 21.5×10^{-4} cm to 8.6×10^{-4} cm and L_1 is practically constant at 1.2×10^{-4} cm. These results are compared to similar measurements by other observers, particularly with regard to the manner of dependence on velocity. The relation of the results to available information on ionization and energy loss is discussed.

Investigation of hydrogen canal rays has shown that there is a definite probability, varying with the velocity of the rays and with the nature of the gas through which they pass, that any proton in the beam may capture an electron[1,2,3,4,5,6] without appreciable loss of velocity.[2] The rapidly moving neutral atom thus formed may again lose an electron. If the beam traverses field-free space an equilibrium is established in which the numbers of charged and uncharged particles are in direct proportion to the probabilities of the changes which produce them. When fast alpha-particles penetrate matter similar interchanges occur between doubly and singly charged states.[7,8,9] At lower velocities the equilibrium shifts; the doubly charged ions disappear and neutral helium atoms appear. The present experiments are in this lower velocity range. They report probabilities for the interchanges between neutral and singly charged helium atoms in helium.

A simple quantitative theory of this phenomenon has been given by Wien[1] and more recently discussed by Rüchardt.[10] If a beam is initially composed of a fraction F_0 of neutral atoms and the remaining portion $(1-F_0)$ of ions, the fraction F of all the atoms which will be neutral at any subsequent point x in the path is given by

[1] W. Wien, Sitz. d. K. P. Akad. d. Wiss., July 1911, p. 773.
[2] J. Koenigsberger u. J. Kutschewski, Ann. d. Physik **37**, 161 (1912).
[3] A. Rüttenauer, Zeits. f. Physik **4**, 267 (1921).
[4] E. Rüchardt, Ann. d. Physik **71**, 377 (1923).
[5] H. Bartels, Ann. d. Physik **6**, 957 (1930).
[6] F. Goldmann, Ann. d. Physik **10**, 460 (1931).
[7] E. Rutherford, Phil. Mag. **47**, 277 (1924).
[8] G. H. Henderson, Proc. Roy. Soc. **A109**, 157 (1925).
[9] J. C. Jacobsen, Phil. Mag. **10**, 401 (1930).
[10] R. Rüchardt, Handbuch der Physik XXIV, p. 90.

$$F = F_\infty + (F_0 - F_\infty)e^{-(1/L_0+1/L_1)x} \tag{1}$$

where dx/L_1 and dx/L_0 are the respective probabilities for capture and loss of an electron by a particle in the distance dx and F_∞ is the equilibrium value approached by F, determined by

$$F_\infty = L_0/(L_0 + L_1) \tag{2}$$

L_1 and L_0 have the interpretation of mean free paths and are inversely proportional to the pressure. If the beam, originally neutral, traverses a path distance x along which a transverse electric field continuously removes all positive ions as they form, before there is time for them to return to the neutral state, the intensity decreases according to a simple absorption law depending only on L_0:

$$I = I_0 e^{-x/L_0}. \tag{3}$$

Preliminary Experiments

Some early experiments were performed with the apparatus shown in Fig. 1, of the type used by Rüchardt and earlier workers. Helium canal rays from a discharge tube were deviated through an angle of about five degrees

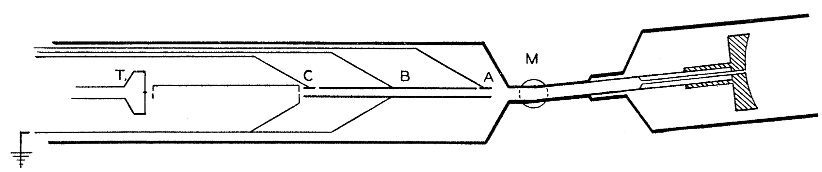

Fig. 1. Preliminary apparatus. M, magnetic field. A, B, C, deflecting condensers. T, thermocouple.

by the magnetic field M, from which ions of relatively homogeneous velocity proceeded to the thermocouple T, passing between the condenser plates A, B, and C. By applying deflecting potentials to these condenser plates one could remove all positive ions existing in the beam at one or both of the points A and C, or continuously over the path ABC. The relative reduction of intensity at the thermocouple was observed when a deflecting field was applied at A only, at C only, at C after A had previously been applied, and finally along B and C after A had previously been applied. Any two of these four measurements could be used to deduce values for the two independent parameters in Eqs. (1) and (3), that is to say F_∞ and $(1/L_0+1/L_1)$, or equivalently L_0 and L_1. This could be accomplished in many different ways varying in precision and convenience; in practice F_∞ and L_0 were most reliably and directly determined. In any event there remained two independent measurements with which to check the validity of the exponential relation (1), without recourse to determination of the variation of L_0 and L_1 with pressure, which is of course another important check.

The results were unsatisfactory in two respects. First, observations were not reproducible from day to day; fluctuations of from ten to fifteen percent in values of F_∞ and L_0 could not be eliminated, though attention was given to careful electrical control of the discharge and to removal of traces of water and mercury vapors by repeated flaming of the tube. The second difficulty was a consistent indication, in each set of observations, of a departure from the behavior implied in Eq. (1) in the sense that F approached its ultimate value F_∞ more rapidly on the early part of the path, between M and A, Fig. 1, than later, between A and C. In other words, $(1/L_0+1/L_1)$ appeared to decrease along the path.

Since the resolution of velocities employed here was necessarily imperfect because of intensity limitations, it seemed that the remaining inhomogeneity was the most probable cause of the difficulties, and a strictly homogeneous source of ions was accordingly sought. Experiments with such a source are described in the following sections; the results there obtained were satisfactorily reproducible, and not significantly different from averages of the values obtained above. The second question, of deviations from the exponential law (1) is not definitely answered because the new apparatus was not adapted to a direct measurement of $(1/L_0+1/L_1)$.

Final Apparatus

The tube in which final measurements were made employed a source of homogeneous ions similar to that used by Batho and Dempster[11] in a study of the Doeppler effect, with which they obtained very sharp displaced lines, indicating homogeneity in velocity. Fig. 2 shows the arrangement. A low

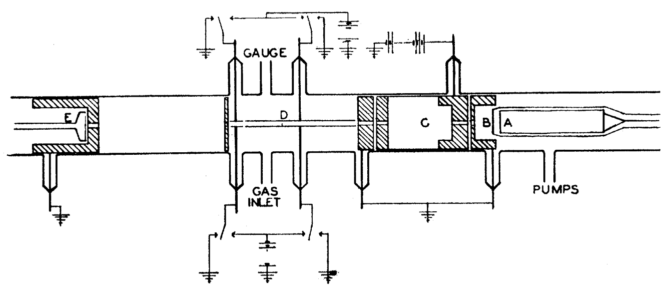

Fig. 2. Diagram of apparatus. A, anode. B, hot cathode. C, accelerating electrode. D, deflecting condensers. E, thermocouple.

voltage arc is operated between the hot cathode B, at ground potential, and the anode A, a hollow cylinder with open ends. Ions thus produced are drawn through the intervening diaphragm into electrode C, which is charged to a high negative potential. Within C many of the ions lose their charge; only these neutral atoms can proceed beyond the retarding field which exists between C and the succeeding grounded diaphragm. Thus a completely neutral beam enters the observation space, in which deflecting condensers D and thermocouple E follow the earlier arrangement except that the condenser A of Fig. 1 is omitted here.

[11] H. F. Batho and A. J. Dempster, to be published shortly in the Astrophysical Journal. Abstract, Phys. Rev. **37**, 100 (1931).

The filament and anode at one end, and the thermocouple at the other, were carried on ground joints, permitting of convenient removal for visual alignment of parts within the tube. The entire path length from filament to thermocouple was 28 cm. The two condensers were 7.5 cm and 1 cm long, their plates about 3 mm apart. These plates were made of nickel gauze in such fashion as to minimize the possibility of specular reflection of ions to the thermocouple. All diaphragm openings were circular, of 2 mm diameter, except the one immediately in front of the filament, which was a half-millimeter larger.

The arrangement of the tube was such that the thermocouple was not exposed to direct radiation from any hot surface, the filament being located off the axis of the tube, and the anode hollow. Those parts which are cross-hatched in Fig. 2 were of solid aluminum of substantial thickness, and probably contributed materially to the adequate protection of the thermocouple from filament radiation. This consideration was important, since in operation the filament end of the tube became decidedly hot to the touch, while the thermocouple was sensitive to temperature changes of the order of 0.001°C. With the arrangement shown, any disturbance caused by the filament was less than that arising from variations in room temperature, and so gradual as to be unnoticed. The shield immediately surrounding the thermocouple protected it in large degree from short period fluctuations in room temperature.

The thermocouple itself was a single junction of a fine platinum wire and an extruded bismuth wire of diameter 0.01 inch. These two were spot-welded to a small piece of platinum foil of area about 1 mm^2 which served as a target for the impinging rays. The two outer ends were joined to the supporting wires with other strips of platinum foil. This couple was connected directly to a galvanometer of resistance 16 ohms and sensitivity 168 megohms.

Helium was purified by two passages through charcoal at liquid air temperature, the second time at low pressure immediately before use. Gas was streamed through the apparatus during all experiments, entering and leaving through liquid air traps. Pressures were measured with a McLeod gauge, also separated from the tube by a liquid air trap.

Storage batteries maintained the hot cathode arc and supplied potentials to the deflecting condensers. A steady accelerating potential was supplied to C, Fig. 2, by a high tension transformer with half-wave rectification, and a condenser in parallel. This potential was measured with an electrostatic voltmeter which had been calibrated against a micrometer sphere gap.

Measurements and Results

Determinations of F_∞ and L_0 were made at pressures between 0.007 mm and 0.070 mm of mercury, and with accelerating potentials between 7.5 kv and 21 kv. The lower limit of pressure was set by the decreasing number of ions formed in the arc. L_0 was determined from Eq. (3) by observing the intensity at the thermocouple with all condensers grounded and again with deflecting potentials applied to both the long and short condensers.

$1/L_0$ was proportional to the pressure at all pressures over 0.015 mm within an experimental uncertainty of about ten percent. At the lowest pressures $1/L_0$ appeared to be 30 to 40 percent higher than was to be expected from the linear relation at higher pressures. No definite explanation is offered for this result. The values at the lowest pressures were omitted from the averages, which are given in Table I, column 4, reduced to 760 mm pressure. The long condenser was considered to extend right up to the electrode C, Fig. 2, where the beam contained only neutral particles. Actually it failed to do so by about 15 mm. The error thus introduced is easily computed and was found to be negligible at all except the highest pressures, where the appropriate small corrections were applied to the data.

TABLE I.

1 Accelerating potential in kv	2 Velocity in cm per sec.	3 F_∞	4 L_0	5 L_1	6 $1/L_0$	7 $2/(L_0+L_1)$
21	1.00×10^8	0.87	8.6×10^{-4}	1.3×10^{-4}	1160	2000
15	.84	.90	10.5	1.2	950	1700
11	.72	.93	14.0	1.1	710	1300
7.5	.60	.95	21.5	1.1	460	880
5	.49		40		250	

The mean free paths are expressed in centimeters, reduced to 760 mm pressure, but uncorrected for temperature. The kinetic theory mean free path in helium at 760 mm and 300°A is 1.9×10^{-5} cm.

For the arrangement of potentials shown in Fig. 2 the beam approached equilibrium from an initial neutral state, for which $F_0=1$. It was also possible to allow a beam to come to equilibrium from an initial state consisting entirely of ions, for which $F_0=0$, by grounding electrode C and applying a high positive potential to all parts shown to the right of C in Fig. 2. F was measured, both for $F_0=1$ and for $F_0=0$, by observing the intensity at the thermocouple with the condensers grounded, and again with a deflecting potential applied to the short condenser only. The two values of F so obtained agreed within an experimental uncertainty of from one to two percent for pressures above 0.020 mm and were then considered to give the equilibrium value F_∞. At the highest pressures F showed small decreases attributable to the finite length of the short condenser. The following figures are the averages obtained for F_∞ at pressures between 0.020 mm and 0.030 mm: 0.86, 0.89, 0.90, 0.94 for the respective accelerating potentials 21, 15, 11, and 7.5 kv. When L_1 was computed by Eq. (2), taking F_∞ from above and L_0 from Table I, the results were somewhat irregular and too high to explain the differences observed between F and F_∞ at low pressures. It will be noted that very small changes in F_∞ give large variations in the computed value of L_1. It was found that the low pressure observations could be fitted by using the values of F_∞ given in Table I, which are higher than those given above by differences of a few percent, only slightly more than the experimental uncertainty. The figures for L_1 in the table, which follow from the adjusted values of F_∞, have a relatively large uncertainty, so that the variation with velocity shown in the table is not at all positively established.

The adjustments made in F_∞ are in the same direction as, and less than, the correction for finite length of the short condenser considered by Rüchardt.[10] This correction is applicable when the condenser removes all ions formed between the plates as well as those which enter as ions. This could not be shown to be the case in these experiments. Curves of thermocouple intensity against deflecting potential showed approximate saturation below 500 volts, as was to be expected, but slight dependence of intensity on voltage persisted up to 2000 volts, as far as the observations were carried. Hence it appears that Rüchardt's full correction should not be applied.

The anode voltages in the arc were always less than 100 volts and the occurrence of doubly charged ions in the arc was considered improbable on the basis of experiments such as those of Bleakney.[12] Extrapolation of Rutherford's data for alpha-particles also indicates that doubly charged ions should be few in number at these velocities.

It was found necessary to use a weak magnetic field to protect the thermocouple from secondary electrons which were accelerated away from electrode C when it was negatively charged. Errors from this cause are present in preliminary data already reported.[13]

Observations with Argon

When these same experiments were tried with argon satisfactory intensity was not obtained at any pressure, and none at all above 0.02 mm. This was in marked contrast to helium, where an abundance of ions reached the thermocouple at all pressures up to the arcing point, about 0.2 mm. This suggests much stronger absorption by scattering in argon than in helium. This factor may enter in the results of Kallman and Rosen,[14] who have also observed greater absorption in argon than in helium. These workers ascribe the absorption to neutralization, but reference to a recent paper by Cox[15] will show that scattering is an equally tenable explanation. The absorption mentioned above, however, could not be attributed to neutralization, as neutral atoms and ions affect the thermocouple equally.

Good measurements were not obtained with argon, but the trials roughly indicated values for F_∞ about the same as in helium, and for L_0 one-half to one-fourth of the values for helium.

Discussion of Results

The results in Table I and similar measurements of other observers are plotted logarithmically as a function of velocity in Fig. 3. The free path for capture of an electron varies approximately as v^5 for the alpha-particles

[12] W. Bleakney, Phys. Rev. **36**, 1303 (1930).
[13] P. Rudnick, Phys. Rev. **37**, 1707 (1931), abstract.
[14] H. Kallmann and B. Rosen, Zeits. f. Physik **61**, 61 (1930).
[15] I. W. Cox, Phys. Rev. **34**, 1426 (1929).

(curve A), but shows no certain variation at all with velocity for the slower helium ions studied here (curve E). The measurements of Rüchardt and Goldmann (curves C and C') were made by very different experimental means and should therefore be compared with some caution, but if one accepts the indication that the free path for capture of an electron by a proton in hydrogen has a minimum in the region of 10^8 cm/sec., it is not surprising that the curve for helium should be nearly horizontal in this same region.

The free path for loss of an electron varies approximately as the inverse square of velocity for both hydrogen (curve D) and helium (curve F) at the lower velocities, but increases with velocity for the singly charged alpha-particle (curve B). This contrast probably corresponds at least roughly to the

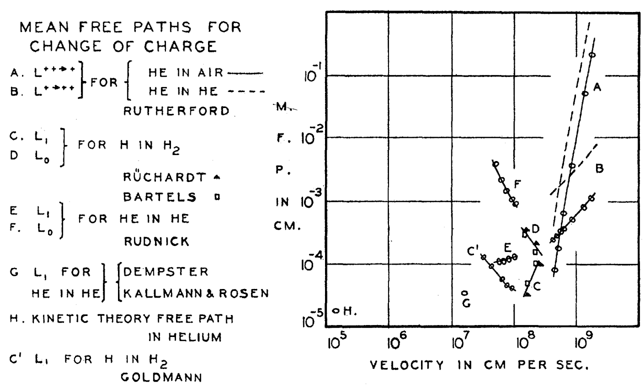

Fig. 3.

occurrence of the maximum of the Bragg ionization curve at intermediate velocities. The broken curve shown for alpha-particles in helium is Rutherford's statement that a few experiments with helium indicated free paths five or six times as great as in air.

Dempster has determined the value 3.5×10^{-5} cm as a mean free path for absorption of 900 volt helium ions in helium.[16] Data for virtually the same experiment given by Kallmann and Rosen[14] permit computation of the free path 3.7×10^{-5} cm for 400 volt ions. An average of these two is plotted in Fig. 3. It will be noted that the point falls below the practically horizontal curve for neutralization of helium ions at higher velocities, as one would expect if the absorption studied at the lower velocities involved scattering as well as neutralization.

If we suppose in these experiments that the fast neutral atoms are in the normal state and hence identical with the molecules of the gas through which they pass, then collisions in which the fast atom ionizes an atom at rest will be just as frequent as collisions in which the fast atom is itself ionized. This means that each particle, in describing its free path as a neutral atom, ionizes only one atom in the gas at rest, although according to kinetic

[16] A. J. Dempster, Phil. Mag. **3**, 115 (1927).

theory about 45 collisions occur over the same path. $1/L_0$ is then the number of ion pairs produced by a neutral atom per centimeter of its path as a neutral. This ionization becomes $1/(L_0+L_1)$ when expressed as the number of ions per centimeter of the path described in both charged and neutral states. If the neutral atoms are not in the normal state[17] they will probably ionize less frequently than they are ionized, and their efficiency of ionization will then be less than $1/L_0$. The increase in $1/L_0$ with velocity, shown in column 6 of Table I, accords with the known increase of ionizing power with velocity for alpha-particles in this range.[18]

From the table the ionizing power of the neutral atom is 1160 ions per cm for the velocity 10^8 cm/sec. In contrast to this, an electron of the same velocity has an energy of only 3 volts and hence no ionizing power whatever in helium. Even at its maximum the ionizing efficiency of electrons,[19] achieved at a velocity of 6 or 8 times 10^8 cm/sec., is only about equal to the value mentioned above for the slower atoms.

For each capture of an electron, a positive ion is formed in the gas; each electron lost also remains in the gas. Accordingly, each particle produces a pair of ions in the distance (L_0+L_1), or $1/(L_0+L_1)$ ion pairs per cm by capture and loss of electrons. Combining this with the ionization by neutral atoms considered above gives $2/(L_0+L_1)$ for the ionization per particle per cm in the composite beam attributable to the neutral atoms and to the alternations of charge. Ionization in excess of this would presumably be produced only by the positive ions. Numerical values are given in column 7 of Table I. The value for $v=10^8$ cm/sec., when multiplied by 24.6, the ionization potential of helium, indicates energy dissipation due to ionization of at least 5×10^4 equivalent volts per cm.

Recent range-velocity data[20] for slow alpha-particles, combined with the value 0.179 for the relative stopping power of helium,[21] show that helium particles of velocity 10^8 cm/sec. lose their energy in helium at a rate of about 1.6×10^5 volts per cm. Thus the minimum ionization $2/(L_0+L_1)$ deduced above represents about one-third of the total energy dissipated by the particles.

The remaining two-thirds of the energy could be spent in either or both of two ways: first, in additional ionization by the positive ions along their short paths, which however, still involve about seven collisions according to kinetic theory, compared to about 45 for the neutral free path; second, in elastic or inelastic collisions not involving ionization. The first of these alternatives is suggested by the conclusion reached by Gurney[22] that alpha-particles in helium expend almost all of their energy in ionization. This result seems clearly established for the average behavior at least below $v=10^9$

[17] M. L. E. Oliphant, Proc. Roy. Soc. **A124**, 228 (1929).
[18] G. H. Henderson, Phil. Mag. **42**, 538 (1921).
[19] P. T. Smith, Phys. Rev. **36**, 1293 (1930).
[20] P. M. S. Blackett and F. C. Champion, Proc. Roy. Soc. **A130**, 380 (1931).
[21] R. W. Gurney, Proc. Roy. Soc. **A107**, 340 (1925).
[22] R. W. Gurney, Proc. Roy. Soc. **A107**, 332 (1925).

cm/sec. A direct estimate of ionizing power at $v=10^8$ cm/sec. from Henderson's curve[18] and the relative value 1.3 for ionization in helium[22] also supports the first hypothesis, as it indicates roughly the formation of 9000 ions per cm, requiring an energy of 2.2×10^5 volts per cm, more than the total dissipation 1.6×10^5 volts per cm estimated above. It thus appears probable that the helium particles studied here produce ionization several times the minimum estimate $2/(L_0+L_1)$, and that the ionization in excess of this minimum must be attributed to the positive ions. This conclusion has the somewhat surprising corollary that the positive helium ion has an ionizing power in helium about 28 times that of the neutral helium atom at the velocity 10^8 cm/sec.

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