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THE CAPTURE OF ELECTRONS BY SWIFTLY MOVING ALPHA-PARTICLES

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Abstract

Relative velocities of an alpha particle and an electron which are favorable for the capture of the electron.—A stream of electrons from a thermionic source is superposed on a beam of α-particles from polonium. To determine the number of captures, the α-particle beam is subjected to a magnetic field and the number of deflected α-particles counted by the scintillation method. If an α-particle captures an electron before entering the magnetic field it will no longer be deflected to so great an extent. The number of scintillations for various velocities of the electrons, both greater and less than that of the α-particles, was observed. It was found that captures take place only at definite electron velocities. These velocities are related to velocities in the Bohr orbits of ionized helium as follows: $v=u-w$ and $v=w'-u$ where u is the velocity of the α-particle, w and w' are two velocities of the electron at which capture takes place and v is the velocity of an electron in any one of the circular Bohr orbits. A plot of the number of captures as a function of the voltage impressed on the electron stream gives a series of maxima on each side of the equivalent volt-velocity of the α-particles which correspond to the energy levels of ionized helium.

IT IS a matter of some surprise that an α-particle as it smashes its way through a gas and comes in contact with electrons should not attach one or more of them to itself. The approach is very close and the force is that due to a doubly charged nucleus. This matter was discussed by one of us (B. D.) in a letter to Nature (May 26, 1923). A possible explanation was given which agreed fairly well with the experimental facts. Experiments by Henderson[1] had shown that first capture took place when the velocity v_1 of the α-particle was reduced to 0.4 v_0, where v_0 is the normal velocity of the α-particle, which was given by him as 2.06×10^9 cm/sec. The second capture took place when $v_2=0.15v_0$ approximately. The point of view advanced in the letter was that the α-particle moved so swiftly that the chasing electron was not able to overtake it. If the α-particle were retarded and moved with a less velocity the electron would be able to catch up. This limiting velocity should be the parabolic velocity, or velocity of fall from infinity to the orbit or energy level in question under the action of the central forces. The computed velocity of fall to the energy level for quantum number one agreed very well with the value $v_1=0.4v_0$ as observed by Henderson.

The present experiments were undertaken to determine more precisely the way in which the chance of the capture of an electron by an α-particle varies with their relative velocity.

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[1] Henderson, Proc. Roy. Soc. **A102**, 496–506 (1923).

It is difficult to retard the velocity of α-particles to a desired value. Since motions are relative the expedient was here adopted of increasing the velocity of the chasing electron by a suitable electric field. It was expected that as the velocity of the electron approached that of the α-particle it would unite with the nucleus and form an ionized helium atom. The striking results obtained in our present experiments might have been anticipated had we calculated the parabolic velocity for other energy levels as well as for the first one.

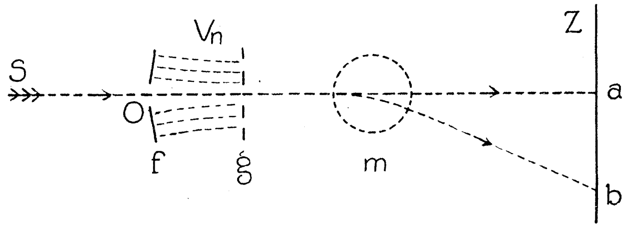

Fig. 1.

A schematic representation of the experimental arrangement is shown in Figure 1. The source of the α-particles is polonium deposited on the end of a pointed rod placed at *S*. The source of the electrons is a large oxide-coated filament *f* with a small aperature at *O* to permit the passage of the α-particles. The electrons are given the desired velocity by a suitable voltage V_n acting between filament and grid *g*. The α-particles are deflected by a magnetic field at *M* and strike the zinc sulphide screen at *b*. The scintillations are counted in the usual manner. If an α-particle captures an electron between *f* and *g* it will not be deflected to *b*. The number of scintillations per minute will decrease. The experimental procedure was to count the scintillations without the electron stream, then to turn on the electron stream and progressively increase the electric field V_n by small steps. The decrease in scintillations gives at once the percent of captures.

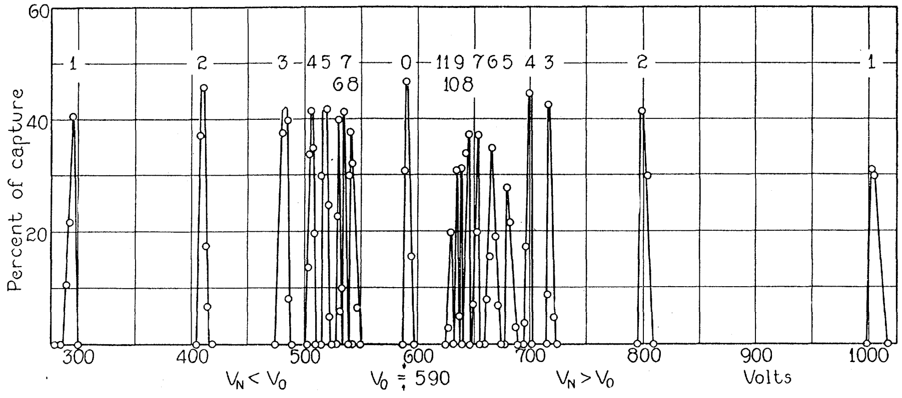

Fig. 2.

The results of our experiment are given in Figure 2 and in the table. The ordinates are percent captures, and the abscissae are applied voltages, V_n. The voltage $V_0 = 590$ is the potential difference that gave the electrons a velocity equal to that of the α-particles. This velocity was 1.45×10^9 cm/sec. The velocity of the α-particles was diminished from their original one of 1.59×10^9 cm/sec by passing through a thin glass window that admitted them into the highly exhausted chamber. It was so arranged that the normal number of scintillations should be about 60 per minute. All observations were made with an electron current of 60 milliamperes excepting in the case of No. 1 on the low voltage side, namely, at $V_n = 295$ volts. This curve was taken at 30 milliamperes.

The observed curves consist of two series of sharp maxima grouped on each side of the central line at V_0. They should correspond to the spectral series of the ionized helium atom.

In the figure the quantum number n is placed at the peak of the curves and V_n designates the potential at which the line of quantum number n is observed.

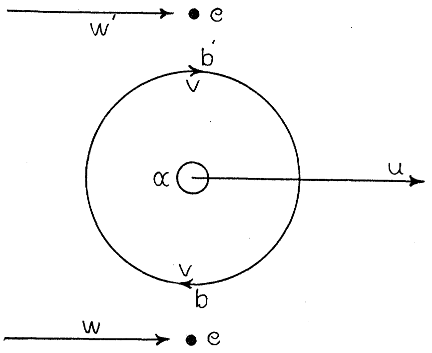

Fig. 3.

The kinematical relation of the chasing electron and the α-particle at the condition of capture is represented in Figure 3. The velocity of the α-particle is designated by u and that of the chasing electron by w. The circle about α represents a Bohr orbit and v is the velocity which an electron would have in this orbit. The condition of capture is that the electron e having velocity w or w' shall be at rest with respect to the hypothetical electron at b or at b'. This kinematical relation may be represented by $v = (u - w)$ and $v = (w' - u)$. This is the condition of capture in any orbit, and approximately represents the observed series of maxima.

The system of coordinates may be transferred to the α-particle. In this case the α-particle is at rest and the electron appears to approach from the right with a velocity v for the case for which V_n is less than V_0. It approaches from the left with velocity v for the case for which V_n is greater than V_0. In each case the velocity v is the relative velocity of α-particle and electron.

The velocities w and w' are those acquired from the applied electric field V_n only. The velocity that the approaching electron may acquire from the doubly charged nucleus does not play a part in the process.

The energy relations may be directly written down;

$$\tfrac{1}{2}mv^2 = \tfrac{1}{2}m(u - w)^2$$

and

$$\tfrac{1}{2}mv^2 = \tfrac{1}{2}m(w' - u)^2.$$

By means of the relations:

$$E_n e = \tfrac{1}{2}mv^2; \quad V_0 e = \tfrac{1}{2}mu^2 \text{ and } V_n e = \tfrac{1}{2}mu^2$$

where E_n is the ionization potential of singly ionized helium from the energy-level characterized by the quantum number n, we derive at once the expression

$$E_n = (V_0^{1/2} - V_n^{1/2})^2$$

for the series of maxima when V_n is less than V_0 and to

$$E_n = (V_n^{1/2} - V_0^{1/2})^2$$

for the case when V_n is greater than V_0.

The series terms as calculated by the above expressions are given in Table I. The first column specifies the quantum number n of the energy level. The second and fourth columns show the applied potentials, and the third and fifth columns give the energy levels as calculated from these potentials. The mean values are given in the last column. In the next to the last column are the energy levels as calculated by

TABLE I.

n	$V_n < V_0$	E_n	$V_n > V_0$	E_n	$E_n = 54.16/n^2$	Mean of E_n
1	295	50.6	1005	54.9	54.16	52.
2	410	16.7	800	15.6	13.54	16.2
3	483	5.33	720	6.45	6.01	5.67
4	505	3.29	700	4.71	3.38	4.00
5	519	2.28	681	3.27	2.16	2.77
6	531	1.56	667	2.41	1.50	1.98
7	535	1.34	653	1.59	1.10	1.46
8	538	1.19	645	1.23	.84	1.21
9	—	—	638	.96	.668	—
10	—	—	635	.88	.54	—

$$E_n = 4(13.54)/n^2 \text{ (volts)}$$

The ionized helium atom is a hydrogen-like structure with a double charge.

The agreement between the two last columns of the table is not good. Probably one should not expect a good agreement with the present arrangement of filament and grid. It is quite probable that a change in the potential V_n alters the distribution of the electrons. Also at these large electron currents (60 milliamperes), the space-charge effect must have been strongly present. This and other matters that may affect the results will be investigated.

The sharpness of the curves, together with the fact that there are no captures between the maxima indicate that the probability of recombination is very great when the relative velocity of an ion and an electron is that corresponding to an energy level. It is very small at all other velocities except for the special case when the relative velocity is zero, as indicated by the strong capture at $V_0=590$ volts.

A point of some interest also is the fact that there are no captures in a region about 40 volts wide on each side of the V_0 position. No decrease in the scintillations can be observed. The captures stop at about the tenth or eleventh energy level. This is far out from the nucleus from the point of view of the original Bohr model. The radius of the tenth orbit is about twenty-five times that of a normal hydrogen atom. The energy level is about 0.5 volts or less. It would appear that the nucleus is not able to retain an electron captured at a level of such small energy. Possibly also an atom may have actually a large radius when an electron is at large quantum number. If so the electron might be stripped off by collisions with the molecules of the residual gas in the vessel. The distance from the grid g to the magnetic field M was 25 centimeters.

The electron is captured only when its relative velocity due to the accelerating field V_n is that of the electron in its orbit. The velocity of fall into an energy level due to mutual attraction of the charges does not appear to be involved. If, however, the electron is subject to the central forces it does not start from rest at infinity as in the Bohr theory. It has an initial energy already equal to the energy level at which it is captured. It arrives with twice the normal energy for that level. This energy must be radiated. Is it radiated in two quanta of normal frequency or in a single quantum of twice that frequency?

This is a preliminary announcement and details and descriptions of apparatus have been purposely omitted. The investigation will be continued by one of us (A. H. B.) and a complete description given in a later paper.