Second Series *February 1, 1930* *Vol. 35, No. 3*

THE

PHYSICAL REVIEW

THE CAPTURE OF ELECTRONS BY ALPHA-PARTICLES

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(Received December 24, 1929)

Abstract

A stream of electrons is superposed upon a beam of alpha-particles. The alpha-particles are then deflected by a magnetic field and counted by the scintillation method. Alpha-particles which have captured electrons will not be deflected to the point where observation is made, and consequently, the decrease in scintillations will indicate the number of captures which occur.

Probability of capture as function of relative velocity.—It is found that electrons are captured when their velocity equals that of the alpha-particle, and also, at a series of discrete velocities both greater and less than that of the alpha-particle. Counting scintillations due to singly charged particles showed that at certain of these discrete velocities one electron is captured. At the other velocities two electrons are captured. This was determined by counting scintillations due to neutral particles which had passed undeflected through the magnetic field. Both single and double capture occur at zero relative velocity, the latter predominating as the electron density is increased.

Calculation of the kinetic energy of the electron with respect to the alpha-particle corresponding to each of the velocities at which single capture occurs, gives a series of energy values which can be associated with the energy levels in the ionized helium atom. Similarily, for the case of double capture, the sum of the kinetic energies due to each of the two electrons, corresponds to the energy of the quantum states of both the parhelium and orthohelium types of atom. There is indication that the hitherto unobserved ground state of orthohelium is being formed. The conclusion is reached that in order for capture to occur, it is necessary that the electron, due to some external field, possess a kinetic energy, which, with respect to the nucleus, is either zero, or equal to the energy of one of the quantum states of the atom. In the latter case double the normal energy must be radiated, and the question arises as to whether it is radiated as two quanta of normal frequency, or as one quantum of twice that frequency.

There is evidence that the *penetrating power* of the singly charged and neutral particles is less than that of the nucleus alone.

Time required for capture of electron by alpha-particle.—The construction of one of the tubes used permitted the time during which the alpha-particle was in the electron stream to be made less than 3×10^{-10} sec without appreciably decreasing the percent of capture. The electron density under these conditions was of the order of 10^7 electrons per cc.

In a previous report[1] an experiment was described which showed that an electron is captured by an alpha-particle only at definite relative velocities.

[1] Bergen Davis and A. H. Barnes, Phys. Rev. **34**, 152 (July 1, 1929).

The series of energy values associated with these velocities was shown to correspond to the energy levels in the ionized helium atom.

The present paper gives the details of the experiment (which were omitted in the preliminary announcement) and presents additional information obtained with a new experimental arrangement.

First Experimental Tube

Two experimental tubes were constructed. The first tube is shown diagrammatically in Figure 1. The alpha-particle source is polonium deposited upon a pointed copper rod placed at *S*. A thin glass window *W*, 0.0005 cm thick, allows the alpha-particles to enter the tube. By thus placing the radioactive source outside the tube, contamination difficulties were entirely avoided.

After passing through the tube, the alpha-particles leave it by means of another window placed at *Y*, or if a sufficient magnetic field be applied at *M*, they will be deflected and pass out through a window at *Z*. The latter windows are each 0.001 cm thick. Zinc sulphide screens are placed outside the windows. Aluminum foil 0.0004 cm thick was placed before each screen to shield it from the light of the filament. The air is exhausted from the spaces between screen and window and also from the space between source and window.

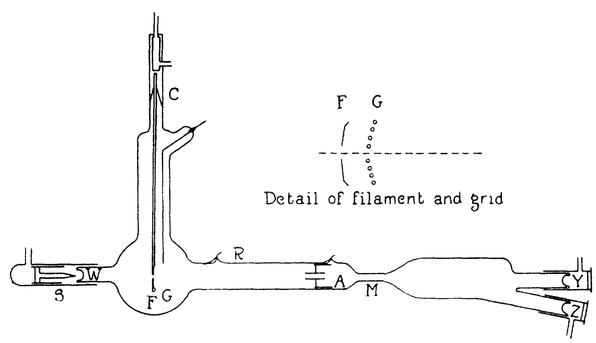

Fig. 1. Diagram of first experimental tube. *S*, radioactive source; *W*, thin glass window; *F*, filament; *G*, grid; *R*, lead to silvered surface; *A*, second anode; *M*, magnetic field; *C*, copper seals; *Y*, and *Z*, zinc sulphide screens.

The source of the electrons is a large oxide-coated filament *F*, 2.5 cm square and made slightly concave. A hole 0.5 cm in diameter allows the alpha-particles to pass through. The current necessary to heat the filament was about 150 amperes and entered the tube through water-cooled copper seals at *C*.

The first anode *G*, is placed one cm from the filament and takes the form of a conical spiral of 60 mil tungsten wire. The diameter of the inner and outer turn is 0.4 cm and 2.5 cm respectively. The spacing between turns is 0.4 cm. The second anode *A*, is a nickle cylinder 0.5 cm in diameter and 3 cm long. It is placed 18 cm behind the grid *G*.

The inside of the glass vessel is silvered and the conducting layer grounded to prevent accumulation of charge on the walls. All metal parts were outgassed in a vacuum furnace before being placed in the tube. The tube was evacuated, baked, and sealed off.

Electrons leaving the filament are accelerated to any desired velocity by the potential impressed upon the grid *G*. Due to the shape of the grid and filament, those electrons which pass through the grid will converge and proceed along the axis of the tube towards the anode *A*. The alpha-particle does not enter into a region of relatively great electron density until it reaches the point of convergence of the electron stream. If an electron is captured at this point, the alpha-particle will arrive at the magnetic field with a decreased charge, and consequently will not be deflected to the lower screen at *Z*. The decrease in scintillations observed at *Z* will therefore determine the number of captures which occur.

Procedure and Results

The procedure followed with this tube was to vary the magnetic field until the alpha-particles were deflected to the lower screen *Z*. The potential applied to the grid *G*, and cylinder *C*, was then varied in small steps and the corresponding change in the number of alpha-particles arriving at *Z* was determined. During most of the runs the current to *G* was 60 milliamperes and to *A*, 0.08 milliamperes.

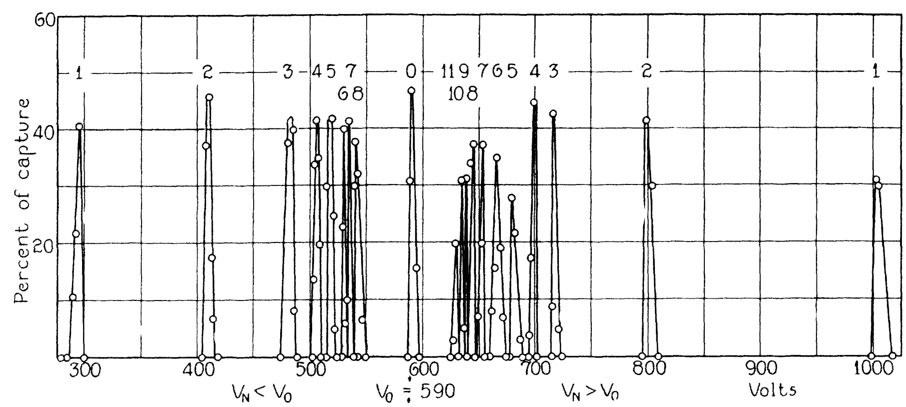

Fig. 2. Electron capture as a function of accelerating voltage.

It was found that capture takes place when the velocity of the electron is equal to that of the alpha-particle also at a series of definite electron velocities both greater and less than that of the alpha-particle. A curve showing the relation between capture and applied voltage as obtained with this tube is given in Figure 2. It consists of a double series of sharp maxima grouped on each side of a central peak. The velocity of the electrons corresponding to the voltage at which the central peak occurs is 1.44×10^9 cm/sec. This agrees closely with the calculated velocity of the alpha-particle after passing through the window of the tube.

If v is the velocity of an electron and u the velocity of an alpha-particle, then the kinetic energy of the electron with respect to the alpha-particle will be,

$$W = (\tfrac{1}{2})m(v-u)^2$$

where m is the mass of the electron.

Let V_n and V_0 be the potential differences through which electrons must fall to acquire the velocities v, and u, respectively, then,

$$eV_n = mv^2/2$$

and,

$$v = (2eV_n/m)^{1/2}$$

similarly,

$$u = (2eV_0/m)^{1/2}$$

substituting,

$$W = \left(\frac{1}{2}\right) m \left(\frac{2e}{m}V_n - \frac{4e}{m}V_n^{1/2}V_0^{1/2} + \frac{2e}{m}V_0\right)$$

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

or,

$$\frac{W}{e} = (V_n^{1/2} - V_0^{1/2})^2 = E_n$$

where E_n is the energy expressed in volts when V_n and V_0 are in volts.

If in this equation we substitute for V_0 the voltage which will accelerate an electron to a velocity equal to that of the alpha-particle, and for V_n successively the voltages at which the observed peaks occur, then we arrive at a series of energy values which correspond to the energy levels in the ionized helium atom.

Table I gives the voltages of the observed peaks and the corresponding values of E_n. The last column gives the values of E_n as calculated from Bohr theory. There are of course two sets of observed values for E_n corresponding to the two cases in which $V_n > V_0$ and $V_n < V_0$.

TABLE I. *Values of E_n for which capture takes place.*

n	$V_n < V_0$	E_n	$V_n > V_0$	E_n	Mean of E_n	$E_n = 54.16/n^2$
1	295	50.6	1005	54.9	52.0	54.16
2	410	16.7	800	15.6	16.2	13.54
3	483	5.33	720	6.45	5.67	6.01
4	505	3.29	700	4.71	4.00	3.38
5	519	2.28	681	3.27	2.77	2.16
6	531	1.56	667	2.41	1.98	1.50
7	535	1.34	653	1.59	1.46	1.10
8	538	1.19	645	1.23	1.21	.84
9			638	.96		.67
10			635	.88		.54

It thus appears that the probability that an alpha-particle will capture an electron is great only when the kinetic energy of the electron with respect to the alpha-particle is either zero, or equal to the energy of one of the quantum states of the ionized helium atom. It is to be noted that the kinetic energy here referred to is that due to the applied field only.

The effect of varying the potential of the second anode A, with respect to the first G, was investigated. It was found that if the potential of A was made greater or less than that of G, then to maintain the condition for capture, it was also necessary to change the potential of G. Thus if the potential of A is decreased, then to maintain capture, it is necessary to increase the potential of G. Another result of making the potential of A different from that of G is a considerable broadening of the peaks, especially when A is at a higher potential than G. These effects indicate that capture is taking place at some point between the first and second anodes, and that the velocity of the electrons is the governing factor.

It will be noticed that the peaks do not continue to the central peak as they might be expected to do, but stop abruptly at about the tenth energy level. It was thought that this might be due to re-ionization caused by collisions with the molecules of residual gas in the tube. This effect was investigated with the second tube and will be discussed later.

An alpha-particle which has picked up one electron will be deflected to the lower screen Z, when the magnetic field is doubled. If it has picked up two electrons it will pass through the magnetic field without deflection and arrive at the upper screen Y. It should therefore be possible to observe an increase in scintillations corresponding to every decrease.

When this procedure was tried no increase could be detected. It was further found that with the magnetic field entirely removed, a decrease in scintillations on the upper screen occurred at the same voltages at which decreases had formerly occurred on the lower screen. This effect indicated that the penetrating power of a singly charged or neutral particle was less than that of the nucleus alone.

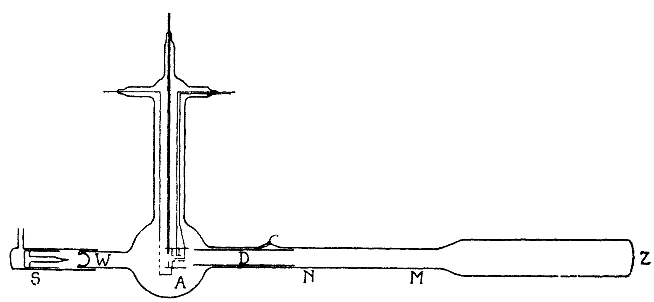

Fig. 3. Diagram of second experimental tube. S, radioactive source; W, thin glass window; A, filament-anode system; M, magnetic field; Z, zinc sulphide screen.

Second Experimental Tube

The second tube was constructed with four objects in view.

1. The reduction of the time of passage of an alpha-particle through the electron stream to a known small value.

2. The detection of scintillations due a singly charged and neutral particles.

3. The investigation of the effect of varying the velocity of the alpha-particle.

4. The investigation of the captureless intervals located on each side of the central peak.

The construction of the second tube is shown diagramatically in Figure 3 and Figure 4. The electron source is an oxide-coated filament F, in the form of a flat disk with a 0.4 cm diameter hole at its center to allow the passage of the alpha-particles. Two mm in front of the filament is placed a plate P, with

0.5 cm diameter hole exactly opposite the hole in the filament. A 60 mil tungsten wire T, extends for one cm along the axis of the tube to a point within one mm of the plate P. Surrounding the wire is a cylinder C, 0.5 cm in diameter and 0.5 cm long. A second cylinder D, 2 cm in diameter and 10 cm long is placed 1 cm behind the first cylinder and on the same axis. The whole assembly is held rigidly in place and mutually insulated. Separate leads are brought out from each of the elements.

Zinc sulphide is placed on the inside of the flattened end of the tube at Z. The window used to admit the alpha-particles was of very nearly the same thickness (0.0005 cm) as that used on the first tube, so that the velocity of the alpha-particles in each tube was very nearly the same. The tube was evacuated and sealed off.

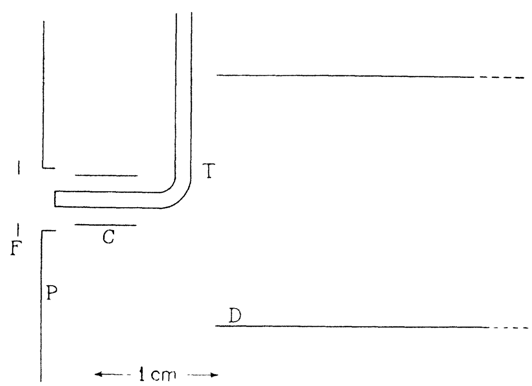

Fig. 4. Detail of filament-anode system in second tube. F, filament; P, plate; T, wire; C, cylinder; D, cylinder.

If the anode assembly (P, C, D, and T) is all put at the same potential the electrons leaving the filament will be accelerated by the field between the filament and the plate P, and wire T. Some will pass between this wire and the cylinder C, and so on to the larger cylinder at D. If however, the cylinder C, is put at filament potential, the field existing between C and T will be sufficient to deflect all the electrons which pass P, to the wire T near its end. The length of path which the electrons can possibly travel is thus limited. Furthermore every electron which reaches the wire T, must cross the paths of the alpha-particles.

Procedure and Results with Second Tube

The effect on capture of various arrangements of the anode system was tried. The plate P, wire T, and cylinders C, and D, were put at the same potential and the percent of capture determined. The cylinders C and D, were then put at filament potential and it was found that the percent of capture remained practically unchanged.

Under the latter conditions the greatest length of path possible for the electrons was approximately 5 mm, and since the velocity of the alpha-particle as it passes through this region is 1.45×10^9 cm/sec it follows that the process of capture must take place in less than 3×10^{-10} sec.

In the second tube the scintillations due to both singly charged and neutral particles could be detected. It was possible to count the increase in scintillations due to alpha-particles which had captured one electron and therefore struck the screen at a point midway between the center and the edge. It was also discovered that at certain voltages neutral particles were produced. They, of course, were not deflected by the magnetic field and struck the center of the screen.

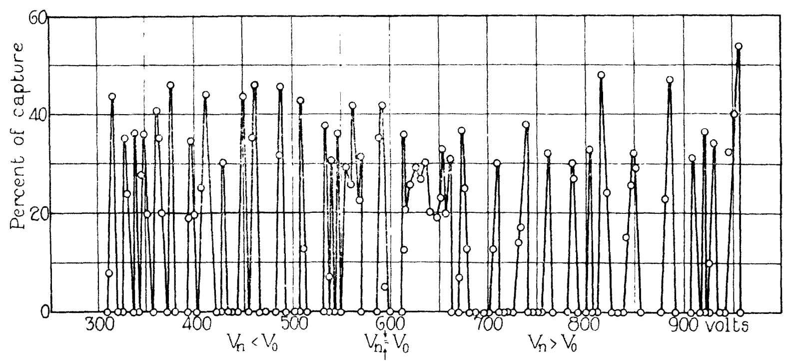

Fig. 5. Double electron capture as a function of accelerating voltage.

It was found by observing at the center of the screen that there exists a whole series of voltages at which double capture occurs. A curve showing the relation between this type of capture and the applied voltage is given in Figure 5. There exists also an independent series of values at which single capture occurs, (Figure 6.). With the first tube it was not possible to separate

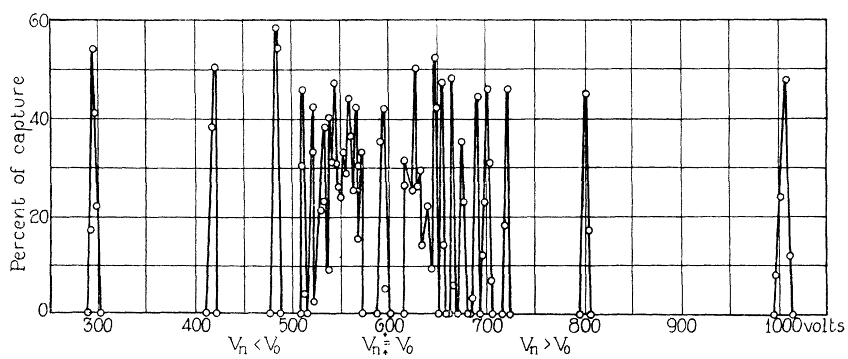

Fig. 6. Single electron capture as a function of accelerating voltage.

these two types of capture, (since only a decrease in scintillations could be observed) and consequently some of the peaks which were thought due to single electron capture were in reality due to double capture. The peak found at 410 volts for example was at first attributed to single capture. The second tube showed however, that this was a voltage at which double capture occured, and that the single capture peak was at 418 volts.

The most striking feature of the curves is the narrowness of the peaks. This indicates that capture takes place at a point where the electrons are moving with a very uniform speed and direction. The electron velocity at this point will in general be somewhat less than that corresponding to anode potential. The observed voltage across the tube will therefore not indicate the true velocity at the point of capture. This condition introduces an error in the determination of the location of the peaks and consequently also in the calculated energy values. It should be possible to design an arrangement in which the electron velocity at the point of capture was very exactly known and so obtain correct values for the energy levels.

The whole range of voltage was investigated and the single capture peaks separated from those due to double capture. A revised table showing single capture voltages and the corresponding energy values is given in Table II.

TABLE II. *Values of E_n for single capture.*

n	$V_n < V_0$	E_n	$V_n > V_0$	E_n	Mean of E_n	$E_n = 54.16/n^2$
1	293	51.8	1005	54.9	53.3	54.16
2	418	14.8	800	15.6	15.2	13.54
3	481	5.53	719	6.45	5.99	6.01
4	508	3.16	700	4.71	3.93	3.38
5	519	2.31	689	3.72	3.01	2.16
6	531	1.56	673	2.69	2.12	1.50
7	535	1.39	662	2.02	1.70	1.10
8	540	1.12	652	1.51	1.31	.84
9	—	—	645	1.21	—	.67
10	—	—	637	.53	—	.54

Applying the energy relation given above to the case of the double capture peaks it is possible to calculate the kinetic energy of each electron with respect to the alpha-particle. If double capture takes place under conditions similar to that for single-capture, then the sum of the kinetic energies of each of the two electrons, (as acquired from the applied field, but with respect to the alpha-particle) should correspond to the energy of one of the quantum states of the helium atom.

Table III shows the voltages at which double capture occurs and the corresponding relative kinetic energy of one and of two electrons.

TABLE III. *Values of E_n for double capture.*

$V_n < V_0$	E_n	$2E_n$	$V_n > V_0$	E_n	$2E_n$	Mean of $2E_n$
315	43.0	86.0	955	43.5	87.0	86.5
327	38.6	77.2	930	38.4	76.8	77.0
338	35.4	70.8	921	36.0	72.0	71.4
347	32.1	64.2	907	33.6	67.2	65.7
360	28.4	56.8	885	29.7	59.4	58.1
375	25.0	50.0	848	24.1	48.2	49.1
395	19.5	39.0	815	18.0	36.0	37.5
410	16.4	32.8	803	16.4	32.8	32.8
428	13.0	26.0	783	13.5	27.0	26.5
448	10.5	21.0	760	10.8	21.6	21.3
460	8.25	16.5	738	8.2	16.4	16.5
486	4.60	9.20	708	5.3	10.6	9.90
507	3.24	6.48	672	2.60	5.20	5.84
533	1.49	2.98	661	1.96	3.96	3.47
537	1.25	2.50	652	1.51	3.02	2.76

The second value (77 volts) given in the last column of the table agrees with the observed total energy of the parhelium type of atom (54.2+24.5 volts). It is suggested that the first value, 86.5 volts, may correspond to the ground state of orthohelium, a configuration hitherto unobserved, but which might be formed under the special transition conditions peculiar to this experiment.

It is also probable that the remaining values constitute a double series, consisting of the energy levels of both the parhelium and orthohelium types.

No significance is to be attached to the fact that the peaks in Figures 2, 5, and 6, do not rise much above 50 percent. It was discovered after these curves had been taken that by a suitable adjustment of the position of the radioactive source it was possible to increase capture to over 90 percent.

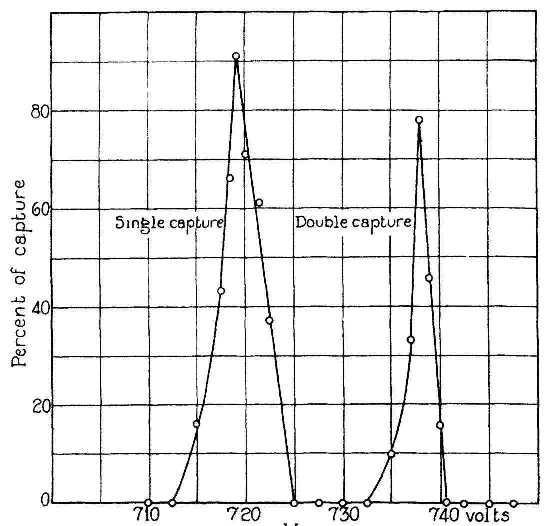

Fig. 7. Typical peaks.

Two typical peaks taken under these conditions are shown in Figure 7. The peak at 719 volts is one due to single capture. The 738 volt peak is due to double capture.

The explanation of this dependence of capture on the position of the source is that the electron stream is not uniformly distributed over the area through which the alpha-particles are passing. Thus, if there is always a portion of the observed alpha-particles which pass through a region where the electron density is always too low for capture to occur, it will be impossible by merely increasing the current to the anode to make the percent of capture rise above a certain value. If however, the position of the source is so adjusted that all the alpha-particles which fall within the field of view of the microscope, (2.4 mm in diameter) must pass through the region of maximum electron density, then by increasing the current to the anode it is possible to make capture approach 100 percent.

The effect of gradually increasing the current to the anode T, when the voltage is held at one of the peak values is illustrated in Figure 8 and Figure

9. The curve in Figure 8 is taken at the single capture peak at 719 volts. Figure 9 is the curve obtained at the double capture peak occurring at 738 volts.

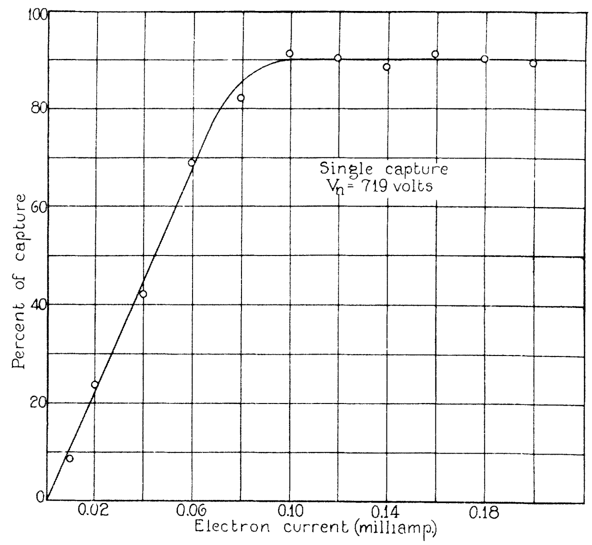

Fig. 8. Capture as a function of electron current. A curve taken at the 719 volt single capture peak.

Since these voltages are relatively close together, the electron density for a given anode current is probably not very different in each case, and there-

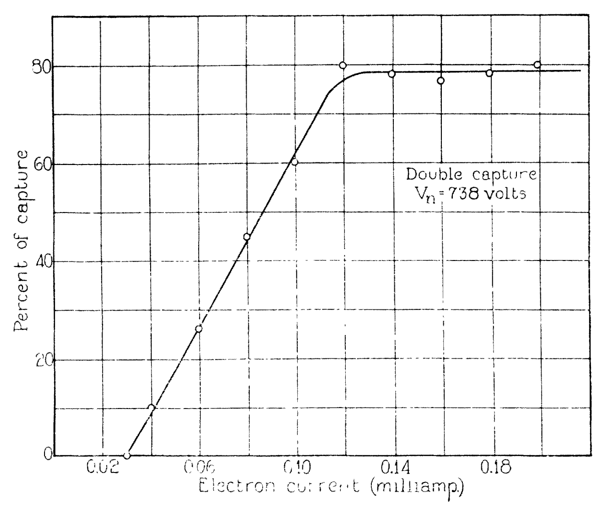

Fig. 9. Capture as a function of electron current. A curve taken at the 738 volt double capture peak.

fore the percentage of capture should be a rough indication of the relative probabilities of single and double capture.

Further information on this question is given in Figure 10 which shows a series of three curves taken at the 590 volt peak which corresponds to zero relative velocity of electron and alpha-particle. Curve (1) shows the manner in which the number of single captures varies with the current going to the anode *T*. It was obtained by counting increases in scintillations due to singly charged particles striking the screen at the midway point. Curve (2) shows the variation with current of the number of neutral particles which strike the screen at its center. Curve (3) shows the total decrease in scintillations as observed at the lower edge of the screen. The ordinates in this case are not given in percent but in the observed variation in scintillations per minute.

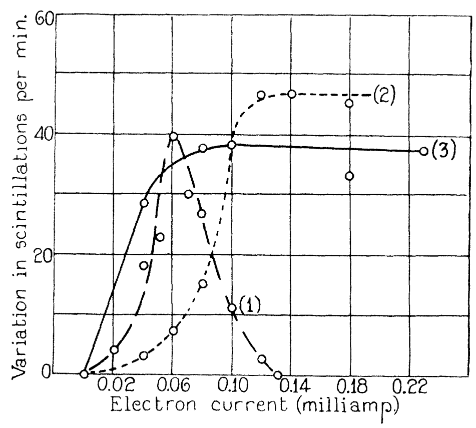

Fig. 10. Capture at zero relative velocity as a function of electron current. (1), single electron capture; (2), double electron capture; (3), total decrease of doubly charged alpha-particles.

For single capture, (Figure 8) saturation is reached when only 0.1 milliampere of current flows to the anode *T*. The order of magnitude of the electron density under these conditions is about 10^7 electrons per cc, which corresponds to an average distance between electrons of 4.6×10^{-3} cm. The process of capture must therefore involve some mechanism, which, when the energy condition is satisfied is effective over a relatively large region of space.

With the second tube it was possible to investigate the effect of reducing the velocity of the alpha-particles. Two different velocities were tried by interposing aluminum foil between the radioactive source and the window. The resultant velocities of the alpha-particles were 1.35×10^9 cm/sec and 1.21×10^9 cm/sec. The whole series of peaks was found to shift in each case. Several of the peaks were located in their new position and the corresponding energy levels calculated by means of the energy relation already given. A comparison of these values with the values found at the higher alpha-particle velocity showed very good agreement.

The intervals on each side of the central peak where no capture occurs were found to be much narrower with the second tube than with the first Whereas with the first tube they were 40 volts wide, with the second they were only about 22 volts wide. In other words capture terminated at the tenth energy level in the first tube and at about the fifteenth energy level in the second. If these captureless intervals were due to re-ionization by collision with the residual molecules of gas in the tube, then the width of the intervals should be dependent on the length of path between the point of capture in the electron stream and the magnetic field. To test this the magnet was placed in two positions along the tube at M, and at N, (Figure 3) such that the distance $(A-M)$ was double the distance $(A-N)$. It was impossible to detect any change in the width of the interval under these two conditions. These captureless intervals must therefore be due to some cause other than collisions of this kind.

Conclusion

In the type of recombination taking place in this experiment the electron does not fall from rest into a given energy level (except in the special case when the velocities of electron and alpha-particle are equal). It has an initial kinetic energy, due to the applied field, equal to that of the energy level at which it is captured. Twice the normal energy must therefore be radiated, and the question arises as to whether it is radiated as two quanta of normal frequency, or as one quantum of double that frequency.

The striking result of this experiment is the discovery that electron capture is governed by a definite energy condition. In order for capture to occur, it is necessary that the electron, due to some external field, possess a kinetic energy, which, with respect to the nucleus, is either zero, or equal to the energy of one of the quantum states of the atom.

It has been shown that electron capture takes place in less than 3×10^{-10} sec in a region where the electron density is probably not greater than 10^7 electrons per cc. Probably the time involved is actually much less than this. The process of capture must therefore involve some mechanism whose action is extremely rapid, and when the energy condition is satisfied, effective over a relatively great region of space. When the energy condition is not satisfied the capture mechanism either does not function at all, or operates in such a manner that the probability of capture is relatively very small. The inference to be drawn is that under certain energy conditions, the mutually effective radius of action of the electron and the nucleus may be relatively very great, while under other energy conditions it is very small.

The results of this experiment are based upon the counting of over 700,000 alpha-particle scintillations.

In conclusion, the writer wishes to express his appreciation and gratitude to Professor Bergen Davis for suggesting this research, and for his continued interest and encouragement throughout the course of the experiment. Many thanks are also due to the other members of the department of Physics.