Angular Distribution of the Products of Artificial Nuclear Disintegration

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(Received October 3, 1935)

Measurements were made of the angular distribution of the alpha-particles emitted during the disintegration of lithium (7) by fast protons. The protons were generated in a low voltage arc and accelerated down a three-section vertical tube by potentials obtained from a rectifying and doubling system. The bombarding beam was analyzed by an electromagnet, defined by a series of circular slits, and allowed to impinge on the target in a special chamber designed to permit observation of the particles at positions spaced by 15° in the plane of the beam. The alpha-particles were recorded by an ionization chamber which actuated a linear amplifier and oscillograph. Readings taken at three voltages between 200 and 240 kilovolts indicate that within the limits of experimental error, estimated as approximately eight percent, emission of alpha-particles is random in direction.

INTRODUCTION

In the observation of disintegration phenomena it is usually possible to observe only the particles coming from the target within a relatively small solid angle. The total number of particles emitted is then obtained by multiplying the number actually observed by the ratio of 4π to the solid angle through which measurements are made. This is not without justification, for Kirchner,[1] observing the yield at various angles by means of cloud-chamber photographs, reported the probability of emission to be the same for all directions between 80° and 160° with the incident beam. Kirchner, however, gives no information as to the constancy of voltage and ion currents in his experiments, nor does he give any estimate of the absolute accuracy of his result other than to say that the fluctuations observed lie within the statistical limits of error. In view of the fact that this result must enter into all determinations of absolute yield, it was felt desirable to investigate further the angular distribution by a different and independent method. In the present paper this has been done by using as a recording device an ionization chamber together with a linear amplifier and oscillograph. The particles studied were the alpha-particles originating in the transformation

$$_3Li^7 + _1H^1 \rightarrow 2_2He^4.$$

APPARATUS

Protons were obtained from a low voltage arc of a conventional type, the construction of which is shown in Fig. 1. The total ion currents obtained depended upon the arc current, the relation being roughly a linear one. At 150 ma of arc current approximately 10 microamperes of ion current were obtained, while at 400 ma of arc the ion current rose to 30 microamperes. The percentage of protons present in the ion beam varied from 10 to 20 percent, being higher for higher pressures, in agreement with the results of Fowler and Gibson[2] and of Lamar and Luhr.[3] In the experiments which follow about 150 ma arc current were used. Variation of the voltage on the electrode F permitted nice adjustment of the size of the ion spot striking the target. The sylphon bellows S permitted the position of the source within the first electrode of the accelerating tube to be varied for preliminary rough focusing. The flow of hydrogen gas to the arc chamber was regulated by means of a simple capillary leak of the type described by R. D. Fowler.[4] Commercial tank hydrogen was found quite satisfactory, without preliminary drying. Care was taken, however, to prevent as far as possible the mixture of air and other gases with the hydrogen in the storage tank and connecting tubes.

The current supply for the source was contained in a shielded box mounted on insulating supports of textalite tubing. It consisted of a 300-watt 110-volt direct-current generator, a 150-watt 110-volt direct-current to 110-volt alternating-current converter, and the necessary transformers, rectifiers, rheostats, etc. The fila-

[1] Kirchner, Physik. Zeits. **34**, 777 (1933).

[2] Fowler and Gibson, Phys. Rev. **46**, 1075 (1934).

[3] Lamar and Luhr, Phys. Rev. **46**, 87 (1934).

[4] R. D. Fowler, Rev. Sci. Inst. **6**, 26 (1935).

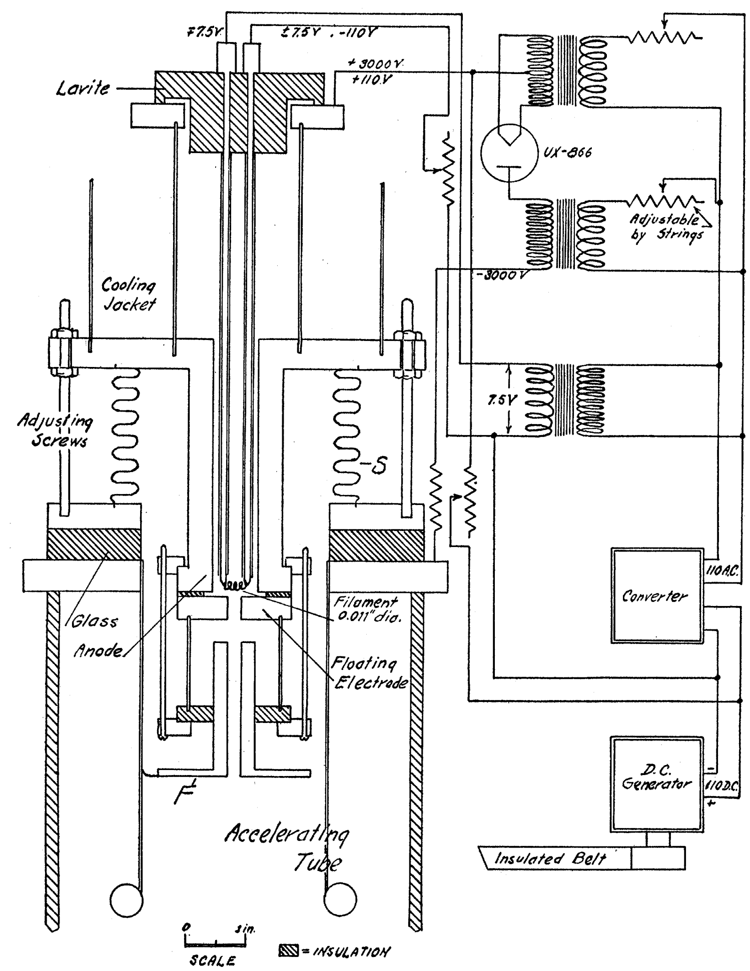

FIG. 1. Proton source.

ment transformer supplied 7.5 volts a.c. to the filament. A rectifier of the UX-866 type, operating from a 5000-volt neon sign transformer supplied direct current voltage for the focusing electrode *F* of the source.

During the early stages of this work the accelerating tube was a single section one made from a glass cylinder 12 inches in diameter and 26 inches in length. This tube proved very unstable, however, and it was found necessary to convert it into a two section tube, isolating the two parts electrically by a flat metal shield clamped in place by an adjustable expansion ring. This tube proved very stable in operation. Because of its short length, however, it would stand only about 170 kilovolts before flashing down the outside surface. This was corrected by the addition of a third section constructed from an 11-inch length of 6-inch diameter Pyrex tubing. In this form (Fig. 2) the tube has stood the maximum available voltage; i.e., 250 kilovolts, with no sign of breakdown.

The various ions, emerging from the accelerating tube, were sorted by means of an electromagnet, giving a field variable from 1000 to 1500 gauss, and a system of diaphragms. The first two diaphragms were grounded, while the third and the target chamber (Fig. 3) to which it was attached, were insulated from ground. The hole in the third diaphragm was $\frac{1}{2}$ inch, that in the second $\frac{3}{8}$ inch, and that in the first $\frac{1}{4}$ inch. Placing the third one immediately be-

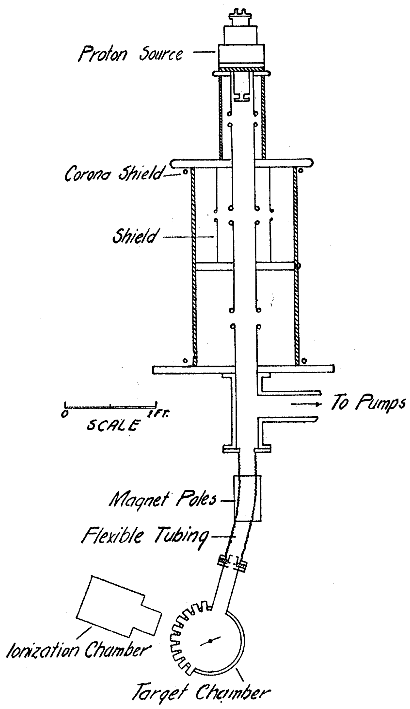

FIG. 2. Accelerating tube.

hind the second prevented the ions striking any surface of the target chamber until they struck the target itself. Because of the geometry of the chamber, the number of secondary electrons escaping through the diaphragms was very small. A microammeter connected between the chamber and ground read, therefore, the true ion current striking the target.

The target backing was of sheet aluminum, supported by a mica sheet which was in turn attached to a metal rod waxed into the large stopcock shown in the figure. The mica sheet served as a thermal insulator between the target, which sometimes became quite hot, and the wax.

The target was prepared by wetting the surface of the backing plate with a concentrated solution of pure lithium fluoride, and then evaporating the water by applying heat. It was found advisable to heat the target rather gently during evaporation, to avoid subsequent cracking of the surface of lithium salt.

The windows through which alpha-particles emerged from the target were of mica sheet, $\frac{3}{8}$ inch in diameter.

The accelerating potential was furnished by a 150-kilovolt transformer working into a rectifying and doubling circuit of the type described by Cockcroft and Walton.[5] The voltage was measured by means of a sphere gap, and it should be noted in this connection that recent checks of the A. I. E. E. standard sparkover potentials for sphere gaps[6, 7] have indicated these standards to be high by 16 to 20 kilovolts in the range of our measurements.

The linear amplifier used to record the disintegration products was constructed after a design kindly furnished this laboratory by Dr. M. A. Tuve, and is an adaptation of the amplifier developed by Wynn-Williams and Ward[8] to American tubes.

For oscillographs we used Peerless dynamic loudspeakers, from which the paper cones were removed. The voice coil was connected to a pivoted mirror by means of a strip of spring brass. These oscillographs were simple of construction and proved rugged in use, but the moving parts had too long a period to make them completely satisfactory for the purpose.

PROCEDURE AND RESULTS

The ionization chamber was very carefully aligned with the particular window of the target chamber through which observations were to be made, and the voltage and magnet current varied until protons of the desired energy entered the target chamber. The disintegration alpha-particles were then counted by the linear amplifier, and oscillograph records were made for periods of from three to ten minutes, the time depending upon the rate at which the products of disintegration were being recorded and upon the constancy of conditions.

The results are tabulated (Tables I, II, and III), and a graph summarizing them is shown in Fig. 4. As will be shown presently, the conditions during these experiments were such that an accuracy of better than 8 percent is not to be expected. The results indicate that within these limits the yield is independent of direction. In

[5] J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. **A149**, 406 (1935); **137**, 229 (1932).
[6] Henderson, Goss and Rose, Rev. Sci. Inst. **6**, 63 (1935).
[7] J. R. Meador, Elec. Eng. **53**, 942 (1934).
[8] Wynn-Williams and Ward, Proc. Roy. Soc. **A136**, 391 (1931).

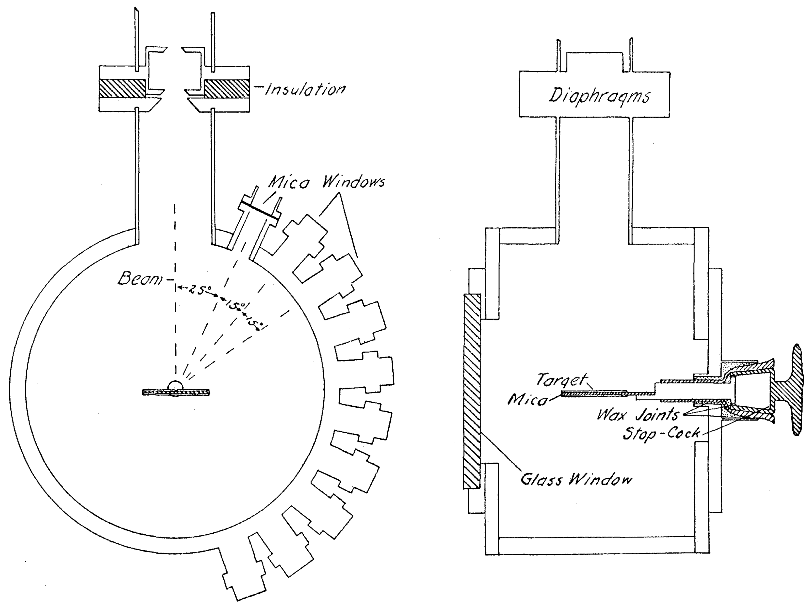

FIG. 3. Target chamber.

Tables I and II, in fact, the variations from mean yield are well within the limits of error, and are comparable in magnitude to the statistical fluctuations to be expected.

It is well to note that in determining the mean corresponding to a given voltage all the points are not of equal weight. This is true since, as was previously pointed out, the time of observation, and hence the number of disintegration products counted, varied from window to window. The statistical fluctuation, taken to be $\sqrt{N}$, where N is the total number of recorded alpha-particles, thus varies from one angle to the next. The magnitude of this fluctuation, expressed in percent, is shown for each point in the tables.

TABLE I.

Angle with Forward Direction of Beam	Proton Energy (kv)	Total Protons (microcoulombs)	Total Counts	Counts per Microcoulomb	% Statist. Fluct.	% Dev. from Mean
65 deg	220	174	370	2.13	5.21	4.46
80	220	184	415	2.25	4.90	0.45
95	220	162	382	2.36	5.13	5.36
110	220	384	856	2.23	3.41	0.45
140	220	399	894	2.24	3.34	0.00
Total all windows		1303	2917			
Mean for all windows				2.24		

TABLE II.

Angle with Forward Direction of Beam	Proton Energy (kv)	Total Protons (microcoulombs)	Total Counts	Counts per Microcoulomb	% Statist. Fluct.	% Dev. from Mean
35 deg	240	751	3006	4.00	1.83	4.99
50	240	329	1355	4.12	2.72	8.14
65	240	344	1262	3.66	2.82	3.94
80	240	720	2700	3.76	1.92	1.31
95	240	537	1955	3.64	2.26	4.46
110	240	352	1255	3.56	2.83	6.53
140	240	822	3171	3.86	1.78	1.31
Total all windows		3855	14704			
Mean for all windows				3.81		

TABLE III.

Angle with Forward Direction of Beam	Proton Energy (kv)	Total Protons (microcoulombs)	Total Counts	Counts per Microcoulomb	% Statist. Fluct.	% Dev. from Mean
35 deg	200	434	657	1.51	3.91	10.13
50	200	430	733	1.70	3.69	1.19
65	200	434	757	1.75	3.64	4.17
80	200	393	658	1.67	3.91	0.60
95	200	402	603	1.50	4.07	10.72
110	200	507	866	1.70	3.40	1.19
125	200	486	867	1.78	3.40	5.96
140	200	548	974	1.77	3.20	5.36
Total all windows		3634	6115			
Mean for all windows				1.68		

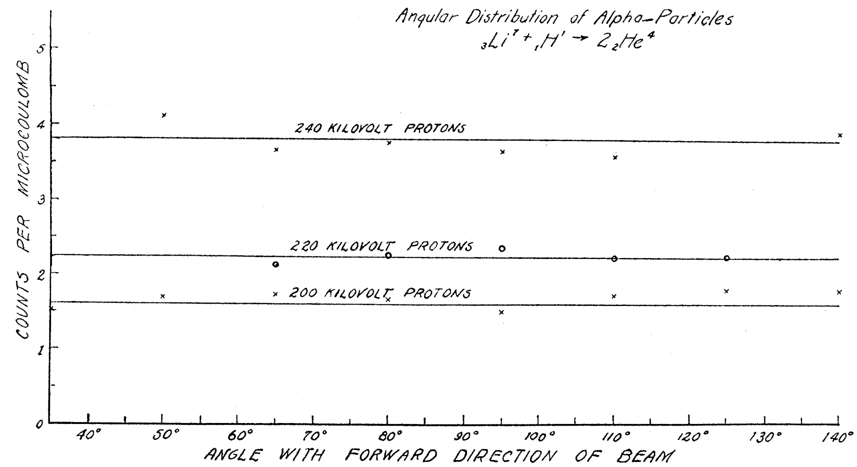

FIG. 4. Results.

The mean at a given voltage is obtained by adding all the counts taken at that voltage at all the windows and dividing the sum by the total number of microcoulombs. This automatically gives each point its proper weight.

Discussion of Errors

One of the main sources of error was the fluctuation of ion current. It was found quite difficult to keep the proton current, measured at the target, constant to better than 5 percent. The fluctuation may be traced to several causes, chief among which were the variations of accelerating voltage due to changing vacuum conditions in the accelerating tube and in the rectifier, and to variations of input to the source.

To keep the current as constant as possible one observer kept watch on the microammeter connected between the target and ground, reading the ion current and counteracting the changes by varying the voltage on the focusing electrode of the source. This was done by means of strings attached to a rheostat placed in the primary of the transformer supplying the focusing electrode voltage. This method of current control has the advantage that it tends to balance out in part the decrease or increase of voltage across the accelerating tube. However, on account of lag in the reaction of the observer to changes in the meter reading, errors in reading the meter, etc., the constancy of the current was at best no better than within 4 percent of the mean value. There were, in fact, brief periods during which the current would suddenly change by as much as 10 percent before the change could be detected and balanced out. Fortunately, the duration of such periods was short, and insofar as it was possible to recognize them the portions of the record corresponding to them were not counted.

The most important source of error, however, was variation of accelerating voltage, both in time and in angle. The latter variations occurred as a result of the shutting down of the analyzer magnet while the ionization chamber was being adjusted to a new position. The same value of magnetizing current was then reset for the new angle, and the assumption made that the voltage was correct when the ion beam attained its former position.[9] This assumption neglects the presence of hysteresis in the magnet iron, of course, but the lack of a convenient direct check on field strength at all times and the high quality of the magnet used made it desirable to run the risk of introducing error in this way. The maximum width of the hysteresis loop for the

[9] It may easily be shown that if the voltage is varied in such a way that the curvature of the ion path through the field remains the same, change in the voltage will be proportional to the change in field strength. Each particle will have a kinetic energy E, where

$$E = \tfrac{1}{2}mv^2 = m^2v^2/2m = \tfrac{1}{2}H^2\rho^2e^2, \qquad \text{since } H\rho = mv/e.$$

Thus for a constant value of curvature ρ and a particle of mass m and charge e

$$E = \text{const.} \times H^2; \qquad dE/E = 2dH/H$$

where H is the magnetic field.

magnet was found to be no more than 3 percent of the total field.

Voltage variations in time were due chiefly to changing vacuum conditions in the accelerating tube and in the rectifiers. Although frequent shut-downs were necessary to adjust the hydrogen leak and refill the cooling jacket of the source, care was taken to "break in" the tubes with voltage until vacuum conditions were fairly steady before resuming readings, since according to the results of Henderson[10] a change of voltage of $2\frac{1}{2}$ percent at 250 kv results in a change of 6 percent in the number of disintegrations.

The stopping power of the windows in the target chamber was approximately 3 cm, while the distance from the windows to the ionization chamber was $1\frac{1}{2}$ cm. The total stopping power of mica and air in the path of the alpha-particles was, accordingly, only $4\frac{1}{2}$ cm. Since the range of the particles was 8.4 cm, slight variations in the thickness of the windows introduced no error in determining the number of particles reaching the ionization chamber.

In order to avoid variations due to the thickness of the target traversed by alpha-particles on their way to the window at which observations were being made, the target was always adjusted so that it occupied a symmetrical position with respect to the incident beam and the direction of observation. (See Fig. 5.) There is, therefore, no correction necessary for target penetration, since conditions are similar for all windows.

In our discussion thus far we have spoken of the target as though it had a perfectly smooth surface. Although this is, of course, not true, we have estimated that the error introduced by neglecting to consider the alpha-particles which

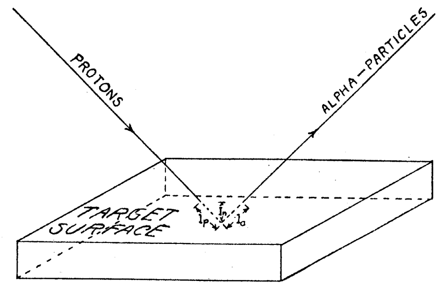

FIG. 5. Target penetration.

may be absorbed by crystals of the salt is negligible.

There still remains to be considered the effect of the change in size and shape of the ion spot on the target as the target is changed in position for the various windows. As the spot changes shape and becomes longer or shorter the solid angle of each of its elements as seen from the window of observation changes from one window to the next. This effect was calculated for the window at 35° and for the window at 140° from the incident beam. The result of the calculations showed the necessary correction to be negligible and of no importance for this range of angles and for a proton beam of $\frac{1}{4}$-inch diameter.

After considering the various sources of error and their relative importance we have concluded that the accuracy to be expected from these experiments is approximately eight percent. The results indicate that within these limits the emission of alpha-particles is random in direction.

The authors wish to express their appreciation to Professor G. Breit, who suggested the investigation and directed its earlier portions, and to Dr. W. H. Crew, and Messrs. R. Cortell, A. Roberts, and T. Zandstra for assistance in constructing the apparatus and taking the readings.

[10] M. C. Henderson, Phys. Rev. **43**, 98 (1933).

Erratum: Fine Structure of $D\alpha$ with Increased Resolution

ROBLEY C. WILLIAMS AND R. C. GIBBS, *Department of Physics, Cornell University* (Phys. Rev. **48**, 971 (1935))

IN the sixth line from the end the word *increased* should be changed to *decreased*. The conclusion that follows is correctly stated.