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Efficiency of Production of Short Range Particles from Lithium and of 4.4-cm Alpha-Particles from Boron Under Proton Bombardment

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The excitation functions for the reactions

$$Li^6+H^1\rightarrow He^3+He^4$$
$$B^{11}+H^1\rightarrow Be^8+He^4$$

have been determined up to 400 kv. The cross section of the Li^6 nucleus for this reaction was found to follow an exponential curve throughout this region. It varies from 1.8×10^{-26} at 200 kv to 7.3×10^{-26} at 400 kv. The resonance in the production of 4.4-cm alpha-particles from boron previously reported by other investigators was found to be located at 172 ± 5 kv. The total yield of 4.4-cm alpha-particles from a thick target was found from the observed yield at 90° by integrating the angular distribution function found by Neuert. At 200 kv 13.5 alpha-particles per 10^{11} protons were observed, rising monotonically to 128 per 10^{11} at 400 kv.

INTRODUCTION

TWO groups of doubly charged particles of approximately 0.65- and 1.15-cm range were found by Oliphant, Kinsey and Rutherford[1] when they bombarded lithium with protons. These were ascribed to the reaction $Li^6+H^1\rightarrow He^3+He^4$ and this reaction was later verified by Oliphant, Shire and Crowther[2] who used separated isotopes of lithium. Neuert[3] by measurements with a cloud chamber, later gave more accurate values of 0.82 and 1.15 cm as the mean ranges of the alpha-particle and the He^3 nucleus, respectively. The curve for the yield of these short range alpha-particles and He^3 nuclei at bombarding potentials ranging from 200 to 400 kv has been obtained in this experiment and the cross section of the Li^6 nucleus calculated for the reaction.

When boron is bombarded by protons, two different groups of alpha-particles seem to be emitted; one with a continuous range distribution from 0 up to about 4 cm, and a homogeneous group of 4.4-cm range. This last group, which probably comes from the reaction $B^{11}+H^1\rightarrow Be^8+He^4$, is much less intense than the continuous one and has been investigated by Kirchner and Neuert,[4] Oliphant, Kempton and Rutherford[5] and many others. Williams *et al.*,[6] in studying the excitation function of this reaction, observed

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[1] M. L. E. Oliphant, B. B. Kinsey and Lord Rutherford, Proc. Roy. Soc. **141**, 722 (1933).
[2] M. L. Oliphant, E. S. Shire and B. M. Crowther, Proc. Roy. Soc. **146**, 922 (1934).
[3] H. Neuert, Physik. Zeits. **36**, 629 (1935).
[4] F. Kirchner and H. Neuert, Physik. Zeits. **35**, 292 (1934).
[5] M. L. E. Oliphant, A. E. Kempton and Lord Rutherford, Proc. Roy. Soc. **150**, 241 (1935).
[6] J. H. Williams, W. H. Wells, J. T. Tate and E. L. Hill, Phys. Rev. **51**, 434 (1937).

a resonance level at about 180 kv which was later verified by Bothe and Gentner.[7] There has also been observed a resonance level in the production of gamma-rays at this same potential.[7, 8] The yield of alpha-particles from this reaction was studied in this experiment to verify the resonance level at 180 kv and the yield curve was then extended to 400 kv.

Apparatus

The apparatus used in this research has been previously described in a paper by G. T. Hatch[9] and only a few of the features will be described here. A voltage quadrupling circuit of the Cockcroft-Walton type, controlled by an auto-transformer, was used to accelerate the proton beam obtained from a low voltage hydrogen arc source. The voltmeter used to measure the accelerating potential consisted of a column of 750 metallized resistors, ten megohms each, whose resistance was calibrated by applying a known potential of about 40 kv to short sections of the total string of resistors and measuring the resulting current. The 40 kv was obtained from an x-ray source of d.c. potential whose output voltage could be measured by means of a potentiometer designed for that purpose. A further check on the voltage of the proton beam was made by bending it in an electrostatic field and measuring the field strength necessary to produce a known radius of curvature. These measurements agreed with the readings of the voltmeter to within about three percent.

After acceleration through a horizontal tube, the proton beam is analyzed magnetically and at the same time deflected into the target chamber where, before striking the target, it passes through a 28-cm aluminum tube used as a collimator. Diaphragms were mounted in the ends of this tube with circular openings 6 mm in diameter which limited the beam and thus determined the size and position of the focal spot on the target. The geometry of the arrangement was such that every proton which passed through the two diaphragms and thus entered the target chamber, necessarily hit the target. This collimation kept the proton currents low, but gave confidence that the galvanometer readings represented the actual proton current impinging on the target. The aluminum tube was raised to a positive potential of 50 volts to prevent the escape of secondary electrons from it to the target chamber, since this chamber was used as a Faraday cage to measure the proton current; and a diaphragm with a nine-mm hole was placed just beyond the end of the collimating tube to prevent the reverse escape of secondary electrons from the target to the aluminum tube. The beam current was measured by means of a galvanometer and currents of the order of a few tenths of a microampere were used in all of the work. Readings were taken at about three-sec. intervals and recorded and averaged on an adding machine.

The lithium target was formed by pressing lithium metal into a cavity 16 mm in diameter in a steel disk which could be mounted on the target holder at an angle of 45° with the proton beam. During this operation, the pure lithium rapidly oxidized in the air and it was assumed that it changed to the hydroxide. Since in LiOH there are 12 extranuclear electrons for each lithium nucleus as compared to three for pure lithium, the observed yields were multiplied by a factor of four to correct for the increased absorption of the protons by these electrons. As a check on these assumptions, a lithium fluoride target was prepared by melting the compound into a similar cavity in a steel disk and mounting as before. LiF has a high melting point and is a very stable chemical compound, so that it is relatively unlikely to decompose under bombardment by the proton beam. There are likewise 12 extranuclear electrons per lithium nucleus in LiF so the same factor of four should hold in this case. The yields thus calculated were found to fall closely on the curve obtained from the contaminated metal, thus supporting the hypothesis that the surface was actually LiOH.

The boron target was prepared by pressing pure amorphous boron into a shallow cavity in the same type of steel disk, and the boron was found to stick together sufficiently without the use of a binder so that the target could be handled without difficulty. Previous to the

[7] W. Bothe and W. Gentner, Zeits. f. Physik **104**, 685 (1937).
[8] B. Waldman, R. C. Waddel, D. Callihan and W. A. Schneider, Phys. Rev. **54**, 543 (1938).
[9] G. T. Hatch, Phys. Rev. **54**, 165 (1938).

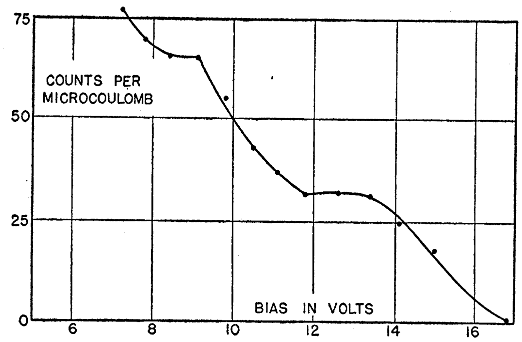

FIG. 1. A sample bias curve. Lithium bombarded by 395-kv protons.

bombardments the targets were heated by a pair of tungsten filaments mounted in a hole in the steel block which comprised the target holder. In this way any film of oil which so often deposits whenever oil diffusion pumps are used was driven off, thus preventing the formation of a carbon deposit on the target as is evidenced by the fact that there is no discoloration of the target even after long use.

The short range particles from lithium were allowed to escape from the target chamber through a window of collodion film whose stopping power was equivalent to two mm of air. This film was mounted on a screen over a hole 0.422 cm in diameter and 3.14 cm from the center of the target. The particles were recorded in an ionization chamber three mm in depth and 1.5 cm in diameter with a positive potential of 500 volts on the front face. This front face of the ionization chamber was placed within a millimeter of the window in the target chamber and the particles were admitted through a one-half inch hole covered with the same type of screen as before. Since the ionization chamber was so close, the window of the target chamber at all times limited the solid angle through which the particles were received.

The screen[10] which covered the windows in the target chamber and the ionization chamber is made of thin copper sheeting with 676 (26^2) regularly spaced holes per square cm. The holes are nearly square and measure 0.216 mm across. The relative area of the holes in the screen is thus seen to be 0.315 of the total area of the screen and this should therefore be the relative number of particles getting through. As a check on this calculation, the transmitting factor of the screen was also measured by means of the natural alpha-particles from polonium. Counts were taken both with and without the screen present between the source of alpha-particles and the ionization chamber and the ratio of these two counts was taken to be the factor desired. This factor came out to be 0.321 and this higher value was the one used in all the calculations. For two screens slightly separated from each other the factor was found to be $(0.321)^2$ since the source used in both cases is an extended one and there is no collimating effect of a single screen. The holes in this screen were found to be small enough so that collodion films of as little as one mm in stopping power would support atmospheric pressure over the area of the hole.

A linear amplifier constructed by J. S. Allen[11] was used to amplify the pulses of the ionization chamber and its output was applied to a scale-of-sixteen counting circuit of the type described by Stevenson and Getting.[12] The output was also applied through an additional stage of amplification to a cathode-ray oscilloscope by means of which a visual check was afforded at all times of the operation of the whole set. Disturbances which would otherwise be recorded as particles can easily be recognized and eliminated by this means.

LITHIUM

The bias on the input to the scaling circuit could be varied so as to control the voltage threshold at which the circuit would begin to record the pulses from the amplifier. In this way bias curves as in Fig. 1 were taken at each value of the accelerating potential and the flat plateaus found were assumed to be a measure of the number of particles entering the chamber at that potential. Since the 8.4-cm range alpha-particles which were always present are not near the end of their range when they are recorded in the ionization chamber, their pulses in the

[10] These screens may be obtained from Evert S. Fink, 230 E. 48 Street, New York City.

[11] J. S. Allen, Phys. Rev. **51**, 182 (1937).

[12] E. C. Stevenson and I. A. Getting, Rev. Sci. Inst. **8**, 414 (1937).

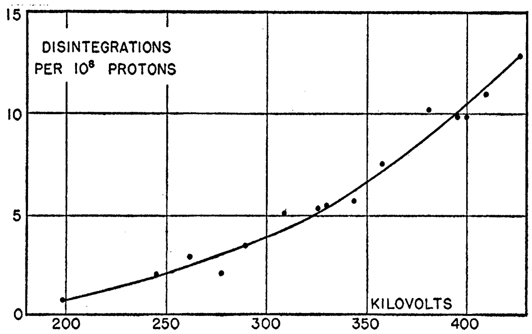

FIG. 2. The thick target yield curve for lithium. The yields as obtained from the experimental data have been multiplied by a factor of 4 to correct for the extra number of electrons per lithium nucleus in the LiOH and LiF targets used.

amplifier are considerably smaller than those of the short range particles. Consequently there were always found two plateaus on the bias curves, the lower one (higher bias voltage) corresponding to the short range particles, and the higher one including both the short range particles and the 8.4-cm range alpha-particles. It was thus found possible to count the short range particles from the reaction in the presence of the long range alpha-particles.

As a check on this, a thin sheet of mica was placed between the target chamber and the front window of the ionization chamber to cut out the short range particles, but thin enough to allow the 8.4-cm alpha-particles to pass through without appreciably cutting down their range. The bias curve taken under these conditions showed only a very slight plateau for the short range particles while the plateau for the 8.4-cm particles remained unchanged; i.e., it was thus shown that the long range alpha-particles produced only the small pulses in the ionization chamber and amplifier.

The observed particle yields from LiOH and LiF, when multiplied by a factor of four, should give the yields from a target of pure lithium bombarded by protons. The factor of four arises from the following considerations. Let $N_{\mathrm{Li}}/N_{\mathrm{LiF}}$ be the ratio of the yields to be expected from a metallic lithium and a LiF target, respectively, from a given proton beam. Then

$$\frac{N_{\mathrm{Li}}}{N_{\mathrm{LiF}}}=\frac{R_{p,\,\mathrm{Li}}\,n(\mathrm{Li,\,Li})}{R_{p,\,\mathrm{LiF}}\,n(\mathrm{Li,\,LiF})},$$

where $R_{p,\,\mathrm{Li}}$ is the range of the protons in the lithium; $R_{p,\,\mathrm{LiF}}$ is the range of the protons in LiF; n(Li, Li) is the number of Li nuclei per cm^3 in Li; n(Li, LiF) is the number of Li nuclei per cm^3 in LiF. Placing the ranges inversely proportional to the numbers of electrons per cm^3, and expressing the n's in terms of the densities leads at once to

$$\frac{N_{\mathrm{Li}}}{N_{\mathrm{LiF}}}=\frac{Z_{\mathrm{Li}}+Z_{\mathrm{F}}}{Z_{\mathrm{Li}}}=4.$$

It is clear that the same ratio will hold for the targets lithium : LiOH.

By assuming a spherically symmetrical distribution of ejected particles, the number of disintegrations per proton (half the observed number of particles) could be calculated from the known solid angle subtended by the window. No correction for the momentum of the proton was made, since such a correction amounts to only a little over one percent at 400 kv. Fig. 2 shows the resultant number of disintegrations per proton from a target of metallic lithium.

The cross section σ of the Li^6 nucleus for the proton reaction was computed as follows. Let dy be the yield from a thin target which the

FIG. 3. The excitation cross section of Li^6.

protons traverse without sensible diminution of their velocity. Let dx be the thickness of such a film, and let it contain dn nuclei of Li^6 per cm^2. Then $\sigma=dy/dn$. The values of dy were found by taking differences along the curve of Fig. 2 at ten-kilovolt intervals. The fraction of the total number of lithium atoms in metallic lithium which are Li^6 is 0.078, and the density of lithium is 0.534. From these values it results that $dn=3.66\times 10^{21}dx$.

In order to find the thickness dx of the thin target of lithium whose stopping power is ten kv, use was made of the data of Haworth and King[13] on the stopping power of lithium films for various proton energies. They have listed values of dE/dx for various proton energies and by setting dE equal to ten kv, one can solve for the value of dx. The values of dx range from 2.39×10^{-5} cm at 175 kv to 3.82×10^{-5} cm at 400 kv. These values for dx were substituted in the equation for the cross section and the values of σ calculated for bombarding potentials of 200, 250, 300, 350 and 400 kv. Fig. 3 shows the cross section of the lithium nucleus for this process as a function of the proton bombarding potentials and the curve is seen to be exponential within experimental error over the range investigated.

Boron

For the work on boron the 0.422-cm diameter window in the target chamber was covered with a thin piece of Cellophane whose stopping power was equivalent to 3.2 cm of air. The ionization chamber was then placed one cm away from this window, but the window in the ionization chamber was large enough ($\frac{1}{2}$ inch) so that the solid angle still remained limited by the opening in the target chamber. Since the 4.4-cm alpha-particles are the longest range produced when boron is bombarded by protons, no other particles reached the ionization chamber and the bias on the scaling circuit was set to record all of the particles which entered. As before, a correction was made to the number of alpha-particles recorded to take account of the screen over the window of the ionization chamber, but in this case no such screen was used to cover the window in the target chamber since the Cellophane was strong enough to support the atmospheric pressure.

TABLE I. *Values of N/N_{90} from Neuert's curve.*

θ	$N\theta/N_{90}$	$N \sin\theta/N_{90}$
20°	1.90	0.65
30	1.85	0.93
40	1.82	1.17
50	1.70	1.30
60	1.55	1.34
70	1.30	1.22
80	1.05	1.03
90	1.00	1.00
100	1.10	1.08
110	1.35	1.27
120	1.55	1.34
130	1.72	1.32
140	1.70	1.09
150	1.72	0.86

Neuert[14] has investigated the angular distribution of alpha-particles from this reaction; and he publishes a curve showing the ratio of the number of particles at an angle θ with the

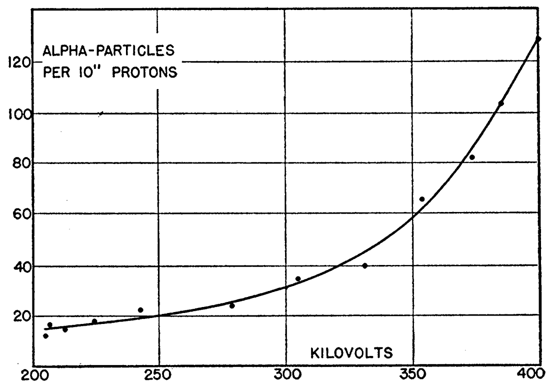

FIG. 4. The yield of 4.4-cm alpha-particles from boron as calculated on the basis of Neuert's data.

incident proton beam to the number at $\theta=90°$. Although Neuert has stated his results as representing the number of particles per unit angular range at an angle θ, it would seem from his experimental arrangement that he has actually measured numbers of particles per unit solid angle. With this assumption in mind, the ordinates on Neuert's curve were multiplied by $\sin\theta$ and the resulting function integrated graphically. This integration gives a factor of 18.6 by which the number of alpha-particles per unit solid angle at $\theta=90°$ must be multiplied to give the total yield. Table I gives the values of N/N_{90} as read from Neuert's curve for various values of θ and the values of $N\sin\theta/N_{90}$ are also listed. The yield of alpha-particles from boron calculated in this way from Neuert's data for various values of the accelerating potential is shown in Fig. 4.

Dr. Williams has kindly furnished me with some of the results of the Minnesota group for the angular distribution of alpha-particles from

[13] L. J. Haworth and L. D. P. King, Phys. Rev. **54**, 48 (1938).

[14] H. Neuert, Physik. Zeits. **38**, 122 (1937).

this reaction at an accelerating potential of 190 kv. They find the ratio of the number per unit solid angle at angle θ to the number at $\theta=90°$ to be represented by the function $1+0.7\cos^2\theta$. If this distribution function is integrated over the surface of a sphere, one gets the factor 15.5 by which the number of alpha-particles at 90° must be multiplied in order to obtain the total yield. In Table II is given a comparison between the total yield as calculated on the basis of Neuert's data and as calculated from the above data of the Minnesota group.

The part of this curve in the neighborhood of 170 kv has been plotted on a larger scale to show the resonance effect and is given in Fig. 5. Since the yield is given for a thick target of boron, the point of steepest slope of this curve is to be taken as the resonance potential. This point comes at 172±5 kv. Other estimates of this resonance potential are as follows:

TABLE II. *Comparison of total yield from Neuert's data and from that of Minnesota group.*

Potential (kv)	Total Yield of Alpha-Particles	
	Neuert	Minnesota Group
175	10×10^{-11} per proton	8.65×10^{-11} per proton
200	14.3	12.4
225	16.5	14.3
250	18.7	16.2
275	23.7	20.5
300	31.2	27.2
325	41.2	35.6
350	58.8	50.8
375	88.8	76.7
400	127.5	110.0

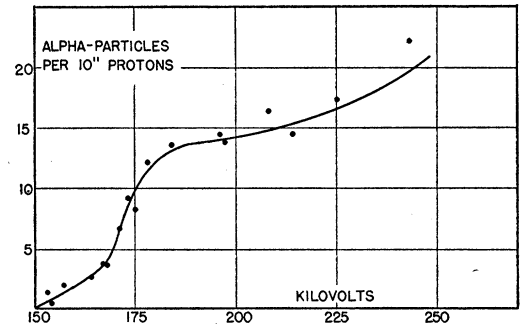

FIG. 5. The yield of alpha-particles from boron in the neighborhood of the resonance potential.

Williams *et al.*[6]	180 kv
Allen, Haxby and Williams[15]	160 kv
Bothe and Gentner[7]	180 kv
Waldman *et al.*[8]	165±4 kv

Acknowledgments

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[15] J. S. Allen, R. O. Haxby and J. H. Williams, Phys. Rev. **53**, 325 (1938).