does not occur until very high energies are reached, and no conclusions can be drawn as to the existence of this increase at high energies.

The results on neon are shown in Figs. 3 and 4. The data are compiled and plotted by the same method as used for nitrogen, except that the theoretical curve is moved up vertically so that it can be plotted on the same scale as the experimental curve. The experimental results in neon may be represented by the equation:

$$I = 12.6\beta^{-1.35\pm0.15}.$$

The ionization potentials for each of the neon electrons is known from measurements on critical absorption wave-lengths, and these correspond to the molecule since neon is monatomic; and thus more accurate comparisons with theory may be made. The experimental results show that the primary ionization varies as the -1.35 power of the velocity, and is within experimental error in agreement with the theoretical predictions. As in the case of nitrogen, however, the increase at high velocities is not observed. The magnitude observed is about 12 percent higher than the calculated on the basis of the formula obtained by hydrogen-like wave functions but are as close as the somewhat arbitrary assumptions involved would allow one to expect. The observed magnitude is six times the classical value.

A few tracks in oxygen have been measured to compare the results with those of Williams and Terroux, and the values obtained check their results closely. Two or three tracks, definitely due to positive electrons, show no distinguishable difference in primary ionization from the negative electrons of similar energy on which ion counts were made. Work is now being done on measurement of the primary ionization in argon and preliminary results obtained indicate a lower value than would be expected by Bethe's formula (2). A complete account of this work will, however, be published soon.

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Disintegration Experiments on the Separated Isotopes of Lithium

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Observations made with targets of 18 micrograms of Li^6 and 200 micrograms of Li^7 under proton and deuteron bombardment have given the following results. (1) Two groups of protons with mean ranges of 25.4 cm and 29.6 cm air-equivalent are emitted by Li^6 under deuteron bombardment at 540 kv. No group of such range was found for Li^7 under similar conditions. (2) Neutrons are emitted by Li^6 under deuteron bombardment at 300 kv and above. (3) Short period beta-ray activity was observed from Li^7 under deuteron bombardment at 500 kv and above with no observable activity from Li^6 under similar conditions. (4) Gamma-rays are emitted by Li^7 under proton bombardment in the neighborhood of 450 kv and of 1000 kv, with no observable gamma-rays or neutrons emitted from Li^6 with protons of these energies.

I. INTRODUCTION

WHILE it is to be expected that the proper parent of most transmutation products may be assigned from energy considerations and mass spectrograph data, the origin of other products may be ambiguous, particularly in case a previously unknown nucleus is formed or the available energy is utilized only partially in a single process. Furthermore, certain nuclear processes in one isotope may be obscured by the products of another isotope. In these instances, the use of targets of single isotopes assumes special significance. An example of such work is that of Oliphant, Shire, and Crowther,[1] using

[1] M. L. Oliphant, E. S. Shire and B. M. Crowther, Proc. Roy. Soc. **A146**, 922 (1934).

isotopic specimens of lithium of about 5×10^{-8} grams, who showed that the correct isotopic origins had been given for the heavy particle and 30 cm proton groups which occur with proton and deuteron bombardment.

II. Apparatus and Procedure

The lithium targets used in this work were from a group of 20 isotopic specimens ranging from 10 to 200 micrograms in mass. The lithium was uniformly deposited as spots about one cm in diameter on small copper disks in a magnetic lens type of mass spectrometer.[2] A few targets were prepared as lithium chloride, but the targets chiefly used were 200 micrograms of Li^7 and 18 micrograms of Li^6 collected simultaneously and allowed to oxidize in air. Targets of Li^6 and Li^7 which were collected simultaneously and similarly handled subsequently, may be called matching targets. Wherever feasible, results with one isotope were compared with matching targets of the other to eliminate contamination effects from other elements. The isotopes were separated and collected with the mass spectrometer at the Bartol Research Foundation of the Franklin Institute.

The two-meter electrostatic generator of the Department of Terrestrial Magnetism[3] was used in the transmutation work. Voltages were read with the calibrated resistance voltmeter with which the generator is equipped. Range and neutron recoil observations were made with a linear amplifier coupled to a cathode-ray oscillograph for identifying particles, and to a dial counter through a scale-of-eight thyratron circuit. The thyratrons were usually biased to count only heavy ionizing particles near the ends of their ranges. Electrons were counted with a Geiger counter. A Lauritsen electroscope, shielded by a quarter-inch of lead, was used both with a paraffin lined chamber and with an aluminum chamber for neutron and gamma-ray measurements. The air equivalents of particle ranges were determined with graded mica foils mounted in two concentric wheels. The solid angle from the target subtended by the amplifier chamber was governed by diaphragming with a disk containing graded circular openings. All observations were made at angles between $90\pm16°$ and $90\pm7°$ with the ion beam. In general, no particular effort was made to determine absolute ranges with greater accuracy than about ±0.7 cm since the ranges of all the main groups in lithium transmutations have been measured by other workers. The range differences of associated groups are much more accurate, the chief limitation being set by the number of points determined on the number-range curves.

The atomic masses used in this work are those calculated by Bonner[4] from transmutation data.

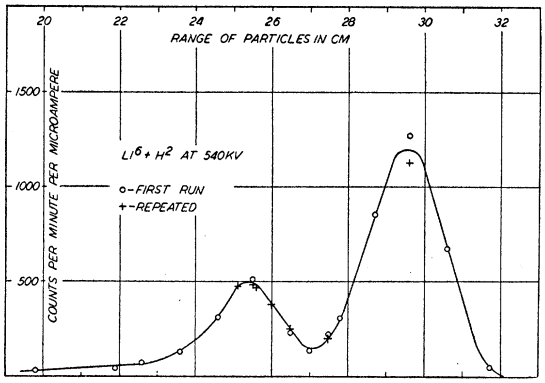

FIG. 1. Range curve for protons from Li^6+H^2.

III. Results

(a) Proton groups from ($Li+H^2$)

Deuteron bombardment of Li^6 yields two prominent proton groups differing in range by 4.2 ± 0.4 cm of air. The differential range curve plotted in Fig. 1 was obtained by biasing the thyratron counter against fast protons. It shows proton groups ending near 27.2 and 31.4 cm of air. Since the shorter group could not be obtained with matching Li^7 targets, it is not due to contamination by another element.

Li^7 targets were examined first for proton groups of 20 cm or more range. A yield curve

[2] L. H. Rumbaugh, Phys. Rev. **49**, 882 (1936); W. R. Smythe, L. H. Rumbaugh and S. S. West, Phys. Rev. **45**, 724 (1934).

[3] M. A. Tuve, L. R. Hafstad and O. Dahl, Phys. Rev. **48**, 315 (1935); L. R. Hafstad, N. P. Heydenburg and M. A. Tuve, Phys. Rev. **50**, 504 (1936).

[4] T. W. Bonner, presented at the symposium on nuclear physics, Cornell University, July 2–4, 1936. These masses closely agree with the recent mass spectrograph determinations of Bainbridge and are probably accurate to ±0.0002 mass unit. The following values are used in this work: $n^1=1.0090$; $H^1=1.0081$; $H^2=2.0147$; $He^3=3.0171$; $He^4=4.0040$; $Li^6=6.0170$; $Li^7=7.0182$; $Be^8=8.0080$; $Be^9=9.0149$.

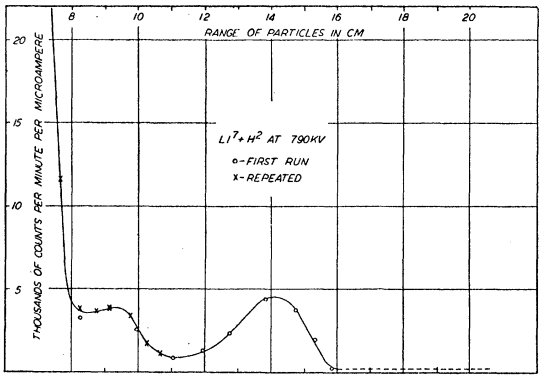

FIG. 2. Range curve for particles from Li^7+H^2.

was taken from 260 to 790 kv, using a 200-microgram target of Li^7, with the absorbing foils set at 20 cm and the thyratrons biased to count all fast protons. The yield curve obtained increased smoothly with voltage, giving no evidence for the existence of resonances. The kicks observed with the oscillograph throughout were of the heterogeneous character of neutron recoils. Next, the interval between 20 and 80 cm was explored at 790 kv and no trace of any group as strong as 20 percent of the neutron recoil background could be observed. Since no evidence for a resonance had been found, it was concluded that no proton groups of ranges greater than 20 cm are emitted by Li^7+H^2.

The Li^7 targets under deuteron bombardment at 790 kv show two weak proton groups ending at about 10.6 and 15.8 cm (Fig. 2). The strong group ending at 7.9 cm is composed of the continuous alpha-particles from Li^7. These groups were the only ones found when the region between 7 and 20 cm was investigated at three voltages; 260, 540, and 790 kv. Later in this paper it will be shown that the proton groups at 10.6 and 15.8 cm may be ascribed to contamination of the target, though no comparison with matching Li^6 targets was made, since in that case the strong 13-cm group of alpha-particles would have marked both proton groups.

(b) Alpha-particles

The five groups of alpha-particles from lithium have been studied by a number of workers since the discovery of lithium transmutation by Cockcroft and Walton. The separated isotopes, Li^6 and Li^7, have been used by Oliphant, Shire, and Crowther to show that the five groups had been attributed to the proper isotopes.[1] Three alpha-particle groups were observed in the course of the present work: one at 8.5 cm, from Li^7+H^1; another at 13 cm, for Li^6+H^2; and the continuous group ending at 7.9 cm, from Li^7+H^2. Though a short group was observed visually, the groups at 0.8 and 1.1 cm, from Li^6+H^1, were not investigated.

(c) Mass and purity of targets

The relative masses of isotopic specimens were obtained from the collector currents observed in the mass spectrometer. The absolute masses of several specimens, of weights up to one milligram, were determined by chemical methods with an accuracy of ± 2 micrograms, so that the correction to be applied to the collector currents for secondary electron emission was known. Thereafter, the masses of the isotopes deposited during any run were computed from the collector currents.

The isotopic purity of targets of Li^6 and Li^7 was found from the comparative strengths at the same voltages of the appropriate alpha-particle groups, diaphragms of different sizes necessarily being used with the amplifier chamber. The ratio Li^6/Li^7 in a Li^6 target is approximately 1000, as determined by comparing the 8.5 cm alpha-particles, produced by the reaction $Li^7+H^1=He^4+He^4$, in a Li^7 target with the same group from a Li^6 target. The ratio Li^7/Li^6 was greater than 30,000 for the Li^7 targets, the 13-cm alpha-particles from $Li^6+H^2=He^4+He^4$ being used for comparison. These alpha-particles, though only about twice as numerous as the background of large neutron recoils, in Li^7 targets, proved very useful in identifying other contamination products, since the range of the group has been carefully determined by Oliphant, Kempton, and Rutherford.[5]

The shorter proton group from Li^7 targets, Fig. 2, having a range of 10.6 ± 0.4 cm at 790 kv was attributed to the reaction $O^{16}+H^2=O^{17}+H^1$, originating in oxygen contamination. The range of this group has recently been determined as 9.2 cm at 575 kv by Cockcroft and Lewis[6] and

[5] M. L. E. Oliphant, A. R. Kempton and Lord Rutherford, Proc. Roy. Soc. **A149**, 406 (1935).

[6] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **A154**, 261 (1936).

the value given agrees satisfactorily, when proper correction is made for voltage.

The other proton group has ranges of 15.8 cm at 790 kv, 14.1 cm at 540 kv and 12.7 cm at 260 kv, and so must have originated from carbon contamination giving the reaction, $C^{12}+H^2=C^{13}+H^1$. The ranges were measured with an accuracy of about ±3 mm by reference to the underlying Li^6+H^2 alpha-particles, and closely agree with the recent determination of 13.9 cm at 560 kv by Cockcroft and Lewis.[6] Fig. 3 gives the differential range curve from this region at 540 kv. The 14.1-cm protons were about 200 times stronger than the alpha-particle group, which was picked up under the protons by biasing the thyratrons to count only alpha-particles near the ends of their ranges. At this voltage, the range of the deuterium protons should be 15.5 cm.[5, 6] Since no group of that range was observed, it was concluded that the deuterium contamination was negligible.

(d) Gamma-rays from (Li+H¹)

The gamma-radiation from matching targets (18 micrograms of Li^6 and 200 micrograms of Li^7), under proton bombardment, was measured with the electroscope shielded by a quarter-inch of lead. The rate of discharge of the electroscope for Li^6 and Li^7 is plotted against voltage in Fig. 4.

Both the strong resonance at 450 kv and the increase in ionization at higher voltages reported by Hafstad and Tuve[7, 8] are clearly indicated as being due to Li^7. The observations with a paraffin lined ionization chamber at about 1000 kv show no appreciable increase in ionization, suggesting that the radiation at this voltage also is predominantly of a gamma-ray nature. The discharge rate for the Li^6 target was practically indistinguishable from the zero drift of the electroscope (0.07 division per minute) both at resonance and at higher voltages, so that the small effect indicated in Fig. 4 is probably spurious.

(e) Neutrons from (Li+H²)

The neutron emission by lithium under deuteron bombardment, first reported by Crane, Lauritsen, and Soltan,[9] was found to come from *both* isotopes, contrary to the results of the Cambridge investigators.[1] A 200-microgram target of Li^7 was exposed to deuterons at 540 kv and the neutron recoils produced in the shielded air-filled chamber of the amplifier were recorded. There were counted 20±3 kicks per microampere per minute, of sizes equal to or greater than those produced by protons in their last 2 cm of range. The discharge rate of the shielded electroscope with a paraffin lined chamber was 11.8 divisions per minute. The ratio of the discharge rate using a paraffin lined chamber to that using an aluminum chamber was 1.7, the increased discharge rate occurring with the paraffin lining being due to proton recoils produced by the neutrons.

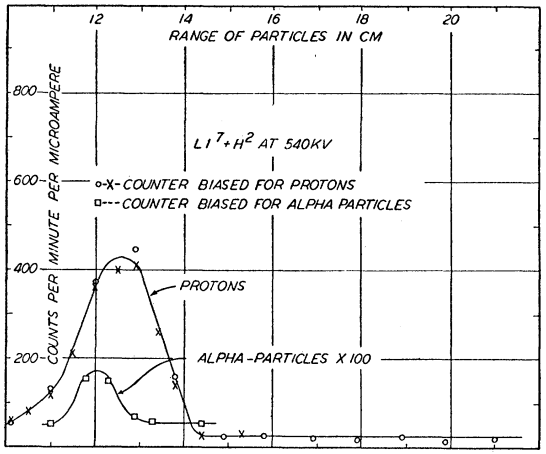

FIG. 3. Range curve for particles from Li^7+H^2.

At the same voltage and thyratron bias, the matching 18-microgram target of Li^6 yielded 4.8±0.8 amplifier kicks per microampere per minute and discharged the lined electroscope at the rate of 4.1 divisions per minute. The ratio of the paraffin lined electroscope discharge rate to that without lining was 2.3 for the 18-microgram target. A shorter observation with 35 micrograms of Li^6, used as Li^6 Cl, gave an electroscope ratio of 2.6.

It appeared impossible to account for any appreciable part of these Li^6+H^2 neutrons by contamination by Li^7 or H^2 in view of the isotopic purity and negligible deuterium contamination of the targets as discussed above. Oxygen and

[7] L. R. Hafstad and M. A. Tuve, Phys. Rev. **48**, 306 (1935).

[8] L. R. Hafstad, N. P. Heydenburg and M. A. Tuve, Phys. Rev. To appear in November 1, 1936, issue.

[9] H. R. Crane, C. C. Lauritsen, and A. Soltan, Phys. Rev. **44**, 692 (1933).

carbon were the only other elements present in amounts detectable by means of their characteristic protons. The activation function of oxygen by deuterons, as determined by Newson,[10] indicates that neutron emission does not occur below 2 Mev. Since carbon is known to emit neutrons at much lower voltages, a graphite disk was exposed to 1.3 microamperes of 540 kv deuterons as a check. The discharge rate produced in the paraffin lined electroscope was 0.07 ± 0.02 division per minute, from which the residual drift of 0.07 division per minute had to be subtracted. While this negative result was to have been expected for carbon neutrons, which are of low energy, it also served as a further check against contamination effects, particularly in those parts of the target chamber from which transmutation groups could not be emitted through the window.

As a further precaution, rough excitation curves were made for neutrons from both Li^6+H^2 and $C^{12}+H^2$, counting air recoils with results as shown by solid lines in Fig. 5. The marked difference in the curves together with the visual observation that the sizes of the deflections on the cathode-ray monitor were several times larger for Li^6 neutron recoils than for C neutron recoils, showed conclusively that the neutrons from Li^6 targets cannot be ascribed to carbon contamination.

To further test the possibility that the neutrons might be due to deuterium, a target of $P_2O_5+D_2O$ was prepared and bombarded with deuterons at 540 kv. Few neutron recoils were observable above the residual count of the detecting chamber, indicating that the neutron yield from Li^6 is large compared to that from such a target of deuterium. This evidence, together with that given in Fig. 3 which was obtained with a target that had had about four times the exposure of the Li^6 target to deuterons, appears to us to eliminate the possibility that the neutrons observed were due to deuterium contamination.

The results of Fig. 5 have a further important significance. Since the yield of neutrons from $C^{12}+H^2$ can be deduced immediately from the yield of radioactive N^{13} which is known,[7, 11]

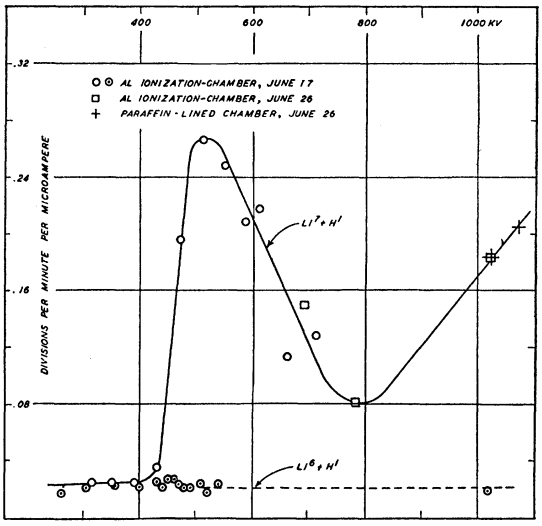

FIG. 4. Excitation curve for gamma-rays from lithium.

an estimate of the yield of neutrons from Li^6 can be obtained. As given, any comparison of the solid curves in Fig. 5 must take into account the fact that the low energy C^{12} neutrons will produce fewer air recoils with sufficient energy to be detected than the high energy Li^6 neutrons. This correction can be greatly reduced by counting recoils with an ionization chamber filled with hydrogen in which case low energy neutrons can be detected. Observed points for 810 kv, obtained with such a chamber, using a pressure of about two atmospheres of hydrogen, are shown in Fig. 5, the dotted lines showing the corresponding excitation curves obtained by adjusting the solid curves to fit the new points at 810 kv. From the intersection of these two curves one may conclude that the yield of neutrons from this 18-microgram target is equal to that from a thick carbon target at about 750 kv. The latter yield is approximately 6 neutrons per 10^8 incident particles at this voltage, and since the excitation curve for Li^6 does not drop rapidly with voltage, thick targets of Li^6 may prove to be of value in the production of neutrons with low voltage ion accelerators.

(f) Radioactivity from $(Li+H^2)$

A 0.5 second half-life beta-radioactivity induced in lithium by deuterons has been reported from the California Institute of Technology.[12]

[10] H. W. Newson, Phys. Rev. **48**, 790 (1935).
[11] S. K. Allison, Proc. Camb. Phil. Soc. **32**, 179 (1936).
[12] H. R. Crane, L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev. **47**, 971 (1935).

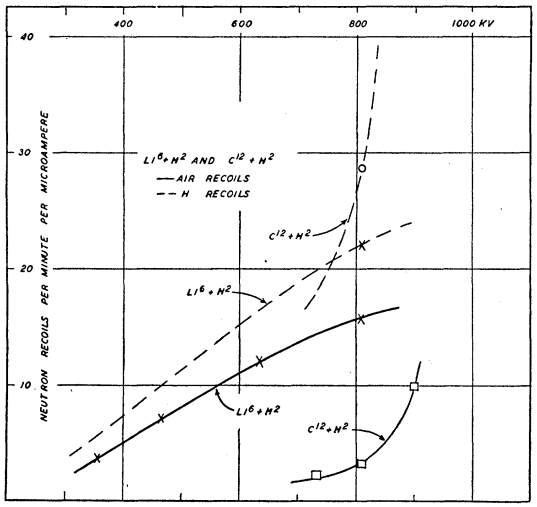

FIG. 5. Excitation curve for neutrons from Li^6+H^2 and $C^{12}+H^2$.

In the present work, the activity was observed from a semi-thick target of Li^7 in a crude but convincing manner. A Geiger counter, covered with thin aluminum equivalent to about 40 cm of air, was placed before the window of the target chamber. Counts were made while the target was exposed to deuterons for a few seconds and were continued when the deuteron beam was interrupted by a movable quartz disk. In this way, a definite and very rapidly decaying activity was observed. At 750 kv, the count was 35 to 40 per second during exposure, and 35 to 45 counts were recorded in the first 5 seconds following manual interruption of the deuteron beam. At 5 seconds, the counting rate had fallen to the background rate of about 0.4 per second. Between observations the counter was checked with the beta-rays of Ra D and E for sensitivity and sharpness of cut-off following rapid counting. The induced activity of lithium, as indicated by counting rates during exposure of the target to deuterons, showed an abrupt threshold at about 500 kv below which it could not be detected. The activation function shown in Fig. 6 was obtained with a 200-microgram target of Li^7.

A target of Li^6 gave no increase in counting rate during exposure of the target to deuterons for periods up to one minute at several voltages between 350 and 750 kv. The slight increase occurring after exposures of more than one minute was attributed to the activation of carbon in the target chamber. Because of the neutron emission for Li^6, which might be interpreted to imply a positron emission of fairly long life, a thick target of ordinary pure lithium chloride was bombarded with two microamperes of 850-kv deuterons for 2.5 hours and examined in the electroscope chamber for positron activity. The only activity detected had the half-life of activated carbon.

(g) Possibility of observing (Li^5+H^2) reactions

Brewer[13] recently has reported evidence indicating that a new isotope, Li^5, constitutes about one part in 20,000 of the lithium ion emission from thermal sources. As part of the present work, three targets were exposed in the mass five position of the magnetic lens mass spectrometer during the collection of three milligrams of the lithium isotopes. The ions fell on the collectors through windows which were opened only when Li^7 showed good focus. The best of the targets was prepared in a discontinuous run totaling 15 hours during which 1.2 milligrams of Li^7 were collected. The electrically measured background at the mass five position varied between one part in 4000 and one part in 15,000 of the Li^7 collector current. The faint deposit on the mass five target only became visible after exposure to the fumes of hydrochloric acid.

A preliminary survey with this target indicated that carbon and Li^7 were the principal contaminations and that a small amount of Li^6 was also present. If Li^5 exists,[14] its mass should be less than that of He^4+H^1. Hence, the maximum range particle to be expected from a Li^5 would be a five cm proton from the reaction $Li^5+H^2=Li^6+H^1$. If the mass is still lower, all particles may be too short in range to be detected. Furthermore, the contamination background would make the search for particles from this reaction a very difficult one. In consequence, no detailed survey of short-range particles from these targets will be made until the ratios of Li^5 to Li^6 and Li^7 have been determined in a mass spectrograph with ion sources prepared at the mass five position. If the results warrant it, the background during collection probably can be decreased by a considerable factor.

[13] A. K. Brewer, Phys. Rev. **49**, 635 (1936).
[14] W. Bleakney (private communication) has failed to observe Li^5.

IV. Discussion of Results

Proton groups from Li^6+H^2

The two proton groups found with Li^6 under deuteron bombardment are important for two reasons. (1) The shorter of these groups is doubtless the one observed by Delsasso, Fowler and Lauritsen[15] with a cloud chamber and generally attributed to the transmutation of Li^7. Calculations of the mass of Li^8 based on the range of this group therefore are wrong. (2) The emission of two line groups of protons from a single nuclear species points to the existence of two absorption or emission levels in one of the reacting nuclei. On the assumption that emission of the shorter group involves the formation of Li^7 in an excited state, the equations for the reactions may be written

$$Li^6+H^2=Li^7+H^1,$$

and $$Li^6+H^2=Li^{7*}+H^1;\quad Li^{7*}\rightarrow Li^7+h\nu$$

where $h\nu=400\pm40$ kv. A more detailed discussion, of particular interest to theorists, may be made when the two groups have been examined at a number of deuteron energies.

Mass of Li^8

The failure to observe any proton group of range greater than 8 cm from Li^7+H^2 introduces difficulties in the previous interpretation of the beta-activation of lithium by deuterons. Since the discovery of this activity at the Pasadena laboratories,[12] Knol and Veldkamp[16] have succeeded in inducing it in lithium with slow neutrons, and the present work has shown that it is derived from Li^7. It follows that the radioactive nucleus formed probably is Li^8, so the equation for the first stage of the reaction is

$$Li^7+H^2=Li^8+H^1.$$

Since by our observations the range of the protons from this reaction at 790 kv is probably less than 8 cm, the mass of Li^8 is given by

$$Li^8>Li^7+H^2-H^1-1.8 \text{ Mev}$$
$$Li^8>8.022(8).$$

The mass of Li^8 also may be computed from the observed energy of 10.5 ± 1 Mev for the upper limit of the beta-spectrum[12] assuming no gamma-radiation:

$$Li^8\rightarrow Be^8+\bar{e}=Be^8+10.5\pm1 \text{ Mev}$$
$$=8.019(3)\pm0.001.$$

The discrepancy between the mass values obtained in the two ways is too large to be explained by experimental error in the determination of the upper limit of the beta-spectrum, particularly since Crane, Delsasso, Fowler and Lauritsen[12] already have extended the apparent value of the limit somewhat to fit the extrapolated Konopinski-Uhlenbeck formula. It appears, therefore, that if this process does occur, then the ejection of the proton and the emission of the beta-particle must be accompanied by yet a third reaction to absorb the excess energy. This reaction probably follows the ejection of the beta-particle and may involve any of three processes:

1. $Li^8\rightarrow Be^{8*}+\bar{e}\rightarrow He^4+He^4+\bar{e}$
2. $Li^8\rightarrow Be^{8*}+\bar{e}\rightarrow He^4+He^4+\bar{e}+h\nu$
3. $Li^8\rightarrow Be^{8*}+\bar{e}\rightarrow Be^8+\bar{e}+h\nu.$

The most definite information pertaining to the formation of Li^8 is given by the activation function for Li^7+H^2 (Fig. 6), which shows that the transmutation to Li^8 with emission of a proton starts abruptly when the deuteron energy reaches 500 kv. The function seems to rise too slowly and extend over too wide a voltage range to be due to resonance in a thin

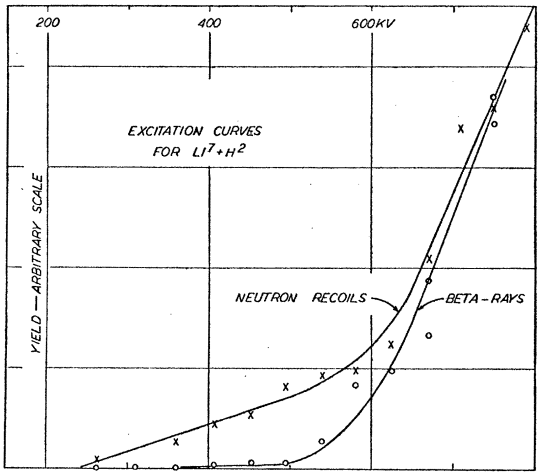

FIG. 6. Excitation curve for beta-rays and neutrons from Li^7+H^2.

[15] L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev. **48**, 848 (1935).
[16] K. S. Knol and J. Veldkamp, Physica **3**, 145 (1936).

target. On the other hand, the sharp threshold is totally different from that predicted by the Oppenheimer-Phillips[17] relation which requires that the experimental curve shall rise tangentially from an indefinite threshold on the voltage axis. It appears, therefore, that the processes are selective rather than endothermic below 500 kv.

Since the Oppenheimer-Phillips relation does not hold, the deuteron may be captured as a whole and the proton emitted from within the resultant Be^9 nucleus. Hence the three known transmutations of Li^7 by deuterons may be written as deuteron capture equations:

$$Li^7+H^2=Be^{9*}\begin{cases}1.\ He^4+He^4+n^1\\ 2.\ Be^8+n^1\\ 3.\ Li^8+H^1.\end{cases}$$

A plausible explanation of the form of the activation function can be given on the basis of selective reactions. Suppose that when the energy of the deuteron is below a certain critical value, $E_0\sim 500$ kv, a proton may be excited to a positive energy level *below* the top of the potential barrier for Be^9. The time necessary for the proton to penetrate the potential barrier, bringing about reaction (3), is long compared to the time for the emission of a neutron, in accordance with reactions (1) or (2), because of the relatively low binding energy of the neutron in the Be^9 nucleus and its immunity to the potential barrier. Hence, proton emission will not occur until a deuteron energy E_0 is supplied, at which protons begin to escape over the top of the potential barrier. In consequence, the transmutation to Li^8 shows an abrupt threshold at that voltage.

Existence of Li^8

The beta-activity induced in lithium by deuterons cannot be ascribed to Li^8 with certainty until a *line* group of protons is found, indicating *two-body* disintegrations and the consequent formation of Li^8. It is plausible that three-body disintegrations may occur and that one of these bodies is the radioactive one, rather than Li^8. In either case, the investigations of Knol and Veldkamp[16] with neutrons require that proton emission shall occur when deuterons are used to produce the activity.

The neutrons from Li^6; approximate mass of Be^7

Neutron emission produced from Li^6 by deuterons may be expected to originate in only two ways:

1. $Li^6+H^2=He^4+He^3+n^1+Q_1$
2. $Li^6+H^2=Be^7+n^1+Q_2$.

The first process is exothermic, since Q_1 is about 1.5 Mev on the Bonner mass scale. The maximum energy of the neutrons would be 1.3 Mev and the mean energy about 400 kv, in marked contrast to the well-known analogous reaction, $Li^7+H^2=He^4+He^4+n^1$. In the latter case the neutron energies are distributed to a maximum of 13.3 ± 0.5 Mev and the mean neutron energy is about 3.9 Mev, according to Bonner and Brubaker.[18]

The energy balance, Q_2, of the transmutation to Be^7 cannot be computed accurately since it contains the mass of the unknown nucleus, Be^7. If Be^7 is radioactive, the reaction must be $Be^7\rightarrow Li^7+e^+$, and it follows that Be^7 is heavier than Li^7 by at least two electronic masses; i.e., Q_2 is not greater than 3.162 Mev, if the possibility of positron emission by Be^7 is admitted. If such radioactivity exists, it must have a fairly long life and a low energy spectrum to have escaped detection, both in the present experiments in which it was investigated, and in the cloud chamber studies of the beta-activity of lithium by Crane, Delsasso, Fowler and Lauritsen.[12] In the latter case, positrons would have been immediately obvious because of their curvature in the magnetic field of the cloud chamber, unless their maximum energy was little greater than 0.3 Mev, the stopping power of the foil surrounding the target. Consequently, if Be^7 is a positron emitter, $Q_2\sim 2.86\pm 0.3$ Mev, possible gamma-radiation being neglected. On the other hand, Be^7 may be non-radioactive and as light as its isobar, Li^7. A close equivalence of isobaric masses has been found for H^3 and He^3 and for Be^{10} and B^{10}. If the mass of Li^7 is taken for Be^7, $Q_2\sim 4.2$ Mev.

It is clear that accurate knowledge of the

[17] J. R. Oppenheimer and M. Phillips, Phys. Rev. **48**, 500 (1935).

[18] T. W. Bonner and W. M. Brubaker, Phys. Rev. **48**, 742 (1935).

energies of the neutrons emitted from Li^6+H^2 is needed to distinguish between the two suggested values of Q_2, and thus indicate the process involved.

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Gamma-Rays of Lithium and Fluorine Under Alpha-Particle Bombardment*

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The energies of the γ-rays emitted from lithium and fluorine under bombardment by polonium α-particles are determined, and their variation with the energy of the incident particles is studied. In the case of lithium no change in γ-ray energy is observed as the range of the incident α-particles is reduced from 3.9 cm to 2.5 cm. This is taken to support the view that the radiation results from excitation of the lithium nucleus without capture of the α-particle. At an incident range of 3.9 cm the γ-radiation from fluorine is shown to consist of two components. When the incident range is reduced to 3.1 cm the harder component disappears. Possible explanations are discussed, and the existence of a hitherto undetected proton group of low energy is suggested.

INTRODUCTION

IT is now generally recognized that the study of the γ-rays resulting from the bombardment of light atoms with high energy particles yields important information concerning nuclear structure. In particular, in the light of present theory the energies of these γ-ray quanta offer a direct measure of excited energy states in the nuclei responsible for their emission, and a knowledge of these energies is essential for the formulation of a quantitative theory of nuclear constitution. Accordingly, the present investigation was undertaken to measure the energy of the γ-rays thus obtained from lithium and fluorine, two of the most favorable elements for such studies. Special attention was paid to the effect on the quality of the radiation of varying the range of the incident α-particles. With a Geiger point counter for detection, the energies of the γ-rays were determined from their absorption in lead.

The existence of induced nuclear γ-rays was first demonstrated by Bothe and Becker,[1] who observed their emission from six of the light elements under intense α-particle bombardment. Subsequently Curie and Joliot,[2] Webster,[3] and others extended their results and defined more accurately the conditions of excitation. Savel[4] has recently investigated the penetrating radiations emitted in artificial disintegration, finding evidence for several different processes giving rise to accompanying γ-rays.

The γ-rays are believed to arise in the following manner. During a collision the incident α-particle is captured, a composite nucleus being formed momentarily, and subsequently one of the constituent nuclear particles is ejected. If the product nucleus is left in an excited state, a γ-ray is emitted in the subsequent return to the ground level. It may happen that the α-particle is not absorbed into the nucleus, but penetrates and then escapes again with reduced energy, the difference being spent in exciting the struck nucleus. In this case also the surplus nuclear energy is later released in the form of a γ-ray.

It is likely that some of the γ-rays from both lithium and fluorine are the result of the latter

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[1] W. Bothe and H. Becker, Zeits. f. Physik **66**, 289 (1930).

[2] I. Curie and F. Joliot, Comptes rendus **194**, 273 (1932); **194**, 708 (1932); **194**, 876 (1932).

[3] H. C. Webster, Proc. Roy. Soc. **A136**, 428 (1932).

[4] P. Savel, Ann. d Physik (II) **4**, 88 (1935).