Experimental Survey of Nuclear Transformations Caused by 2-Mev Lithium Ions*

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Ion beams of Li^7 or Li^6, between 1 and 2 Mev in kinetic energy, produced in a Van de Graaff accelerator were used to bombard targets containing light elements and some of the induced nuclear reaction products were detected. Detection was by observation of the induced radioactivity, or by counting charged particles, or by activation of copper by means of the fast neutrons produced. Existence of the following reactions was demonstrated:

Target	Beam	Products
Li^6	Li^6	$C^{11}+n$; He^5+Be^7
Li^6	Li^7	$C^{11}+2n$; $B^{12}+p$; $C^{12}+n$
Li^7	Li^7	$B^{13}+p$; $B^{12}+d$; Be^8+He^6; $C^{13}+n$
Be^9	Li^6	$N^{13}+2n$; $N^{14}+n$
Be^9	Li^7	$B^{12}+He^4$; Be^8+Li^8; $N^{15}+n$
B^{10}	Li^6	$O^{15}+n$; $O^{14}+2n$; $C^{11}+He^5$
B^{10}	Li^7	$O^{15}+2n$
C^{12}	Li^6	$F^{17}+n$
C^{12}	Li^7	$F^{18}+n$

Yield *vs* bombarding-energy curves were obtained for the Li—Li reactions and the Be^9 reaction producing Li^8. Resonances in the yield were not observed. Some of the reactions are capable of producing neutrons of 20-Mev energy; the existence of neutrons above 11 Mev was demonstrated by initiating the reaction $Cu^{63}(n,2n)Cu^{62}$, which requires this energy.

A search for the production of N^{13} from the reaction $B^{10}(Li^7, H^4)N^{13}$ through the range of bombarding energy indicated by the mass range through which H^4 would be stable against heavy-particle breakup gave a null result, indicating that H^4 is unstable.

Estimates for the yield at 2-Mev bombarding energy were made for all reactions except that leading to F^{17}.

INTRODUCTION

ONLY a small number of nuclear reactions between lithium ions and nuclei heavier than helium have been reported to date.[1] In order to gain an over-all view of these effects so that more detailed experiments can be planned, a study was made of the yields of a rather wide variety of lithium-induced reactions. It was found that 2-Mev lithium nuclei penetrate the Coulomb barriers of nuclei up to carbon to a detectable extent. Many of the induced reactions are characterized by large energy releases, from 10 to 20 Mev. It is also noteworthy that sufficient yields of particles for experimentation can be obtained from collisions in which the relative velocity of the two nuclei is very low; for instance, in 2-Mev Li—Li collisions the energy in the barycentric system is only 71 kev per nucleon.

APPARATUS

The 2-Mev Van de Graaff accelerator and the ion source used have been previously described.[2] For this study the platinum filament in the ion source was coated with synthetic β-eucryptite made with approximately equal amounts of the two lithium isotopes.

We were then able to obtain either a Li^6 or a Li^7 beam of the order of a microampere by the appropriate setting of the sorting magnet. Suitable beam stops and an insulating section permitted the measurements of the beam current incident on the target.

For accurate measurements on the longer lived radioactive products, we were able to use β counters of known geometry and low background which had circuits giving automatic printout of the counts collected during preset time intervals. Bombardments were carried out on freshly prepared targets which were removed from the target chamber and transferred into counters in the counting room in 2 to 3 minutes. The rapid removal of the targets from the vacuum system was facilitated by the use of steel V-band couplings[3] to hold "O" ring flanges together.

To detect low-energy gamma emission, including positron emitters, an activated NaI(Tl) scintillating crystal 4.45 cm in diameter, 5.08 cm long, with a 1.90-cm diameter well was used.[4] Beta activities which were too short-lived to allow removal from the vacuum system for counting were detected with a well-shaped piece of plastic scintillating material of similar dimensions. The scintillators were viewed by photomultiplier tubes used with conventional high-voltage supplies, amplifiers, and scalars.

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[1] Allison, Murphy, and Norbeck, Phys. Rev. **102**, 1182 (1956); E. Norbeck, Jr., Phys. Rev. **105**, 204 (1957); P. G. Murphy, Phys. Rev. **108**, 421 (1957).

[2] See references 1, and J. P. Blewett and L. J. Jones, Phys. Rev. **50**, 465 (1936); S. K. Allison and C. S. Littlejohn, Phys. Rev. **104**, 959 (1956).

[3] Marman Products Company, Inglewood, California.

[4] Obtainable from the Harshaw Chemical Company, Cleveland, Ohio.

The beam could be cut off either by the manual release of a spring-loaded mechanical beam stop having a relay and switch which turned on the counters after a fixed delay of from 0.05 to 0.1 second, or by applying a 7000-volt square wave to a pair of plates between which the beam passed, this latter method cutting off the beam within 0.001 second.

In order to measure very short half-lives and obtain relative yields, a special time to pulse-height conversion circuit was constructed. The time to pulse-height converter was built around the step-function output of the Hewlett-Packard model AC-4A decade counter operated from signals generated by the 60-cycle line. The first and highest step is connected to the input of the 7000-volt square-wave generator, which sweeps the beam either on or off the target. The output from the particle detector is shaped and mixed with the remaining nine steps. The counts on these steps were then recorded on nine channels of a multichannel pulse-height analyzer. This 18-channel analyzer (consisting of three six-channel units made by Marconi Ltd.) was also used in the conventional manner to observe gamma and beta spectra.

A special integrating arrangement was used to facilitate the measurement of the yields of the short-lived activities of He^6 (0.82 sec) and Li^8 (0.84 sec). Since variations in the beam intensity over the interval of a second are of importance, we found it convenient to use an integrator which measured the effective beam which had impinged on the target during the activation time, that is, an integrating circuit with a decay constant equal to the decay time of the radioactive species in question. For the two activities mentioned, we used a quadrant electrometer which measured the voltage on a 0.15-microfarad condenser with an 8-megohm resistance leak, corresponding to a discharge half-life of 0.83 sec.

Targets were prepared individually for separate measurements. Thick targets of isotopically separated lithium salts were prepared by heating Li^6F on iron target buttons and $(Li^7)_2SO_4$ on nickel buttons until hard glassy surfaces were obtained. To look at weak betas, thin 0.002-in. iron shim was used as backing. Metallic beryllium was machined to shape to make thick targets of beryllium, and thin targets of beryllium were produced by evaporation of the metal onto nickel buttons.

Boron targets were specially prepared for us through the courtesy of the Institute for the Study of Metals of this University. Boron powder (either the natural isotopic mixture or enriched in B^{10}) was compressed to 50 tons per square inch in a powder-briquetting die and sintered at 800°C in a vacuum. The oxide which collects on all stored boron powder provides the necessary binder. Targets prepared in this manner should be kept in a desiccator in order to prevent disintegration in humid weather. Carbon targets were machined from graphite.

BETA ACTIVITIES OF SHORT HALF-LIFE AND THEIR EXCITATION FUNCTIONS

In order to study the mechanism of reaction, we measured excitation functions for some selected reactions taking place during the bombardment of various targets with lithium beams. It was thought to be of interest to compare the excitation functions of several decay modes for a given projectile and target, in order to discover whether there would be any indication that certain reactions took place through compound-nucleus formation, or through nucleon-transfer processes between otherwise only slightly perturbed nuclei. Excitation curves have been measured so far only for lithium and beryllium targets; the considerably lower yields from boron and carbon require prolonged counting periods for comparable accuracy.

Thick-target excitation functions were measured directly for the formation of B^{12} from the reaction $Li^6(Li^7, p)B^{12}$, $Q=8.325$ Mev, and for B^{12} and presumably also B^{13} from the reactions $Li^7(Li^7, p)B^{13}$, $Q=5.967$ Mev, and $Li^7(Li^7, d)B^{12}$, $Q=3.306$ Mev. This was done by counting the 13.4-Mev beta particles emitted during decay in a well-shaped plastic scintillator designed specifically for this purpose. The brass tubing of the vacuum wall around the target was sufficiently thick to stop the 3.5-Mev β rays from the decay of He^6, which is also produced in the Li-Li reactions, from entering the scintillator. External shielding was used to reduce spurious backgrounds. The solid angle through which recoils could escape was 0.4 steradian and was in the backward direction, so that changes in the angular distribution of the reaction products with beam energy would not affect the excitation curve. The curves are shown in Fig. 1.

In order to measure the soft betas from He^6 formed in the reaction $Li^7(Li^7, Be^8)He^6$, $Q=7.229$ Mev, the LiF for the target was fused onto 0.002-inch steel shim. The well of the plastic scintillator was used directly as a target chamber since it was found possible to attach the entire scintillating plastic to the vacuum system. The inner walls of the well in which the target was placed were lined with thin aluminum foil to stop heavy particles and protect the scintillator from the fluorescence of the target under the beam. The manual release of the spring-loaded beam stop turned on the counters after a fixed delay of 0.05 to 0.1 sec following beam cutoff. The "leaky integrator" circuit was also used in these runs. The yield curve for He^6 formation is included in Fig. 1.

Figure 1 also shows a curve giving the number of protons from $Li^7(Li^7, p)B^{13}$ emitted into unit solid angle at 90° to the beam per microcoulomb of lithium ions incident. The original data for this curve are the same as those used by Norbeck[1] for Fig. 3 of his paper. Our Fig. 1 shows Norbeck's data corrected for the deficiency in transmission of a screen used by him, and not properly allowed for in the prior article. Table I

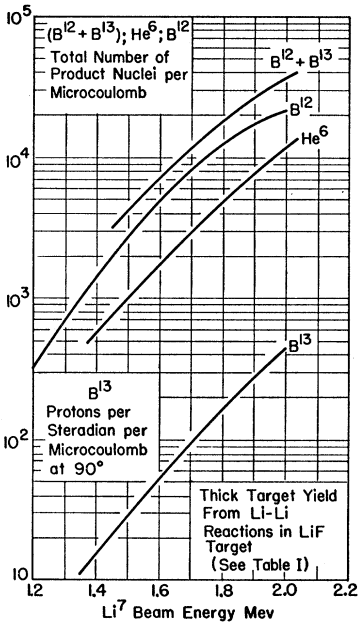

FIG. 1. The upper three curves give the total production of radionuclei per microcoulomb of lithium ion beam from [$Li^7(Li^7, p)B^{13}$ $+Li^7(Li^7, d)B^{12}$], $Li^6(Li^7, p)B^{12}$, and $Li^7(Li^7, Be^8)He^6$ in thick LiF targets. The lower curve, obtained from counting the protons from $Li^7(Li^7, p)B^{13}$ gives numbers of protons emitted into unit solid angle at 90° in the laboratory.

gives values of certain thick-target yields from 2-Mev Li^7 ions.

Figure 2 shows cross sections which have been deduced from Fig. 1, except for the cross section for the sum of the activities $B^{12}+B^{13}$, which was obtained from a yield curve taken with a $(Li^7)_2SO_4$ target instead of the usual Li^7F. A cross-section curve deduced from the LiF yield curve of Fig. 1 for this reaction agrees within experimental error (perhaps 30%) with the one presented in Fig. 2. The cross sections have been deduced by means of the formula,

$$\sigma=-\frac{1}{N_P N_T}\frac{dY}{dE}\frac{dE}{dx},$$

in which N_P is the number of lithium ions hitting the target per microcoulomb, N_T is the number of Li nuclei per cm^3 in the target material, dY/dE is the slope of the yield-energy curve in radionuclei per microcoulomb produced due to increment dE (Mev) in beam energy, and dE/dx is the stopping power of the target material for lithium ions in Mev/cm.

The stopping power of LiF and Li_2SO_4 for lithium ions was roughly estimated from data published by Allison and Littlejohn,[2] and by Devons and Towle.[5]

The dashed curve in Fig. 2 is from calculations kindly made for us by Biedenharn and Thaler,[6] using an electronic computer. Calculations were made of the factor s_0, which concerns the probability[7] of penetration of the Coulomb barrier in a Li^7-Li^7 collision. The channel radius assumed in the calculation was $2\times1.4\times7^{\frac{1}{3}}\times10^{-13}$ cm. The ordinates of the dashed curve are proportional to $\lambda^2 s_0$, where λ is the de Broglie wavelength of approach of the two nuclei, and the curve is normalized to fit the observed cross section for [$Li^7(Li^7, p)B^{13}$ $+Li^7(Li^7, d)B^{12}$] at 1.8 Mev.

It is conceivable that the reaction $Li^7(Li^7, He^6)Be^8$ proceeds by the transfer of one proton between the colliding Li^7 nuclei without profound disturbance of either one, and that this transfer might be accomplished at internuclear distances large compared to those of "contact" and welding of the two nuclei together, as would be necessary to produce B^{12} in $Li^7(Li^7, d)B^{12}$. The excitation cross sections of Fig. 2 do not give support to the idea that less penetration of the barrier is necessary for proton transfer since the curves for the production of He^6 and B^{12} have essentially the same slope.

Excitation curves for the formation of Li^8 from the reaction $Be^9(Li^7, Li^8)Be^8$, $Q=0.371$ Mev, were measured directly with the scintillating plastic well crystal (in the manner of B^{12}) with the beam on, and also by measuring the delayed counts, with the "leaky integrator" circuit and manual beam stop used for He^6. The yield curves (Fig. 3) for the equilibrium counting rates by these two methods coincided within the experimental errors of either one, indicating that no appreciable amount of spurious counts from other sources than Li^8 were detected by the scintillator when the beam was on. Unfortunately, no other excitation curves for Li^7-Be^9 reactions have yet been measured, so the results cannot be easily interpreted. However, the Li^8 yield is much larger than that of any other Li^7-Be^9 reaction observed, which suggests that this reaction may proceed largely by a direct-type process, with the transfer of the rather loosely bound last neutron of beryllium to the lithium projectile, without regular compound-

TABLE I. Yields of radioactive products having half-lives less than one second (2-Mev lithium ion beam).

Beam	Target	Radioactive products	Thick target yield per microcoulomb
Li^7	Li^6F	B^{12}	2.0×10^4
Li^7	Li^7F	$B^{12}+B^{13}$	3.8×10^4
Li^7	$(Li^7)_2SO_4$	$B^{12}+B^{13}$	2.2×10^4
Li^7	Li^7F	He^6	1.2×10^4
Li^7	Be^9	Li^8	3.8×10^4
		B^{12}	2.3×10^3

[5] S. Devons and J. H. Towle, Proc. Phys. Soc. (London) **A69**, 345 (1956).

[6] L. C. Biedenharn and R. M. Thaler (private communication) of work done at the Los Alamos Scientific Laboratory.

[7] See J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 333, Eq. (250). s_0 is the value of s_l for zero angular momentum.

nucleus formation. Further studies with angular distribution measurements are anticipated.

Both the radioisotopes B^{12} and Li^8 are produced when a beryllium target is bombarded with Li^7 ions. Since the half-lives (0.018 and 0.84 sec) are easy to separate, it was possible to obtain an estimate of the ratios of the two reactions from the same target and at the same beam energy. The identification of B^{12} in the beryllium-target reaction (and in the lithium-target reaction also) was accomplished by means of the time to pulse-height converter already described, and to measure the ratio in question the instrument was operated with the time intervals of the steps corresponding to intermediate values between the two decay periods, so that both decays could be seen simultaneously.

The yields are given in Table I, with the ratio between them being more accurate than either absolute value.

HIGH-ENERGY NEUTRONS FROM LITHIUM REACTIONS

By using a BF_3 counter in paraffin, one observed that all of the lithium bombardments studied seem to generate neutrons in moderate yields. No direct conclusions can be drawn about the probabilities of the neutron-producing reactions because there are a number of energetically possible reactions for each target, with three or more final products, resulting from the emission of one or more neutrons per collision. Cross sections for the anticipated production of high-energy (10 to 20 Mev) neutrons from Li—Li and Li—Be reactions are large enough so that the neutrons could be detected before moderation to lower energies. The presence of fast neutrons was verified by means of the $(n,2n)$ reaction in Cu^{63} which has a threshold at about 11 Mev and a cross section of 0.97 barn at 18.5 Mev.[8] The presence of the reaction can be demonstrated by observation of the 9.9-minute positron decay of Cu^{62}. In order to expose copper to the maximum flux of the neutrons we placed the end of a $\frac{5}{8}$-in. copper bar directly against the back of the target chamber (i.e., in the forward direction relative to the beam) with only a millimeter gap to permit current integration. After suitable irradiation the bar was transferred immediately into the well of a NaI(Tl) scintillating crystal so that the positron annihilation could be detected and the decay observed.

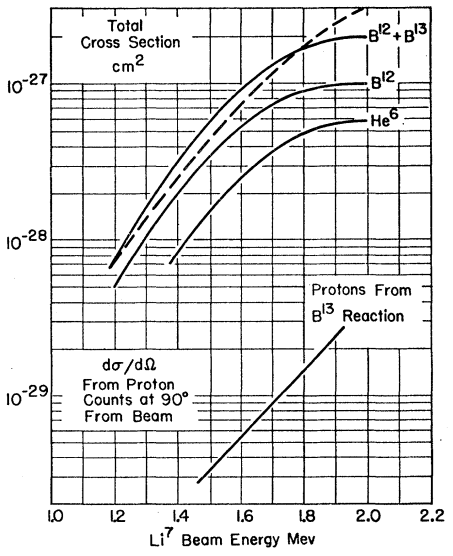

FIG. 2. Cross sections for reactions whose yields are exhibited in Fig. 1. The dashed curve is theoretical and has been normalized to the $B^{12}+B^{13}$ curve at 1.8 Mev.

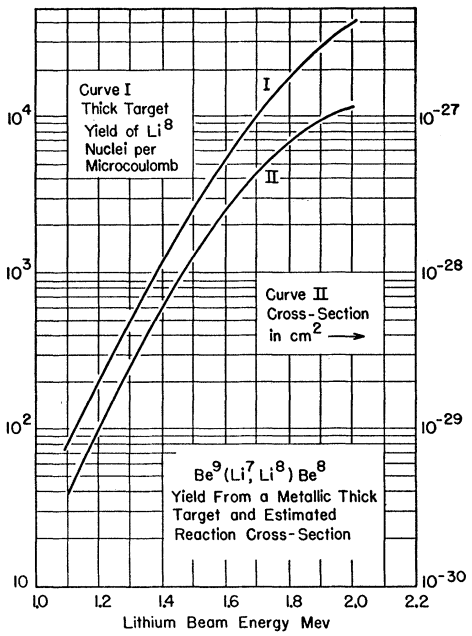

FIG. 3. Yields and cross sections for $Be^9(Li^7, Li^8)Be^8$ estimated from measurements of the β-counting rate of the Li^8 produced.

With a Li^6 beam on a Li^6F target, no counts above background were observed by this method. The reaction leading to the highest energy neutrons is $Li^6(Li^6, n)C^{11}$, with a Q-value of 9.447 Mev; thus these neutrons could not initiate the $(n,2n)$ reaction in copper. The existence of the reaction leading to C^{11} was demonstrated by observing the characteristic positron emission of C^{11}, as described in the next section of this report.

The following rough estimates of the neutron yield were made on the assumption that the output of neutrons is isotropic in the laboratory coordinate system, and on other assumptions to be given later. With a Li^6 beam on a Li^7F thick target, the Cu^{62} activity extrapolated back to beam cutoff time was about 1000 counts per minute.

The reaction $Li^7(Li^6, n)C^{12}$, $Q=20.913$ Mev, yields neutrons in the forward direction with an energy of

[8] J. L. Fowler and J. E. Brolley, Jr., Revs. Modern Phys. **28**, 103 (1956).

TABLE II. Fast neutron yields observed by copper activation.

Beam	Target	Products	Calculated max neutron energy forward direction (Mev)	Thick-target yield per microcoulomb	Assumption
Li^6	Li^7F	$n+C^{12}$	22.8	2.2×10^4	All transitions to ground state
				2.5×10^4	Ground and first 3 exc. states
Li^7	Li^7F	$n+C^{13}$	20.6	8.3×10^3	All transitions to ground state
				8.8×10^3	Ground and first 4 exc. states
Li^6	Be^9	$n+N^{14}$	16.5	8.7×10^2	All transitions to ground state
				1.5×10^3	Ground and first 2 exc. states
Li^7	Be^9	$n+N^{15}$	20.0	1.5×10^3	All transitions to ground state
				2.2×10^3	Ground and first 4 exc. states

22.8 Mev when the C^{12} nucleus is left in its ground state. Corresponding to the first three excited states of the C^{12} nucleus, the neutrons in the forward direction have energies 18.4, 15.1, and 13.2 Mev, respectively. No information is yet available as to the distribution of the C^{12} product nuclei throughout the excited states; thick-target yields for the high-energy neutrons have been calculated on the assumption that all of the neutrons are from the ground state, and also on the assumption that equal contributions arise from the ground and first three excited states. These yields are given in Table II. Neutrons produced from (Li, $2n$) reactions in the Li—Li or Li—Be reactions are not energetic enough to be detected by this copper method.

When a Li^7F target was exposed to a Li^7 beam, neutrons were again observed by activation of copper, but at somewhat lower yield. Here the principal reaction is $Li^7(Li^7, n)C^{13}$, having a Q-value of 18.62 Mev. The $(n,2n)$ reaction leading to C^{12} has a Q of 13.67 Mev and its neutrons should make a small contribution to the activation of the 9.9-minute Cu^{62} period. The yields of high-energy neutrons on the various assumptions for their partition between the ground and the excited states are given in Table II.

Only the reaction $Be^9(Li^6, n)N^{14}$ provides sufficiently energetic neutrons to be observed by this technique when beryllium targets are bombarded by the Li^6 beam. Here the neutrons in the forward direction corresponding to no excitation in nitrogen nucleus will have an energy of 16.5 Mev; for these the cross section for the $(n,2n)$ reaction in Cu^{63} is approximately 0.85 barn. Neutrons corresponding to the first two excited states may also contribute appreciably; yields for ground state neutrons only and a uniform distribution in the ground and first two excited states are tabulated. The neutrons from the $2n$ reaction leading to N^{13} are below threshold; however, the yield for this reaction was obtained by observing the characteristic 10-minute positron decay of the N^{13}, which is described later in the paper.

When the 2-Mev Li^7 beam bombards a beryllium target, only neutrons from the reaction $Be^9(Li^7, n)N^{15}$, $Q=18.084$ Mev, will be above the threshold. Here neutrons corresponding to the first four excited states of the N^{15} nucleus as well as the ground state might contribute. Yields have been calculated for ground state only and uniform population of ground and first four excited states. The 3-body decay leading to N^{14} was below threshold and was not observed.

Neutrons from boron targets have not been studied by this technique since the yields at 2 Mev are prohibitively low. However, it should be noted that the reaction $B^{10}(Li^7, n)O^{16}$ has a Q-value of 23.6 Mev, and since the first excited state of O^{16} is 6 Mev above the ground state, one could expect to obtain, to this limit, a monoenergetic source of quite high-energy neutrons. Similar considerations apply to the other reactions. We have observed the presence of single neutron reactions on C^{12} with both beams by beta-decay techniques, as described later.

RADIOACTIVE PRODUCTS OF HALF-LIFE LONGER THAN ONE MINUTE

These activities were measured directly off the targets in the low-background automatic-printout counters already mentioned.

Bombardments of a few minutes with a 1-μa beam on lithium (fluoride or sulfate) targets gave counting rates of the order of 10^5 counts per minute of C^{11} activity with the Li^6-Li^6 and Li^6-Li^7 reactions. This demonstrates the occurrence of the reactions $Li^6(Li^6, n)C^{11}$, $Q=9.447$ Mev, and $Li^7(Li^6, 2n)C^{11}$, $Q=2.202$ Mev. The C^{11} was identified by its 20.5-minute decay and by its 0.51-Mev annihilation radiation which we observed with the NaI(Tl) scintillation crystal and pulse-height analyzers, calibrating with a Na^{22} source. Yields for this reaction are given in Table III. It should be noted that this gives no indication of how much of the C^{11} is formed in the ground state and how much in various excited states.

The Li^7-Li^7 reaction, which is not expected to produce any long-lived activity, had a counting rate of only 15 counts/min above background of a 2-hour activity after 10 minutes of bombardment totaling 1000 microcoulombs. This activity was thought to be F^{18} formed by the reaction $C^{12}(Li^7, n)F^{18}$ with carbon impurities in the target.

A 10-hour bombardment with the Li^6 beam on a Li^6F target gave a long-lived (54 ± 10 day) pure gamma activity of about 2400 counts per minute. The activity was measured at intervals over a 3-week period to determine the half-life. Using the NaI(Tl) well scintillator with an 18-channel pulse-height analyzer to compare the gamma-ray energy with that of the 0.511-Mev annihilation radiation of Na^{22} and the 0.662-Mev gamma of Cs^{137}, we found the energy to be approximately 0.49 Mev. This may be produced according to the reaction $Li^6(Li^6, n+He^4)Be^7$, having $Q=1.893$ Mev. Assuming a 12% branching ratio[9] to the excited state of

[9] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 87 (1955).

Li^7 which decays by gamma emission of this energy and correcting for the efficiency of the crystal, we arrive at the yield listed in Table III. It seems probable that this reaction may proceed through a proton transfer process.

After bombardment of clean beryllium targets with the Li^7 beam, no long-lived activity whatever could be observed above the ten counts per minute counter background. Among other things, this indicated that the targets were relatively free of impurities which would produce spurious activities.

With the Li^6 beam on a beryllium metal target, a positron emitter with a half-life of 10.1 minutes was found. This is N^{13} formed in the reaction $Be^9(Li^6, 2n)N^{13}$; $Q=3.950$ Mev. The yield for this reaction is given in Table III. As this was a pure activity with a reasonably high yield, we did a short calculation with the Peierls formula[10] and measured the half-life to be 10.07 ± 0.06 minutes. It might be noted in passing that quite accurate measurements can be made on C^{11}, N^{13}, and F^{18} employing lithium reactions since the activities can be obtained pure of competing half-lives.

When B^{10} is bombarded by Li^7, only the 2.2-minute decay of O^{15} occurs through the reaction $B^{10}(Li^7, 2n)O^{15}$; $Q=8.012$ Mev. A bombardment was made at 2.1 Mev and a careful search made for the 10-minute activity characteristic of N^{13} to check for the presence of the reaction $B^{10}(Li^7, H^4)N^{13}$. If H^4 exists at all, it must have an $(M-A)$ value greater than 19.69 Mev, for Li^8 is known to be stable against breakup into He^4+H^4. If it is stable against neutron emission into tritium, it must have an $(M-A)$ value less than 24.19 Mev. With the above reaction, it is possible for us to cover almost the entire range for the possible mass values of H^4; in fact with a bombarding energy of 2.1 Mev we come within 162 kev in the center-of-mass system of the threshold for the 3-body decay giving tritium and a neutron. We obtained a null result; less than one H^4 could have been formed per 3×10^{13} incident lithium nuclei.

When Li^6 bombards B^{10}, four decays within our range are energetically possible: $B^{10}(Li^6, 2n)O^{14}$; $Q=1.958$ Mev; $B^{10}(Li^6, n)O^{15}$; $Q=15.257$ Mev; $B^{10}(Li^6, H^3)N^{13}$; $Q=5.848$ Mev; $B^{10}(Li^6, He^5)C^{11}$; $Q=4.045$ Mev. Several exposures were made for varying time intervals in order to bring out the separate components, and the composite decay curves were unraveled with the results given in Table III. The N^{13} activity was not resolved above the others present, but the reaction producing it will be studied by the emitted tritons. The relative yields of O^{14} and O^{15} tabulated should not be taken too seriously, as it was rather difficult to separate these two activities with such similar lifetimes. The large yield for C^{11} may be understood on the basis of its being formed in a direct process or proton transfer reaction; while this seems likely, we have no further evidence yet to substantiate this conclusion.

[10] R. Peierls, Proc. Roy. Soc. (London) **A149**, 467 (1935).

TABLE III. Yields of radioactive products having half-lives longer than one minute.

Beam	Target	Products	Thick-target yield per microcoulomb
Li^6	Li^6F	Be^7+He^5	2.8×10^5
		$C^{11}+n$	4.3×10^4
Li^7	Li^6F	$C^{11}+2n$	3.7×10^3
Li^6	Be^9	$N^{13}+2n$	3.5×10^2
Li^6	B^{10}	$C^{11}+He^5$	3.7×10^2
		$O^{15}+n$	1.5×10^2
		$O^{14}+2n$	1.8×10^2
Li^7	B^{10}	$O^{15}+2n$	4.3×10^1
Li^7	C^{12}	$F^{18}+n$	1.2×10^1

When graphite targets were exposed to the Li^7 beam, the characteristic 1.87-hour F^{18} decay was observed from the reaction $C^{12}(Li^7, n)F^{18}$; $Q=5.954$ Mev. This reaction was detectable with other targets when they were contaminated with a carbon film. This occurs even though the yield from this reaction is low because the penetration of the lithium ions into the target is so small.

With the Li^6 beam on graphite, the 66-sec F^{17} decay was observed, but no quantitative work has yet been done. The only long-lived activity found could be explained by the $Li^6(Li^6, n)C^{11}$ reaction, where the Li^6 on the target was laid down by the beam itself. This effect was not observed when lower Z targets were bombarded with Li^6 because the bombardment times were not very long and there was considerable activity from other reactions. The bombardment time on the graphite target was not long enough to expect to see F^{18} activity from a reaction with the 1% C^{13} in the target.

A 50-min, 2900-μcoul bombardment of a SiO_2 target with Li^6 over an area of approximately $\frac{1}{4}$ cm^2 gave 800 counts/min of 20-min C^{11} activity at the end of the bombardment. The amount of Li^6 laid down with this much bombardment is clearly small, but the cross section for forming C^{11} is quite high. Evidently it is possible to detect minute amounts of low-Z impurity in targets with the lithium beams. With the SiO_2 target, the reaction $O^{16}(Li^6, He^4)F^{18}$ was too weak to be detected.

When a titanium nitride target was exposed simultaneously to both beams, a small activity was observed but did not permit identification. Elements of higher Z (in particular fluorine) gave no activity.

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