for nuclei having $12 < A < 32$ decrease significantly when the binding energy of the transferred nucleon in the heavier nucleus increases from 3 Mev to 9 Mev. Such an effect, if present in $1p$ single-particle reduced widths, might explain the small value of $\Theta_0^2 = 0.0031$ since the binding energy of the transferred neutron in O^{16} is 15.652 Mev.

ACKNOWLEDGMENTS

The author wishes to thank J. N. McGruer for his interest and guidance in this work and A. J. Allen for his support. He wishes to acknowledge helpful discussions with J. B. French, M. H. Macfarlane, E. U. Baranger, J. R. Cameron, J. C. Armstrong, A. G. Blair, and E. W. Hamburger.

PHYSICAL REVIEW VOLUME 121, NUMBER 3 FEBRUARY 1, 1961

Lithium-Induced Reaction Yields Below 4 Mev*

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(Received September 19, 1960)

Thick-target yields of the following reactions were measured by counting the beta active products: $Li^7(Li^6,2n)C^{11}$, $Be^9(Li^6,2n)N^{13}$, $C^{12}(Li^6,n)F^{17}$, $C^{12}(Li^7,n)F^{18}$, $N^{14}(Li^6,He^5)O^{15}$, $N^{14}(Li^6,d)F^{18}$, $N^{14}(Li^7,t)F^{18}$, $O^{16}(Li^6,n)Na^{21}$, $O^{16}(Li^6,He^4)F^{18}$, $F^{19}(Li^6,Li^5)F^{20}$, $Na^{23}(Li^6,Li^5)Na^{24}$. The reactions $F^{19}(Li^6,2p)Ne^{23}$ and $Na^{23}(Li^7,Li^6)Na^{24}$ had too small a yield to permit accurate measurement. All of the yield curves show a very rapid but smooth increase of yield with energy. Some general rules are given for estimating the yield to be expected for any positive "Q" lithium beam reaction in the energy range under consideration.

IN a previous work[1] yields are reported for a number of nuclear reactions with lithium beams under 2.0 Mev. In one recent paper, the excitation curve for $Be^9(Li^7,Li^8)Be^8$ has been extended up to 3.9 Mev.[2] In the present work the beam energy is in the range of 1.2 to 3.7 Mev. Although all possible reactions are not covered by this survey, there is enough variety so that one may make reasonable estimates of the yields to be expected from other reactions. From the thick-target yield curves presented here, one can read directly the expected thin-target yield if the target thickness is expressed in terms of the energy loss by the beam. By making use of stopping-power information, one could calculate actual nuclear cross sections for these reactions.

EXPERIMENTAL

The production and analysis of lithium ion beams by the Minnesota Van de Graaff machine has been described previously.[2] The thick targets to be bombarded were mounted at the bottom of a Faraday cup. After the bombardment they were removed and counted under a low background, end window counter. The number of counts were recorded by a printer which was activated by a clock so that it would print every 1, 5, 10, 20, or 60 minutes. The shorter-lived activities were timed with a stopwatch and the number of counts recorded by hand.

A variety of methods were used for making targets. The carbon and beryllium targets were cut from the elements. The nitrogen targets were made by heating titanium in an atmosphere of anhydrous ammonia, the oxygen targets by heating titanium in oxygen. The other targets were made by melting salts onto thin steel backings, LiF for lithium, NaF for fluorine, and NaCl for sodium. In each case, because of decrease in reaction yield as the atomic number is increased, the

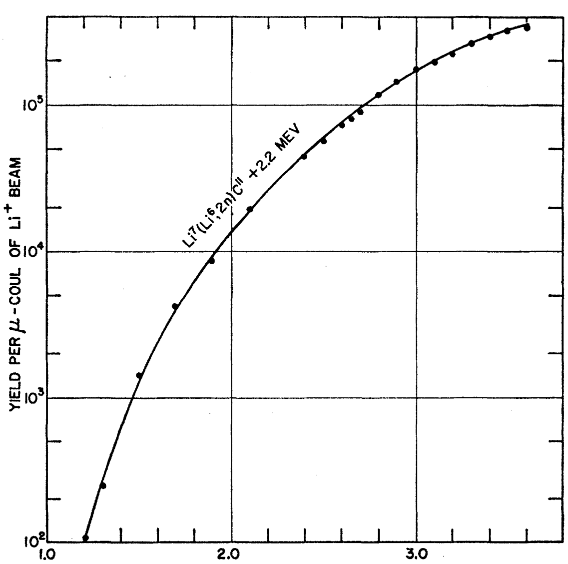

FIG. 1. Thick-target yields of C^{11} from a Li^6 beam on enriched LiF targets.

* This work was supported in part by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.
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[1] E. Norbeck, Jr., and C. S. Littlejohn, Phys. Rev. 108, 754 (1957).
[2] E. Norbeck, J. M. Blair, L. Pinsonneault, and R. J. Gerbracht, Phys. Rev. 116, 1560 (1959).

background activity induced in the heavier component of the salt was negligible.

The yields have been calculated on the basis of the target materials actually used. If a metallic lithium target, for example, were used instead of a LiF target, the yield would be found to be higher than that indicated on our graph. A 15% backscattering correction for the beta rays was assumed for all cases. In some cases this may make a significant error in the absolute yield. The relative error in the points along a single curve is indicated by the scattering of these points.

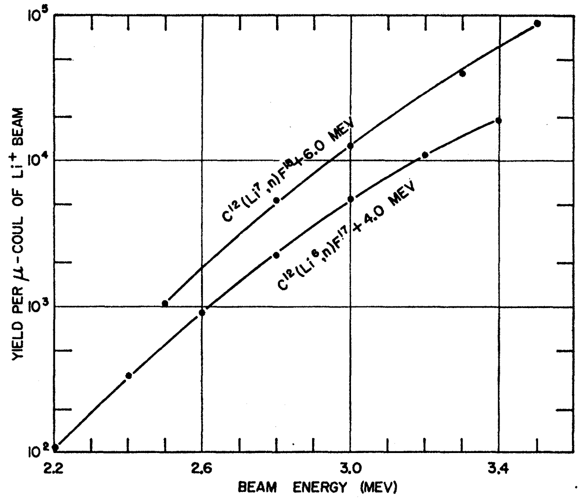

FIG. 3. Thick-target yields of F^{18} from lithium beams on graphite targets.

DISCUSSION

The reactions with lithium and beryllium targets, Figs. 1 and 2, are both $(Li^6,2n)$ reactions and so can be compared directly. The beryllium curve is considerably steeper, as might be expected with a higher Coulomb barrier, and indicates a lower cross section. The fluorine in the LiF cuts down the total reaction yield enough so that the total yield for the metallic beryllium target is actually larger in the higher energy range.

Although the total yield for the $C^{12}(Li^7,n)F^{18}$ reaction is clearly greater than for the $C^{12}(Li^6,n)F^{17}$ reaction as shown in Fig. 3, the yield for each energy level of the final product is actually greater for the second reaction. There is almost an order of magnitude larger number of states available for F^{18} as compared with F^{17}. Since the two reactions are so similar one would expect to find about the same yield for each state of the final product. From this pair of reactions one must then conclude that Li^6 is more reactive than Li^7. It is not clear why the energy dependence of the Li^7 reaction should be so much steeper than for the Li^6 reaction.

The ratio of O^{15} to F^{18} from the reaction pair, $N^{14}(Li^6,He^5)O^{15}$ and $N^{14}(Li^6,d)F^{18}$ in Fig. 4, were determined with considerable precision, except for the constant multiplicative error resulting from backscattering corrections. The greater steepness of the F^{18} curve may be due to the fact that as the energy is increased more levels of F^{18} become available, but that in the entire range studied only the ground state of O^{15} is available. All the states of F^{18} are therefore produced no more often than the one state of O^{15}. This would support the conjecture that both reactions are of the transfer type. To make O^{15} only, a proton needs to travel across the Coulomb barrier, whereas for F^{18} an alpha particle is needed. The Coulomb barrier plays a dominant role in all these low-energy lithium reactions. For lithium on nitrogen, in the energy range studied, the classical distance of closest approach runs from 12 to 20×10^{-13} cm.

The O^{15}–F^{18} ratio was measured by making a short but uniform bombardment of a nitrogen target and

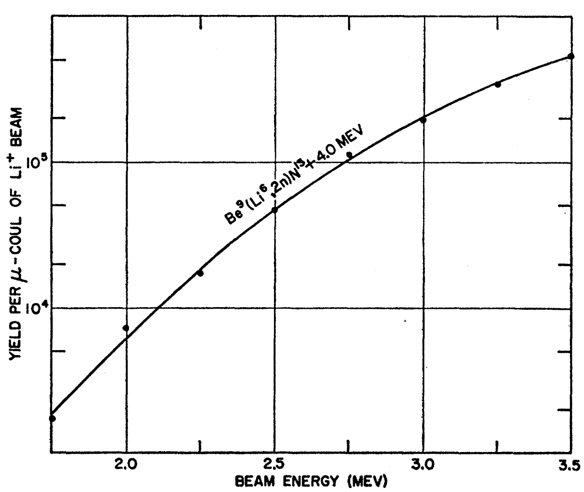

FIG. 2. Thick-target yields of N^{13} from a Li^6 beam on beryllium metal targets.

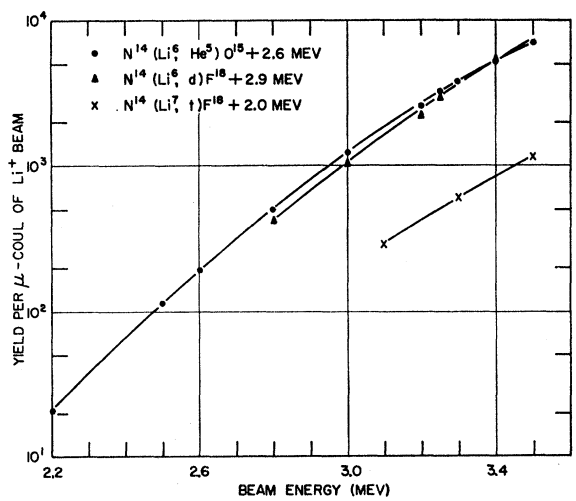

FIG. 4. Thick-target yields from lithium beams on titanium nitride targets.

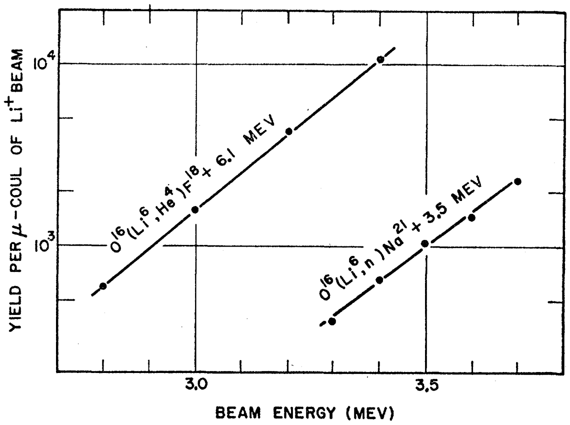

FIG. 5. Thick-target yields from a Li^6 beam on titanium dioxide targets.

then determining the decay curve under the thin window Geiger counter. Both activities were calculated from this same decay curve. It was found that the amount of nitrogen in the titanium varied considerably with very small changes in the nitriding technique. In order to determine the relative yield of the three nitrogen reactions, the same set of targets were used in determining all three curves. One should not expect to reproduce the absolute magnitude of this set of curves as a whole to much better than a factor of two.

The ratio of the yields for the two reactions, $N^{14}(Li^6,d)F^{18}$ and $N^{14}(Li^7,t)F^{18}$ in Fig. 4, should be quite accurate since the same targets were used, and also the same product was formed, thereby eliminating errors arising from backscattering corrections. An alpha-particle transfer is involved in both cases, so one might expect very similar reaction yields. The effect of the slightly higher Q value for the Li^6 reaction and the slightly higher center-of-mass bombarding energy could hardly be expected to make the difference of a factor of six in reaction yield. This is then another example where a Li^7 reaction seems to be inhibited in some way. The slope of the excitation curve for this particular Li^7 reaction is probably not accurate enough to be compared closely with that of the Li^6 reaction.

The yields from the TiO_2 targets were very reproducible. The $O^{16}(Li^6,He^4)F^{18}$ reaction, Fig. 5, gives an excitation curve that is steeper than the nitrogen curves and indicates as high or even a higher yield. The steepness follows from the increased Coulomb barrier.

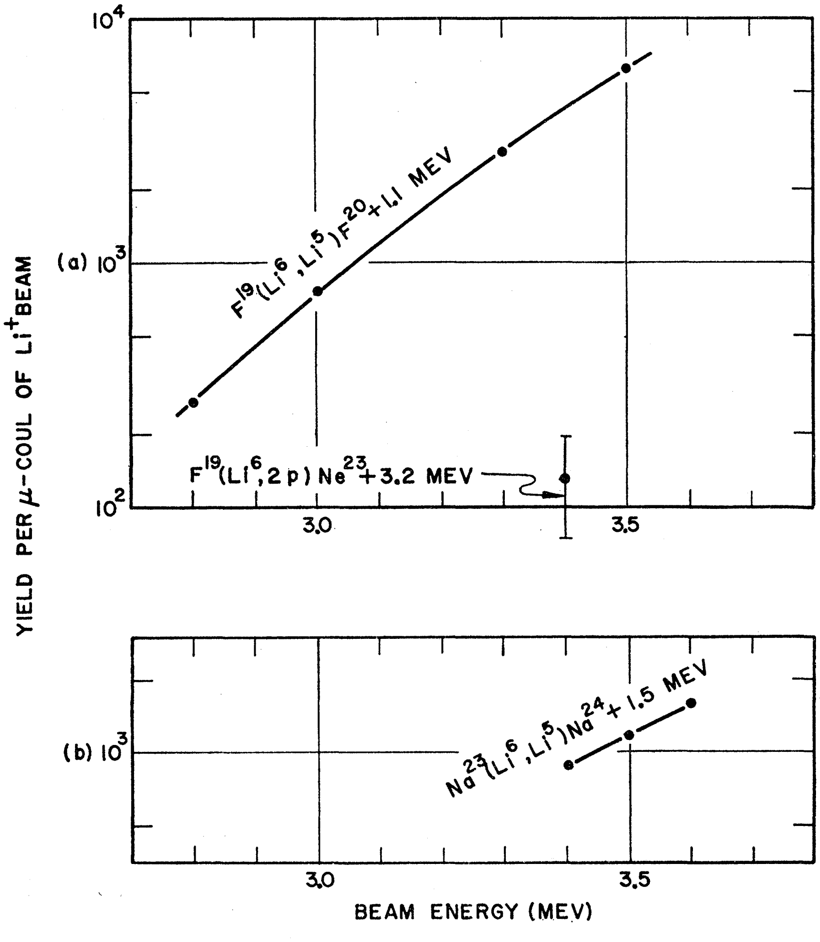

FIG. 6. Thick-target yields from a Li^6 beam on (a) NaF targets and (b) NaCl targets.

The high yield is due partly to the high percentage of oxygen in the TiO_2 targets. It is probably also helped by the rather small barrier seen by the transferring deuteron and by the very large number of states possible in F^{18} when the Q value is 6.1 Mev. By contrast, the $O^{16}(Li^6,n)Na^{21}$ reaction, where an entire lithium nucleus must pass through the Coulomb barrier, is 17 times smaller.

The 40-sec activity from the $F^{19}(Li^6,2p)Ne^{23}$ reaction could be barely detected in the presence of the very large amount of 11-sec F^{20} from the $F^{19}(Li^6,Li^5)F^{20}$ reaction, Fig. 6. The high yield for the F^{20} reaction is undoubtedly due to the ease with which the neutron can tunnel from one nucleus to the other. The Ne^{23} reaction probably involves an entirely different mechanism.

In spite of the very high atomic number of the target, the yield of the $Na^{23}(Li^6,Li^5)Na^{24}$ reaction, Fig. 6, is about the same as that of $O^{16}(Li^6,n)Na^{21}$. As in the F^{20} reaction, the neutron encounters a small nuclear barrier, but no Coulomb barrier. There is a larger error in the sodium reaction points than with most of the other reactions. The long, 15-hr half-life of Na^{24} required long bombardments which resulted in considerable buildup of F^{18} activity from impurities and sometimes in a sputtering away of part of the target. The reaction $Na^{23}(Li^7,Li^6)Na^{24}-0.3$ Mev was searched for without success. This sets an upper limit for this reaction of 1.6 atoms of Na^{24} for each microcoulomb of 3.5-Mev Li^+ beam incident on the NaCl target. The Li^6 reaction is then at least 750 times stronger than the Li^7 reaction. This may be the result of the low reaction energy along with the general inhibition of Li^7 reactions noted earlier.

CONCLUSIONS

Considering all these reactions together, one could say that the general characteristics of lithium beam reactions below 4 Mev are:

(a) A small increase in energy always results in a large increase in yield.

(b) The reaction rate goes down rapidly as the nuclear charge of the target is increased.

(c) The yield will be low when a large amount of nuclear material is transferred between the beam and target nuclei, and will be considerably larger when a smaller amount is transferred. A (Li^6,Li^5) reaction, for example, will be much more prolific than the (Li^6,n) reaction with the same target.

(d) There is some indication that Li^6 reactions are somewhat more prolific than Li^7 reactions.

ACKNOWLEDGMENTS

The author would like to express his thanks to Donald G. Seal for assembling the low-background beta-counter apparatus, to Stanley J. Brodsky who assisted with the calculations, and to the many others who gave valuable assistance in carrying out this work.

PHYSICAL REVIEW VOLUME 121, NUMBER 3 FEBRUARY 1, 1961

$Al^{27}(n,\alpha)Na^{24}$ Cross Section as a Function of Neutron Energy

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(Received September 16, 1960)

The cross section for the $Al^{27}(n,\alpha)Na^{24}$ reaction has been measured as a function of neutron energy in the range $6.1 \leqslant E_n \leqslant 8.3$ Mev and at 14.8 Mev. Measurements were made relative to the fission cross section of U^{238}; activation techniques were used to determine the number of $Al^{27}(n,\alpha)$ events. While a number of peaks and valleys appear in the cross section versus energy curve, there is a general increase in cross section with increasing energy consistent with the Coulomb penetrability of the alpha particle.

INTRODUCTION AND METHOD

The $Al^{27}(n,\alpha)Na^{24}$ reaction is of interest in the study of neutron interactions in intermediate nuclei. In addition, it is of practical importance in reactor technology, inasmuch as it is a threshold reaction which is suitable and convenient in certain circumstances, for high-energy neutron flux monitoring. This paper reports a measurement of the $Al^{27}(n,\alpha)Na^{24}$ cross section as a function of neutron energy, relative to the known[1] fission cross section of U^{238}.

The Q value for the reaction is -3.136 Mev,[2] although, as will be seen, the cross section increases to values of the order of a few millibarns only at a neutron energy of about 6 Mev.

The experimental arrangement used in these measurements is shown schematically in Fig. 1. Monoenergetic neutrons were obtained from the $D(d,n)He^3$ reaction using the ORNL 5.5-Mv Van de Graaff generator. Neutrons in a small cone about 0° with respect to the charged-particle beam were incident on an aluminum metal sample and on a thin deposit of

[1] W. D. Allen and R. L. Henkel, *Progress in Nuclear Energy* (Pergamon Press, New York, 1958), Vol. 2, Series 1. Cross-section values were taken from the smooth curve of Fig. 30.

[2] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).