suspect that the 0.49-Mev transition which follows the 3-hr beta decay is the same as the 0.51-Mev transition in the 2.2-min decay. In order to check this, the energies of the two transitions were compared without altering the spectrometer settings. It was determined that there were indeed two distinct gamma rays with energies that differed by about 0.03 Mev. The absence of common states in the two decay schemes might be due to some selection rule other than those arising from the conservation of total spin and parity.

The total energy of the $Zn^{71}$ decay is measured to be about 2.9 Mev. This value is in good agreement with that predicted from the beta decay systematics.[8]

[8] K. Way and M. Wood, Phys. Rev. 94, 119 (1954).

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

# Tritium Production from Lithium by Deuteron Bombardment

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(Received August 23, 1954; revised manuscript received October 25, 1954)

The tritium production cross section has been measured for $Li^6$ bombarded by deuterons from 0.4 Mev to 4.0 Mev. The cross section rises fairly rapidly to 190 millibarns near 1 Mev, then more slowly to 290 millibarns near 4 Mev. The cross section for $Li^7$ rises steeply from the 1.27 Mev threshold to 95 millibarns at 2.4 Mev; then more slowly to about 165 millibarns at 4.1 Mev.

## INTRODUCTION

DEUTERON reactions with light nuclei are of considerable theoretical interest, but no detailed study of the reaction with $Li^7$ seems to have been made. The reactions of deuterons with $Li^6$ have been studied previously[1] by magnetic analysis at 1 Mev deuteron energy. The reaction $Li^6(d,t)Li^5$, $(p)He^4$ was reported with disintegration energies of $Q=0.9\pm0.1$ Mev and $Q=1.6$ Mev for the two steps. The width of the $Li^5$ ground state was indicated as 1.5 Mev, and a pronounced forward distribution of the tritons was suggested.[1] We have studied the total triton production by a technique similar to that of Wolfgang and Libby,[2] in which the tritium is recovered and its beta disintegrations counted.

## EXPERIMENTAL ARRANGEMENTS

### Target Preparation

The target material was lithium fluoride[3] enriched in either isotope. The enriched $Li^6$ contained $76.31\pm0.04$ atom percent $Li^6$ as determined mass spectrometrically. The degree of enrichment of the $Li^7$ was determined by using a Frisch grid chamber in the thermal column of the Oak Ridge National Laboratory (ORNL) Graphite Pile. The yield of the $Li^6(n,t)He^4$ reaction was observed in a comparison with natural lithium fluoride, and the material was found to contain about 55 ppm (parts per million) of $Li^6$. Thin uniform deposits of this material were vacuum evaporated onto high-purity aluminum disks. The target thickness in terms of deuteron energy loss was chosen as about 80 kev. For the $Li^6$ cross section no dependence on target thickness was found, with the possible exception of the single thickest target, where a brief deuteron burst of abnormally high intensity apparently caused a few percent volatilization.

In the case of the $Li^7$ reaction, tritium loss from the lithium fluoride layer was found for a series of thick targets used for the energy range 2.3 to 4.1 Mev.[4] Below 2.5 Mev a modification of the target was employed which avoided such loss. Following a technique described by John Strong,[5] a layer of aluminum thick enough to stop all backward tritons was vacuum-evaporated over the active material of the targets. The thickness of the aluminum overcoat was determined for each target by weight or, preferably, by observing the shift of the $Li^7(d,n)Be^8$ resonance near 1.0 Mev.

### Deuteron Bombardment

The $D^+$ beam of the ORNL 2.5-Mev Van de Graaff was used in the energy range 0.4 to 2.5 Mev while deuterons from 2 to 4 Mev were made available at the ORNL 5.5-Mev Van de Graaff. A correction of $(2\pm\frac{1}{2})$ percent for $H_2^+$ in the beam was required in the latter case. The beam current falling on the target was integrated[6] to determine the number of deuterons available for reaction. The secondary electrons produced at the collimator (or the target) were driven back to their origin by an electrostatic field. Two $67\frac{1}{2}$-volt batteries connected from ground to the insulated

[1] R. I. Frost and S. S. Hanna, Phys. Rev. 91, 462 (1953), and R. W. Gelinas and S. S. Hanna, Phys. Rev. 86, 253 (1952).
[2] R. L. Wolfgang and W. F. Libby, Phys. Rev. 85, 437 (1952).
[3] Supplied by the Stable Isotope Research and Production Division.
[4] See section on Results, $Li^7$ Cross Section.
[5] John Strong *et al.*, *Procedures in Experimental Physics* (Prentice Hall, New York, 1943), pp. 178–179.
[6] This integrator, due to F. W. Manning and F. M. Glass, is to be described in a forthcoming paper.

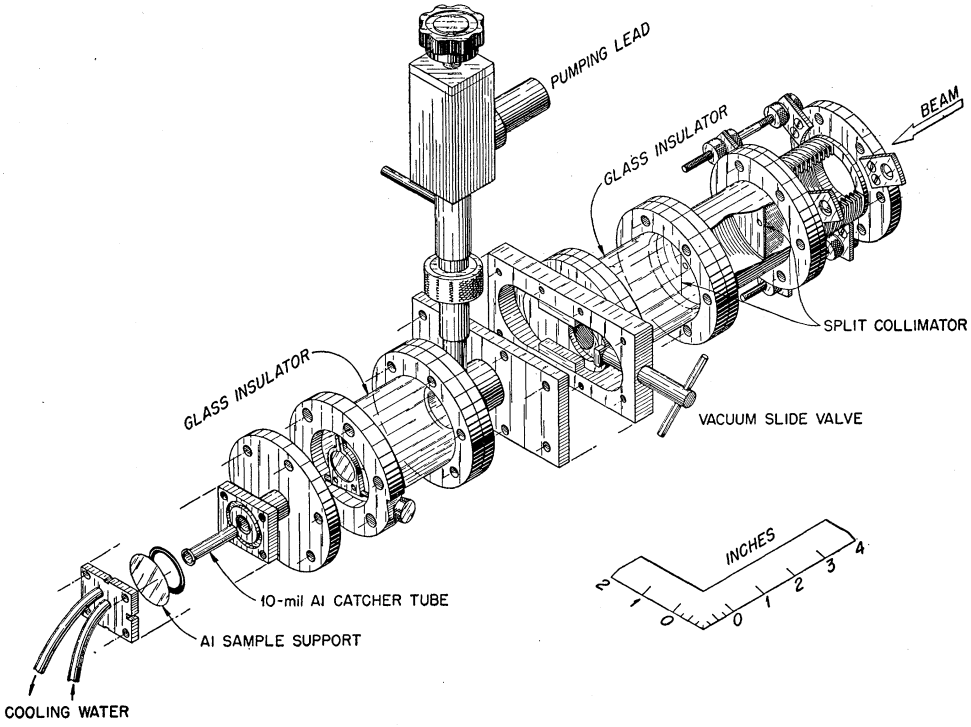


FIG. 1. Deuteron activation apparatus.

vacuum valves between the collimator and target holder (see Fig. 1) sufficed.

To intercept the energetic tritons emerging at back angles from the target, a catcher tube was used (see Fig. 1). This was an aluminum tube $\frac{1}{4}$ inch in diam and $1\frac{1}{4}$ inches long, with a 0.010-inch wall and a rolled lip on which the target pressed. The deuteron beam was carefully aligned, after collimation, so it passed through the catcher tube to the target. The collimator was made of two segments of tantalum disks to allow higher pumping speeds (see Fig. 1). The few bombardments showing deuteron induced beta activities in the catcher tube were discarded. The induced target backing activities decayed to negligible levels in two to three days. The fractional solid angle for triton escape from the target back through the catcher tube is less than 0.2 percent and such loss has been neglected. The target was cooled by a water jet impinging on the back of the aluminum disk (see Fig. 1). Current densities from 5 to 30 microamperes per square centimeter were used successfully. Because of generator characteristics, current densities were lowest at both the lowest and the highest energies.

For the targets with aluminum overcoating, a $\frac{3}{8}$-inch diameter collimator, and a target holder with a $\frac{7}{8}$-inch throat were used.

The beam energy was determined with a nuclear resonance device, which measured the magnetic field necessary to bend the beam through ninety degrees. The nuclear resonance device was in turn calibrated by the $Li^7(p,n)Be^8$ threshold and other reactions. In some cases the beam energy was taken from the generating voltmeter of the Van de Graaff generator, after it had been calibrated by the nuclear resonance device. These were raw energy data, and were corrected by overcoat thickness and target thickness, expressed in energy lost by the beam. The beam energies reported are those midway through the target material.

## Tritium Recovery and Analysis

The target area accessible to the charged particle beam was punched out and put into a clean graphite crucible. The aluminum catcher tubes, when used, were put into separate crucibles. The crucible was supported by a $\frac{1}{4}$-inch quartz spacer at the bottom of a quartz "test tube" which in turn was encircled by a two turn radio frequency heating coil.[7]

The tritium was quantitatively recovered by cooking the sample twice at 1100°C in an atmosphere of argon containing 1 percent hydrogen. The gas was transferred to a beta proportional counter tube after cooling to 300°C and argon containing 10 percent methane added for counting.[8] By repeating the entire procedure several times on a high-activity sample, it was possible to evaluate the recovery. With the procedure used this

[7] Many details of the cookout apparatus and procedure were adapted from the work of George Ledicotte and others at the Oak Ridge National Laboratory.

[8] Preliminary results were obtained near the $Li^7$ threshold using 2 cm alcohol and 14 cm argon with the counter operating in the Geiger region. At higher counting rates, poor reproducibility and excessive deadtime led to the abandonment of this method.

was 98 percent for targets and 96 percent for catcher tubes.

The counting equipment consisted of an *A*1-*A* preamplifier and a modified Nuclear Model 117 alpha counter.[9] The counters were $1\frac{1}{2}$-inch×12-inch stainless steel tubes with a 0.002-inch×$10\frac{15}{16}$-inch W central wire. These counters were designed and constructed by R. K. Abele.[10] A 2-inch shield around the counter gave about 2.5 counts/sec background. Using an external $Cs^{137}$ source near the center of the counter, plateaux of several hundred volts which were essentially flat were obtained. With tritium in the counter a slope of 1.6 percent per hundred volts was typical. This slope has been attributed[11] to improved collection at higher voltages in the vicinity of the central wire end clamps.

In order to investigate the possibility of tritium loss during bombardment, two bombardments of $Li^7$ were made with about a factor of eight difference in current densities. These two points, at about 1.86-Mev deuteron energy, repeated within 1 percent.

The half-life of the active material resulting from the reaction was investigated. The decay of one sample was followed for a period of one month without demonstrable departure from the decay rate of tritium. Also, some $A^{37}$ was added to a counter containing active material. This, on pulse height analysis, gave a calibration peak at 2.83 kev. Using this calibration, the expected $\beta$ spectrum of tritium was observed. Less than one percent of the observed pulses exceeded 18 kev, and these may well have been part of the background.

## Calibration

The number of tritons produced in a target was first computed from the observed counting rate using the half-life,[12] the recovery efficiency, and the counter efficiency. The counter end effects were measured by scanning with a narrow fan of $Cs^{137}$ gamma rays. An effective volume of 85 percent was found for the proportional counters at 2000 volts. Since the wall losses with tritium are both small and largely compensated by photoelectric emission[13] they have been ignored, and the counter efficiency taken at 85 percent.

A direct calibration of the equipment, including the current measurement, was effected by measuring the charge delivered to an aluminum blank by a 350-kev triton beam from the Cockcroft-Walton accelerator.[14]

A few attempts at calibration by exposing $Li^6$ to pile neutrons were made. Evaporated targets of natural LiF were made by the same procedure as the enriched $Li^6F$ targets. The scatter of the pile results is quite large so that the most that can be said is that the other two calibrations fall within their range. The reproducibility of the tritium count rate per mg of LiF for the several samples exposed in a group was quite good, however (Table I). These group consistencies give a measure of random errors both in the tritium recovery and counting procedure and in the target preparation and weighing. The LiF weight varied by a factor of 5 among the samples in one of these groups. Yet, the 95 percent confidence interval for the average was only 1.8 percent. The corresponding error to be expected per target, based on both groups, is ±3.6 percent, a value which may be expected to apply also to the targets used for the cross-section measurements.

The target efficiency calibration gives $6.70\times10^8$ T/(count/sec) for the proportional counter and the Cockcroft-Walton calibration gives $6.58\times10^8$ T/(count/sec)±2.7 percent. The difference, 1.8 percent, lies well within the limit of statistical uncertainty. Since the Cockcroft-Walton method was subject to contamination which, though greatly reduced, was probably not entirely eliminated, the former calibration was adopted.

TABLE I. Tritium samples from $Li^6(n,t)He^4$ in natural LiF.

| Pile exposure *A* | | | Pile exposure *B* | | |
|---|---|---|---|---|---|
| 100 sec | | | 420 sec | | |
| LiF(μg) | *T*(counts/sec) | Hole 58 counts/sec mg | LiF(μg) | *T*(counts/sec) | Hole *P*2 counts/sec mg |
| 1116 | 97.6 | 87.5 | 876 | 414 | 473 |
| 1153 | 99.9 | 86.6 | 940 | 440 | 468 |
| 2105 | 179.6 | 85.4 | 4091 | 1880 | 459 |
| 1972 | 174.0 | 88.3 | 2174 | 1045 | 481 |
| 1067 | 93.9 | 88.1 | 2374 | 1106 | 466 |
| | | | 1158 | 536 | 463 |
| | | av 87.2±1.7% L.E.[a] | | | av 468±1.8% L.E.[a] |

Computed statistical deviation per target ±3.61% L.E.[a]

[a] L.E. indicates the 95 percent statistical confidence interval.

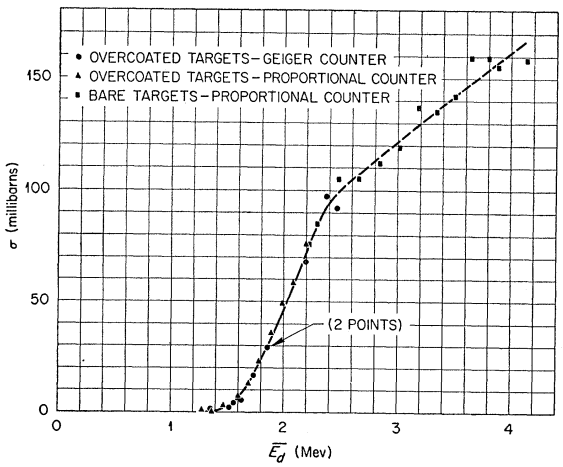


FIG. 2. $Li^7(d,t)Li^8$ cross section.

[9] See ORNL Instrument Information Exchange, p. 97.
[10] ORNL Instrumentation and Controls Division, Counter Laboratory.
[11] C. J. Borkowski, Oak Ridge National Laboratory (private communication).
[12] Values of 12.257 and 12.256 (±0.003) yr have recently been reported from Los Alamos Scientific Laboratory.
[13] A. G. Engelkemeir and W. F. Libby, Rev. Sci. Instr. **21**, 553 (1950).
[14] This method was suggested by W. Kunz of the Oak Ridge National Laboratory.

## RESULTS

### $Li^7$ Cross Section

The cross section *vs* energy curve for $Li^7$ is shown in Fig. 2. The threshold for the reaction was computed from mass data as 1.27 Mev. The results using aluminum overcoated targets on the ORNL 2.5-Mev Van de Graaff are plotted as triangles and circles. As previously mentioned, the point at 1.86 Mev is due to two separate observations which coincide.

It is suggested that the sharp rise exhibited by the cross-section curve above threshold is not entirely due to triton barrier penetrability, but probably involves a resonance in $Be^9$, as evidenced by similar behavior in the $(d,n)$ and $(d,p)$ cross-section curves.

The lowest point shown as a square (2.23 Mev) was obtained with a thin bare target (50 kev) and very low beam current on the 2.5-Mev ORNL Van de Graaff. It agrees well with the other data using aluminum-overcoated targets. The remaining points shown as squares are from a single series of thick targets on the 5.5-Mev ORNL Van de Graaff and have been corrected empirically for tritium loss from the lithium fluoride layer of the targets. This correction was taken as a constant fraction of the tritons stopping in the fluoride layer. The fraction was normalized to give 85 millibarns at 2.30 Mev and the number of tritons stopping in the fluoride was computed from range curves, assuming isotropy for the reaction. The correction ranged from 25 percent at 2.3 Mev to 17 percent at 4.1 Mev and is considered only approximate. Accordingly an uncertainty of $\pm 15$ percent is attached to the upper end of the cross section curve shown (Fig. 2).

Studies of the yield of the $Li^6(n,t)He^4$ reaction indicated less than 2 percent standard deviation for LiF targets prepared and analyzed as were those used in this study. Also, the calibration for tritium sensitivity by two different methods gave results agreeing within 1.8 percent. The current integrators contain a constant-current source; cross-comparison indicated errors less than 1 percent in current measurement. Energy measurement was based on known nuclear reactions. As corrected, however, these data involve energy loss in the overcoat and target material, and probably are good to $\pm 2$ percent above 1 Mev, 20 kev below. Considering the above factors, it is concluded that cross-section values above 10 mb are correct to $\pm 5$ percent (excepting the values above 2.3 Mev as noted above), and the energy values to $\pm 2$ percent.

### $Li^6$ Cross Section

The cross sections obtained for tritium production by the $Li^6$ are shown in Fig. 3. Above 1.3 Mev, a correction has been made for the tritium produced from the $Li^7$ in the targets.[15] This correction increases monotonically above the threshold, reaching 15 percent at 4 Mev. The dashed curve at very low energies was obtained by extrapolation according to the theoretical Gamow penetrability formula, normalized at 0.37 Mev. The errors are estimated at $\pm 5$ percent of the cross section (see discussion in "Results" above).

A study of the separate triton yields in the forward and backward directions as a function of energy has not led to entirely clear cut results. The tritium from each $Li^6$ target and that from the corresponding catcher tube were extracted separately. Because of the appreciable target thickness, however, some of the tritons emitted at greater than 90° to the beam were retained in the target. Thus, the results cannot be interpreted directly, without correcting for this effect. The correction, in turn, is uncertain since the ground state of $Li^5$ is broad (1.5 Mev) and there is some contribution from three body breakup.

A calculation has been made assuming the proper average correction to be equal to that for the reaction leaving the $Li^5$ at the center of the gound state level; i.e., $D+Li^6 \rightarrow T+Li^5+0.9$ Mev. The fraction of the tritium expected in the catcher tube was calculated,

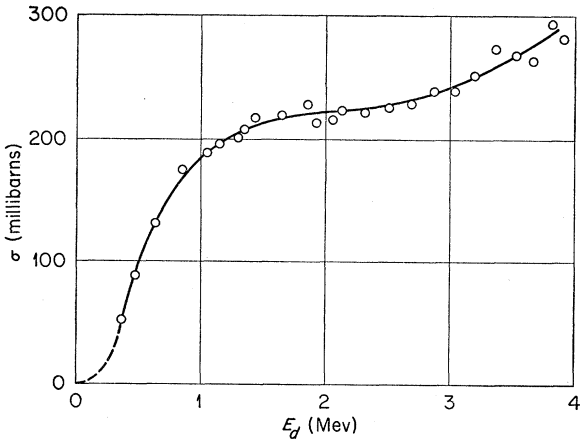


FIG. 3. $Li^6(d,t)Li^5$, $(p)He^4$ cross section.

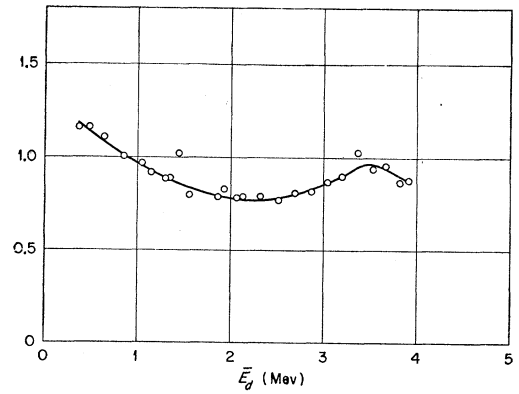


FIG. 4. Ratio of observed to isotropic backward triton yields, assuming $Li^6(d,t)Li^5+0.9$ Mev.

[15] The $Li^6(n,t)$ contribution is readily computed to be less than 0.01 percent of the $Li^6(d,t)$ yield.

assuming isotropy in the center of mass system. A comparison of the observed fractional catcher yield with the calculated one is shown in Fig. 4.

Ratios below 1.0 cannot be considered inconsistent with isotropy if the average triton energy at the back angles is sufficiently lower than corresponds to the two body reaction considered above at each energy. If, on the other hand, the average is higher, an upper limit can be set by considering the reaction $D+Li^6 \rightarrow T+He^4+H+2.51$ Mev to be isotropic for the case where the proton and the alpha particle have no relative motion. Near 0.4 Mev, this assumption barely corresponds to the observed points. This is the limiting case, and it seems likely the average is far from it. The observed effect near 0.4 Mev cannot be explained as due to greater target heating and consequent tritium loss from the targets, as much thinner targets and lower beam currents were used at this energy than above 1 Mev where the assymetry appears reversed.

A more detailed study of the angular distribution should be possible with a modified technique using several tritium catcher foils at various angles to the beam.

## SUMMARY

Within the limits of experimental error, the threshold for the $Li^7(d,t)Li^6$ reaction agrees with the computed value, 1.27 Mev. The cross section rises with energy above threshold to about 95 millibarns at 2.4 Mev, and then to about 165 millibarns at 4.1 Mev. The $Li^6(d,t)Li^5$, $(p)He^4$ cross section rises to 190 millibarns near 1 Mev, then to 290 millibarns near 4 Mev. Thanks are due to many of our colleagues at the Oak Ridge National Laboratory who contributed materially to this study.

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

# Recoil Deuterons and Disintegration Protons from the *n-d* Interaction, and *n-p* Scattering at $E_n = 14.1$ Mev*

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(Received October 22, 1954)

A counter-telescope consisting of two proportional counters and a NaI scintillator in triple coincidence has been used to study the angular distribution of scattered deuterons and disintegration protons from the interaction of 14.1-Mev neutrons with deuterium. Charged reaction products were identified by simultaneous observation of particle energy and rate of energy loss. Thin radiators of deuterated and normal polyethylene were used, the latter to investigate the incident neutron spectrum and *n-p* scattering at 14.1 Mev.

The absolute differential cross sections observed over the recoil angular range 0 to 55 degrees in the laboratory for elastic *n-d* and *n-p* scattering are in good agreement with the recent nuclear-emulsion results of Allred, Armstrong, and Rosen, and with the theoretical results of Christian and Gammel. The anisotropy of *n-p* scattering was found to be about six percent. Protons from disintegration of deuterium were observed over the angular range of 0 to 80 degrees in the laboratory, and the integrated cross section for the forward hemisphere is larger than has been observed previously. The energy distributions appear more nearly uniform than those estimated by Frank and Gammel, and the angular distribution more strongly peaked forward.

## INTRODUCTION

THE study of nucleon-deuteron interactions has been the subject of many theoretical and experimental investigations. A comprehensive survey of the general problem, together with a bibliography to 1953, may be found in a recent review article by Massey.[1] At relatively low energies (below 6 Mev), comparison of *n-d* and *p-d* scattering favors change symmetry (i.e., equivalence of *n-n* and *p-p* nuclear forces) and some type of exchange force, but experimental uncertainties have made detailed comparison difficult. At higher intermediate energies, only two *p-d* experiments have been performed, at 9.66 Mev[2] and at 20.6 Mev.[3] Several *n-d* experiments between 10 and 15 Mev have been reported[4–7] but the results have not been entirely consistent. Since *n-d* elastic scattering is highly anisotropic, it is quite essential for theoretical interpretation that absolute cross section measurements be made. Moreover, neutrons over 3.3 Mev are energetically able to disintegrate the deuteron, and this interaction, which is the simplest case of inelastic scattering and an im-

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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