PHYSICAL REVIEW VOLUME 95, NUMBER 1 JULY 1, 1954

Angular Distribution and Cross Section of $Li^6(n,\alpha)H^3$ for Neutrons of 1.1, 1.5, and 2.0 Mev*

JAMES B. WEDDELL† AND JAMES H. ROBERTS
Northwestern University, Evanston, Illinois
(Received March 29, 1954)

The angular distribution of $Li^6(n,\alpha)H^3$ has been determined for 1.1, 1.5, and 2.0 Mev neutrons by track measurements in 100-micron Ilford *C*2 and *E*1 lithium-six loaded emulsions. The triton yield function has been expressed as a finite series of spherical harmonics in the center-of-mass system. The *s* and *p* components of the neutron wave appear to predominate in the reaction, but the data are not sufficiently accurate to exclude the possibility of contributions from higher angular momentum components.

The cross section was also determined for the reaction at neutron energies of 1.5 and 2.0 Mev relative to that at 0.60 Mev. This was done by exposing the same plate to 0.60-, and to 1.5- or 2.0-Mev neutrons; a long counter was used to measure the neutron flux at each energy. Tracks were selected in a suitable cone so as to resolve the two energy groups. Ther esults were 0.32 ± 0.06 and 0.27 ± 0.04 barn at 1.5 and 2.0 Mev, respectively.

1. INTRODUCTION

MEASUREMENTS on the angular distribution of $Li^6(n,\alpha)H^3$ at neutron energies of 200, 270, 400, and 600 kev have been previously reported.[1] In order to extend to higher energies the range of usefulness of this reaction for neutron spectroscopy, and to obtain more data of theoretical interest, measurements have been performed at neutron energies of 1.1, 1.5, and 2.0 Mev. Measurements have also been made at these energies of the cross section of the reaction. Preliminary results were reported previously.[2]

The technique in the angular distribution measurements is essentially the same as that used at the lower energies.[1] Ilford *E*1 and *C*2 plates loaded with enriched Li^6 were exposed to unidirectional monoergic neutrons. The cross section of the reaction is determined, relative to that at 600 kev,[3] by exposing the same plates to measured fluxes of this energy and of one of the higher energies. The sums of ranges, $\sum R$, of tracks having neutron-triton angles ϕ less than selected values, fall into two groups associated with the two exposures. From the relative numbers of tracks in these two groups, and the angular distributions at the two energies, the cross sections at 1.1, 1.5, and 2.0 Mev are calculated.

2. EXPOSURE AND PROCESSING OF PLATES

The 100-micron Ilford *C*2 and *E*1 plates loaded with enriched Li^6 were exposed to neutrons from $Li^7(p,n)Be^7$ at the large electrostatic generator of the Oak Ridge National Laboratory. The exposure geometry is shown in Fig. 1. Each plate was in a cadmium box. The long-counter was calibrated with a Po–Be source placed as close as possible to the Li target. To reduce attenuation of the neutron beam in the emulsion, the neutrons were incident at an angle $\nu=8°$ to the emulsion plane.

The proton energies were chosen so that the neutron energies would peak at the desired values. The target for the 600-kev exposure had a thickness of 18 ± 3 kev; for the higher energies a target 57 ± 5 kev thick was used. At 600 kev the flux at the center of each plate was 7.0×10^8 neutrons/cm^2; at the higher energies it was 8.5×10^8 neutrons/cm^2.

The plates were processed essentially as before.[1] All were restored to their original thickness, at the time of exposure, by soaking in an aqueous solution of glycerin.

3. TRACK MEASUREMENTS

Track measurements[1] and observer training[4] have been discussed previously. Some tracks were difficult to interpret correctly. A misinterpreted track, in which the triton direction had been reversed, could often be identified from its length;[5] such identification rested upon the assumption that the track was produced by a neutron of full energy coming directly from the target. No doubt some tracks were caused by neutrons scattered in the laboratory. Since the

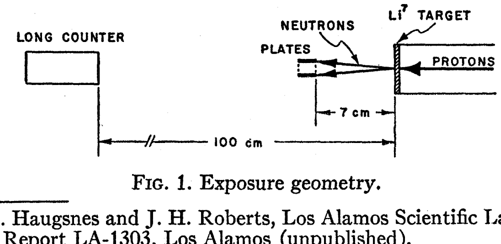

FIG. 1. Exposure geometry.

* This work was supported by a U. S. Atomic Energy Commission contract. It formed the subject of a dissertation submitted to the Graduate School of Northwestern University by James B. Weddell in partial fulfillment of the requirements for the degree of Doctor of Philosophy, June, 1953.

† Now at Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania.

[1] J. H. Roberts and H. M. Mann, Phys. Rev. **83**, 202 (1951); W. O. Solano and J. H. Roberts, Phys. Rev. **89**, 892 (1953); Darlington, Haugsnes, Mann, and Roberts, Phys. Rev. **90**, 1049 (1953).

[2] J. B. Weddell and J. H. Roberts, Phys. Rev. **89**, 891 (1953); Phys. Rev. **93**, 924 (1954).

[3] J. M. Blair and R. Holland, cited in Neutron Cross-Sections, Atomic Energy Commission Report 2040 (Office of Technical Services, Department of Commerce, Washington, D. C., 1952).

[4] J. Haugsnes and J. H. Roberts, Los Alamos Scientific Laboratory Report LA-1303, Los Alamos (unpublished).

[5] G. R. Keepin, Jr., and J. H. Roberts, Rev. Sci. Instr. **21**, 163 (1950).

number of questionable tracks was generally about 10 percent of the total number measured, no attempt was made to correct for these misinterpretations. On the average, errors resulting from misinterpretation tend to cancel. As the neutron energy is increased, the difference in length increases for tracks having neutron-triton angles ϕ and $(180°-\phi)$, as measured in the laboratory system. This fact enabled the observers to reduce the fraction of misinterpreted tracks below that experienced in work at lower neutron energies.

In the determination of the reaction cross section, ϕ was restricted to $\leq 30°$ in the plate exposed at 600 and 1100 kev, and to $\leq 60°$ at the other pairs of energies. This is necessary in order that the groups of tracks associated with the two exposures be adequately resolved on the basis of the sum of ranges, $\sum R$.

4. GEOMETRICAL AND BACKGROUND CORRECTIONS

For a track of given $\sum R$ and ϕ, there is a certain probability P that it satisfy the geometrical selection criteria. These criteria were that the vertical projection of a track not exceed 25 microns and that no part of a track lie less than 3 microns from either emulsion surface. These restrictions refer to a plate which has had its emulsion thickness restored to the value which existed at the time of exposure. If one end of the track (e.g., the alpha) is at least 25 microns from either surface, the triton end will lie on a circle of radius $\sum R \sin\phi$; P is the fraction of the circumference of this circle less than 25 microns above or below the alpha end. Consequently,

$$\frac{1}{P}=\frac{\pi/2}{\sin^{-1}(25/\sum R\sin\phi)}. \tag{1}$$

If the alpha end is at a distance $\gamma<25$ microns from the emulsion surface toward which the triton has traveled,

$$\frac{1}{P}=\frac{\pi/2}{\sin^{-1}(\gamma/\sum R\sin\phi)}. \tag{2}$$

These formulas must be corrected for the fact that the angle of incidence of the neutrons with respect to the emulsion plane is not zero, but 8°. The correction is small and is treated in detail elsewhere.[6] Each track is then assigned a statistical weight $1/P$.

A background of tracks produced by epithermal neutrons resulting from room scattering is present. With few exceptions such tracks have $\sum R<49$ microns and the measured alpha-triton angle $\theta>170°$; furthermore, they have a spherically symmetric angular distribution.[1] Now for $75°\leq\phi\leq 105°$, tracks produced by neutrons of energy greater than 1 Mev have $\sum R>55$ microns and $\theta<170°$; within this range of values of ϕ, the epithermal background tracks can usually be identified. From the number of these tracks in that interval, and their isotropic distribution in ϕ, the total number of epithermal background tracks is determined. The corrections for such tracks were small, their number never exceeding 7 percent of those measured.

Be^7 has an excited state at 430 kev.[7] The threshold for the production of the group of neutrons associated with this state in $Li^7(p,n)$ is not attained until the neutrons associated with the ground state have an energy of 660 kev. In the energy region which concerns us, the group of neutrons associated with this excited state is about 10 percent as abundant as the main group, and the two groups emitted in the forward direction differ in energy by about 480 kev.[7] Since the angular distribution and cross section were measured for neutron energies differing by about this amount, it was possible to correct for the presence of this secondary group of neutrons.

5. DATA AND RESULTS

In order to determine the angular distribution, the tracks were grouped in 10° intervals of ϕ. Each track was assigned its statistical weight P^{-1}, and $\sum P^{-1}$ was determined for the tracks in each interval. After the background corrections were made, the results were transformed to the center-of-mass system and expressed in terms of equal 10° intervals of ϕ_0, the neutron-triton angle in this system. The results are shown in Table I. The results are normalized so that the sum of the weighted numbers of tracks in all ϕ_0-intervals is numerically equal to the capture cross section σ_c in barns, at each neutron energy. At each

TABLE I. Relative number of tritons per 10° interval in the center-of-mass system. (Sum normalized to cross section.)

ϕ_0 interval (degrees)	Neutron energy (Mev) 1.1	1.5	2.0
0–10	0.006	0.006	0.004
10–20	0.019	0.017	0.008
20–30	0.019	0.021	0.014
30–40	0.025	0.023	0.013
40–50	0.030	0.028	0.019
50–60	0.028	0.025	0.025
60–70	0.029	0.026	0.030
70–80	0.029	0.032	0.024
80–90	0.024	0.033	0.027
90–100	0.017	0.028	0.019
100–110	0.014	0.020	0.021
110–120	0.013	0.016	0.017
120–130	0.012	0.014	0.016
130–140	0.007	0.011	0.009
140–150	0.004	0.008	0.010
150–160	0.002	0.006	0.007
160–170	0.001	0.004	0.004
170–180	0.001	0.001	0.001
0–180	0.28[a]	0.32	0.27

[a] This value was taken from the data of F. L. Ribe (private communication).

[6] J. B. Weddell, dissertation, Northwestern University (University Microfilms, Inc., Ann Arbor, 1953).

[7] Johnson, Laubenstein, and Richards, Phys. Rev. 77, 413 (1950).

energy, the total number of measured tracks was from 1400 to 1500.

To determine σ_c for $Li^6(n,\alpha)$, about 400 tracks were measured for $\phi_0 \leq 68°$ in a plate exposed to 600-kev neutrons alone. About 400 tracks were also measured for $\phi_0 \leq 68°$ in the plates exposed at both 600 kev and 1100, 1500, or 2000 kev. Tracks in this same forward cone were selected from the angular distribution data obtained from the plates exposed only at 1100, 1500, or 2000 kev. (The forward cone was $\phi_0 \leq 33°$ for the work at 1100 kev.) The neutron flux to which each plate was exposed was determined by a long-counter placed 1 meter from the target of the electrostatic generator (Fig. 1).

Figure 2 shows the number of tracks, weighted by P^{-1}, plotted as a function of $\sum R$ for the three plates used to determine σ_c at 2000 kev. From the reaction kinetics, the range-energy relationships for the emulsions, and straggling, about 90 percent of the tracks from 2.0-Mev neutrons in $0° \leq \phi_0 \leq 68°$ should have $\sum R$ in the range from 72 to 105 microns. The corresponding values for 0.6 Mev are from 48 to 66 microns. After adjusting the area under curve (c) to that under curve (b), the tracks in the region from 48 to 66 microns resulting from the higher energy exposure can be subtracted. The tracks remaining in this region are then attributed to 0.6-Mev neutrons with $0° \leq \phi_0 \leq 68°$. The ratio of the longer group of tracks to the shorter, adjusted to equal neutron fluxes, gives the ratio of $\int_0^{68°}(d\sigma_c/d\Omega_0)2\pi \sin\phi_0 d\phi_0$ for 2.0 and 0.6 Mev, where $d\Omega_0$ is the solid angle between ϕ_0 and $(\phi_0+d\phi_0)$ in the center-of-mass system, after small corrections are made for the presence of neutrons associated with the 430-kev state of Be^7. From these measurements and the data in Table I, the relative values of σ_c are determined at these two energies. Using 0.45 barn as the value of σ_c at 0.6 Mev, from the data of Blair and Holland,[3] the values of σ_c at 1.5 and 2.0 Mev are 0.32±0.06 barn and 0.27±0.04 barn, respectively. Our measurement of σ_c at 1.1 Mev gave 0.19 barn, but this is believed to be less reliable because of poorer resolution and statistics. Our data in Table I at 1.1 Mev are therefore normalized to 0.28 barn, as reported by Ribe.[8]

TABLE II. Coefficients of the triton yield function in barns per steradian. (± gives statistical accuracy only.)

Neutron energy (Mev)	a_0	a_1	a_2
0.20	0.167±0.004	0.102±0.007	0.156±0.009
0.40	0.095±0.003	0.049±0.005	0.078±0.006
0.60	0.040±0.001	0.012±0.002	0.019±0.002
1.10	0.022±0.001	0.022±0.001	0.006±0.002
1.50	0.026±0.001	0.017±0.002	0.003±0.002
2.00	0.022±0.001	0.008±0.001	0.001±0.001

[8] F. L. Ribe, Phys. Rev. **87**, 205 (1952); also private communication.

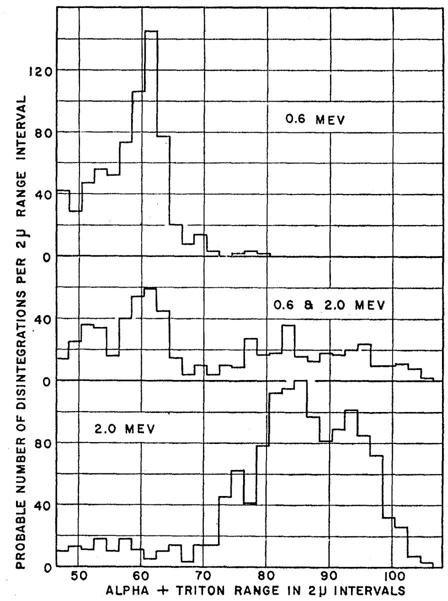

FIG. 2. Weighted numbers of tracks in each 2 micron interval of ΣR. Upper curve, plate exposed to 0.6-Mev neutrons alone. Middle curve, plate exposed to 0.6-Mev and 2.0-Mev neutrons. Lower curve, plate exposed to 2.0-Mev neutrons alone.

6. YIELD FUNCTION

We assume that the yield function $Y(\phi_0)$ can be expanded into spherical harmonics:

$$Y(\phi_0)=\sum_{i=0}^{\infty} a_i P_i(\phi_0), \tag{3}$$

and furthermore that the yield function can be adequately approximated by the finite series

$$Y(\phi_0)=\sum_{i=0}^{2} a_i P_i(\phi_0), \tag{4}$$

where $P_0(\phi_0)=1$, $P_1=\cos\phi_0$, and $P_2=\frac{3}{2}\cos^2\phi_0-\frac{1}{2}$. The coefficients a_i are obtained by a numerical integration from

$$a_i=(i+\tfrac{1}{2})\int_0^{\pi} 2\pi Y(\phi_0)P_i(\phi_0)\sin\phi_0 d\phi_0, \tag{5}$$

or, if written as a summation,

$$a_i=2\pi(i+\tfrac{1}{2})\sum_{k=1}^{n} P_{ik}(\phi_0)Y_k(\phi_0)(\Delta\cos\phi_0)_k, \tag{6}$$

where P_{ik} is the mean value of P_i in the kth 10° interval of ϕ_0, and Y_k is the mean value of Y in the same interval.

Now in our measurements we have determined

$$Y_k(\phi_0)(\Delta\cos\phi_0)_k=(\sum P^{-1})_k, \tag{7}$$

normalized such that

$$\sigma_c=\int_0^{\pi} 2\pi Y(\phi_0)\sin\phi_0 d\phi_0, \tag{8}$$

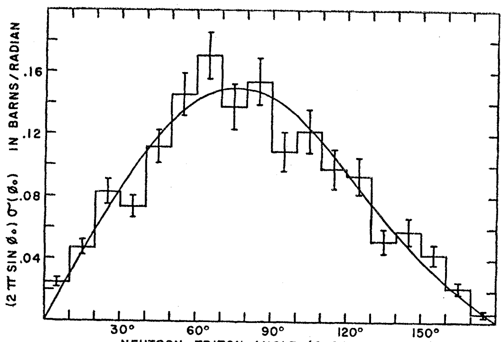

FIG. 3. Weighted number of tracks in each 10° interval of ϕ_0 (histogram). Integrated yield function (smooth curve). Data are for 2.0-Mev neutrons.

and k has values from 1 through $n=18$, for the 18 intervals of 10° each in the angle ϕ_0. Making this substitution, we have

$$a_i = 2\pi(i+\tfrac{1}{2}) \sum_{k=1}^{n} P_{ik}(\phi_0)(\sum P^{-1})_k. \tag{9}$$

The standard deviation of $(\sum P^{-1})_k$ is equal to $(\sum P^{-1})_k/\sqrt{N_k}$, where N_k is the actual measured number of tracks in the kth interval; N_k is of the order of 50 to 100 for most intervals. Let a'_{ik} be the standard deviation of the contribution to a_i from the kth interval:[9]

$$a_{ik}' = (i+\tfrac{1}{2})P_{ik}(\phi_0)(\sum P^{-1})_k/\sqrt{N_k}. \tag{10}$$

Therefore the standard deviation of a_i is given by

$$a_i' = (i+\tfrac{1}{2})\{\sum_{k=1}^{n}[(\sum P^{-1})_k^2/N_k]P_{ik}^2(\phi_0)\}^{\frac{1}{2}}. \tag{11}$$

Table II gives the values of a_0, a_1, and a_2 as calculated from Eq. (9), not only for the neutron energies studied in this paper, but also for the energies previously investigated in this laboratory.[1] The variations given after the values of a_i are the values a_i' as found from Eq. (11). The yield function, including only the first three coefficients, is therefore

$$Y(\phi_0) = a_0 + a_1P_1(\phi_0) + a_2P_2(\phi_0), \tag{12}$$

which can also be written as

$$Y(\phi_0) = A + B\cos\phi_0 + C\cos^2\phi_0, \tag{13}$$

where $A = a_0 - \frac{1}{2}a_2$, $B = a_1$, and $C = \frac{3}{2}a_2$. The values of these coefficients as thus determined for the lower neutron energies agree within their statistical accuracy with those previously reported.[1]

It should be noted that, from Eq. (5) and the orthogonality of the spherical harmonics, the first three terms of Eq. (12) are independent of the possible existence of terms of higher order, but in the power series (13) in $\cos\phi_0$ this is not so. The statistical accuracy is not adequate at any of the neutron energies definitely to exclude the existence of terms of higher order in (12) arising from d, f, etc., components of the neutron wave. But if the given series are complete, only the s and p components enter into the reaction; in any case these appear to be the predominant components.

The smooth curve in Fig. 3 is a plot of $2\pi Y(\phi_0)\sin\phi_0$ including terms through a_2 for $E_n = 2.0$ Mev. The agreement with the histogram of the data is satisfactory in view of the statistical accuracy of the latter. Figure 4 shows a plot of $Y(\phi_0)$ at neutron energies of 1.1, 1.5, and 2.0 Mev.

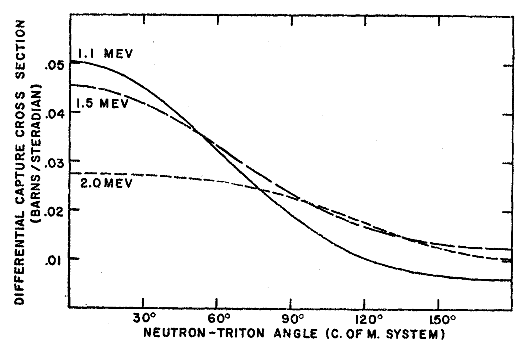

FIG. 4. Normalized yield functions vs ϕ_0.

7. ACKNOWLEDGMENTS

The authors wish to express their appreciation of the work of those who participated in the previous investigations: Lillian E. Darlington, Jack Haugsnes, and Harry M. Mann. They also wish to thank H. B. Willard, J. K. Bair, and others at the Oak Ridge National Laboratory for their assistance in exposing the plates; F. L. Ribe for an advance copy of his results regarding the reaction cross section; H. B. Billington for developing the plates; Jack Haugsnes for preparing the figures and Lillian Darlington for help with the calculations; and especially Mrs. Margaret Steele, Jerome Green, Richard Leach, William Meltzer, Bernard Turbow, and Daniel Wilson, who for long hours faithfully measured tracks and performed routine calculations.

[9] P. M. Endt, Physica 18, 421 (1952).