since the Doppler-broadened curve and the experimental curve agree so well, and since the shape is so symmetrical (see Fig. 4).

The results reported here do not provide conclusive evidence for the existence of two distinct groupings of radiation widths. It is generally assumed that the Porter-Thomas distribution[14] for radiation widths would be quite narrow due to the large number of degrees of freedom, i.e., the large number of exit channels for the process. The value of Γ_γ for the Eu^{153} resonance at 6.16 ev is anomalously large, and would not fit such a distribution. The possibility cannot be excluded that this one resonance belongs to one spin state while the five remaining resonances belong to the opposite spin state.

In Eu^{151}, the two resonances at -6×10^{-4} ev and 0.327 ev, previously reported as having smaller Γ_γ, were not remeasured. Since none of the four resonances reported here fall into this group, it would be worthwhile to remeasure these and check the earlier results. The correlation between the activation[7] of the isomeric state of Eu^{152} and the smaller values of Γ_γ tends to support the earlier results. It would be interesting to extend Wood's activation measurements to higher energies using the enriched samples to see if the correlation is really significant.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Vance L. Sailor, Dr. Harvey Marshak, and Dr. Ferdinand J. Shore for helpful discussions.

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[14] R. G. Thomas and C. E. Porter, Phys. Rev. **104**, 483 (1956).

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$Li^6(n,t)He^4$ Reaction at Intermediate Energies*

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The $Li^6(n,t)He^4$ reaction cross section has been measured in a neutron energy interval extending from 9 kev to 340 kev. The cross section descends from 1.77 barns at 9 kev to a minimum of 0.74 b at 100 kev before rising to a peak resonance value of 2.75 barns at 258 kev. The cross section from 9 kev to 90 kev is not proportional to $E^{-\frac{1}{2}}$, but can be represented by $\sigma=3.96E^{-0.367}$ with σ in barns and the neutron energy E in kev. Angular distributions of the tritons are presented for neutron energies of 150, 200, 258, 300, 350, and 565 kev. These distributions, measured in a relative manner, are placed on an absolute scale by normalizing to the cross section data of this experiment, extended to 565 kev by use of previously measured cross sections.

INTRODUCTION

When Li^6 is bombarded by neutrons with energies between thermal and 1 Mev, three nuclear reactions are energetically possible—elastic scattering, radiative capture, and the $Li^6(n,t)He^4$ reaction. The (n,t) reaction cross section is 945 barns at thermal energies[1] and is expected to decrease with increasing neutron energy, obeying the $1/v$ law up to rather appreciable energies. At higher energies, between 140 and 650 kev, Blair and Holland[2] have observed a strong resonance centered at 250 kev. This resonance also appears in the total neutron cross section[1,3] of Li^6 and has been attributed to the presence of an excited state in Li^7 at 7.46 Mev with $J=5/2^-$.[3,4]

Of particular interest is the behavior of the cross section at lower energies where the $1/v$ dependence of the cross section might be modified by the 250-kev resonance. Gorlov *et al.*[5] report cross-section measurements in the energy interval 9 to 700 kev. They observe the resonance due to the 7.46-Mev state of Li^7, but at a somewhat higher energy. The cross sections at the lowest energies of 9, 20, and 50 kev are about 15, 32, and 47% higher than a $1/v$ extrapolation of the cross section from the thermal value. Since it might be expected that the cross sections at these energies should be smaller, corresponding more nearly to the $1/v$ extrapolation, the present experiment was undertaken. The measurements of this experiment are in essential agreement with Gorlov *et al.* However, the position of the resonance

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[1] *Neutron Cross Sections*, compiled by D. J. Hughes and J. A. Harvey, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955), and D. J. Hughes and R. Schwartz, Supplement No. 1, 1957.

[2] J. M. Blair and R. E. Holland (unpublished). These results, corrected for more recent measurements of the U^{235} fission cross section, are given in Supplement No. 1 of reference 1.

[3] Johnson, Willard, and Bair, Phys. Rev. **96**, 985 (1954).

[4] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955)].

[5] Gorlov, Gokhberg, Morozov, and Otroshchenko, Doklady Akad. Nauk S.S.S.R. **111**, 791 (1956) [translation: Soviet Phys. Doklady **1**, 705 (1956)].

determined by this experiment agrees more nearly with the position found by Blair and Holland.

The angular distributions of the $Li^6(n,t)He^4$ reaction at various energies over the 250-kev resonance yield information regarding the properties of the 7.46-Mev level of Li^7. Angular distributions have been measured by Darlington *et al.*[6] at four energies in this region. Measurements made by the late H. C. Martin, Jr., are presented for the first time in this paper.

EXPERIMENTAL

$Li^6(n,t)He^4$ Cross Section Variation with Energy

The $Li^6(n,t)He^4$ reaction proceeds with an energy release $Q=4.78$ Mev, so both the triton and the alpha particle resulting from the disintegration are quite energetic. With the development of the $Li^6I(Eu)$ scintillation crystal, it became possible to detect the absolute number of (n,t) events occurring in a known mass of crystal. The detector for this experiment was a crystal $1\frac{1}{2}$ inches in diameter and 2 mm thick, with a Li^6 abundance of 96%. It was encased in a lightweight, stainless steel can, having a 0.002-inch thick window between the neutron source and the crystal face. Conventional photomultipliers, amplifiers, and multichannel analysers were used in the experiment.

The neutron source was the $Li^7(p,n)Be^7$ reaction produced in thin normal lithium layers by a proton beam from a 2.5-Mev Van de Graaff accelerator. The thickness of the Li target was measured by determining the proton energy difference between the threshold for neutron production at 0° (i.e., $E_p=1.883$ Mev) and the energy of the maximum forward yield of neutrons. The accelerator beam energy was determined by electrostatic analysis of the mass 2 beam, and the neutron yield was measured for calibration purposes with a flat sensitivity "long counter." Two targets were used in the experiment with thicknesses of 13 and 17 kev for protons at threshold energy. The energies of the neutrons obtained at various proton bombarding energies were obtained from the tables of Langsdorf *et al.*[7] Neutrons with energies from 140 to 340 kev were obtained at 0° to the proton beam. Energies below 170 kev were obtained in separate runs at angles of 120°, 60°, and 45° to the proton beam.

Monoenergetic neutrons interacting with the Li^6 in the crystal produced a well-defined peak in the pulse-height distribution from the counter. A small tail on the low-energy side of the peak was caused by the escape of one of the reaction particles when the reaction occurred near a crystal surface. This tail, which had a height of about 2% of the peak height, extended at lower pulse heights into a background caused by gamma and x-rays. It was possible to obtain the total number of the (n,t) reactions occurring in the crystal to an accuracy of a few percent by integration of the number of counts contained in the tail and peak in the pulse-height distribution.

The number of neutrons producing the (n,t) disintegrations was determined with a flat-response long counter which had been previously calibrated on an absolute scale with a thin-walled U^{235} fission detector placed in the position at which the crystal was to be exposed. The fission detector, operated as a parallel plate ionization counter, contained a disk on which was deposited a uniform, thin layer of $U_2{}^{235}O_5$. The weight of U^{235} in this layer was determined very precisely by Diven[8] in an experiment performed to measure the fission cross section of U^{235}. The number of fission counts from the detector was related to the neutron yield from the target through the fission cross section.[9] One of the greatest uncertainties in the experiment is the uncertainty of the fission cross section which we estimate to have a standard deviation of about ±15% at 10–20 kev, improving to ±5% above 150 kev.

Because the $Li^6(n,t)He^4$ cross section rises to high values for low-energy neutrons, it was necessary to determine the background in the Li^6I crystal produced by thermal and epithermal neutrons. The experimental area was located in a sheet metal building about 20 feet above the ground, so the background was relatively low. A $1/r^2$ determination of this background was made and the data were corrected accordingly. The maximum correction due to this effect was 20% at 120° and the lowest neutron energy. At 0° and at higher energies, the correction became negligible. Neutrons backscattered from the glass disk on which the crystal was mounted and also from the photomultiplier would be expected to increase the number of (n,t) events in the crystal. A calculated correction of 5 to 10% was applied to the data for this effect. The error in the calculated correction was estimated to be half its value.

$Li^6(n,t)He^4$ Angular Distribution

The angular distribution of tritons from the $Li^6(n,t)He^4$ reaction was measured by the late H. C. Martin, Jr., at neutron energies of 150, 200, 258, 300, 350, and 565 kev. For these measurements the $Li^7(p,n)Be^7$ reaction was used to produce neutrons with a total energy spread of 20 to 25 kev. An evaporated target of metallic Li^6 about 1 mg/cm^2 thick was placed in a thin-walled counter telescope system and exposed to the neutron source. Angular distributions were obtained by rotating the detector around the Li^6 target, and counting the reaction tritons as a function of angle. The tritons were detected by the counter telescope which consisted of two proportional counters followed by a scintillation counter. The gas pressure of the system was adjusted

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[6] Darlington, Haugnes, Mann, and Roberts, Phys. Rev. **90**, 1049 (1953).

[7] Langsdorf, Monahan, and Reardon, Argonne National Laboratory Report ANL-5219 (unpublished).

[8] B. C. Diven, Phys. Rev. **105**, 1350 (1957).

[9] Fission cross sections were taken from a recent compilation by W. D. Allen and R. H. Henkel in *Progress in Nuclear Energy* (Pergamon Press, Limited London, 1958), Ser. I, Vol. II, p. 31.

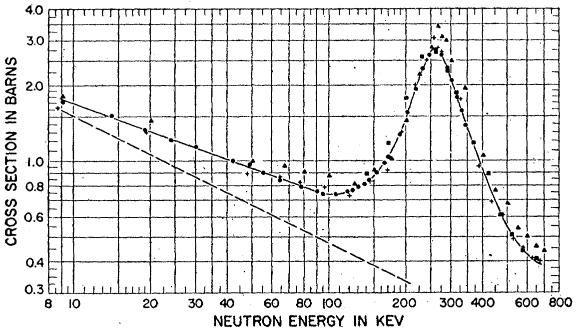

FIG. 1. Cross section of $Li^6(n,t)He^4$ as a function of neutron energy. The round points are the data of this experiment; square points are those of Blair and Holland[2]; triangles are the results of Gorlov *et al.*[5] With an arbitrary reduction of the energy scale by 4% and the cross section scale by 10%, the data of Gorlov *et al.* yield the crosses which agree well with the results of this experiment in the resonance region. The dashed line is a $1/v$ extrapolation of the thermal cross section of 945 barns.

so that the α-particles were stopped in the gas before getting to the scintillation counter. A triton which passed through the proportional counters and stopped in the scintillation counter was identified by a threefold coincidence and by pulse-height analysis in the third counter. The half-angle resolution of the detector was 3.5°. The angular distributions were measured on a relative basis and have been assigned a relative standard error of ±15%. The distributions were placed on an absolute basis by normalizing them to the total (n,t) cross section reported in this paper.

Results

The $Li^6(n,t)He^4$ cross section values obtained in this experiment as a function of neutron energy are shown in Fig. 1. The points between 40 and 170 kev are the average of four sets of data taken at different angles from the neutron source. The results of Blair and Holland[2] and of Gorlov *et al.*[5] are also shown in this figure. The results of Blair and Holland agree well with the present results, although their resonance peak appears to be about 10 kev broader than the present peak. This greater resonance width could possibly be explained by different energy resolutions in the two experiments combined with slightly differing energy scales. The agreement of this experiment with Blair and Holland on the high-energy side of the resonance seems to be quite good, so their experimental points have been used to continue the cross section curve beyond 565 kev. The cross section in the resonance region above 150 kev is believed to have a standard deviation of about ±8%. Below 150 kev, the standard deviation increases to ±10% at 60 kev and to about ±15% at the lowest energies.

The cross-section points obtained by Gorlov *et al.* are also shown in Fig. 1. Their experiment was done using ionization counters containing thin deposits of known weight of Li^6F exposed to neutrons from a $T(p,n)He^3$ source. The neutron flux in their experiment was measured with flat energy response detectors composed of boron counters in paraffin assemblies. These counters were calibrated with a standard neutron source with the flux known to ±7%. Experience in this laboratory indicates that this technique might yield results with a standard deviation of ±10 to 15%, since "long counters"[10] have been found to be not strictly flat in energy response.[11] The resonance peak position found by Gorlov *et al.* is 268 kev as compared to 258 kev for this experiment. Because of the result of this experiment and that of Blair and Holland,[2] as well as the total cross-section experiments,[1] it seemed reasonable to make the assumption that 258 kev is the correct value, so the data of Gorlov *et al.* has been shifted down 4% in energy, and the absolute cross-section scale reduced by 10% to agree with the peak cross section of the other $Li^6(n,t)He^4$ experiments. These modified points are seen to agree very well with the present data over the entire energy range. In addition, the modified data agrees well with the higher energy points of Blair and Holland. It should be noted that the unmodified data of Gorlov *et al.* are in reasonable agreement with the present results, considering the experimental accuracy of both experiments.

Cross sections at higher energies have been measured by Ribe.[12] The data of the present experiment join these higher energy data in a satisfactory manner.

The relative angular distributions were placed on an absolute energy scale by normalizing to cross sections taken from the smooth curve in Fig. 1. These distributions, which are shown in Fig. 2, can be compared to the results of Darlington *et al.*[6] which have been normalized to the corrected cross sections of Blair and Holland and are given in the compilation of Hughes and Carter.[13] The angular distributions given in reference 6 are normalized to an older set of the Blair and Holland data which was based on less accurate fission cross-section measurements. On a relative basis the two sets of angular distributions agree within ±30%.

DISCUSSION

The present experimental results on the $Li^6(n,t)He^4$ cross section are in reasonable agreement with previous experimental results.† The character of the 7.46-Mev level of Li^7 as derived by fitting the $Li^6(n,t)He^4$ cross section in the 250-kev resonance energy region[3,5] remains

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[10] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

[11] Nobles, Day, Henkel, Jarvis, Kutarnia, McKibben, Perry, and Smith, Rev. Sci. Instr. **25**, 334 (1954); and Haddad, Perry, and Smith (private communication), also see reference 9, page 26.

[12] F. L. Ribe, Phys. Rev. **103**, 741 (1956).

[13] D. J. Hughes and R. S. Carter, Brookhaven National Laboratory Report BNL-400, June, 1956 (unpublished).

† *Note added in proof.*—Recent measurements given by Gabbard, Davis, and Bonner, Phys. Rev. **114**, 201 (1959), are in disagreement with earlier measurements of the same group in the energy range 25–150 kev, which are given in *Neutron Cross Sections*, compiled by D. J. Hughes and J. A. Schwartz (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), Brookhaven National Laboratory Rept. BNL-325, second edition. The data of the present experiment are in excellent agreement with the later results of this group.

the same. It should be pointed out that attempts to fit the older data[3,14] have not been completely successful. Of particular interest is the manner in which the low-energy cross section joins in with the cross section in the resonance region. Although the cross section at low energies is expected to vary approximately as $1/v$, the thermal value of 945 barns extrapolated as $1/v$ into the 3–10 electron volt region lies about 6% higher than the measured value of the total cross section.[1] This deviation from the $1/v$ law might be explained by the influence of the wide level in Li^7 at about 6.6 Mev, which is below the Li^6+n excitation energy of 7.245 Mev.[4] In the 9–100 kev region covered in this experiment the cross-section variation with energy is slower than $1/v$. This deviation might be due to the influence of higher lying levels in Li^7. Futher efforts toward fitting this data might prove of interest.

An experimental determination of the ratio of the $Li^6(n,t)He^4$ cross section to the $He^3(n,p)T$ cross section in the energy range of a few ev to 30 kev has been made by Bergman *et al.*[15] Assuming that the Li^6 cross section decreases as $1/v$ with increasing energy, they found that the He^3 cross section decreases with energy much faster than the $1/v$ law. This behavior of the He^3 cross section was interpreted to imply that He^4 may have an excited state at an excitation 250 to 750 kev below the binding energy of a neutron in He^4. It is interesting to note that if the Li^6 cross-section variation with energy determined by the present experiment is used with the ratio results of Bergman *et al.*, the He^3 cross section is found to vary as $1/v$ with energy between 9 and 30 kev. Thus, the energy variation of $\sigma[Li^6(n,t)]/\sigma[He^3(n,p)]$ does not necessarily imply the existence of an excited level in He^4.

The energy range of a few kev to 100 kev is one of the difficult ranges for measuring neutron induced reaction cross sections, because of the problem of measuring the neutron flux. The $Li^6(n,t)He^4$ reaction taking place in $Li^6I(Eu)$ scintillation crystals gives promise of providing a simple measurement of the flux from monoenergetic neutron sources such as the $Li^7(p,n)Be^7$, $Cu^{65}(p,n)Zn^{65}$, and $V^{51}(p,n)Cr^{51}$ reactions. In addition, the $Li^6I(Eu)$ crystal can possibly be used for broader energy spread sources with a time-of-flight technique, since there appears to be a low-amplitude, fast component of the light emitted from the crystal. The experimental results of this experiment make possible flux measurements with a standard error of 10 to 15%. The largest part of the error comes from the uncertainty of the U^{235} fission cross section. Future independent measurements of the $Li^6(n,t)He^4$ cross section at a few energies between 1 and 100 kev would be very desirable, from the point of view of providing a simple method of measuring neutron fluxes in the low-energy range.

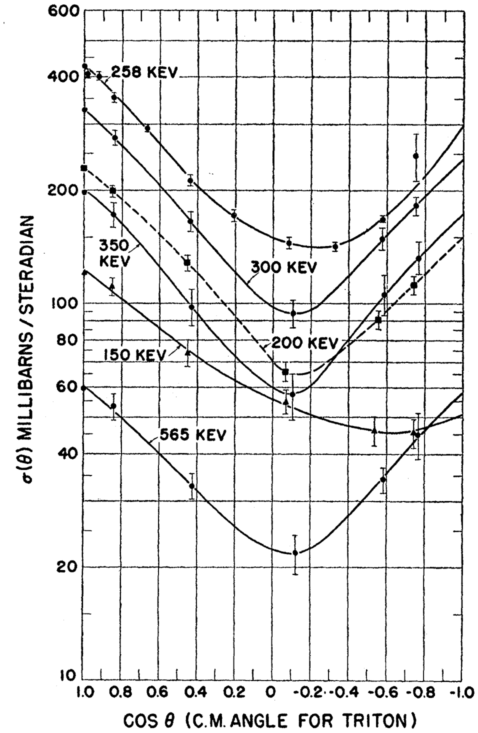

FIG. 2. Angular distributions of $Li^6(n,t)He^4$. The laboratory neutron energy for each distribution is given on the graph. The absolute cross-section scale was obtained by normalizing the distributions to the smooth curve in Fig. 1.

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[14] J. J. Devaney, Los Alamos Scientific Laboratory Report LA-1960 (unpublished).

[15] Bergman, Isakov, Popov, and Shapiro, Atomic Energy Commission Report TID-7547, 1957 (unpublished), p. 191.