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DETERMINATION OF THE 14-MEV $Li^7(n, n'\alpha)T$ CROSS SECTION FROM SPHERE MULTIPLICATION AND TRANSMISSION MEASUREMENTS

by

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ABSTRACT

By utilizing lithium spherical shell transmission and multiplication measurements, the $Li^7(n,n'\gamma)Li^7$ and the He^6-production cross sections, it is possible to deduce that the 14-Mev $Li^7(n,n'\alpha)T$ cross section is 325 ± 75 mb. A spectrum for neutrons degraded in energy between 0 and 12 Mev is also given.

ACKNOWLEDGMENT

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1. The Li^7 + n Reactions

The following basic reactions are energetically possible from the interaction of 14-Mev neutrons with Li^7:

No.	Reaction Products	Q	σ at 14 Mev	Ref.
1	Li^7 + n (elastic scattering)	0.00	1.05 ± 0.08 b	This report
2	Li^{7*} (0.48 Mev) + n	- 0.48	75 ± 15 mb	2
3	He^4 + T + n	- 2.47	325 ± 75 mb	This report
4	He^6 + p + n	- 9.68	9.8 ± 1.1 mb (reactions 4 and 5)	3
5	He^6 + d	- 7.45		
6	Li^6 + 2n	- 7.25	~ 0	1
7	Li^{6*} (3.58 Mev) + 2n	-10.83	~ 0	1
8	He^4 + d + 2n	- 8.72	~ 0	1
9	He^4 + p + 3n	-10.95	~ 0	1
	Total		1.45 ± 0.03 b	4

Reactions involving He^5 and other unstable configurations are not explicitly listed because they are special cases of some of the above many-body reactions. Gamma-ray emission is expected to be negligible, say < 1 mb, except from the de-excitation of the 0.48-Mev level of Li^7 (Ref. 2) and possibly from the de-excitation of the 3.58-Mev level of Li^6. As the $Li^7(n,\gamma)Li^8$ cross section is less than 0.1 mb at the 0.256-Mev resonance,[3] it is reasonable to assume it to be negligible except in the vicinity of thermal energies where

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it is 33 mb.[5] If nuclides such as H^4, He^7, etc., are stable, their associated Q values are almost certainly too highly negative to allow their production at 14 Mev. The sum of the 14-Mev cross sections for reactions 4 and 5 was observed by the measurement of the He^6 activity.[3]

The Q values of the Li^7 + n reactions and the known levels of Li^7 (Ref. 5) are indicated on Fig. 1. Evidently the only non-neutron producing reaction is 5, and the excitation of Li^7 states between the 2.47-Mev (He^4 + T) threshold and the 7.25-Mev (Li^6 + n) threshold must result in (He^4 + T) emission, except for minor competition from gamma emission. Above the latter threshold, T emission is subject to competition from n, p, and d emissions. It is also evident from the listing that by subtracting σ_2, $\sigma_4 + \sigma_5$, $\sigma_{n,2n} = \sigma_6 + \sigma_7 + \sigma_8$, and $\sigma_{n,3n} = \sigma_9$ from the inelastic cross section $\sigma_i = \sum_{i=2}^{9} \sigma_i$, which may be obtained from a sphere transmission measurement, there remains σ_3. Information concerning the (n,2n) and (n,3n) cross sections may be derived from the measurement of the neutron multiplication by a Li sphere.

Measurements have been reported by Frye[6] of the fast tritons in photographic emulsions after emerging from metallic Li targets. It is evident from their angular distributions that the fast tritons arise from the two-stage processes $Li^7(n,t)He^5$, $He^5 \rightarrow He^4 + n$, which are special cases of the three-body reaction 3. The cross

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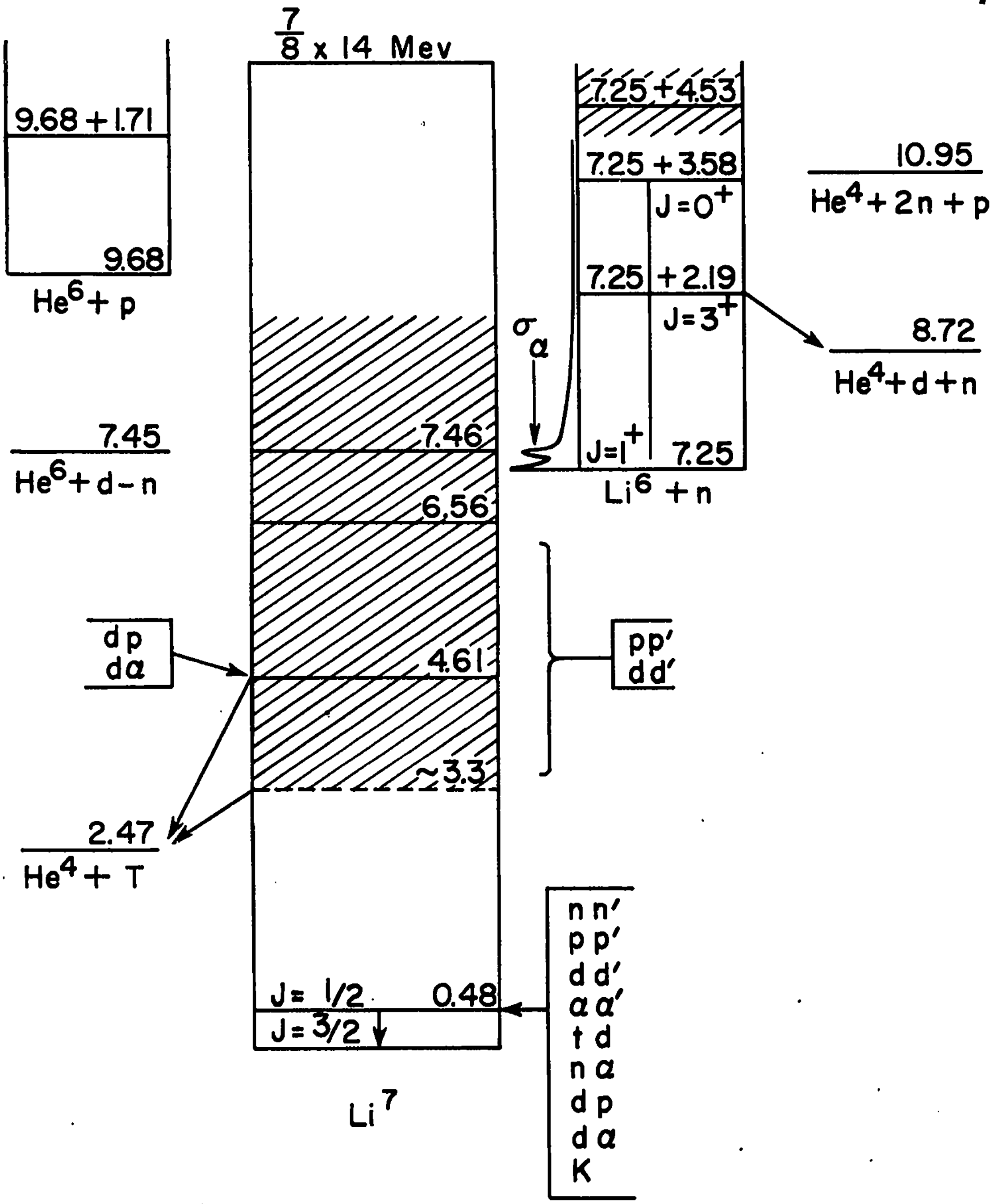

Fig. 1. The energy levels of Li^7 and the Q values for the $Li^7 + n$ reactions.

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section was observed to be 55 ± 8 mb for those tritons associated with the formation of He^5 in its unstable $P_{3/2}$ lowest state. There is also suspected to be an additional 50 mb of short-range tritons associated with the formation of He^5 in the $P_{1/2}$ and $S_{1/2}$ states at higher excitations. Due to the target thickness and the properties of the emulsion, tritons with energies less than about 2.7 Mev were not observed. Slow tritons could arise from two-stage type processes $Li^7(n,n')Li^{7*}$, $Li^{7*} \rightarrow He^4 + T$ proceding through Li^7 states below about 7 Mev, from which an appreciable contribution to the total triton cross section may be expected as in the case of the corresponding $Li^7(p,p')$ experiments.[7,8] Although the cross sections of these (p,p') measurements were given in relative units, they do reveal frequent excitation of the 4.61- and 6.56-Mev levels of Li^7 as well as a broad level with an apparent threshold at 3.3 Mev. It was also noted in the (p,p') measurements that the 4.61-Mev level does not significantly decay by gamma-ray emission and therefore that it must decay by (He^4 + T) emission.[9] The decay tritons from this level have actually been observed in the $Be^9(d,\alpha)Li^{7*}$ reaction.[10]

2. Determination of the 14-Mev $Li^7(n,n'\alpha)T$ Cross Section

2.1 The Sphere Multiplication Measurement

In this measurement, the ratio M of sphere-on to sphere-off

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counting rates of an external flat-response long counter is obtained, the neutron source being located at the sphere center.[1,11] If secondary neutron multiplication is negligible, this ratio is related to the various inelastic cross sections according to the expression

$$\sigma_i \left[1 - \exp(-\sigma_i N \ell)\right]^{-1} (M-1) = \sigma_{n,2n} + 2\sigma_{n,3n} + \cdot\cdot - \sigma_{n,on}$$

where ℓ is an effective path length of the neutrons in the absence of inelastic scattering, N is the atomic density, and σ_i is the total non-elastic cross section; $\sigma_{n,on} = \sigma_5$. At 14 Mev the elastic scattering distribution is concentrated in the forward directions so that the path length ℓ for a thin sphere may be well approximated by the sphere thickness t which was 1 in. in the measurement by Graves, the sphere diameter being 4 in. As indicated below, $\sigma_i \approx 0.4$ b so that $\sigma_i\left[1 - \exp(-\sigma_i N\ell)\right]^{-1} \approx (Nt)^{-1} = 9.60$ b. The observed value $M = 0.9994 \pm 0.0032$* thus indicates that $\sigma_{n,2n} + 2\sigma_{n,3n} - \sigma_{n,on} =$

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* This uncertainty is taken as the square root of the sum of the squares of the counting rate uncertainty $\Delta M = \pm 0.0023$ and an estimated uncertainty $\Delta M = \pm 0.0025$ due to a possible energy dependence of the long counter sensitivity. The latter uncertainty is estimated as the product of the probability 0.05 for neutron energy degradation by the sphere below 11 Mev and a possible deviation by a fraction $\pm$ 0.05 of the long counter sensitivity for about 4-Mev neutrons with respect to 14-Mev neutrons.

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-6 ± 32 mb. Since $\sigma_{n,on} < 10$ mb, $\sigma_{n,2n} + 2\sigma_{n,3n} = 4\begin{cases}+32\\-4\end{cases}$ mb indicating that for the present considerations the sum of the cross sections of reactions 6, 7, 8, and 9 is zero. Considering also that $\sigma_4 + \sigma_5$ is very small, it may be concluded that the 14-Mev Li^7 + n reactions consist almost entirely of inelastic scattering with the excitation of the 0.48-Mev level and higher levels which disintegrate into He^4 + T. The 14-Mev cross section σ_2 for excitation of the 0.48-Mev level was measured by Battat as 75 ± 15 mb by counting of the decay gamma radiation.[2]

2.2 Sphere Transmission Measurements

Offhand it would appear possible to obtain σ_3 by the subtraction of σ_2 from a value σ_i derivable from a sphere transmission measurement. However, with a light scattering material such as Li^7 there is the complication that as a result of the energy degradation in scattering, those neutrons elastically scattered in backward directions cannot be distinguished from those inelastically scattered in forward directions after excitation of low levels. Fortunately, most of the elastic scattering occurs into the so-called forward diffraction cone. In the photographic plate measurements of the angular distribution of 14-Mev neutrons elastically scattered by Li^6, it was observed that about 760 mb of scattering was through angles smaller than 70° corresponding to energies greater than 12 Mev whereas about

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60 mb was through larger angles.[12] It is reasonable to consider the same forward cone and associated energy for the diffraction scattering by Li^7.

The cross section for neutron absorption and energy degradation below 12 Mev was measured by Ribe with a small Li spherical shell, 2 in. in diameter, to be 0.59 ± 0.15 b, using a coincidence spectrometer in conjunction with a polythene radiator for neutron detection and energy measurement.[13] A somewhat more precise value, 0.49 ± 0.05 b, was obtained in recent work by Graves[1] using the larger diameter spherical shell described in connection with the multiplication measurement and a stilbene crystal for detection.

If the inelastic neutrons associated with the excitation of the 0.48-Mev level are distributed isotropically, 55 mb of σ_2 would appear in the neutron spectrum below 12 Mev. It is likely, however, that they are somewhat peaked forward so that this fraction may be smaller. It may seem reasonable to assume the Li^6 value of 60 mb[12] for the Li^7 elastic scattering with energy degradation below 12 Mev. However, this scattering is predominantly of the so-called compound elastic type, as distinct from the forward diffraction scattering, and could be considerably different in the two cases. Since the ground and first excited states of Li^7 presumably have the same nuclear structure, it may be reasonable to assume that the compound elastic scattering is related to σ_2 in the ratio 2 of their respective statistical

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factors. Thus a value 2 x 55 mb, with an estimated uncertainty of 50 mb, is assumed for the contribution to Li^7 elastic scattering with energy degradation below 12 Mev. The conclusion is therefore that $\sigma_3 = (490 \pm 50) - (55 \pm 15) - (110 \pm 50) = 325 \pm 75$ mb.

It should be mentioned that more accurate and direct determinations of σ_3 are presently being made by absolute beta counting of the tritium activity[14] and by the counting of ($T + He^4$) stars in Li-loaded photographic plates.[15] This cross section has already been reported for Po-Be and fission-spectrum neutrons.[16] However, as the latter measurement is in considerable disagreement with a preliminary measurement by Wyman[17] for the same spectrum, these results are considered as doubtful at the present.

3. The Li^7 + n Neutron Spectrum

The 4- to 12-Mev neutron spectrum from the small normal Li spherical shell bombarded by 14-Mev neutrons also was measured by Ribe.[13] For this spectrum, which is reproduced in Fig. 2,*

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* The spectrum in Ribe's report is actually for Li^7. However, the correction for the effect of Li^6 in the normal Li spectrum reproduced here is negligible.

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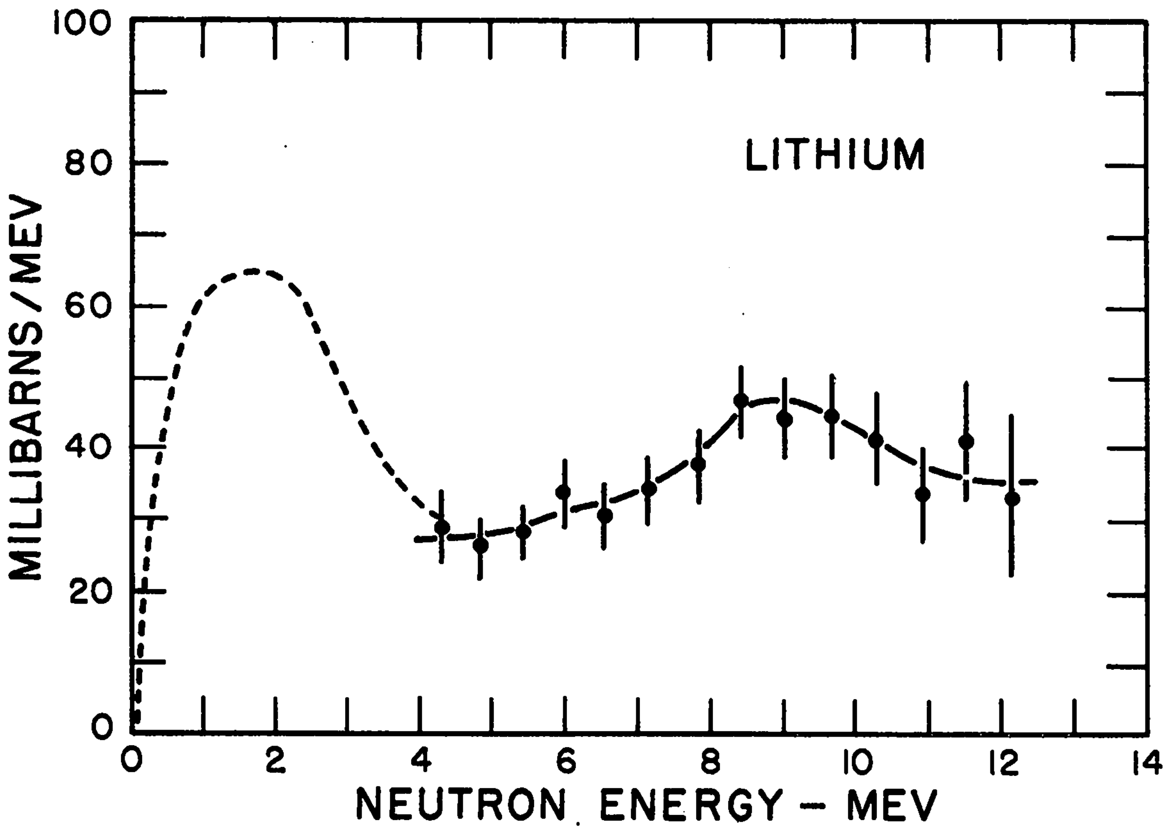

Fig. 2. The solid curve from 4 to 12 Mev is a reproduction of the measurement by Ribe of the neutron spectrum from the bombardment of a small normal Li sphere with 14-Mev neutrons. The dotted curve from 0 to 4 Mev is drawn in such a way that the total integral from 0 to 12 Mev is equal to the large sphere absorption measurement by Graves.

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$\int_4^{12}(d\sigma/dE)dE = 0.29 \pm 0.02$ b. By subtracting this integral from Graves' value 0.49 b for the cross section for degradation below 12 Mev, a value $\int_0^4 (d\sigma/dE)dE = 0.20 \pm 0.06$ b is obtained. There is included in Fig. 2 a dashed spectrum from 0 to 4 Mev with this integral.

The integral of the neutron spectrum from 12 to 14 Mev is of course equal to the total cross section minus the integral from 0 to 12 Mev: $\int_{12}^{14} (d\sigma/dE)dE = 0.96$ b, about 0.020 b of which may be associated with inelastic scattering after excitation of the 0.48-Mev level, the remainder being elastic scattering. If it is assumed that as in the case of Li^6 the elastic scattering with energy degradation less than 2 Mev can be described by the diffraction scattering formula[18]

$$d\sigma(\theta)/d\Omega = 1/4 a^2(1 + x^{-1})^2 \cot^2(1/2\ \theta)\ J_1^2 \left[(x + 1) \sin \theta\right] ,$$

then the total elastic scattering in the diffraction peak, $\pi a^2(1 + x^{-1})^2$, corresponds to a nuclear radius $a = 4.1 \times 10^{-13}$ cm. In these formulas, $x = ka$, k being the neutron wave number.

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