PHYSICAL REVIEW VOLUME 96, NUMBER 4 NOVEMBER 15, 1954

Total Cross Section of Li^6 for Neutrons*

C. H. Johnson, H. B. Willard, and J. K. Bair
Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Received August 13, 1954)

The total cross section of Li^6 for neutrons has been measured for neutron energies from 0.035 to 4.2 Mev. A resonance was observed with its maximum at 0.255 ± 0.010 Mev, which corresponds to 7.46-Mev excitation energy in Li^7. The observed width of the resonance at half-maximum is 100 kev. It is interpreted according to the nuclear dispersion theory as resulting from p neutrons forming a state of total angular momentum 5/2. The cross section rises gradually in the region from 1.5 Mev to 4.2 Mev.

I. INTRODUCTION

Considerable attention has been devoted to the level structure of Li^7 because it is one of the simplest of the light nuclei.[1] In particular, a level at 7.46 Mev in Li^7 was found from a resonance in the $Li^6(n,\alpha)H^3$ reaction.[2] Later it became questionable that this resonance should be attributed to interaction of neutrons with Li^6 since the total cross section of Li^7 shows a resonance at about the same neutron energy.[3] Protons, deuterons, and α particles inelastically scattered from Li^7 have given no indication of the 7.46-Mev level;[1,4] however, a group of α particles from the bombardment of Be^9 with deuterons probably results from Li^7 being left in this excited state.[1] The $Li^7(\gamma,\alpha)H^3$ reaction shows a peak at 7.25 Mev which was interpreted as resulting from this level.[5] The mirror level in Be^7 was found by bombarding Li^6 with protons[6] and also from the neutron spectrum of the $Li^7(p,n)Be^7$ reaction.[7] In the present paper the neutron total cross section of Li^6 was measured in order to study this state in Li^7 and to extend the level survey to higher energies.

II. EXPERIMENTAL METHOD

The total cross section of Li^6 for neutrons was measured by a transmission experiment. Scattering samples were prepared from isotopically enriched lithium metal produced by the Stable Isotopes Division at Oak Ridge. Dr. P. S. Baker of the Stable Isotopes Division supervised the casting of the lithium into cylindrical thin-walled stainless steel cans. To test the casting procedure several cylinders were made using limited quantities of normal lithium. The density of these samples was correct within 0.5 percent. Table I describes the five Li^6 samples that were made. The chemical purity shown in the table is the percent by weight of lithium metal. Samples 1, 2, and 3, which were used for the first measurement in 1952, had several percent by weight of impurity which a quantitative spectroscopic analysis showed to be Na, Mg, Al, Si, K, and Cu. Since the atomic weight of the impurities is several times that of lithium, these percentages correspond to less than one atomic percent of impurity. The number of atoms/cm² shown in the table is the number of atoms of all types including the small atomic percent of impurity. If these numbers of atoms/cm² were reliable, the impurity would cause a negligible error in cross section; however, the densities of the three samples as given in Table I were not consistent with the quoted impurities. This is not surprising since the spectroscopic analysis is not accurate for the alkalies and gives no analysis for the halides. It was estimated that the number of atoms/cm² may be five percent high for these three samples. For this reason samples 4 and 5 were made with high purity and used for a repeat measurement in 1954. The atoms/cm² for these samples is believed accurate to one percent. In the measurement of cross sections, scatterers were chosen to give about 50 percent transmission.

Various neutron sources and detectors were used to cover the energy range from 0.035 to 4.2 Mev. Protons from the Oak Ridge National Laboratory 5.5-Mev Van de Graaff bombarded a lithium target of 15-kev stopping power to produce neutrons with energy up to 1.5 Mev. Neutrons of greater energy were obtained from the $T(p,n)$ reaction by use of a Zr-T target[8] with 35-kev stopping power at threshold. Because of the decrease in stopping power with energy the tritium target was less than 20 kev thick for most of the measurement.

Table I. Description of the Li^6 scattering samples.

Sample No.	Atoms/cm²	Chemical purity	Percent error in density	Isotopic percentage of Li^6	Sample diameter (cm)
1	0.0708×10^{24}	96.72	8.0	89.0	2.2
2	0.1086	95.49	0.5	88.9	3.0
3	0.2223	98.14	6.0	89.7	3.0
4	0.0641	99.97	1.0	93.8	2.0
5	0.1280	99.97	1.7	93.8	2.0

* This document is based on work performed for the U. S. Atomic Energy Commission at the Oak Ridge National Laboratory.

[1] H. E. Gove and J. A. Harvey, Phys. Rev. **82**, 658 (1951). This includes references to previous work.
[2] J. M. Blair and R. E. Holland, data reproduced in *Neutron Cross Sections*, Atomic Energy Commission Report AECU 2040 (Office of Technical Services, Washington, D. C., 1952).
[3] R. K. Adair, Phys. Rev. **79**, 1018 (1950).
[4] W. Franzen and J. G. Likely, Phys. Rev. **87**, 667 (1952).
[5] P. Stoll and M. Wächter, Nuovo cimento **10**, 347 (1953).
[6] S. Bashkin and H. T. Richards, Phys. Rev. **84**, 1124 (1951).
[7] D. M. Thompson, Phys. Rev. **88**, 954 (1952).

[8] The tritium target was loaned to us by T. W. Bonner of Rice Institute.

In the energy region from 0.035 to 0.18 Mev, a BF_3 detector similar to that described by Seagondollar and Barschall[9] was placed with its axis at 97 degrees to the proton beam and with its front face 30 cm from the neutron source. The transmission of samples 2 plus 3 when placed 8 cm from the source was determined relative to that of identical empty cans, and the total cross section was found assuming exponential attenuation of the neutron flux. Since in this geometry 2.0 percent of the scattered neutrons would reach the detector if the scattering were isotropic in the center-of-mass system, a 2.0 percent scattering-in correction was applied. From 0.14 to 0.20 Mev sample 3 was used in this same scattering geometry at zero degrees to the proton beam.

For neutron energies of 0.18 to 1.5 Mev the detector was a propane-filled proportional recoil counter 2.5 cm in diameter and 10 cm long, placed with its axis coincident with that of the proton beam and with its center 30 cm from the neutron source. The amplifier bias was set to discriminate against the low-energy neutron group from the $Li^7(p,n)Be^7$ reaction.[10] Scatterers were placed midway between source and detector so that the scattering-in correction was 1.6 percent for samples 2 and 3 and 1.0 percent for sample 1. A second run was made near the resonance by using samples 4 and 5 with the counter 37 cm from the source. The scattering-in correction was then 0.45 percent. Within 50 kev of the resonance all of these scattering-in corrections were multiplied by 1.3 to give an approximate correction for the nonisotropic scattering[11] from Li^6.

For energies above 1.5 Mev, a high-pressure hydrogen chamber 2.5 cm in diameter and 13 cm long replaced the propane counter. It operated as an electron collection chamber using a 0.02-inch central wire. The filling was 100 atmos of electrolytic hydrogen further purified by passing over hot magnesium for several hours. To obtain a good signal-to-noise ratio the chamber was shock-mounted and the pulses were amplified with a slow amplifier[12] with rise and decay time constants each adjusted to 30 microseconds. The counter had an efficiency of about 6 percent.

Background corrections, measured by interposing a paraffin shadow cone 25 cm long between source and detector, were appreciable for the BF_3 counter but were negligible (less than 1 percent) for the recoil counters. For all measurements, current integration of the proton beam served to monitor the neutron flux.

The total cross section of the lithium was determined by assuming the total number of atoms given in Table I to be the number of lithium atoms and the total cross section of Li^6 was found by correcting for the presence of Li^7 using the known cross sections.[13–15] Near the resonance we used the 5-kev resolution data[14] on Li^7 by correcting for the energy resolution of the present measurements and assuming the resonances in the two isotopes coincide. Since the Li^6 and Li^7 cross sections are similar, the Li^7 correction was of the order of 1 percent, except on the sides of the resonance where it is as large as 6 percent.

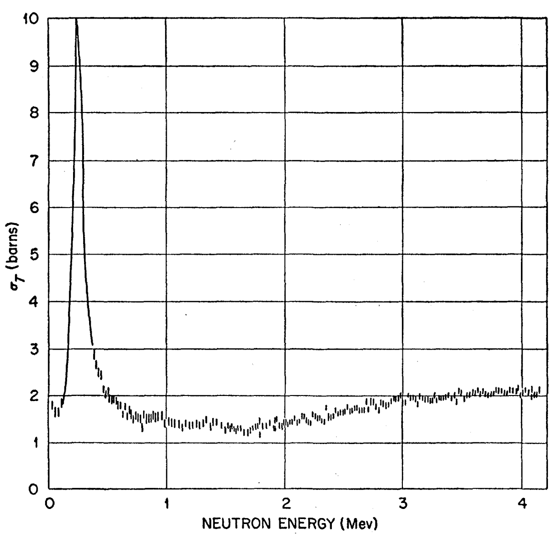

FIG. 1. Total cross section of Li^6 for neutrons, measured by a transmission experiment using a scatterer of enriched Li^6 metal.

III. RESULTS

Figure 1 shows the total cross section of Li^6 as a function of the neutron energy which has been corrected for target thickness. The lengths of the vertical lines indicate standard statistical errors of the data points. Our best estimate of the error arising from the sample impurities is that the observed cross section is 3 percent low off-resonance. It is interesting that the entire curve is nearly identical to the total cross section of Li^7. Both cross sections show a resonance at nearly 255 kev, although the widths of the two resonances differ by about a factor of two. In addition, a slow rise in cross section at high energies is observed for both nuclei. The upper curve of Fig. 2 shows the details of the resonance which was observed with various scatterers and detectors. Samples 1, 2, and 3 are shown with open symbols in an attempt to de-emphasize these results near the peak. It is estimated that the effect of unknown impurities in those three samples could make the cross section 5 to 10 percent low at the peak. The high-purity samples 4 and 5 are shown as solid symbols. The resonance has a maximum of 10.2 barns and an observed width at half-maximum of 100 kev. The peak lies at 255 ± 10 kev in

[9] L. W. Seagondollar and H. H. Barschall, Phys. Rev. **72**, 439 (1947).
[10] Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).
[11] Willard, Bair, and Kington (to be published).
[12] P. R. Bell Model A-2 Amplifier (private communication).
[13] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).
[14] P. H. Stelson and W. M. Preston, Phys. Rev. **84**, 162 (1951).
[15] Published curves extend to 3.4 Mev. Measurements at this laboratory show that the cross section of normal lithium rises smoothly to 2.5 barns at 4.2 Mev.

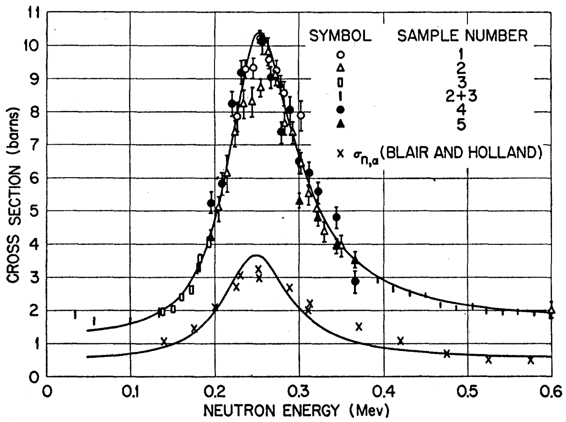

FIG. 2. The upper curve is the total cross section of Li^6 for neutrons as determined using five different scattering samples. Table I describes the five samples. The lower curve presents the data of Blair and Holland[2] on the $Li^6(n,\alpha)H^3$ reaction. The solid curves are calculated from the nuclear dispersion theory by assuming the resonance results from p neutrons forming a state of $J=5/2$.

agreement with the $Li^6(n,\alpha)$ peak found at 250 kev.[2] According to known mass values,[16] the peak corresponds to 7.46-Mev excitation in the Li^7 nucleus.

IV. DISCUSSION

According to the nuclear dispersion theory, the total cross section near an isolated resonance consists of resonant scattering and absorption of neutrons in addition to potential elastic scattering. It will be shown that the magnitude of the resonance is too large to be ascribed to s-wave resonant interaction; hence, the resonance scattering will not interfere coherently with the potential scattering which is predominantly s wave for these neutron energies.[17] The total cross section near the isolated resonance may then be written as the sum of a resonance term, plus a potential term,[17,18]

$$\sigma_T=\frac{\pi}{k^2}\frac{2J+1}{6}\frac{\Gamma_n(\Gamma_n+\Gamma_\alpha)}{(E_\lambda+\Delta_\lambda-E)^2+(\Gamma_n+\Gamma_\alpha)^2/4}+\frac{4\pi}{k^2}\sin^2\delta_0, \quad (1)$$

where J is the total angular momentum of the λth level in the compound nucleus Li^7; k is the neutron wave number corresponding to the energy E; Γ_n and Γ_α are the neutron and α-particle widths; E_λ and Δ_λ are the characteristic energy and energy shift of the level; and δ_0 is the s-wave potential phase shift. If one assumes the potential scattering is hard sphere, then $\delta_0=-ka_n$, where a_n is the radius of interaction of the neutron and Li^6. All energies refer to center-of-mass coordinates.

[16] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[17] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 142 (1947).
[18] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).

In Eq. (1) it is assumed the only process of significance other than elastic scattering is the $Li^6(n,\alpha)H^3$ reaction. The **×**'s in Fig. 2 show the preliminary (n,α) data of Blair and Holland.[2] Since the Breit-Wigner formula as written above cannot account for the observed off-resonance (n,α) cross section, it is necessary to add another term which presumably results from tails of other distant resonances. A simple addition which gives an approximate description of the data near resonance is a constant equal to 0.5 barn. To describe the off-resonance total cross section, which includes this constant plus potential scattering, we have chosen $a_n=1.4\times 6^{1/3}\times 10^{-13}$ cm $=2.54\times 10^{-13}$ cm.

At resonance the observed total cross section corrected for energy resolution is 10.3 barns and the (n,α) cross section is 3.2 barns. By choosing the ratio Γ_n/Γ_α at resonance in Eq. (1) to fit the total cross section, one finds that for $J=3/2$, $5/2$, and $7/2$ the (n,α) cross section (resonant term $+0.5$ barn) should be 0.52, 3.65, and 5.12, respectively. Only $J=5/2$ agrees within experimental error with the observed cross section; therefore, it is assumed in the following discussion that the resonance results from a single compound state with $J=5/2$.

In forming this state, total angular momentum can be conserved by neutrons of orbital angular momentum from $J-\frac{3}{2}$ to $J+\frac{3}{2}$ so that the resonance cannot result from s-wave neutrons. Orbital angular momentum enters the Breit-Wigner formula through the level shift and partial widths which may be written[18,19]

$$\Delta_\lambda=\sum_s\Delta_{\lambda s}=-\sum_{sl}\gamma_{sl}^2a_s^{-1}\times[l+d\ln(F_{sl}^2+G_{sl}^2)^{\frac{1}{2}}/d(\ln k_sa_s)], \quad (2)$$
$$\Gamma_{sl}=\sum_l 2k_s\gamma_{sl}^2(F_{sl}^2+G_{sl}^2)^{-1},$$

where γ^2 is an energy-independent reduced width; $(F^2+G^2)^{-1}$ is a barrier penetration factor; and l and s refer to the relative orbital angular momentum l of the pair of particles s. In the reaction being considered, s includes two possible pairs which have been denoted by subscripts n and α. Since the α-particle energy is large compared to the energy range considered, Γ_α and $\Delta_{\lambda\alpha}$ are approximately constant. As stated above, four possible l values may be considered for the neutron; however, the penetration factor decreases so rapidly with increasing l that only the lowest l value for each parity need be considered, namely, $l=1$ and 2. For d neutrons the resonance could not have a width exceeding 10 kev even if $\gamma_n^2\rightarrow\infty$, so that the resonance must result from p-wave neutrons. For p neutrons it was possible to choose Γ_n and Γ_α at resonance (114 kev and 60 kev in the center-of-mass system) to give a good description of the total cross section. In Fig. 2 the upper solid curve is the fit to the total cross-section data and the lower curve is the corresponding fit to the preliminary (n,α) data of Blair and Holland.

[19] R. G. Thomas, Phys. Rev. **81**, 148 (1951).

TABLE II. Parameters to describe the resonance shown in Fig. 2.

Resonance energy in the lab system	255 kev
Total angular momentum	$J=5/2$
Neutron orbital angular momentum	$l=1$
Interaction radius	2.54×10^{-13} cm
Constant (n,α) cross section	0.5 barn
Neutron width in the center-of-mass system at resonance	114 kev
α-Particle width in the center-of-mass system	60 kev

The reduced neutron width is then 11.8×10^{-13} Mev-cm which is 42 percent of the sum-rule limit, $3\hbar^2/2\mu a$, where μ is the reduced neutron mass. The single-particle model of this level is, therefore, approximately valid[20] even though the excitation energy is several Mev. An estimate of the α-particle reduced width and level shift was obtained from Eq. (2) by assuming a radius of 3.5×10^{-13} cm and f-wave interaction. This gave $\gamma_n^2/\gamma_\alpha^2\cong10^3$ and $\Delta_{\lambda n}\gg\Delta_{\lambda\alpha}$. The total level shift is then essentially $\Delta_{\lambda n}$, so that the characteristic energy E_λ is $E_\lambda=7.46$ Mev$+\Delta_{\lambda n}=7.70$ Mev. Table II summarizes the parameters used to describe this resonance.

Additional evidence exists that this resonance results from p neutrons. Bashkin and Richards[21] concluded that this state and a level at $E_\lambda=7.31$ Mev in Be^7 are mirror levels formed by p-wave neutrons or protons on Li^6. Roberts *et al.*[22] found that the angular distribution of the $Li^6(n,\alpha)H^3$ reaction indicates primarily p-wave interaction at the resonance. Peshkin and Siegert[23] presented an analysis which, when applied to the more recent data of Roberts *et al.*, shows the angular distribution to be consistent with the assignment $J=5/2$.

No other clearly defined resonance was found for energies up to 4.2 Mev; however, Fig. 1 shows that the total cross section rises from 1.3 barns at 1.5 Mev to 2.1 barns at 4 Mev. This rise could be attributed to p neutrons forming a state of $J=5/2$ providing the background of potential scattering and of the (n,α) reaction remains essentially constant in the same energy interval. Measurements[24] at 2.49 and 14.2 Mev suggest that the (n,α) cross section is decreasing in this region. It seems probable that the rise in total cross section is too large to be assigned to $J<7/2$ and too broad to be assigned to $l>1$ so that it cannot be described by the single-level Breit-Wigner formula. A very similar increase exists in the total cross section of Li^7 which cannot be described by the single-level formula.

Recent observations[25,26] of the differential elastic scattering for neutrons on light nuclei are not well described using phase shifts predicted for hard-sphere potential scattering. An analysis of the high-energy cross section should await data on the scattering phase shifts. It may also be that the potential scattering near the resonance should not be calculated for hard sphere scattering as was done above. In any case, the data near the resonance are well described by assuming an approximately constant s-wave potential scattering of 0.75 barn.

ACKNOWLEDGMENTS

The authors are indebted to Dr. P. S. Baker and G. F. Wells of the Stable Isotope Division for the preparation of the Li^6 samples, to J. D. Kington for aid in performing the experiment, and to Dr. A. Simon and Dr. L. C. Biedenharn for helpful discussions.

[20] T. Teichmann and R. P. Wigner, Phys. Rev. **87**, 123 (1952).

[21] See reference 6. Since these authors used a larger interaction radius than that of the present paper, their γ^2 and Δ_λ are smaller than those found here; however, their final conclusions do not depend critically upon the assumed radius.

[22] Roberts, Darlington, and Haugsnes, Phys. Rev. **82**, 299 (1951); W. O. Solano and J. H. Roberts, Phys. Rev. **89**, 829(A) (1953); Darlington, Haugsnes, Mann, and Roberts, Phys. Rev. **90**, 1049 (1953).

[23] Murray Peshkin and A. J. F. Siegert, Phys. Rev. **87**, 735 (1952).

[24] R. L. Ribe, Phys. Rev. **87**, 205 (1952).

[25] Willard, Bair, and Kington, Phys. Rev. **94**, 786 (1954).

[26] C. H. Johnson and J. L. Fowler, Phys. Rev. **95**, 637 (1954).