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Elastic Scattering of Neutrons by Li^6 and Li^7

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Differential cross sections for elastic scattering of neutrons by Li^6 and Li^7 have been measured in the region of 200- to 600-kev incident energy. The results for Li^6 confirm the assignment of $5/2^-$ for the 7.46-Mev level in Li^{7*} and indicate that the s-wave potential scattering has a statistical channel spin mixture and negative phase shift. Similarly in the case of Li^7, the 2.28-Mev level in Li^{8*} is indeed 3^+, the s-wave potential scattering has very nearly a statistical channel spin mixture, but the phase shift is positive.

I. INTRODUCTION

NEUTRONS interacting with Li^6 undergo a strong resonance at 255-kev bombarding energy which has been observed in the emission of alpha particles[1] and in the total cross section.[2] Analysis of the two sets of data, assuming only elastic scattering and the (n,α) reaction take place, leads to the conclusion that the compound level in Li^7 at 7.46-Mev excitation is formed by p-wave neutron capture to form a state of $5/2^-$. The observed total width of this level is 100 kev in the laboratory system.

Total cross-section measurements[3–5] of Li^7 show a strong resonance at 256-kev bombarding energy with an observed width of 32 kev in the laboratory system. Since only elastic scattering and capture radiation (which can be neglected at this energy) are energetically possible, analysis of the data leads to the conclusion that the level in Li^8 at 2.28 Mev is formed by p-wave neutron capture to form a state of 3^+.

These two p-wave scattering resonances can produce strong interference terms with the s-wave potential scattering which would be observable in the angular distributions. Therefore to check the above assignments and to study this interference, differential cross-section measurements were made for several energies and angles for the two lithium isotopes.

II. EXPERIMENTAL PROCEDURE

Monoenergetic neutrons up to 0.6 Mev were produced by the $Li^7(p,n)Be^7$ reaction and scattered by cylindrical samples located 10 inches from the target in the forward direction in a manner similar to that described earlier.[6] Li^6 samples enriched to 93.8% (chemical purity 99.97%) were produced by the Stable Isotopes Division at Oak Ridge. Dr. P. S. Baker of that division supervised the casting of the lithium metal into cylindrical cans of stainless steel with 10-mil wall thicknesses. Two samples were used: (*a*) 1-cm diameter by 7.5-cm length, and (*b*) 2-cm diameter by 3-cm length. Li^7 samples of normal isotopic abundance (chemical purity 98.4%) were prepared in a similar manner with sizes (*a*′) 1-cm diameter by 7.5-cm length, and (*b*′) 2.5-cm diameter by 10-cm length. Samples (*a*) and (*a*′) were used at and near resonance; (*b*) and (*b*′) were used off resonance.

Scattered neutrons were detected by recoil counters filled to 0.5 and 1 atmosphere with propane gas. These counters of diameter 1 inch and sensitive length 4 inches were located a mean distance of 5 inches from the samples. At the incident neutron energies used here it was not possible to set the bias of these detectors for a flat response. Accordingly, corrections were applied to the data to compensate for the decreasing sensitivity for neutrons scattered through increasing larger angles. This was done by obtaining relative efficiency curves with respect to the long counter, assumed flat from 100 to 600 kev.

Paraffin wedges were used to shield the detector from neutrons coming directly from the target. Backgrounds, measured by replacing the samples with duplicate empty cans, varied from 10 to 75%. The latter figure is for the lowest neutron energy and the largest scattering angle.

All cross sections were transformed to the center-of-mass system and corrected to 100% isotopic abundance. No corrections were made for multiple scattering or for

Table I. A list of the constants used in the calculations. All energies are in the laboratory system.

	Li^6	Li^7
Interaction radius $r=1.40(A^{\frac{1}{3}}+1)\times10^{-13}$ cm	3.94×10^{-13} cm	4.08×10^{-13} cm
Resonance energy E_0	255 kev	256 kev
Characteristic energy E_λ	−710 kev	−49 kev
Neutron width at $E_0,\Gamma_n(E_0)$	95.8 kev	35.8 kev
Alpha width (constant) Γ_α	50.3 kev	...
Reduced p-wave neutron width γ^2	1100 kev	351 kev
Potential scattering $\sigma_{\text{pot}}{}^n$	0.85 barn	1.00 barn
Background alpha cross section σ_α	0.50 barn	...
J^π	$5/2^-$	3^+
Observed total width Γ_t	100 kev	32 kev

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

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

[3] R. K. Adair, Phys. Rev. **79**, 1018 (1950).

[4] P. H. Stelson and W. M. Preston, Phys. Rev. **84**, 162 (1951).

[5] C. Hibdon, data reproduced in *Neutron Cross Sections*, Supplement 3, Atomic Energy Commission Report AECU-2040 (Office of Technical Services, Department of Commerce, Washington, D. C., 1954).

[6] Willard, Bair, and Kington, Phys. Rev. **98**, 669 (1955).

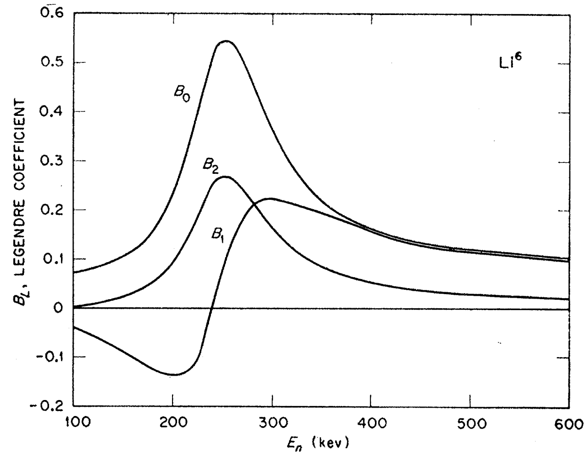

FIG. 1. The theoretical coefficients B_L for the Legendre expansion of the differential elastic neutron scattering cross section (center-of-mass system) of Li^6 are shown as a function of incident neutron energy (laboratory system).

the large solid angles employed. Errors shown are statistical only.

Angular distributions for Li^6 were taken with 20-kev resolution at 210, 258, and 300 kev, and asymmetry data were taken at 220, 258, 300, and 400 kev with the same resolution.

In the case of Li^7, distribution measurements were taken with 20-kev resolution at 200, 255, and 600 kev. Asymmetry ratios were made with 5-kev resolution at 200, 220, 255, 287, 400, and 510 kev. (All neutron energies quoted are the incident values in the laboratory system.)

III. DISCUSSION

Since both resonances are produced by p-wave neutrons with a single channel spin orientation, the calculation of the expected angular distributions can be made with a minimum of adjustable parameters. The method of Blatt and Biedenharn[7] was used. It was assumed that the potential scattering was pure s-wave with a statistical channel spin mixture. The result, in the center-of-mass system, is

$$\sigma_\Omega(\phi)=B_0P_0(\cos\phi)+B_1P_1(\cos\phi)+B_2P_2(\cos\phi),$$

where

$$B_0=\frac{\sigma_T{}^n}{4\pi}=\frac{\sigma_{\text{pot}}{}^n+\sigma_{\text{res}}{}^n}{4\pi}$$

$$=\bar{\lambda}^2\left[\sin^2\xi+\frac{2J+1}{(2i+1)(2I+1)}\cdot\frac{\Gamma_n{}^2/4}{(E_\lambda+\Delta_\lambda-E)^2+\Gamma_t{}^2/4}\right],$$

$$B_1=-2\bar{\lambda}^2\frac{2J+1}{(2i+1)(2I+1)}\frac{\Gamma_n/2}{[(E_\lambda+\Delta_\lambda-E)^2+\Gamma_t{}^2/4]^{\frac{1}{2}}}\times\sin\xi_0\sin(\beta-\xi_0),$$

$$B_2=\bar{\lambda}^2\frac{Z^2(1J1J,s2)}{(2i+1)(2I+1)}\frac{\Gamma_n{}^2/4}{(E_\lambda+\Delta_\lambda-E)^2+\Gamma_t{}^2/4}$$

$$=\frac{\sigma_{\text{res}}{}^n}{4\pi}\frac{Z^2(1J1J,s2)}{(2J+1)}.$$

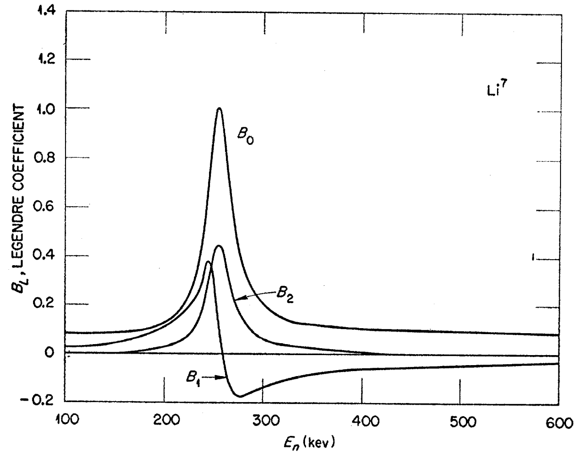

FIG. 2. The theoretical coefficients B_L for the Legendre expansion of the differential elastic neutron scattering cross section (center-of-mass system) of Li^7 are shown as a function of incident neutron energy (laboratory system).

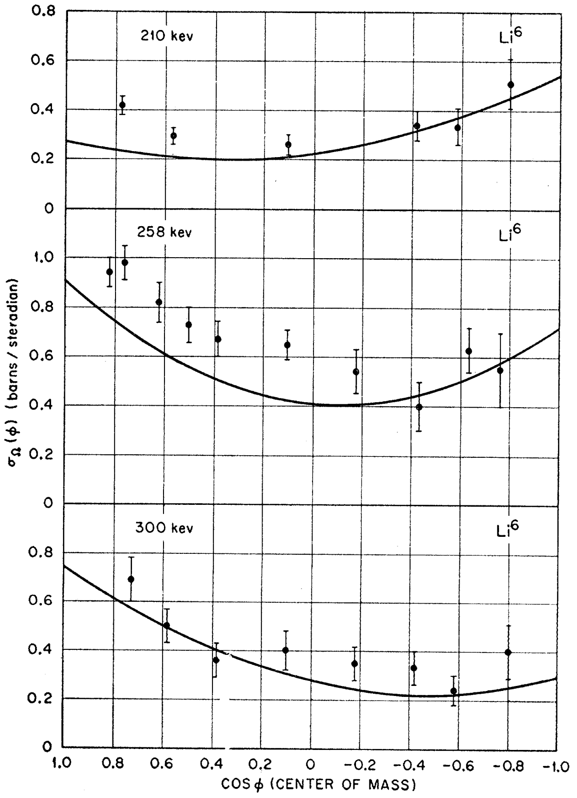

FIG. 3. Differential cross sections for elastically scattered neutrons from Li^6 at 210, 258, and 300 kev. Solid curves are theoretical, see text.

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[7] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. 24, 258 (1952).

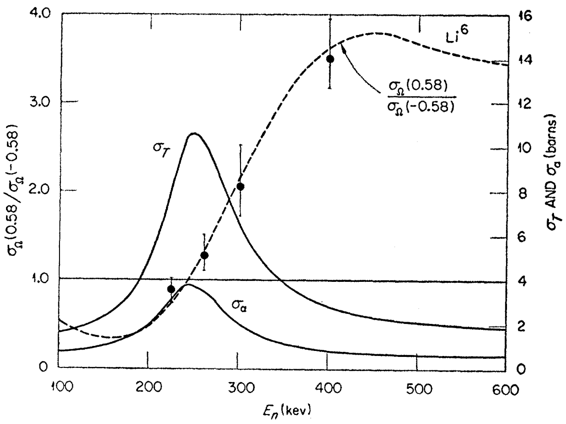

FIG. 4. The ratio of the measured Li^6 differential cross section for cos$\phi=0.58$ to that for cos$\phi=0.58$ as a function of the incident neutron energy. The dotted curve is theoretical. Solid curves are shown for σ_t and σ_α.

In the above formulas, the notation of Blatt and Biedenharn[7] is used, but in addition σ_T^n is the total cross section for elastic neutron scattering; σ_{pot}^n is the total cross section for potential neutron scattering; σ_{res}^n is the total cross section for resonance neutron scattering;

$$\Gamma_n/2=[x^3/(1+x^2)]\gamma^2,$$

where $x=kR$, γ^2 is the reduced width in energy units, and $x^3/(1+x^2)$ is a penetrability factor for p-wave neutrons; E_λ is the characteristic energy associated with the level shift Δ_λ for p-wave neutrons, and

$$\Delta_\lambda=\gamma^2/(1+x^2),\quad E_\lambda+\Delta_\lambda(E_0)-E_0\equiv 0.$$

The sign of the s-wave potential phase shifts ξ_0 can be determined from the angular distributions or from thermal scattering data. Thomas[8] has shown that ξ_0 is negative for Li^6 and positive for Li^7. Using these signs and the constants shown in Table I, the coefficients B_L have been calculated as a function of incident neutron energy (laboratory system). The results are plotted in Figs. 1 and 2. It will be noted that the constants used for Li^6 are not the same as the original paper on the total cross-section measurements.[2] They were altered to give a more reasonable interaction radius, but the fit to σ_T and $\sigma_{n,\alpha}$ remains equally good.

IV. RESULTS

A. Li^6

The center-of-mass differential elastic scattering cross sections at 210, 258, and 300 kev are plotted in Fig. 3 as a function of cosϕ, the center-of-mass angle with their statistical errors. The agreement with the solid theoretical curves is quite good, although the absolute cross sections seem a little high at 258 kev. A more sensitive test of the interference term can be made by plotting the ratio of the cross sections at cos$\phi=+0.58$ and -0.58. The results shown in Fig. 4 agree very well with the theoretical dotted curve. The calculated values of σ_T and σ_α are also shown for reference. It is concluded from these data that only the assignment of $5/2^-$ is correct, the s-wave potential scattering phase shift is indeed negative, and the potential scattering channel spin mixture is statistical.

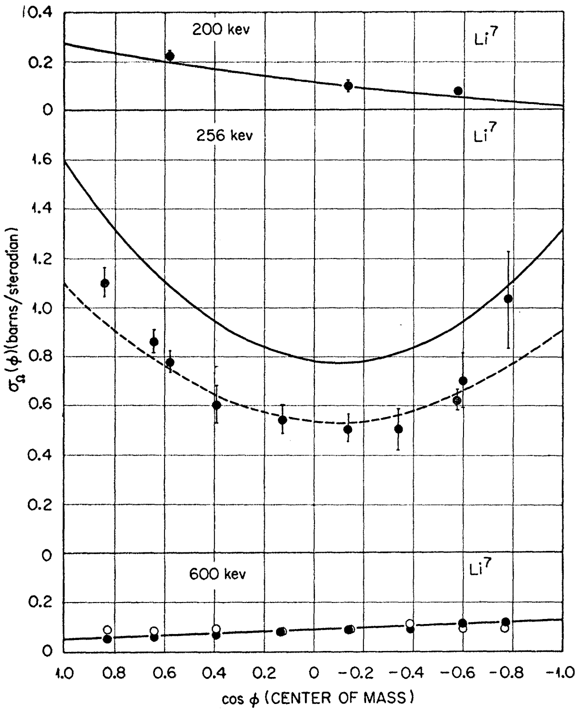

FIG. 5. Differential cross sections for elastically scattered neutrons from Li^7 at 200, 256, and 600 kev. The open circles for the 600-kev data are the results of an early run with a 2-in. diameter, 3-in. high scattering sample. Solid curves are theoretical, see text.

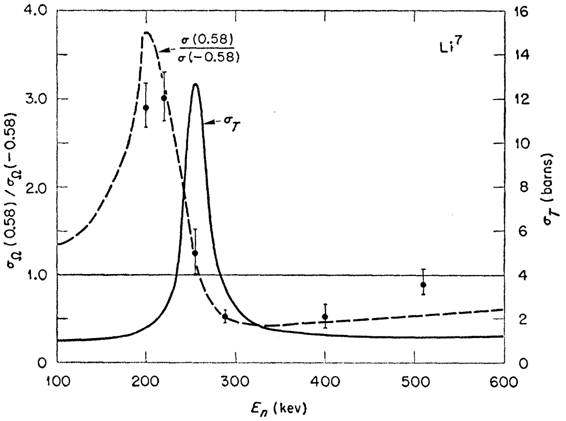

FIG. 6. The ratio of the measured Li^7 differential cross section for cos$\phi=0.58$ to that for cos$\phi=-0.58$ as a function of the incident neutron energy. The dotted curve is theoretical. σ_t is also shown.

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[8] R. G. Thomas, Phys. Rev. 84, 1061 (1951), and R. G. Thomas (private communication).

B. Li^7

Angular distributions at 200, 256, and 600 kev are shown in Fig. 5. Agreement at 200 and 600 kev is quite good. In order to compare the on resonance results with the theoretical curve, shown solid, a correction was made for the 20-kev resolution used, shown dotted. Again agreement is quite good.

Thomas *et al.*[9] have shown from the thermal scattering data that the potential scattering must be either all channel spin 1, or all channel spin 2. Extrapolating to the energies under consideration, this would lead in the case of $s=2$ to a much stronger interference term than that obtained using a statistical mixture. If the potential scattering were all channel spin 1, there would be no interference term. Accordingly, asymmetry ratios were measured with 5-kev resolution for bombarding energies of 200, 220, 255, 287, 400, and 510 kev as shown in Fig. 6. The dotted curve is theoretical for a statistical mixture. All channel spin 1 would produce no asymmetry; all channel spin 2 would have a ratio of 5 at 220 kev. Multiple-scattering corrections would tend to raise the experimental values below 260 kev but not enough to agree with all $s=2$ potential scattering. It is concluded that $J=3^+$ is correct, the s-wave scattering phase shift is positive, and a statistical channel spin potential scattering mixture gives the best fit to the data.

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[9] Thomas, Walt, Walton, and Allen, Phys. Rev. **101**, 759 (1956).

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Angular Distribution of Neutrons from $O^{18}(p,n)F^{18}$†

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The reaction $O^{18}(p,n)F^{18}$ has been studied using monoenergetic protons from the Rockefeller electrostatic generator. Resonances in the neutron yield in the forward direction are found at proton energies $E_p=2.657$, 2.732, 2.778, 3.045, 3.170, 3.268. 3.386, 3.495, 3.600, and 3.755 Mev. The angular distribution of neutrons from this reaction at proton energies $E_p=3.045$, 3.170, 3.268, and 3.386 Mev has been measured with a proton recoil counter. The most probable values of the spins of the excited states in F^{19} corresponding to these resonances are $J=\frac{3}{2}^{\pm}$, $\frac{1}{2}^{\pm}$, $\frac{3}{2}^{\pm}$, and $\frac{1}{2}^{\pm}$ respectively.

I. INTRODUCTION

ANGULAR distribution experiments may be used in several ways to study the dynamics of a nuclear reaction. If the reaction goes through a compound system with well-defined energy levels, it may be possible to determine the angular momentum quantum numbers of these levels.[1,2] On the other hand, if the compound system has broad, overlapping energy levels, then a knowledge of the angular distribution of the reaction products as a function of energy may lead to information regarding the competing states by which the reaction may take place.[3,4]

The reaction $O^{18}(p,n)F^{18}$ has been studied previously by several workers. Blaser *et al.*[5] measured the neutron yield between proton energies of 2.5 and 7.0 Mev with relatively poor resolution and found seven broad resonances in this region. Richards *et al.*[6] measured the neutron yield with much better resolution between 2.5 and 3.75 Mev and were able to show that some of the broad resonances observed by Blaser *et al.* are actually due to the superposition of several sharp, well-defined resonances in the yield. These authors also made an accurate determination of the $O^{18}(p,n)F^{18}$ threshold. The sharp resonances in the yield and the relatively large cross section make this reaction well suited for a more detailed study.

II. TARGETS

The target used in the experiment was obtained by oxidizing a 10-mil tantalum disk in an atmosphere of enriched (20% O^{18}) oxygen. It was found that the amount of oxygen deposited could be varied by controlling the pressure of oxygen in the chamber. In this manner it was possible to obtain targets with a surface layer containing a known amount of oxygen. The target used in this experiment had roughly 10^{19} atoms of O^{18} per square centimeter.

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[1] S. Devons, Proc. Roy. Soc. (London) **A62**, 580 (1949).

[2] R. Day and J. Perry, Phys. Rev. **81**, 662(A) (1951).

[3] R. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

[4] Willard, Bair, and Kington, Phys. Rev. **90**, 865 (1953).

[5] Blaser, Boehm, Marmier, Preiswerk, and Scherrer, Helv. Phys. Acta **22**, 598 (1949).

[6] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).