Photoneutron Reactions in Lithium

T. W. RYBKA AND L. KATZ
Physics Department, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
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The photoneutron cross section for the (γ,n) reaction in natural lithium was measured and found to have its maximum at 16.8 Mev, a peak value of 2.3 mb, and a width at half maximum of 9.3 Mev. Fine structure in the region to 10 Mev was resolved as follows: $Li^6(\gamma,np)He^4$ threshold at 3.61±0.15 Mev, $Li^6(\gamma,p)He^5$ threshold at 4.64±0.08 Mev, a level in Li^6 at 5.24±0.05 Mev, $Li^6(\gamma,n)Li^5$ threshold at 5.73±0.05 Mev, $Li^7(\gamma,n)Li^6$ threshold at 7.30±0.04 Mev, and a level in Li^7 at 9.66±0.04 Mev.

INTRODUCTION

PHOTON-INDUCED reactions in lithium resulting in the emission of one or more neutrons have been the subject of a number of studies.[1–6] In particular Heinrich and Rubin[6] measured the $Li(\gamma,n)$ cross section and found three giant resonance peaks with maxima at 15, 21, and 29 Mev, separated by deep minima at 17.7 and 25 Mev. This cross section is quite different in shape from that reported by Goldemberg and Katz,[4] who found only one maximum at 17.5 Mev, with the curve quite symmetric about this energy to 24 Mev.

The experiments reported in this paper were carried out partly in an attempt to resolve this discrepancy and partly to investigate the fine structure in the neutron yield curve below 8 Mev. This energy is the lower limit of the fine structure measurements reported by Goldemberg and Katz.[5]

EXPERIMENTAL TECHNIQUES

The neutron-detecting apparatus used in these experiments has been previously described.[7] It consisted of a paraffin cylinder 3 ft long and 2 ft in diameter in which were embedded 4 enriched BF_3 neutron counters. A 2-in. diameter hole along the axis of this cylinder allowed lithium samples to be placed and irradiated at its center. The x-ray beam was collimated to strike the sample only.

One of the BF_3 neutron counters had its position adjusted as outlined in reference 7, to be equally sensitive to neutrons of all energies emitted from the sample. The other 3 counters were placed in a position to give the highest sensitivity. The energy insensitive counter was used in all measurements of neutron yield for the cross-section determination, while all four were used to detect the breaks in the yield curve.

NEUTRON YIELD CURVE

Neutron yield from an LiH sample was measured as a function of peak bremsstrahlung energy in steps of $\frac{1}{2}$ Mev or less. In all measurements, the dose delivered was monitored with a high-pressure, thick-walled aluminum ionization chamber. The chamber was calibrated with a Baldwin Farmer[8] roentgen meter whose thimble was in the center of an 8-cm Lucite cube during irradiation. A correction was applied for attenuation of the photon beam within the sample as outlined in reference 7.

Comparison of the neutron yield from a small LiH sample to a copper sample at 22 Mev showed this ratio to be 0.048±0.01 per mole per unit dose. Taking the yield from copper as[9] $(2.71\pm0.27)\times10^8$ neutrons/(100r mole) at this energy, we get $(1.30\pm0.13)\times10^7$ neutrons/(100r mole) from lithium at 22 Mev.

Four separate yield curves were measured over a period of 18 months. One of them is shown in Fig. 1. In no case did one of these curves exhibit anything but a smooth behavior (we are ignoring here the fine structure which does not show when experimental points are a few hundred kev apart and the yield curve is a smooth line drawn through them). To get the multiple resonance structure in the cross section observed by Heinrich and Rubin the yield curve should

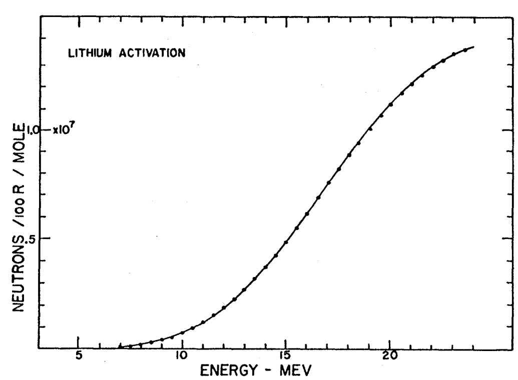

FIG. 1. $Li(\gamma,n)$ yield curve as a function of peak bremsstrahlung energy. Normalization gave $(1.30\pm0.13)\times10^7$ neutrons/100r mole at 22 Mev.

[1] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).
[2] E. W. Titterton and T. A. Brinkley, Proc. Phys. Soc. (London) **A64**, 212 (1951).
[3] Sher, Halpern, and Mann, Phys. Rev. **84**, 387 (1951).
[4] J. Goldemberg and L. Katz, Can. J. Phys. **32**, 49 (1954).
[5] J. Goldemberg and L. Katz, Phys. Rev. **95**, 471 (1954).
[6] F. Heinrich and R. Rubin, Helv. Phys. Acta **28**, 186 (1955).
[7] Montalbetti, Katz, and Goldemberg, Phys. Rev. **91**, 659 (1953).

[8] Baldwin Farmer Sub-Standard X-Ray Dosemeter manufactured by the Baldwin Instrument Company, Ltd., Dartford, Kent, England.
[9] This value is 10% less than our previously published value[7] since absolute measurements in our laboratory have shown the Victoreen roentgen meter previously used was in error by this amount.

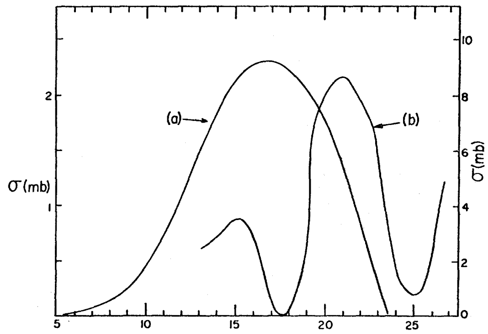

FIG. 2. (a) Cross-section curve obtained from the yield curve of Fig. 1. (b) The cross section obtained by Heinrich and Rubin; its ordinate scale is on the right-hand side.

exhibit some fairly large bumps, similar to those found by them.

At low energy there is a fairly important contribution to the neutron yield from deuterium in the sample. This has been measured and corrected for. Unavoidable LiOH contamination in the sample is not serious; the oxygen content in a 5% such contamination would result in a 0.7% increase in neutron yield at 22 Mev and less at lower energies. Our sample was considerably purer than this. At all energies counts were taken using a dummy sample (actual sample holder was reproduced except it contained no LiH) and were subtracted from the recorded counts.

LITHIUM PHOTONEUTRON CROSS SECTION

The photoneutron cross section, Fig. 2(a), was calculated from the yield curve shown in Fig. 1 by the inverted-spectrum method of Penfold and Leiss,[10] using their tables. Also shown on the same diagram is the cross section obtained by Heinrich and Rubin, curve (b) with the ordinate scale on the right-hand side.

In Table I we summarize the pertinent parameters of the cross section obtained by us and others. Although the present neutron yield curve is in excellent agreement with that published by Goldemberg and Katz[4] and the cross section resulting from the analysis using the tables of Penfold and Leiss has the same general shape, it is considerably smaller. The reason for this is twofold.

(i) Newer electronic absorption coefficients[11] altered our previous calculations of the number of roentgens per erg of radiation as published by Johns *et al.*,[12] on which our older tables were based.

(ii) The newer tables were calculated from Schiff's integrated spectrum formula[13] with $C=111$, while the older tables were based on Schiff's thin-target spectrum with $C=191$.

In an earlier publication, Rubin and Walter[14] reported a double-humped cross section for the $\mathrm{Li}(\gamma,p)$ reaction, the two humps corresponding in position to the first two of the three found by Heinrich and Rubin. No yield curve has been published by them for the (γ,p) reaction, while that of the (γ,n) reaction in reference 6 seems to indicate a statistical probable error of 8% for the individual points. In a private communication Dr. Heinrich has, however, indicated that the same results were obtained in five separate runs.

TABLE I. Characteristic parameters[a] of the $\mathrm{Li}(\gamma,n)$ cross section.

	E_m Mev	W Mev	σ_m mb	$\int_0^{24}\sigma dE$ Mev-barn	Neutron yield (per 100r per mole at 22 Mev)	Reference
Price and Kerst					1.30×10^7	1
Heinrich and Rubin	15 and 21	3.5		0.04		6
Goldemberg and Katz[b]	17.5	9.8	3.6	0.033	1.30×10^7	4
Rybka and Katz	16.8	9.3	2.3	0.018	1.30×10^7	

[a] In this table the giant cross section has its maximum value σ_m at E_m. The full width at half-maximum value is W and the area under the curve to 24 Mev is $\int_0^{24}\sigma dE$.
[b] σ_m, $\int_0^{24}\sigma dE$, and the yield shown are lower by 10% than the previously published value.

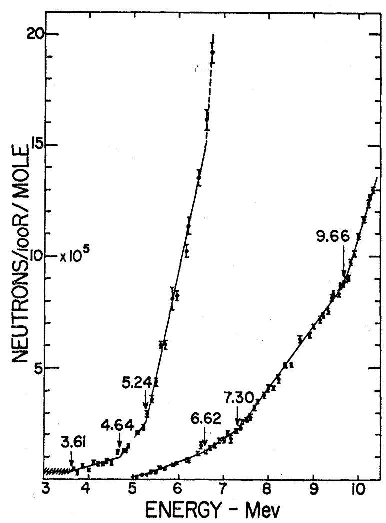

FIG. 3. Fine structure in the neutron yield curve. This is obtained by irradiating natural lithium with bremsstrahlung whose maximum energy is varied in small steps.

FINE STRUCTURE

If the lower part of the neutron yield curve is examined in greater detail, the curve shown in Fig. 3 is obtained. The number of recorded counts at each point in this energy region was greatly increased as follows:

(i) A much larger lithium sample was used (≈450 g LiH). The high attenuation of the x-ray beam in this sample only altered somewhat the general shape of the

[10] A. S. Penfold and J. E. Leiss (private communication).

[11] Gladys White Grodstein, National Bureau of Standards Circular No. 583 (U. S. Government Printing Office, Washington, D. C., 1957).
[12] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).
[13] L. I. Schiff, Phys. Rev. **83**, 252 (1951).
[14] R. Rubin and M. Walter, Helv. Phys. Acta **27**, 163 (1954).

yield curve; it has no effect on the position of the discontinuities.

(ii) At energies below the Pb(γ,n) threshold ($\sim$7 Mev), it was possible to place the paraffin cylinder with its BF_3 counters close to the betatron without encountering serious background trouble. Normally the apparatus is situated about 30 ft from the bremsstrahlung target behind a heavy concrete wall. At its new position this was reduced to 8 ft, resulting in a 14-fold gain in beam intensity.

(iii) All four BF_3 counters were used, resulting in a fourfold increase in counting rate ($\sim$10% of the emitted neutrons were detected in this case). Again as in (i) the resulting slight distortion in curve shape is not important.

Even with this large increase in counting rate, the minimum energy at which photoneutrons first appear was very difficult to locate accurately. Scattered photons produced neutrons from the D_2 content of the hydrogen in our sample and the paraffin cylinder, and this background was particularly troublesome. In order to accumulate counts, measurements in the threshold region were repeated several times. To cover the balance of the curve, over ten separate experiments were performed, each lasting one or more days. Every part of the curve was covered at least twice. The points shown in Fig. 3 represent averages of these measurements, with the vertical lines through these points indicating counting statistics only.

Before each run the energy scale of the betatron was calibrated against the photoneutron thresholds in H^2 (2.226 Mev)[15] and Bi^{209} (7.429±0.050 Mev)[15] and the residual activity resulting from the reaction $Cu^{63}(\gamma,n)Cu^{62}$ (10.826±0.020 Mev).[16]

It was possible to locate each of these thresholds to better than 30 kev. The helipot setting I of our energy control circuit is related to the peak bremsstrahlung energy E_0 by the equation

$$I=a+b[E_0(E_0+1)]^{\frac{1}{2}}.$$

Constants a and b were determined for each calibration by a least-squares fit of I to $[E_0(E_0+1)]^{\frac{1}{2}}$, determined from the above three calibrations. By this method the energy scale of the betatron was known to better than ±40 kev.

DISCUSSION OF FINE STRUCTURE RESULTS

3.61±0.15 Mev

The first discontinuity in the neutron yield curve was found at the indicated energy. The accuracy quoted is mainly determined by the difficulty in locating this break. It seems reasonable to identify this with the $Li^6(\gamma,np)He^4$ reaction whose threshold is 3.697 ±0.005 Mev.[15]

[15] A. H. Wapstra, Physica **21**, 367 (1955).

[16] Quisenberry, Scolman, and Nier, Phys. Rev. **104**, 461 (1956).

4.64±0.08 Mev

This break in the neutron yield curve probably results from the neutrons emitted in the breakup of He^5 following a (γ,p) reaction in Li^6. Mass data[17] give the threshold for this reaction at 4.655±0.030 Mev.

5.24±0.05 Mev

We assign this break to a level in Li^6. Galonsky *et al.*[18] reported a broad $T=0$ level at 5.4±0.5 Mev with $J=1^+$, while Allen *et al.*[19] have observed a sharp $T=1$ level at 5.35±0.07 Mev with $J=2^+$. Ajzenberg and Lauritsen[20] quote this level at 5.31±0.07 Mev.

Since the ground-state spin of Li^6 is 1^+, to reach either of these levels we must have $M1$ and/or $E2$ photon absorption.

5.73±0.05 Mev

This break in the neutron yield curve is readily identified with the $Li^6(\gamma,n)Li^5$ threshold. If Q is the energy released in the breakup

$$Li^5 \rightarrow p + He^4 + Q,$$

then the threshold for the (γ,n) reaction is $Q+3.697$ Mev, the latter number being the threshold energy for the reaction $Li^6(\gamma,np)He^4$.

The value of 5.73 Mev for this threshold gives $Q=2.03\pm0.04$ Mev and leads to a mass defect for Li^5 of 13.21±0.05 Mev. Summarizing the literature to 1955, Ajzenberg and Lauritsen[20] arrive at a mass defect of 12.99±0.15 Mev. Wapstra's mass tables give the same value but a somewhat larger error. On the other hand, Mattauch *et al.*,[17] in a survey of the literature using a least-squares adjustment, find 12.96±0.07 Mev. Our value is thus in excellent agreement with the first two of these values but not with that of Mattauch *et al.*

Sher, Halpern, and Mann[3] measured the $Li^6(\gamma,n)Li^5$ threshold at 5.35±0.2 Mev while Titterton[21] finds 5.6±0.1 Mev.

6.62±0.08 Mev

A weak break is observed at this energy, and while Ajzenberg and Lauritsen[20] indicate a level in Li^6 at 6.63±0.08 Mev, it is not possible to rule out the $Pb^{207}(\gamma,n)Pb^{206}$ threshold which occurs at 6.73 Mev.[15] This reaction would presumably take place in the lead collimator. Above 7 Mev the apparatus was moved behind the concrete wall mentioned before, to avoid just this background.

[17] Mattauch, Waldmann, Bieri, and Everling, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1956), Vol. 6, p. 179.

[18] A. Galonsky and M. T. McEllestrem, Phys. Rev. **98**, 590 (1955).

[19] Allen, Almquist, and Bigham, Phys. Rev. **99**, 631 (1955).

[20] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 79 (1955).

[21] E. W. Titterton, Progr. Nuclear Phys. **4**, 31 (1955).

7.30±0.04 Mev

Wapstra's[15] mass tables give the threshold for the $Li^7(\gamma,n)Li^6$ reaction at 7.25±0.01 Mev, while those of Mattauch *et al.*[17] give 7.252±0.007 Mev. Our break at 7.30±0.04 Mev probably results from the onset of this reaction.

9.66±0.04 Mev

This break has been observed previously by Goldemberg and Katz[5] at 9.6±0.1 Mev. The excitation function for phototritium emission from Li^7, obtained from an analysis of Li-loaded emulsions, was found by Titterton and Brinkley[22] to exhibit a peak at 9.3 Mev. Stall and Wachter[23] observed a peak at 9.25 Mev in the same excitation function, while Miwa[24] found it at 9.6 Mev.

ACKNOWLEDGMENT

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[22] E. W. Titterton and T. A. Brinkley, Proc. Phys. Soc. (London) **66**, 194 (1953).
[23] P. Stall and M. Wachter, Nuovo cimento **10**, 347 (1953).
[24] Mitsuo Miwa, J. Phys. Soc., Japan **10**, 173 (1955).

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Variational Wave Function for Nuclear Matter*

MANUEL ROTENBERG† AND LAWRENCE WILETS‡
Los Alamos Scientific Laboratory, Los Alamos, New Mexico
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A variational wave function for large nuclear systems is proposed. The function is written as a product of plane wave and deuteron-like functions. The exclusion principle is conveniently introduced by explicitly cutting out overlap between the plane wave and pair states in a manner equivalent to antisymmetrization. The method is limited to nonsingular potentials. Numerical calculations with saturating Yukawa potentials yield a correlation energy of 1.1 Mev per particle at low density, decreasing with increasing density. The method of introduction of the exclusion principle is applied to a qualitative discussion of elastic scattering by a complex projectile, e.g., an alpha particle. The distortion of the projectile wave function due to the exclusion of low-momentum components reduces the depth of an effective optical potential with respect to the sum of the potentials seen by the component nucleons.

I. INTRODUCTION

THE Fermi gas approximation forms the starting point for most statistical calculations of the nucleus. The nuclear wave function is written as a Slater determinant of single-particle plane wave functions, each state of a given momentum being occupied by one nucleon of each spin and charge up to some maximum momentum. Such an approximation is valid only for noninteracting particles, since forces among the particles distort the plane wave functions. In the language of the perturbation theory, the forces induce transitions to states out of the Fermi sea.

A powerful method for attacking the nuclear many-body problem has been developed by Brueckner and coworkers.[1] Calculations[2] based on the method have yielded very nearly the observed nuclear binding energy at the observed nuclear density. A different approach has been proposed by Jastrow,[3] who uses a wave function explicitly displaying two-body correlations. Neither of these methods is variational in nature, so that upper bounds to the energy are not available.

In this paper we suggest a variational wave function from which an upper bound can be calculated numerically. Once the trial wave function is written down, no approximations are made in computing the energy with one minor exception: an approximation which can be shown to decrease the binding energy slightly. The final result is still an upper bound.

Since the wave function introduced takes the Pauli principle into account easily, it is also shown how the effective depth of a Hartree potential is altered when a complex particle such as a deuteron or alpha particle is scattered from it.

The wave function consists of an antisymmetrized product of plane wave functions and bound two-body functions. The two-body functions anticipate some of the clustering or correlations which occur, particularly at low nuclear densities. In some respects the method is reminiscent of Wheeler's resonating group structures.[4]

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‡ On leave of absence to The Institute for Advanced Study, Princeton, New Jersey.
[1] See, for example, a review by K. A. Brueckner, Revs. Modern Phys. (to be published).
[2] K. A. Brueckner and J. Gammel, Phys. Rev. **109**, 1023 (1958).
[3] R. Jastrow, Phys. Rev. **98**, 1479 (1955).
[4] J. A. Wheeler, Phys. Rev. **52**, 1083 (1937).