Polarization of $\text{Li}^7(\text{p},\text{n})\text{Be}^7$ neutrons⁺H. R. Striebel,⁺⁺ S. E. Darden,⁺⁺⁺ and W. Haerberli

University of Wisconsin, Madison, Wisconsin

+ Work supported by the U. S. Atomic Energy Commission and by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.

++ On leave from the University of Basel, Switzerland.

+++ Now at University of Notre Dame, South Bend, Indiana.

Abstract

The polarization of neutrons emitted from the $\text{Li}^7(\text{p},\text{n})\text{Be}^7$ reaction at an angle of 50° was measured for neutron energies between 0.7 and 1.5 Mev. The polarization was deduced from the right-left asymmetry in the scattering of these neutrons from liquid oxygen. The results indicate that the polarization is close to -0.3, independent of bombarding energy. One measurement for neutrons emitted at 30° yields a polarization only slightly smaller than for neutrons emitted at 50° for the same proton energy. The total neutron cross section of oxygen was remeasured for neutron energies between 0.7 Mev and 1.4 Mev.

1. Introduction

Neutrons emitted in nuclear reactions are in general expected to be polarized ¹⁾. Measurements of the degree of polarization contribute to the study of the reaction mechanism

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

and are also of interest since polarized neutrons are useful for the study of spin-orbit effects in the neutron-nucleus interaction. Reactions which have been investigated to date include the $\text{Li}^7(p,n)\text{Be}^7$ ²⁻⁵⁾, the $\text{D}^2(d,n)\text{He}^3$ ⁶⁻⁹⁾, and the $\text{Cl}^{35}(d,n)\text{Nl}^{36}$ ¹⁰⁾ reactions. In all of these cases the procedure followed to determine the polarization has been to measure the right-left asymmetry in the scattering of the neutrons from a suitable nucleus. Provided the neutron scattering phase shifts for this nucleus are known, the polarization of the incident neutrons can be calculated from the observed right-left asymmetry.

Adair ²⁾, Okazaki ⁵⁾, and Willard ³⁾ have investigated the polarization of $\text{Li}^7(p,n)\text{Be}^7$ neutrons emitted at laboratory angles of 50° ^{2,5)} and 42° ³⁾ and ranging in energy from 270 kev to 600 kev. The polarization was determined from measurements of the asymmetry in the scattering by oxygen. In this energy region polarization values⁺ of the order of -0.40 were found.

+ The positive direction of the polarization is chosen in the direction of the vector $\mathbf{k} \times \mathbf{k}_0$, where $\mathbf{k}$ and $\mathbf{k}_0$ are the propagation vectors of the outgoing and incident beams respectively.

In the present experiment the same procedure has been used to extend the previous measurements to neutron energies between 700 kev and 1500 kev. An analysis of the total cross section and angular distribution data for oxygen provides sufficiently accurate values of the phase shifts to allow a calculation of the polarizing power of the oxygen scatterer.

2. Polarization of Neutrons Scattered from Oxygen

In order to calculate the polarizing power of oxygen, i.e., the polarization which would result in the scattering of an initially unpolarized beam, the scattering phase shifts must be known over the energy interval of interest. In general the phase shifts can be obtained from the measured total and differential cross sections. In the present experiment the phase shifts were obtained from the oxygen total cross section. For neutron energies below 1.4 Mev the total cross section of oxygen has been measured ¹¹⁾ using $\text{Li}^7(p,n)\text{Be}^7$ neutrons and an energy insensitive neutron detector. Since in the meantime a low energy group of neutrons due to the $\text{Li}^7(p,n)\text{Be}^7$ reaction has been found, these measurements may be inaccurate. The total cross section was remeasured by the transmission method, using SnO_2 and Sn scattering samples. Again the $\text{Li}^7(p,n)\text{Be}^7$ reaction served as a neutron source, but the low energy neutrons were discriminated against by using a propane filled recoil counter and by accepting only the largest counter pulses. The neutron energy spread was 8 kev. It was determined from the apparent width of the 685-kev resonance in sulfur. Measured values of the cross sections for neutron energies between 0.7 and 1.4 Mev are plotted in Fig. 1. Also included in Fig. 1 are the data of Okazaki ⁵⁾ below 0.7 Mev. An in-scattering correction was applied to the data. The magnitude of the correction varied between 1.5% and 3% depending on neutron energy. The statistical uncertainties are indicated in the figure. Where no error bars are shown the uncertainties are

less than the diameter of the dots.

At most energies the cross sections agree with the older measurements ¹¹⁾ within about 10%. Resonances occur at 442 kev, 1000 kev, and 1312 kev with widths at resonance of 48 kev, 100 kev, and 44 kev. The total angular momenta and parities of the corresponding levels in O^{17} are known to be $3/2^-$, $3/2^+$, and $3/2^-$ respectively ¹²⁾.

In analyzing the total cross section the S-wave potential phase shift was first obtained for two neutron energies, one below and one above the energy interval of interest here. For a neutron energy of 2.3 Mev the S-wave potential phase shift was determined from the shape of the S-wave resonance at this energy. From angular distribution experiments of neutrons scattered from oxygen ⁵⁾ it is known that orbital angular momenta larger than zero make negligible contribution to the total cross section at 0.2 Mev energy. Therefore the S-wave potential phase shift at 0.2 Mev may be obtained directly from the total cross section. The phase shifts at 2.3 Mev and at 0.2 Mev so obtained require a hard sphere radius of 5.60×10^{-13} cm. For the energy interval between these two points, the potential S-wave phase shift was calculated using the above radius. The assumption of a constant radius is not unreasonable, since the spacing of the S-wave size resonances is large compared to the energy interval considered here. Indeed calculations based on a square well ¹³⁾ yield S-wave phase shifts practically identical to the ones used here. The total cross section between resonances is well reproduced by using these S-wave phase

shifts and the tails of the P- and D-wave resonances. This indicates that the potential P- and D-wave phase shifts must be small. The addition of either a $3/2^-$ or a $3/2^+$ potential phase shift of -2° causes, in disagreement with the experiment, a perceptible decrease of the calculated cross section in the energy region below and an increase above the corresponding resonances. Since it is impossible to remove such a disagreement without introducing an inflection point into the curve of the S-wave phase shift versus energy, the potential P- and D-wave phase shifts were taken to be zero. For the calculation of the resonance phase shifts a Breit-Wigner single-level formula ¹⁴⁾ was used. A radius of 5.5×10^{-13} cm was chosen for the calculation of the penetrabilities. The tangent of the $3/2^-$ -phase shift was taken to be the sum of the tangents of the phase shifts from the two $3/2^-$ resonances.

Total cross sections calculated from the phase shifts discussed above are shown by the solid curve in Fig. 1. Fowler and Cohn ¹³⁾ have measured angular distributions of neutrons scattered from oxygen. From their data they obtained phase shifts essentially identical to the phase shifts used in the present investigation except at a neutron energy of 730 kev, where a $3/2^+$ -phase shift of -8° was required to fit their data. This discrepancy will be discussed later.

Values of the polarizing power $P_2(\theta)$ calculated from the phase shifts ¹⁵⁾ discussed above are shown in Fig. 2 as a function of neutron energy for a center-of-mass scattering

FIG. 1

Total neutron cross section of oxygen. The statistical uncertainties are indicated, where larger than the dots. The data below $E_n = 700$ kev are those of Okazaki⁵).

FIG. 2

P_2 of oxygen for a scattering angle of 60° averaged over 80 kev. The experimental points represent the measured values of $P_1 P_2$ (58°) divided by a fixed value of $P_1 = -0.3$.

angle of $\theta = 60^\circ$. In Table I are listed polarizations $P_2(\theta)$ at those energies and angles for which asymmetry measurements were performed. Since the neutrons used had an estimated energy spread of 80 kev, the P_2 given are values of $\overline{\sigma(\theta)} \cdot P_2(\theta) / \overline{\sigma(\theta)}$, where the average is taken over the energy spread. Though of no practical importance it should be mentioned that the above calculations were carried out for $\theta = 60^\circ, 90^\circ$, and 130° while in the experiment scattering angles $\theta_{cm} = 58^\circ, 90^\circ$, and 128° were used.

In order to estimate uncertainties of P_2 , variations in the phase shifts were introduced. In particular the effect of possible $1/2^-$ and $3/2^-$ potential phase shifts was studied. Since practically no information can be obtained about the $1/2^-$ -phase shift from the total cross section alone, the angular distributions ¹³⁾ were also considered. While it is difficult to make reliable statements about the uncertainty in $P_2(\theta)$, it is estimated that the $P(60^\circ)$ as shown in Fig. 2 have a maximum error of ± 0.1 near 700-kev neutron energy and of ± 0.15 near 1.2 Mev and probable errors somewhat less than half as large. The uncertainties in $P_2(\theta)$ become appreciably smaller near 950-kev neutron energy, but somewhat larger for energies above 1.4 Mev.

3. Experimental Procedure

The experimental arrangement and procedure used to measure the right-left asymmetry of scattered neutrons were essentially the same as used in earlier work ^{4,8)}. Some details are given in the preceding paper. Neutrons emitted at an angle of 60°

from a metallic Li target were scattered from a sample of liquid oxygen. The liquid oxygen was contained in a thin-walled (0.2 mm) can 2 cm in diameter and 13 cm high. Surrounding the can was a styrofoam jacket of 0.7 cm thickness. The collimated neutron beam irradiated the sample only over a length of 6 cm, so that the exposed part of the container was filled for the entire duration of each run. The proportional counter was filled with 2.4 atmospheres of propane and biased sufficiently high to discriminate against the low energy group of target neutrons. Background measurements were taken with the empty can in position. The number of background counts ranged from 48% to 67% of the counts obtained with the filled container.

4. Results and Discussion

The measured right-left ratios R/L are listed in Table I. This ratio is related to the polarizing power $P_2(\theta)$ of oxygen and to the polarization P_1 of the $Li^7(p,n) Be^7$ neutrons by the equation

$$P_1 P_2(\theta) = \left[\frac{R}{L}(\theta) - 1 \right] \left[\frac{R}{L}(\theta) + 1 \right]^{-1} \quad (1)$$

Values of $P_1 P_2(\theta)$ obtained from the measured right-left ratios using eq. (1) were corrected for multiple scattering and for the variation of the neutron flux across the sample. In most cases the multiple scattering corrections amounted to about 10% of the values of $P_1 P_2(\theta)$, except at a neutron energy of 965 kev, where the correction was 20%. The multiple scattering

corrections were calculated in the manner described in the preceding paper, but here the effect of the energy loss of the neutrons in the first collision was taken into account in calculating the fraction of neutrons scattered more than once. Corrected values of P_1P_2 are given in column 6 of Table I.

At a neutron energy of 985 keV $P_1P_2(\theta)$ was determined for center-of-mass scattering angles of 58° , 90° , and 128° . The results confirm the assignment of $J^\pi = 3/2^+$ to the level corresponding to the 1.0-MeV resonance. As expected $P_1P_2(\theta)$ changes sign between $\theta = 58^\circ$ and $\theta = 128^\circ$ and is close to zero for $\theta = 90^\circ$. Similarly, a value of P_1P_2 close to zero at a neutron energy of 1430 keV confirms the assignment $J^\pi = 3/2^-$ to the level corresponding to the 1312-keV resonance, since this assignment predicts a value close to zero for P_2 at this energy.

Values of P_1 , the polarization of the $\text{Li}^7(p,n)\text{Be}^7$ -neutrons, are presented in the last column of Table I. They were obtained by dividing the measured values of $P_1P_2(\theta)$ by the calculated oxygen polarizations $P_2(\theta)$. In cases for which $P_2(\theta)$ is so small that no meaningful value of P_1 can be obtained, no value is given. The uncertainties of Table I indicate the statistical uncertainties only. Uncertainties of P_2 and the multiple scattering correction are discussed in Section 2 and in the previous paper respectively. The dependence of the polarization P_1 on energy is shown in Fig. 3. For proton energies below 2.50 MeV the results are those of Okazaki ⁸⁾. It can be seen from the figure that P_1 does not vary appreciably over the energy range covered by the present experiment. Most points are consistent with a polarization of $P_1 = -0.30$. The measurement at 1357-keV neutron energy for $\theta_2 = 90^\circ$

has been omitted from Fig. 3 because this point is less reliable than the others since P_2 is most uncertain in the 1400-kev neutron energy region and varies very rapidly with energy. That the polarization of the neutrons remains fairly constant is, for the present data, also illustrated in Fig. 2. The points indicated are the measured values of $P_1P_2(68^\circ)$ divided by an assumed constant polarization $P_1 = -0.30$. The points lie quite close to the calculated $P_2(60^\circ)$ which demonstrates that the observed variation of $P_1P_2(\theta)$ can be attributed essentially to the variation of $P_2(\theta)$.

The use of a -5° $3/2^+$ -phase shift at 730-kev neutron energy as indicated by the angular distribution data ¹¹⁾ results in a calculated $P_2(60^\circ)$ which passes through zero at an energy around 800 kev. This is in disagreement with the measured values of $P_1P_2(\theta)$ which do not change sign in this energy region.

In Fig. 2 the calculated P_2 passes through zero at a neutron energy of 1030 kev. Since the measured P_1P_2 must pass through zero at the same energy, this point was used as a reference point for the neutron energy scale. If the neutron energies are calculated from the proton bombarding energies, neglecting the finite thickness of the lithium target, the experimental points in Fig. 2 are displaced by 40 kev to higher energies with respect to the calculated curve. This difference is reasonably attributed to the finite thickness of the target, and indicates an 80-kev energy spread of the neutrons. A determination of the target thickness by the rise method ¹⁶⁾ indicated a thickness corresponding

FIG. 3

Polarization of $\text{Li}^7(p,n)\text{Be}^7$ neutrons as a function of proton and neutron energy for a neutron emission angle of 50° in the laboratory system.

to only 50 keV energy spread. This discrepancy is not surprising in view of the uncertainties associated with the rise method. As long as the energy scale is fixed by the reference point mentioned above, results are insensitive to the energy spread assumed.

The results of the present investigation indicate that the polarization of $\text{Li}^7(\text{p},\text{n})\text{Be}^7$ neutrons emitted at 80° with respect to the proton beam is approximately $-.30$ over the range of proton bombarding energies from 2.6 to 3.4 MeV. A polarization value of -0.240 ± 0.018 was measured at 2.72 MeV proton energy for an emission angle of 30° . This is to be compared to a value of -0.272 ± 0.027 for an emission angle of 60° at essentially the same proton bombarding energy. Polarizations of the same sign and similar magnitude were found at lower proton bombarding energies by Willard *et al.* ³⁾ and by Okazaki ⁵⁾. There is some evidence in these data ^{3,5)} for a variation of P_1 with energy, although the two measurements do not entirely agree with each other. Such a variation has been predicted by Adair ⁴⁾ who has assumed that the well known resonance in the $\text{Li}^7(\text{p},\text{n})\text{Be}^7$ reaction at a proton bombarding energy of 2.25 Mev is due to a $J^\pi = 3^+$ state in Be^8 . The background reaction intensity was assumed to arise predominantly from 1^- and 2^- states, *i.e.*, by incident protons of zero angular momentum.

According to Adair's calculations, the polarization should decrease appreciably in magnitude as the proton bombarding energy is varied away from the region of the resonance energy.

This is in disagreement with the experimental results which suggest that the background reaction intensity may involve orbital angular momenta greater than zero, since s-wave interaction alone would not produce any polarization of the outgoing neutrons. Although a strong resonance has been observed in the $\text{Li}^7(p, \alpha)$ cross section ¹⁷⁾ at a proton energy of 3.0 Mev, no corresponding variation is evident in either the polarization or the forward yield of the $\text{Li}(p, n)$ reaction ¹⁸⁾. It is possible that the $\text{Li}(p, n)$ reaction may be interpreted more easily in terms of a direct interaction mechanism ¹⁹⁾.

We wish to thank Professor Barschall for his stimulating interest in this work.

Table I

Summary of experimental results

E_p (MeV)	E_n (MeV)	Angle of neutron emission (degrees, lab. system)	Neutron scattering angle θ (degrees c.m.)	R/L	Corrected $P_1 P_2$	P_2	P_1
2.618	0.744	50	58	0.813 ± 0.040	-0.110 ± 0.024	+0.362	-0.304 ± 0.066
2.667	0.788	50	58	0.771 ± 0.032	-0.139 ± 0.020	+0.442	-0.314 ± 0.045
2.739	0.855	50	58	0.723 ± 0.027	-0.174 ± 0.017	+0.610	-0.272 ± 0.027
2.798	0.912	50	58	0.655 ± 0.025	-0.228 ± 0.016	+0.892	-0.256 ± 0.018
2.857	0.965	50	58	0.630 ± 0.011	-0.258 ± 0.008	+0.849	-0.304 ± 0.009
2.857	0.965	50	90	1.035 ± 0.029	$+0.023 \pm 0.015$	+0.020	
2.857	0.965	50	128	1.405 ± 0.063	$+0.193 \pm 0.029$	-0.605	-0.319 ± 0.048
2.935	1.036	50	58	0.986 ± 0.028	-0.094 ± 0.016	+0.013	
2.990	1.086	50	58	1.333 ± 0.051	$+0.186 \pm 0.027$	-0.524	-0.355 ± 0.052
3.127	1.213	50	58	1.645 ± 0.072	$+0.283 \pm 0.030$	-0.773	-0.366 ± 0.039
3.284	1.357	50	90	0.751 ± 0.036	-0.154 ± 0.024	+0.635	-0.243 ± 0.033
3.366	1.432	50	58	0.966 ± 0.082	-0.014 ± 0.045	-0.090	
2.722	0.948	30	58	0.622 ± 0.022	-0.222 ± 0.017	+0.923	-0.240 ± 0.018

References

- 1) A. Simon and T. A. Welton, Phys. Rev. 90 (1953) 1036
- 2) R. K. Adair, S. E. Darden and R. E. Fields, Phys. Rev. 96 (1954) 503
- 3) H. B. Willard, J. K. Bair and J. D. Kington, Phys. Rev. 96 (1954) 1359
- 4) R. K. Adair, Phys. Rev. 96 (1954) 709
- 5) A. Okazaki, Phys. Rev. 99 (1955) 55
- 6) E. Baumgartner and P. Huber, Helv. Phys. Acta 26 (1953) 545
- 7) R. W. Meier, P. Scherrer and G. Trumpy, Helv. Phys. Acta 27 (1954) 577
- 8) B. M. McCormac, M. F. Steuer, C. D. Bond and F. L. Hereford, Phys. Rev. 104 (1956) 718
- 9) I. I. Levintov, A. V. Miller and V. N. Shamshev, Nucl. Phys. 3 (1957) 221
- 10) W. Haerberli, to be published
- 11) G. K. Bockelman, Phys. Rev. 80 (1950) 1011
- 12) R. K. Adair, Phys. Rev. 92 (1953) 1491
- 13) Fowler and Cohn, Phys. Rev., to be published
- 14) R. K. Adair, Phys. Rev. 86 (1952) 155
- 15) L. Wolfenstein, Ann. Rev. Nucl. Science 6 (1956) 43
- 16) R. Taschek and A. Hemmendinger, Phys. Rev. 74 (1948) 373
- 17) N. P. Heydenburg, C. M. Hudson, D. R. Inglis, and W. D. Whitehead, Phys. Rev. 74 (1948) 405
- 18) J. K. Bair, H. B. Willard, C. W. Snyder, T. M. Hahn, T. D. Kington and F. P. Green, Phys. Rev. 85 (1952) 946
- 19) J. Sawicki, Phys. Rev. 104 (1956) 1441

Figure Captions

- 1) Total neutron cross section of oxygen. The statistical uncertainties are indicated, where larger than the dots. The data below $E_n = 700$ kev are those of Okazaki ⁵⁾.
- 2) P_2 of oxygen for a scattering angle of 60° averaged over 80 kev. The experimental points represent the measured values of $P_1 P_2$ (58°) divided by a fixed value of $P_1 = -0.3$.
- 3) Polarization of $Li^7(p,n)Be^7$ neutrons as a function of proton and neutron energy for a neutron emission angle of 60° in the laboratory system.