could lead to states with partial vibrational character giving enhanced $E2$ transition rates but with Ω not a very good quantum number.

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Scattering of Polarized Neutrons by Heavy Nuclei*

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The polarization of Li(p,n) neutrons emitted at a laboratory angle of 50° was measured as a function of proton energy from 2.21 to 2.40 Mev. Analysis of the polarization of the neutrons was performed by measuring the left-right asymmetry in scattering by oxygen. To determine more accurately the polarization produced in scattering by oxygen, the total cross section and angular distribution of scattered neutrons were remeasured.

Measurements of the polarization of neutrons produced in the scattering by intermediate and heavy nuclei have been continued. The results were compared with polarizations calculated by assuming the complex square-well model proposed by Feshbach, Porter, and Weisskopf and modified by the addition of a spin-orbit interaction.

INTRODUCTION

MEASUREMENTS of the polarization of neutrons produced in the scattering by intermediate and heavy nuclei have been reported previously by Adair, Darden, and Fields.[1] These measurements have been continued to study further the dependence of the polarization produced in scattering on the atomic weight. As in the previous experiment the polarization was determined by measuring the left-right asymmetry in scattering of polarized neutrons produced in the $Li^7(p,n)Be^7$ reaction. Before the polarization produced in scattering can be obtained from the measured asymmetries, the polarization of the incident neutrons must be determined. The polarization of the neutrons from the reaction was measured as a function of the incident proton energy using oxygen as the analyzer. The method of analysis has been described previously.[1]

The polarization of neutrons produced in the scattering by oxygen can be expressed in terms of the phase shifts describing the scattering. In order to obtain a more accurate determination of the phase shifts, the total cross section and the angular distributions of scattered neutrons in the energy region of the 440-kev resonance were remeasured.

SCATTERING OF NEUTRONS BY OXYGEN

The total cross section was measured by a conventional transmission experiment in which the transmission of a SnO_2 sample was compared with that of a Sn sample containing the same number of Sn nuclei per cm^2 as were present in the oxide sample. Neutrons were produced by bombarding with protons a lithium target which had a stopping power of about 6 kev for the incident protons. The observed total cross sections corrected for inscattering are plotted in Fig. 1.

Measurements of the angular distribution of neutrons scattered by oxygen were made for neutron energies 410, 438, 465, and 493 kev by a method previously described.[2] For the incident protons the lithium target used for the production of neutrons had a stopping power of 16 kev. To shield the neutron detector from neutrons coming directly from the source, a paraffin block was placed between the detector and source. In addition, the paraffin block served to collimate the neutrons so that at the sample position an area 3.7 cm wide and 6 cm high was irradiated by neutrons. The liquid oxygen scattering sample was contained in a

* Work supported by the U. S. Atomic Energy Commission and the Wisconsin Alumni Research Foundation.
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[1] Adair, Darden, and Fields, Phys. Rev. **96**, 503 (1954).

[2] M. Walt and H. H. Barschall, Phys. Rev. **93**, 1062 (1954).

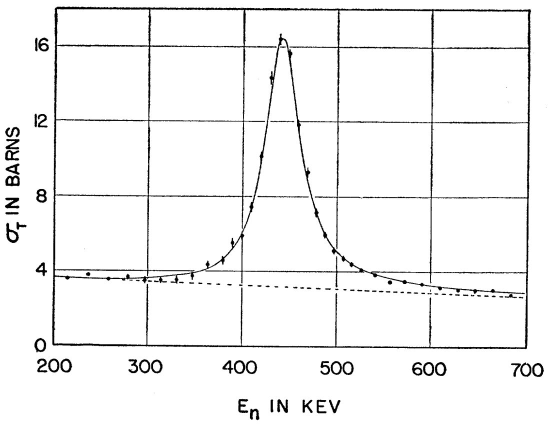

FIG. 1. The total cross section of oxygen *versus* neutron energy. The solid curve was calculated assuming resonance parameters $\Gamma=48$ kev and $E_r=442$ kev and S-wave scattering indicated by the dashed line.

thin-walled stainless steel cylinder 1.3 cm in diameter which was surrounded by a cylindrical piece of styrofoam 0.7 cm thick. Scattered neutrons were detected with a recoil counter having an active counting volume 2.5 cm in diameter and 10 cm long and filled with hydrogen to a pressure of 7 atmos. Upon being scattered from oxygen the neutrons lose an appreciable fraction of their energy in the laboratory system with the attendant decrease in the probability of being detected. The energy sensitivity of the counter was measured and corrections for the energy loss were applied to the data.

Making the simplifying assumption that the scattering takes place in a plane perpendicular to the axis of the scattering sample, an estimate of the effect of multiple scattering on the angular distribution was obtained by graphical means. As a check a Monte Carlo calculation similar to that described previously[2] has been performed[3] for neutron energies of 438 and 465 kev where the multiple scattering effect is most pronounced. The two methods give similar results. Since the number of scattering nuclei was not accurately known, only relative angular distributions could be determined. The observed angular distributions, which were normalized so that the integral over all solid angles gave the total cross sections, are plotted in Fig. 2.

In the energy region investigated it is expected that only S- and P-wave scattering are important. The resonance in the total cross section for a neutron energy of about 440 kev is due to an odd parity level with total angular momentum $\frac{3}{2}$ in O^{17} formed by P-wave neutrons.[4] At the resonance energy the contribution of resonance scattering to the total cross section is known and subtraction of this cross section from the observed cross section gives the potential scattering. For energies sufficiently far from the resonance energy, the scattering is mainly the result of background potential scattering which was assumed to decrease linearly with energy. An attempt was made to fit the total cross section and angular distribution measurements with various $P_{\frac{1}{2}}$ and $P_{\frac{3}{2}}$ phase shifts and S-wave phase shifts calculated from the assumed background potential scattering cross section. With a $P_{\frac{1}{2}}$ phase shift equal to zero and a $P_{\frac{3}{2}}$ resonance phase shift calculated for a resonance width of 48 kev at the resonance energy of 442 kev, good agreement with the data was obtained. The resonance phase shift was calculated by using the one-level dispersion formula[5] which takes into account the level shift. The solid line in Fig. 1 shows the calculated total cross section. In Fig. 2, the calculated angular distributions averaged over the energy spread of the incident neutrons are indicated by the curves. Reasonable agreement with the observed angular distributions was obtained for neutron energies of 410, 465, and 493 kev. Over the energy interval used in the 438-kev measurement, the angular distribution changes rapidly with energy, and inasmuch as the energy spectrum of the incident neutrons was not accurately known, the average of the calculated angular distribution could not be determined reliably.

The calculated polarization produced by the oxygen analyzer depends sensitively on the assumed $P_{\frac{1}{2}}$ phase shift. There are spin $\frac{1}{2}$, odd-parity states in O^{17} at excitation energies of 3.06 and 5.93 Mev. At the energies investigated here the contribution to the $P_{\frac{1}{2}}$ phase shifts from the latter level is less than 0.2°. The 3.06-Mev bound level probably corresponds to the 3.10-Mev state in the mirror nucleus F^{17} which has a small reduced width, and the effect of this level on the scattering is negligible. Although a good fit to the

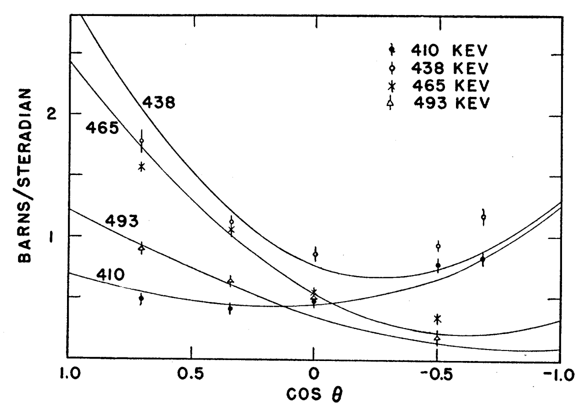

FIG. 2. Angular distribution of neutrons scattered by oxygen at neutron energies of 410, 438, 465, and 493 kev. The indicated errors include statistical errors and estimated errors in the multiple scattering corrections. The curves are the calculated distributions averaged over the neutron energy spread.

[3] The author should like to thank Dr. M. Walt of the Los Alamos Scientific Laboratory for performing the Monte Carlo calculation.

[4] C. K. Bockelman, Phys. Rev. **80**, 1011 (1950); R. K. Adair, Phys. Rev. **92**, 1491 (1953).

[5] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).

total cross section and angular distribution measurements was obtained for a P-potential scattering phase shift equal to zero the measurements were not sufficiently accurate to allow the determination of a P-potential scattering phase shift less than 3°. For a neutron energy of 500 kev the hard sphere P-wave phase shift is about 6°. A calculation of the P-wave phase shift assuming the complex square well model proposed by Feshbach, Porter, and Weisskopf,[6] gives a value of less than 1°.

Using the phase shifts obtained from the total cross section and angular distribution measurements, calculations were made of the polarization produced by the oxygen analyzer.

POLARIZATION OF Li(p,n) NEUTRONS

Oxygen was used to measure the polarization of the neutrons produced in the $Li^7(p,n)Be^7$ reaction and emitted at a laboratory angle of 50° with respect to the incident proton beam. To determine the polarization of the neutrons from the reaction, the left-right asymmetry in scattering of the neutrons from oxygen was measured with the same apparatus used in the angular distribution measurements and with an experimental arrangement similar to that described previously. For a proton energy of 2.23 Mev a lithium target 65 kev thick was used and measurements of the asymmetry in scattering were performed for scattering angles of 60° and 90° c.m. All the other measurements were made with a lithium target which had a stopping power of about 35 kev for the incident protons. At proton energies of 2.27 Mev and 2.30 Mev the asymmetry was measured for six scattering angles from 45° to 120°. Measurements at the other energies investigated were made for scattering through 90°. The observed left-right asymmetries were corrected for multiple scattering and together with the calculated polarization produced by the oxygen analyzer allowed the determination of the polarization of the neutrons from the reaction. In Fig. 3, the corrected left-right asymmetries for a scattering angle of 90° are plotted as a function of the incident proton energy. As expected, the left-right scattering ratio changes from a value greater than one to a value less than one for the neutron energy at which the polarization produced in scattering by oxygen changes sign. The measured polarizations of the Li(p,n) neutrons are plotted *versus* the incident proton energy in Fig. 4. For the energies at which measurements were made for several scattering angles, the averages of the polarizations obtained for the different angles are shown.

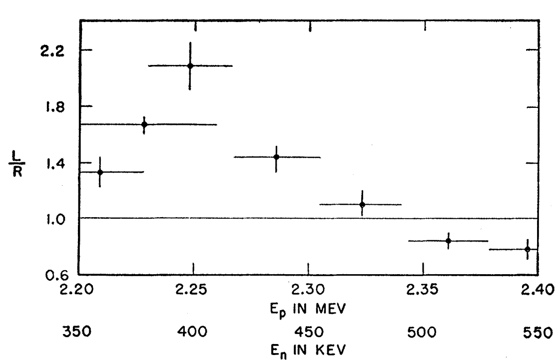

FIG. 3. Observed left-right ratios for neutron scattering at 90° c.m. by oxygen *versus* proton energy and corresponding neutron energy. The vertical lines represent standard statistical errors. The horizontal lines represent the spread in neutron energy.

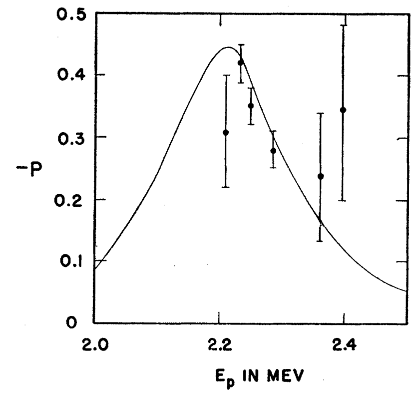

FIG. 4. Polarization of $Li^7(p,n)$ neutrons *versus* proton energy. The neutrons were emitted at 56° c.m. with respect to the incident proton beam. The solid curve is the polarization calculated by Adair for neutrons emitted at 60° c.m.

Adair[7] has calculated the polarization of neutrons produced in the reaction as a function of the proton energy, and the calculated polarization of neutrons emitted at 60° c.m. is indicated by the solid curve in the figure. In the present experiment the measurements were made for neutrons emitted at 50° laboratory angle or 56° c.m. There is good agreement between the measurements with small statistical errors and the calculated values. The small polarization produced by the oxygen analyzer for some neutron energies results in large errors in the measured polarization of neutrons with these energies.

Willard and co-workers[8] have reported measurements of the polarization of neutrons produced in the Li(p,n) reaction and emitted at a laboratory angle of 42° with respect to the incident protons. Their results indicate a nearly constant value of 0.50 ± 0.04 for neutrons with energies from 300 to 550 kev and are larger than the values obtained in the present investigation.

POLARIZATION OF NEUTRONS SCATTERED BY HEAVY NUCLEI

The polarized neutrons from the $Li^7(p,n)$ reaction were used to measure the polarization of neutrons scattered by intermediate and heavy nuclei. In these measurements 380-kev neutrons from the reaction

[6] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).

[7] R. K. Adair, Phys. Rev. **96**, 709 (1954).

[8] Willard, Kington, and Bair, Phys. Rev. **95**, 1359 (1954).

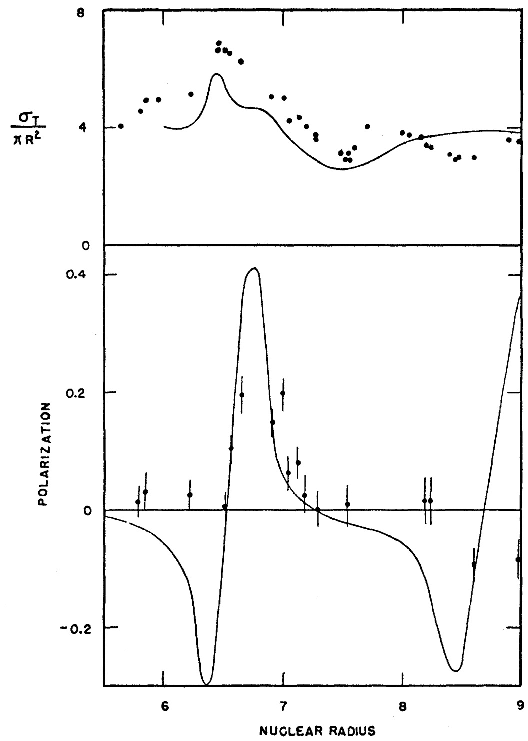

FIG. 5. In the upper part of the figure, the total cross section divided by the geometric area of the nucleus is plotted *versus* the nuclear radius in units of 10^{-13} cm. The polarization of neutrons scattered by nuclei is plotted as a function of the nuclear radius in the lower part of the figure. The nuclear radius was assumed to be $1.45A^{\frac{1}{3}}\times10^{-13}$ cm. Experimental measurements for 380-kev neutrons are shown by the points. The curves are the values calculated by using the complex square-well potential $V=[-42\times(1+0.03i)-3.0\ \mathbf{l}\cdot\mathbf{s}]$ Mev.

emitted at a laboratory angle of 50° were scattered from the element under consideration and the left-right asymmetry in scattering through 90° was observed. The polarization of the incident beam of neutrons which had an energy spread of 65 kev was 42 ± 6 percent. There is good agreement between the observed asymmetries and those previously reported. However in the previous experiment the polarization of the incident neutrons was found to be 53 ± 6 percent compared with 42 ± 6 percent measured in the present investigation. Hence the polarization produced in scattering by the intermediate and heavy nuclei was assigned a value 20 percent smaller than in the present measurements. The measured polarizations are shown in the lower part of Fig. 5 as a function of the nuclear radius which was assumed to be given by $1.45A^{\frac{1}{3}}\times10^{-13}$ cm, where A is the atomic weight. The vertical bars represent statistical errors only and do not include the uncertainty in the polarization of the incident beam. For atomic weights near 100 the polarization reaches a maximum value of about 20 percent. The lightest elements investigated, Cu and Zn, produce little polarization while the heaviest elements, Bi and U, produce small polarizations of sign opposite to that observed for the other elements.

Feshbach, Porter, and Weisskopf[6] have proposed a model in which the interaction between a neutron and a nucleus is described by a complex square-well potential $V=-42(1+0.03i)$ Mev for $r<R$. The nuclear radius R is given by $1.45A^{\frac{1}{3}}\times10^{-13}$ cm, where A is the atomic weight. While this model has been successful in reproducing qualitatively the variations of the total cross section with atomic weight and neutron energy, it does not contain a spin-dependent interaction which was shown to be present by the observed polarizations. Calculations of the polarization produced in the scattering of 378-kev neutrons were performed by assuming a spin-orbit interaction of the form $V'\ \mathbf{l}\cdot\mathbf{s}$ in addition to the complex square well potential. S and P-wave scattering were considered. The solid curve in Fig. 5 represents the polarization calculated for $V'=-3.0$ Mev. The model gives correctly the small polarizations observed for the lightest elements and also the position of the peak in the polarization though the magnitude appears to be too large. However, the model gives a large negative polarization in the region of $R=6.3\times10^{-13}$ cm whereas the measurement for Se with $R=6.23\times10^{-13}$ cm indicates little polarization. Further, large positive values are predicted for the region of U in disagreement with the observed polarization which has the opposite sign.

Recently Thomas[9] has calculated the polarization produced in scattering for a complex square-well potential and a spin-orbit interaction which is effective only at the nuclear surface where it has the form of a delta function. In these calculations neutrons with orbital angular momentum up to and including three units were considered. The results for the surface spin-orbit interaction are qualitatively the same as those obtained for the uniform spin-orbit interaction. For both spin-orbit interactions the maxima and minima in the calculated polarization occur for the same atomic weights.

Calculations have also been made of the total cross sections of intermediate and heavy elements for 378-kev neutrons as a function of the atomic weight assuming the presence of a spin-orbit interaction. In the upper part of Fig. 5, the calculated and observed total cross sections divided by the geometric area of the nucleus are plotted *versus* the nuclear radius. The addition of a spin-orbit interaction to the complex square-well potential makes the fit to the observed total cross sections worse. Failure of the models in the prediction of the total cross sections indicates that better agreement between the calculated and observed polarizations cannot be expected.

[9] R. G. Thomas (private communication).