The figure shows the corrected ratio of the elastic to inelastic intensities as a function of the monochromator setting. Some typical counting rates observed in the experiment are given in Table I, lines 5 and 6.

Analysis of the data gives 125.95 ± 0.01 keV for the energy of the resonance and $(1.1 \pm 0.3) \times 10^{-6}$ eV for the width. From the value for the width one obtains a mean life of $(0.6 \pm 0.2) \times 10^{-9}$ sec for the excited state. Chupp *et al.*[14] also measured the energy of this level. They found 125.87 ± 0.05 keV for the resonance energy. Using fast timing techniques Holland and Lynch[16] have measured the mean life of this level to be $(0.34 \pm 0.10) \times 10^{-9}$ sec. The $B(E2)$ transition probability of this level in manganese has been measured by Temmer and Heydenburg.[17] From their result the $E2$ mean life is calculated to be 4.2×10^{-8} sec. Comparing this with our result one obtains 0.014 for the ratio between the intensities of $E2$ and $M1$ radiation. This is in agreement with angular correlation measurements by Bernstein and Lewis[18] which indicate that the value of this ratio is less than 0.02.

V. CONCLUSION

We have shown experimentally that it is possible to excite low lying states of nuclei with diffracted x rays from a bent crystal monochromator. Our method has been successful in the case of F^{19} and Mn^{55}, and our results on the level width are in good agreement with experiments using other techniques.

The observations made here indicate two general directions in which further work is required. (i) Experimental work should be directed towards increasing the intensity and resolution of the incident diffracted beam. This might be attained through the use of larger diffraction crystals in higher order reflections and through the use of a more intense x-ray source. (ii) A second problem which needs to be solved is that resulting from the background coming from electronic scattering in the sample. For nuclei with large atomic numbers, Rayleigh scattering from the atomic electrons places a severe restriction on the size of the nuclear scattering effect which can be observed. This problem might be solved taking advantage of the instantaneous character of atomic scattering as compared to the relatively long life time of the nuclear excited states. Through the use of a pulsed x-ray beam and a properly gated detector it should be possible to observe only the nuclear excitation events in the sample.

ACKNOWLEDGMENTS

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[17] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[18] E. M. Bernstein and H. W. Lewis, Phys. Rev. **100**, 1367 (1955).

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Polarization of 24-MeV Neutrons Elastically Scattered from C, Al, Fe, Sn, Pb, and Bi†

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Employing the 64% polarized neutron source from the $T(dn)He^4$ reaction at 30° for an incident deuteron energy of 7.7 MeV, the angular dependence of the polarization for elastic scattering of 24-MeV neutrons from C, Al, Fe, Sn, Pb, and Bi has been measured from 20° to 70° in 5° steps. The "left" and "right" measurements are obtained by precessing the neutron spin magnetic moment plus and minus 90° with a suitably designed solenoid. The measured polarizations are in reasonable agreement with the optical-model predictions of Bjorklund and Fernbach, provided that the sign of the spin-orbit potential agrees with that deduced from the shell model. The magnitude of the spin-orbit potential (25 times Thomas) is in agreement with that deduced from fitting the proton polarization data.

INTRODUCTION

THE nuclear optical model[1,2] has had considerable success in correlating many features of the nucleon-nucleus interaction, such as total cross sections, nonelastic cross sections, elastic angular distributions, and polarization data (mainly for protons). The experimental effort at Livermore has been directed, for some years, towards evaluating the parameters of the Bjorklund-Fernbach optical-model potential[3] by performing

† This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] For a complete bibliography see L. Rosen, J. E. Brolley, and L. Stewart, Phys. Rev. **121**, 1423 (1961).
[2] *Proceedings of the International Conference on the Nuclear Optical Model, Florida State University Studies, No. 32* (Rose Printing Company, Tallahassee, Florida, 1959).
[3] F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958).

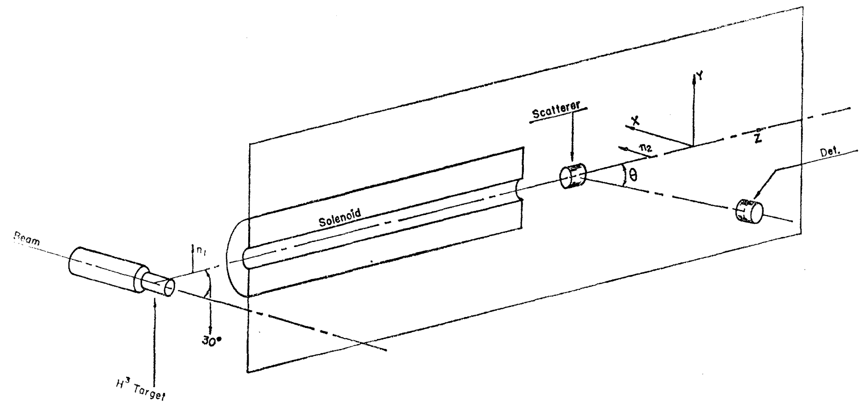

FIG. 1. Schematic diagram of the experimental geometry.

total neutron cross-section measurements,[4,5] neutron nonelastic cross-section measurements,[6–8] back-angle elastic scattering measurements with 14.6-MeV neutrons,[9] and elastic scattering measurements with 24-MeV neutrons.[10] Since no polarization data were available in the neutron energy region between 7 and 30 MeV, the spin-orbit potential for neutrons in this region was largely undetermined. The only available neutron experiments sensitive to the presence of the spin-orbit potential were the large-angle elastic scattering measurements[9,11,12] with 14-MeV neutrons. It was shown[3] that a spin-orbit potential was necessary for fitting these data; however, the magnitude of the spin-orbit potential could be varied over wide latitudes without significantly affecting the agreement between theory and experiment. In fact, it has recently been discovered that reversing the sign of the spin-orbit potential does not significantly affect the predictions of total cross sections, nonelastic cross sections, and large-angle differential cross sections. However, reversing the sign of the spin-orbit term reverses the sign of the polarization, and the polarization magnitudes are somewhat affected. (Reversing the sign of the spin-orbit potential for Pb at 14 MeV changes the magnitude of the polarization by 50% at 135°.[13,14])

[4] A. Bratenahl, J. M. Peterson, and J. P. Stoering, Phys. Rev. **110**, 927 (1958).
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[9] J. D. Anderson, C. C. Gardner, M. P. Nakada, and C. Wong, Phys. Rev. **110**, 160 (1958).
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[11] J. H. Coon, H. E. Felthauser, and D. B. Nicodemus, Phys. Rev. **111**, 250 (1958).
[12] S. Berko, W. D. Whitehead, and B. C. Groseclose, Nuclear Phys. **6**, 210 (1958).
[13] Previous optical-model calculations by Fernbach and Bjorklund used a spin-orbit potential whose sign was opposite to that required by the shell model. Apparent agreement (see reference 14) was obtained with the sign of the proton polarization measurements since the polarization convention was also reversed.
[14] F. Bjorklund and S. Fernbach, University of California Radiation Laboratory Report UCRL-5028, 1958 (unpublished).

In contrast, the spin-orbit potential for protons is well determined since there are many proton polarization measurements[15] in the 7- to 30-MeV range. The general conclusion[1] is that the proton spin-orbit potential is in harmony, both in magnitude and sign with the nuclear shell model. This experiment was performed to determine the sign and the magnitude of the spin-orbit potential for 24-MeV neutrons.

EXPERIMENTAL METHOD

Instead of performing the usual "left" and "right" measurements, a suitably designed solenoid[16] was employed to precess[17] the neutron spin magnetic moment plus and minus 90° to obtain the polarization asymmetry. The source of polarized neutrons was the $d+t$ reaction at 30° for an incident deuteron energy of 7.7 MeV.[18] The 90° precession arises from the fact that the production and scattering planes are perpendicular to each other (see Fig. 1). The obvious advantage of the precession method is that instrumental polarization asymmetries are eliminated, since the only difference between a "left" and "right" measurement is that the neutron spin direction is reversed. In the conventional method false asymmetries can arise from: (1) Nonuniform illumination of the scatterer due to the angular distribution of the source neutrons, (2) geometrical positioning and alignment inaccuracies, and (3) differing efficiencies for the "left" and "right" detectors. On the other hand, the precession method can introduce false asymmetries if the magnetic field affects the detector. The detector was well shielded magnetically, and elaborate checks (see section on systematic errors) were made to ensure that the magnetic field did not produce artificial asymmetries.

[15] K. W. Brockman, Jr., Phys. Rev. **110**, 163 (1958); W. A. Blanpied, *ibid.*, **113**, 1099 (1959); reference 1; E. Boschitz, Nuclear Phys. **30**, 468 (1962); L. Rosen, J. E. Brolley, Jr., M. L. Gursky, and L. Stewart, Phys. Rev. **124**, 199 (1961).
[16] The solenoid dimensions are: 40 in. long; 3-in. i.d.; 10.5-in. o.d. There are 546 turns (7 layers) of 0.467-in. square by 0.363-in.-i.d. hollow-core copper conductor.
[17] P. S. Dubbeldam *et al.*, Nuclear Instr. and Methods **4**, 234 (1959).
[18] R. B. Perkins and J. E. Simmons, Phys. Rev. **124**, 1153 (1961).

GEOMETRY

Figure 1 shows the experimental geometry; 7.7-MeV deuterons impinge on a tritium gas target producing $+65\%$[19] polarized[18] 24-MeV neutrons at 30°. The polarized neutrons travel down the solenoid and strike cylindrical scatterers 3 in. in diameter and with thicknesses varying from $\frac{1}{3}$ to $\frac{3}{4}$ of a total mean free path. The scattered neutrons are detected in a 2-in. diameter $2\frac{3}{4}$-in. thick plastic scintillator. The distance between scatterer and detector was typically 17 in. The detailed method for detecting 24-MeV elastically scattered neutrons and for monitoring the neutron production has been described in a previous paper.[10]

The polarization measurement at a particular angle θ (variable from 20° to 70° in 5° steps) involved four measurements—scatterer in and out measurements for positive and negative 90° precession. The opposite precession is obtained by reversing the direcston of the solenoid current. Since

$$P_1P_2=(N\uparrow\uparrow-N\uparrow\downarrow)/(N\uparrow\uparrow+N\uparrow\downarrow),$$

where $P_1=+0.65$, $N\uparrow\uparrow$ denotes net scattered counts for the polarization vectors $\mathbf{n}_1$ and $\mathbf{n}_2$ parallel (counterclockwise precession in Fig. 1), and $N\uparrow\downarrow$ net counts for $\mathbf{n}_1$ and $\mathbf{n}_2$ antiparallel (clockwise precession in Fig. 1), a knowledge of the direction of precession is essential for arriving at the correct sign for P_2, the polarization from elastic scattering. The direction of precession has been ascertained by determining the field direction and noting that the direction of precession is given by $\mathbf{M}\times\mathbf{B}$ or $\mathbf{B}\times\mathbf{S}$ where $\mathbf{M}$ is the neutron magnetic moment, $\mathbf{S}$ the neutron spin, and $\mathbf{B}$ the magnetic field.

SOLENOID CALIBRATION

The solenoid was calibrated by measuring the current required to precess the neutron spin magnetic moment

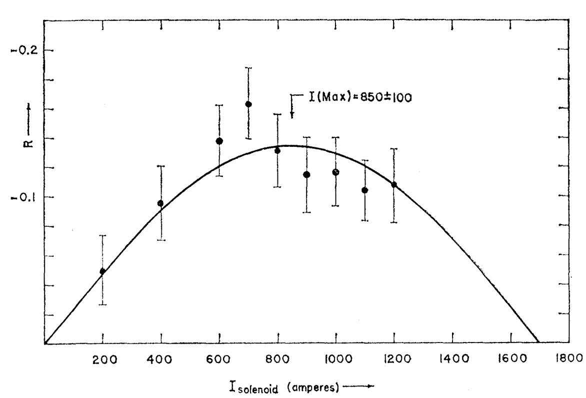

FIG. 2. Solenoid calibration curve for 24-MeV neutrons.

[19] The Basel convention is employed. The source polarization is defined as positive if more neutrons have their spins parallel to the direction $\mathbf{n}_1=(\mathbf{k}_d\times\mathbf{k}_n)/(|\mathbf{k}_d\times\mathbf{k}_n|)$ (see Fig 1). Similarly, the positive direction of polarization in scattering is given by $\mathbf{n}_2=(\mathbf{k}_i\times\mathbf{k}_s)/(|\mathbf{k}_i\times\mathbf{k}_s|)$ where i and s represent, respectively, the incident and scattered neutron.

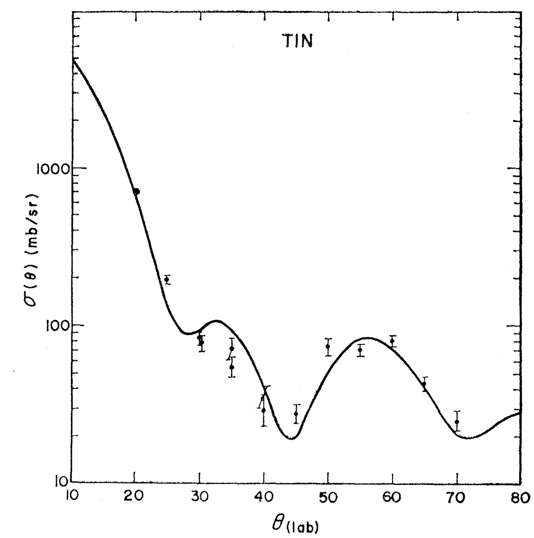

FIG. 3. Tin elastic scattering angular distribution obtained by averaging the "left" and "right" measurements. Errors are computed from the counting statistics. Solid line represents a smooth curve through the measurements of reference 10. Both sets of measurements employed a detector bias of 20.5 MeV.

90°. The scatterer was Al and the detector was placed at 30°. The asymmetry parameter R is a sinusoidal function of the solenoid current I:

$$R=P_1P_2\sin\left(\frac{\pi}{2}\frac{I}{I(\max)}\right)=\frac{N_{I+}-N_{I-}}{N_{I+}+N_{I-}};$$

the maximum asymmetry is P_1P_2 and results when $I=I(\max)$, where $I(\max)$ is the current necessary for a precession of 90°. Figure 2 shows the measured values of R as a function of solenoid current. N_{I+} denotes net scattered counts for one direction of solenoid current and N_{I-} denotes the same for reversed current. The solid curve of Fig. 2 represents a sinusoidal fit to the data yielding a value of 850 ± 100 A for $I(\max)$. The value of $I(\max)$ calculated assuming an infinitely long solenoid is 848 A. The agreement between measured and calculated values of $I(\max)$ is not surprising since the actual solenoid approximates quite well an infinitely long solenoid. For the polarization measurements, the solenoid current was 850 A.

CHECK ON SYSTEMATIC ERRORS

To check the effect of the magnetic fringe field from the solenoid on photomultiplier gain, the counting rates with a Na^{22} source were measured for a solenoid current of zero and ±850 A. In addition, the detector was placed at zero degrees in order to view the source neutrons. For a fixed neutron production, the detector counts were measured for the above three values of solenoid current. Both experiments show no detectable effect of magnetic field on detector efficiency.

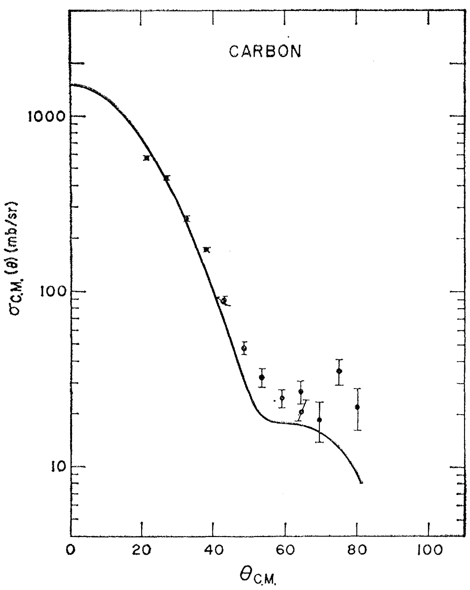

FIG. 4. Carbon elastic scattering angular distribution (center-of-mass) obtained by averaging the "left" and "right" measurements. Solid curve represents the prediction employing the Bjorklund-Fernbach optical model. Detector bias was 19.8 MeV.

As an over-all check, the unpolarized elastic scattering angular distributions were redetermined by averaging the "left" and "right" measurements. The tin differential cross section, corrected for effects of multiple scattering, is shown in Fig. 3. The solid curve represents the previously measured angular distribution.[10] The good agreement attests to the correctness of our multiple scattering calculations, and, more importantly, shows no evidence for systematic errors in our polarization measurements.

To check the effect of inelastic neutrons on the measured polarizations, the polarization measurements were carried out for four detector biases, the lowest being 16 MeV. For all elements at all angles, the polarization does not change significantly with bias.

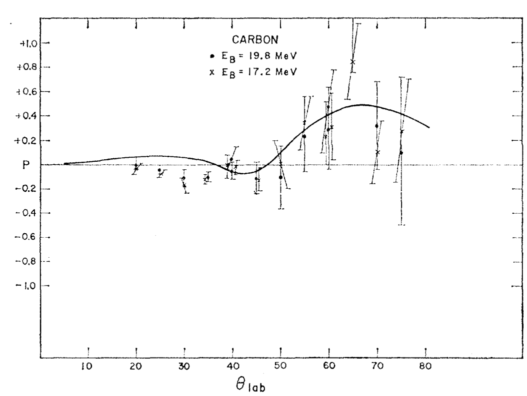

FIG. 5. Polarization of 24-MeV neutrons elastically scattered from carbon. Dots and crosses refer to measurements taken with detector biases of 19.8 and 17.2 MeV, respectively. Solid curve is the prediction employing the Bjorklund-Fernbach optical model.

Therefore, the detection of inelastic neutrons[10] does not significantly alter the polarization measurements.

MULTIPLE SCATTERING CORRECTIONS

The multiple scattering corrections were calculated with a Monte Carlo code on the IBM 7090. The unpolarized differential cross sections were used to compute single (p_1), double (p_2), and triple (p_3) scattering events. Quadrupole and higher scattering events were negligible ($<1\%$ contribution). The denominator in the expression for P_1P_2 was corrected for multiple scattering by multiplication with $p_1/\sum_1^3 P_i$. The numerator (being a difference) was not corrected, since to a close approximation the second and higher order scattering events cancel. Since the second and higher order scattering events tend to have the same polarization as the single scattering event, this procedure of not correcting the numerator thus overestimates the polarization magnitudes.[20] To calculate the degree of polarization of the second and higher order events would require a knowledge of the presently unknown triple-scattering parameters.

A more refined calculation involves using separately the "left" and "right" scattering cross sections for the first collision, and the unpolarized cross sections for subsequent collisions. This was tried for carbon with the result that the "left" and "right" calculations, combined properly for the 65% source polarization, did not differ by more than 5% from the unpolarized calculation.

As an additional check, measurements were made using aluminum scatterers $\frac{1}{4}$ and $\frac{1}{2}$ a total mean free path in thickness. Using the unpolarized cross sections, the corrected polarizations (Fig. 6) for the two thicknesses agree within statistics.

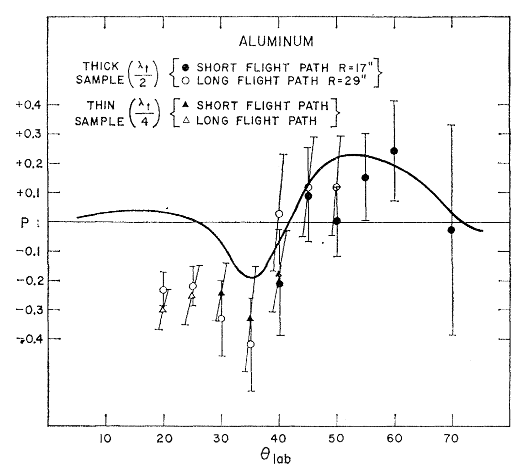

FIG. 6. Polarization of 24-MeV neutrons elastically scattered from aluminum. Detector bias was 19.8 MeV. Solid curve is the theoretical prediction.

[20] For a full discussion see A. J. Elwyn and R. O. Lane, Nuclear Phys. 31, 78 (1962).

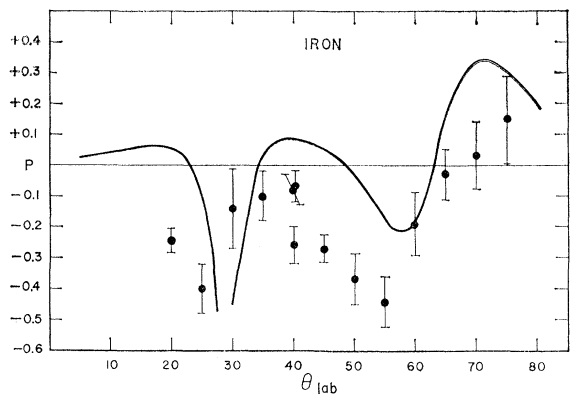

FIG. 7. Polarization of 24-MeV neutrons elastically scattered from iron. Detector bias was 20.5 MeV. Solid curve is the theoretical prediction.

RESULTS

Since the carbon elastic differential cross sections have not been previously measured, Fig. 4 shows the carbon angular distribution obtained by averaging the "left" and "right" measurements and correcting for the effects of multiple scattering. The angular dependence of the polarization (P_2) for the various elements is shown in Figs. 5 through 10. The values of P_2 have been corrected for the effects of multiple scattering in the scattering samples.

The errors on P_2 are computed from the statistical counting errors on P_1P_2 since it was felt that the counting errors are larger than either the error in P_1 or the error in the multiple scattering correction factor. The latter two errors are probably less than 10%, while the counting errors in general are greater or equal to 20%. Perkins and Simmons[18] did not assign an error to $P_1=+0.65$ because of the difficulty in estimating the error in computing the $n+\mathrm{He}^4$ polarization from extrapolated $p+\mathrm{He}^4$ phase shifts. In any case, the error on P_1 cannot be smaller than 8% since this represents the statistical counting error. Recently, Benenson and coworkers[21,22] have confirmed the asymmetry measurements of Perkins and Simmons, but the $n+\mathrm{He}^4$ polarization at 24 MeV is still in doubt.[23]

The solid curves (Figs. 4 through 10) represent the predictions using the Bjorklund-Fernbach optical potential[3]

$$V(r,\boldsymbol{\sigma},\mathbf{l})=V_{CR}\rho(r)+iV_{CI}\exp[(r-R)/b]^2 +(V_{SR}+iV_{SI})(\hbar/\mu c)^2(1/r)(d/dr)\rho(r)\boldsymbol{\sigma}\cdot\mathbf{l},$$

where

$$\rho(r)=[1+\exp(r-R)/a]^{-1},$$

and μ is the π-meson mass. The values of the parameters

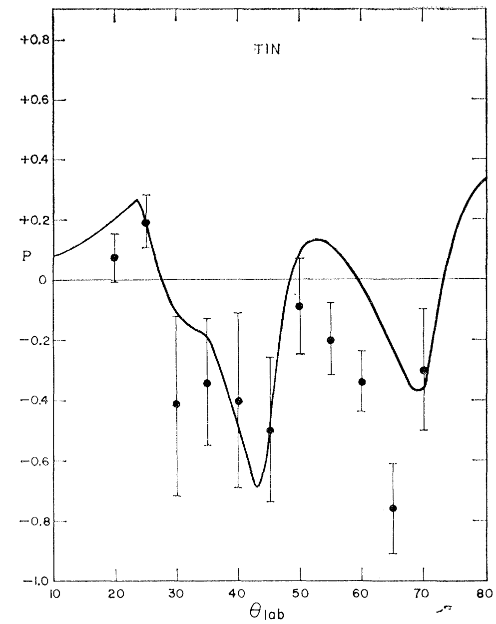

FIG. 8. Polarization of 24-MeV neutrons elastically scattered from tin. Detector bias was 20.5 MeV. Solid curve is the theoretical prediction.

were

$$\begin{aligned} V_{CR}&=-40\text{ MeV}, & R&=1.25\,A^{1/3}\text{ F},\\ V_{CI}&=-11\text{ MeV}, & a&=0.70\text{ F},\\ V_{SR}&=+5.5\text{ MeV}, & b&=1.00\text{ F}.\\ V_{SI}&=0\text{ MeV}, \end{aligned}$$

With the exception of carbon, the above values generate predictions in excellent agreement with measured elastic scattering distributions,[10] total cross sections,[5] and nonelastic cross sections.[8]

CONCLUSIONS

The polarization predictions for Bi and Pb are in excellent agreement with the measurements. In the case of C, Al, Fe, and Sn, the agreement is fair; although at

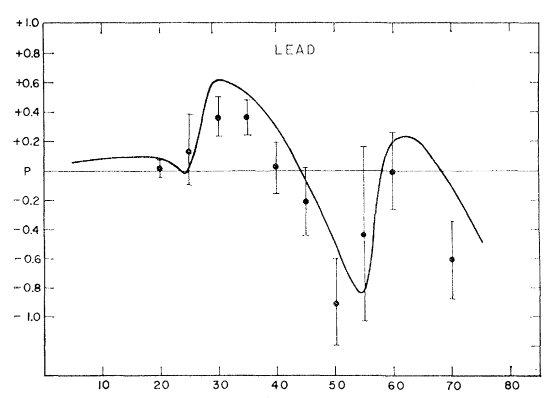

FIG. 9. Polarization of 24-MeV neutrons elastically scattered from lead. Detector bias was 19.8 MeV. Solid curve is the theoretical prediction.

[21] W. Benenson, R. L. Walter, and T. H. May, Phys. Rev. Letters 8, 66 (1962).

[22] R. L. Walter, W. Benenson, T. H. May, and A. S. Mahajan, Bull. Am. Phys. Soc. 7, 268 (1962).

[23] T. H. May, W. Benenson, R. L. Walter, and P. Vander Maat Bull. Am. Phys. Soc. 7, 268 (1962).

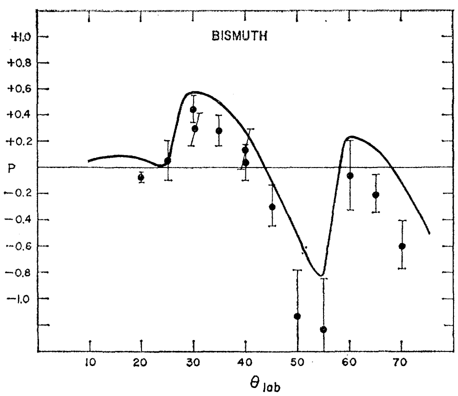

FIG. 10. Polarization of 24-MeV neutrons elastically scattered from bismuth. Detector bias was 20.5 MeV. Solid curve is the theoretical prediction.

certain angles the sign of the computed polarization is incorrect, the qualitative shapes are predicted correctly. The disagreement in the case of C (Figs. 4, 5) and Al (Fig. 6) is not surprising since Al is deformed and carbon is perhaps too light to be described by an optical model. If an optical-model description of carbon is possible,[24] there is no guarantee that the values of the parameter would agree with those for heavier nuclei. Over-all agreement between theory and experiment for Fe, Sn, Bi, and Pb is considered good; detailed agreement over a wide range of elements is not expected since any optical model can only describe the gross average structure of the nucleus.

The sign of the spin-orbit potential has been unambiguously determined, and agrees with that deduced from the nuclear shell model. A V_{SR} value of $+5.5$ MeV implies $\lambda=25$, or 25 times the Thomas term for the strength of the spin-orbit coupling. Ross, Mark, and Lawson[25] found a value of $\lambda=39$ from a calculation of nucleon energy levels in a diffuse potential. For protons the value of λ obtained from fitting polarization data varies with incident energy as shown in the following table taken from the review article by Glassgold[26]:

E_p (MeV)	λ
-8	36
17	25
60	$\sim$13
140	$\sim$7
300	3.2

Hence, the strength of the spin-orbit coupling for neutrons at 24 MeV agrees roughly with that deduced for protons at the same energy.

ACKNOWLEDGMENTS

We are indebted to Dr. Hans Mark for bringing to our attention the precession method for polarization measurements. Thanks are also due Dr. Erwin Schwarcz for making calculations with the Bjorklund-Fernbach optical potential, and for confirming the fact that the incorrect sign of the spin-orbit potential was used in previous calculations. Lastly but not least, we are grateful to Don Davis and Don Reeves for programming and performing the Monte Carlo calculation on the IBM 7090.

[24] J. S. Nodvik, C. B. Duke, and M. A. Melkanoff, Phys. Rev. **125**, 975 (1962).

[25] A. A. Ross, Hans Mark, and R. D. Lawson, Phys. Rev. **102**, 1613 (1956).

[26] A. E. Glassgold, *Progress in Nuclear Physics* (Pergamon Press, New York, 1959), Vol. 7, p. 123.