Scattering and Polarization of Neutrons from Al, Si, Fe, and Co at 2 MeV*

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Angular distributions of elastic scattering and polarization from $\theta=30$ to 120°, have been obtained for Al, Si, Fe, and Co at $E_n=1.95\pm0.09$ MeV, using polarized neutrons from the $T(p,n)He^3$ reaction. Scattering and polarization from the 0.845—MeV level of Fe^{56} were also measured; an isotropic angular distribution and zero polarization were found for this level. The angular distributions of the elastic polarization for Si, Fe, and Co were negative at forward and backward angles with two zero cross-over points; the first zero of the polarization occurs approximately at the minimum of the elastic scattering for these three elements. In distinct contrast, the angular distribution of the polarization for Al is positive and constant at forward angles, becoming negative at backward angles. Absolute cross sections were obtained by scattering from polyethylene and an optical-model analysis of the experimental results was made.

I. INTRODUCTION

MEASUREMENTS of the polarization of nucleons from nuclear reactions and scattering can give information on the validity of nuclear models, in particular the magnitude and sign of the spin-orbit part of the optical-model potential. Because of the success of the shell model with strong spin-orbit coupling in describing nuclear single-particle levels, it is expected that some spin-orbit coupling may occur in the elastic scattering of nucleons from nuclei. This coupling has been confirmed by many measurements over a wide range of energies and masses, and the optical model has had considerable success in fitting the experimental results[1]; in particular, the theoretical fit to the differential cross section at backward angles is improved by the inclusion of a spin-orbit term in the optical-model potential.

In the present experiment, angular distributions of the elastic scattering and polarization of 1.95-MeV neutrons on Al, Si, Fe, and Co were measured, as well as the inelastic scattering from the 0.845 level of Fe^{56}. An attempt was made to fit the experimental elastic data with curves obtained from an optical-model calculation. Previous experiments have shown that the optical model is less successful in fitting experimental data in this energy region, than at higher energies.[2–5] This is not surprising since, at a few MeV, many elements in the intermediate mass region have resonances in the total cross section, with widths comparable to the experimental energy resolution.

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[1] L. Rosen, *Proceedings of the International Conference on the Nuclear Optical Model, Florida State University, 1959* (Florida State University, Tallahassee, Florida, 1959).

[2] F. Bjorklund, *Proceedings of the International Conference on the Nuclear Optical Model, Florida State University, 1959* (Florida State University, Tallahassee, Florida, 1959).

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[4] F. G. Perey and B. Buck, Nucl. Phys. **32**, 353 (1961).

[5] H. H. Barshall, in *Progress in Fast Neutrons Physics*, edited by G. C. Phillips, J. B. Marion, and J. R. Risser (The University of Chicago Press, Chicago, 1964).

II. EXPERIMENTAL PROCEDURE

Monoenergetic polarized neutrons from the $T(p,n)He^3$ reaction were used to bombard the scattering samples. The proton energy was measured by the time-of-flight technique using the natural phase bunching of the Brookhaven National Laboratory 18-in. cyclotron, and found to be $E_p=3.11\pm0.04$ MeV. The target was made by absorbing tritium on a gold-backed titanium film. The proton energy spread was ±60 keV and was due to a combination of beam spread and target thickness. About 10^6 neutrons/sec were produced. The polarization of these neutrons has been measured[6] and found to have a maximum value of about $25\pm5\%$ at an angle of 35° to the proton beam for $E_p=2.9$ MeV.

The experimental setup for the scattering and polarization measurements is shown in Fig. 1. The scattering samples were cylindrical ($\frac{3}{4}$ in. in diameter $\times1\frac{1}{2}$ in. high), and were set at an angle of $\theta_n=35°$ to the proton beam at a distance of $4\frac{1}{2}$ in. from the target; the energy of neutrons incident on the scatterer was 1.95 ± 0.09 MeV.

The scattered neutrons were observed at angles θ to the left (L) and right (R) of the incident neutron direction; the polarization $P_2(\theta)$ determined from this scattering is given by[7]

$$P_1(\theta_n)P_2(\theta)=(L-R)/(L+R),$$

where $P_1(\theta_n)$ is the polarization of the incident neutrons and $P_2(\theta)$ is the polarization which would be produced

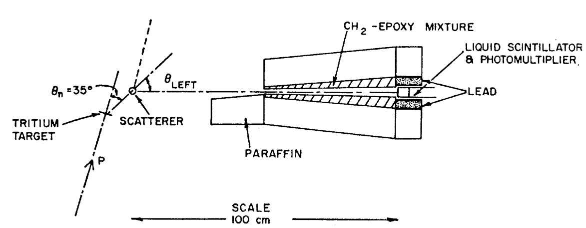

FIG. 1. Experimental arrangement.

[6] R. L. Walter, W. Benenson, P. S. Dubbeldam, and T. H. May, Nucl. Phys. **30**, 292 (1962).

[7] L. Wolfenstein, Ann. Rev. Nucl. Sci. **6**, 43 (1956).

in the scattering if the incident neutrons were unpolarized. The direction of positive polarization is defined as

$$\mathbf{P} = P\mathbf{n},$$

where $\mathbf{n}$ is a unit vector in the direction of $\mathbf{k}_{\text{incident}} \times \mathbf{k}_{\text{scattered}}$. The scattered neutrons were collimated by a cone made of a mixture of polyethylene and epoxy resin, and were detected by a 2-×2-in. Ne213 liquid organic scintillator to obtain pulse-shape discrimination. The detector was shielded from target and background neutrons with paraffin, and from gamma rays by several inches of lead. Additional background discrimination was achieved with a pulse-shape discriminator circuit of the Owen type[8] and by time-of-flight. The time-to-pulse-height converter used was a servo-stabilized version of the rf vernier type described by R. L. Chase.[9] The signal-to-background ratio for the system was about 3 to 1. The time-of-flight distance was 1 m and complete energy resolution could be achieved only for energy levels about 500 keV or more from the ground state.

Possible sources of spurious asymmetry in the system were examined and eliminated. These were:

(1) Errors in determining the zero position of the proton beam. Measurements were taken of the neutron yield from the $T(p,n)He^3$ reaction at 1° intervals around the mechanically determined zero. In this way, the zero beam position was determined to an estimated accuracy of ±1°.

(2) Changes in the alignment of the collimator as it is rotated around the scatterer. Measurements were made of left and right scattering around 0°, and the values of L/R obtained, were randomly distributed about $L/R=1$, indicating that there were no mechanical asymmetries.

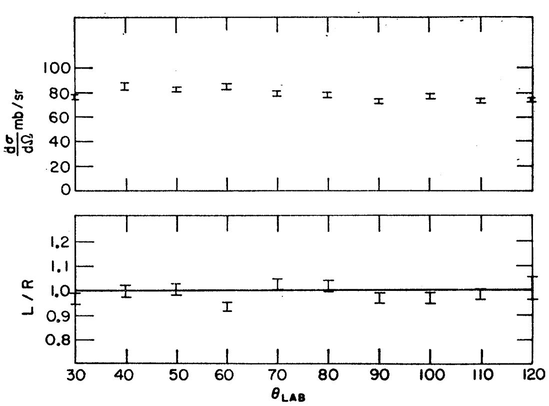

FIG. 2. Angular distribution for 1.95-MeV neutrons, inelastically scattered from the 0.845-MeV level of Fe^{56}. The differential cross section and the asymmetry L/R are both isotropic within the experimental errors.

[8] R. B. Owen, IRE Trans. Nucl. Sci., **NS-5**, 198 (1958).

[9] R. L. Chase and W. A. Higinbotham, Rev. Sci. Instr. **28**, 448 (1957).

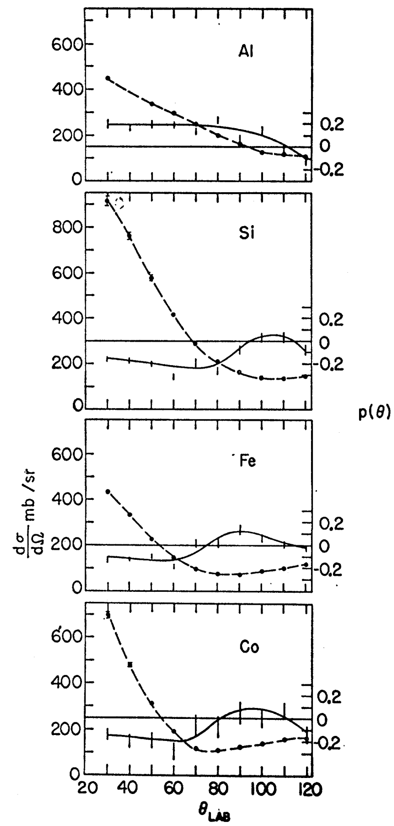

FIG. 3. Angular distributions for the elastic scattering and polarization of 1.95-MeV neutrons scattered from Al, Si, Fe, and Co. The dotted lines are smooth curves drawn through the experimental values of $d\sigma/d\Omega$, and the solid lines are smooth curves drawn through the experimental values of $P(\theta)$.

(3) Different illumination by the neutron beam of one side of the scatterer from the other. To check this, the size of the scatterer was varied and no such effect was found.

(4) The possibility that the proton beam position might change was checked by repeating measurements at random intervals; no such change was indicated by the measurements.

The criterion for absence of asymmetry in these checks was that L/R should be randomly distributed about $L/R=1$ over the angular range used, and that L/R should be equal to unity within the statistical error.

During the experiment, measurements at randomly selected angles were done on the samples, separately and together, to test the possibility that spurious asymmetries might have entered the system. The angular distributions of both elastic scattering and polarization are, however, the result of a single set of left-right measurements and the errors shown are mainly statistical.

The efficiency of the detector was obtained by comparing the measured yield from the $T(p,n)He^3$ with the known angular distribution for this reaction.

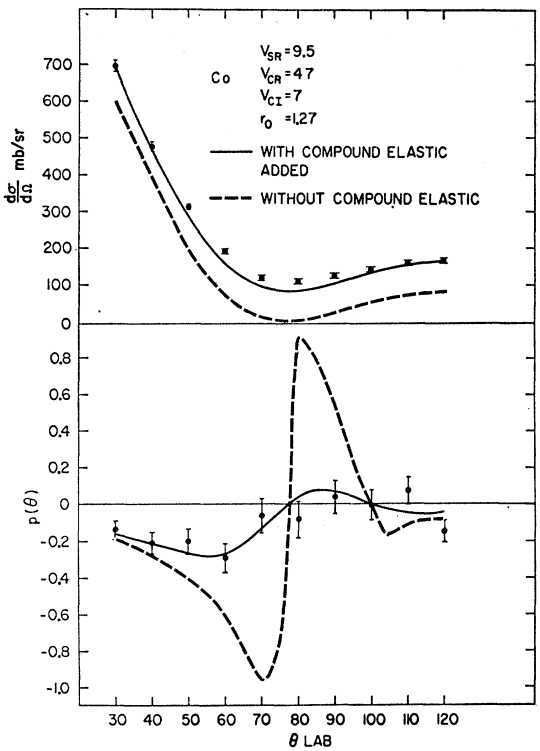

FIG. 4. Comparison of experimental angular distributions of elastic scattering and polarization for Co^{59} with the best-fit curves obtained from an optical model calculation, with and without compound elastic scattering.

Absolute cross sections in millibarns/steradian were obtained by scattering from polyethylene.

III. EXPERIMENTAL RESULTS

Figure 2 shows the angular distribution obtained for inelastic scattering from the 0.845-MeV level of Fe^{56}. The scattering angular distribution is isotropic, which confirms previous measurements[10] at about this neutron energy, and is consistent with the predictions for a compound nucleus type of reaction. The L/R asymmetry is seen to be essentially isotropic and equal to one within statistics, indicating the zero polarization that is expected from a compound nucleus reaction. These results agree with the measurements of L. Cranberg.[11]

The angular distributions for elastic scattering are shown in Fig. 3. The experimental points for the differential cross section and polarization are on the same plot to show two comparisons: (1) for Si, Fe, and Co, the sign of the polarization is the same as the slope of the scattering. (2) the zero cross-over point of the polarization, approximately follows the minimum of the scattering. These two features are in agreement with a calculation done by Rodberg,[12] who showed that, if the shape of the elastic-scattering angular distribution is assumed to be unaffected by the spin-orbit potential, then the polarization is proportional to the derivative of the elastic scattering.

The errors shown on the polarization experimental points are statistical. For the scattering, the errors involved in obtaining absolute cross sections are also included.

IV. OPTICAL-MODEL CALCULATIONS

The optical-model potential which was used in our attempts to fit the experimental results, is a local optical potential with surface absorption and spin-orbit coupling (see Ref. 1). The calculations were carried out on the Brookhaven 7094 computer, with the ABACUS–2 code written by E. Auerbach.[13] This code calculates angular distributions for elastic scattering and polarizations. It can also calculate angular distributions for inelastic scattering, based on the Hauser and Feshbach statistical model[14]; this feature enabled compound elastic scattering to be calculated and included in the elastic scattering and polarization calculations. It follows, from the statistical model, that the compound elastic scattering has zero polarization. Most of the optical-model parameters were varied simultaneously over a fairly wide range of values, to see if more than one region of fit could be found for any or all

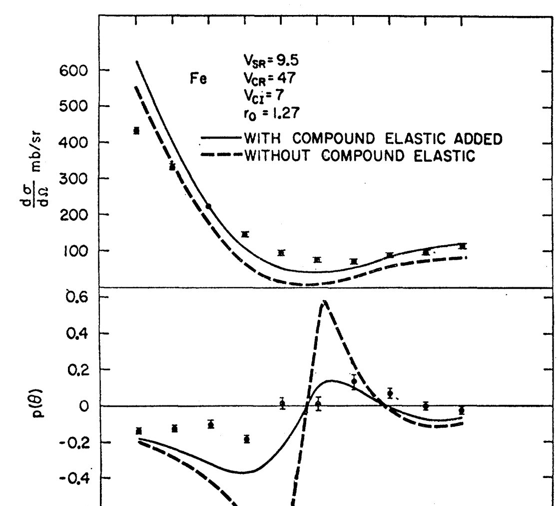

FIG. 5. Comparison of experimental angular distributions of elastic scattering and polarization for Fe^{56} with the best-fit curves obtained from an optical model calculation, with and without compound elastic scattering.

[10] M. D. Goldberg, V. M. May, and J. R. Stehn, Angular Distributions in Neutron-Induced Reactions, BNL 400, 2nd ed., Vol. II, 1962 (unpublished).

[11] L. Cranberg, in *Proceedings of the International Symposium on Polarization Phenomena of Nucleons, Basel, 1960*, edited by P. Huber and K. P. Meyer [Helv. Phys. Acta Suppl. 6 (1961)].

[12] L. S. Rodberg, Nucl. Phys. **15**, 72 (1960).

[13] E. Auerbach, BNL Report 6562 (unpublished).

[14] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952)

of the four elements studied. The range of values tried were limited chiefly by a consideration of the values found by most experimenters to give the best agreement at low energies (see, e.g., Ref. 1). It was found that, for the four elements, the value $a=0.65$ F for the real well diffuseness, gave the best fits. The values $b=0.98$ F for the imaginary well diffuseness, and $V_{SI}=0$ MeV for the imaginary spin-orbit well depth, were held constant throughout the search, since these values are widely accepted (Ref. 1).

V. DISCUSSION

Co^{59}

The best fit of the four elements studied, was obtained with Co^{59}, shown in Fig. 4. This figure shows quite strikingly that the inclusion of compound elastic scattering[15] is necessary, to obtain any kind of reasonable fit to the data. The polarization plot shows that not only the magnitude but the shape, of the calculated polarization, is changed by the addition of compound elastic scattering. It is interesting to note that here, as for all four elements studied, the same set of parameters gave the best fit to both the elastic scattering and the polarization data.

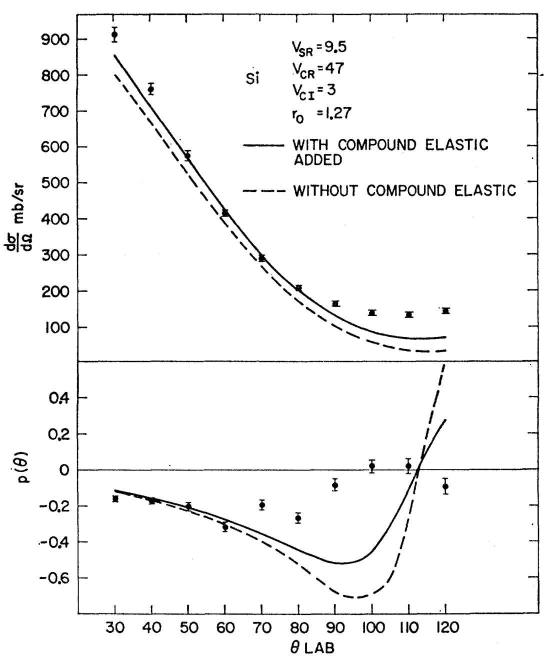

FIG. 6. Comparison of experimental angular distributions of elastic scattering and polarization for Si^{28} with the best-fit curves obtained from an optical-model calculation, with and without compound elastic scattering.

[15] Four of the levels in Co^{59} to which the compound nucleus part of the interaction can contribute, have unknown spins and parities. The compound elastic scattering was calculated using all combinations of $J^\pi=\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$, and $\frac{7}{2}^-$ for these four levels and the variation in the total elastic cross section was found to be $\pm 4\%$.

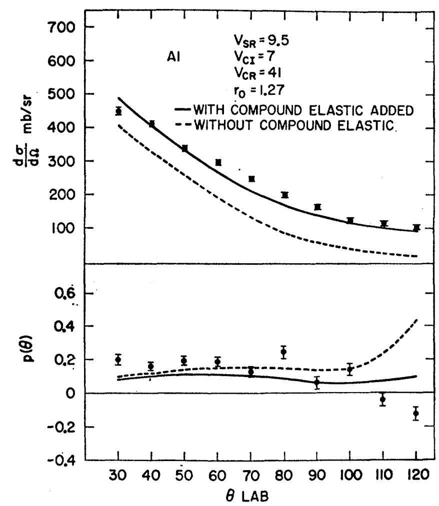

FIG. 7. Comparison of experimental angular distributions of elastic scattering and polarization for Al^{27} with the best-fit curves obtained from an optical-model calculation, with and without compound elastic scattering.

Fe^{56}

Figure 5 shows that the theoretical fit for this element is poor. However, the best fit for both scattering and polarization was obtained with the same set of parameters as for Co^{59}. Again, the inclusion of compound elastic scattering improves the agreement.

Si^{28}

No good agreement over the whole angular range could be obtained for this element with any set of parameters. However, the value $V_{CI}=3$ MeV for the imagninary part of the central potential, gave the only curve that was in any sort of agreement with the experimental points; $V_{CI}=7$ was definitely too high. (Fig. 6).

Al^{27}

The positive polarization obtained for this element could be fitted only by reducing the real part of the central potential from the value $V_{CR}=47$, used for the other three elements, to $V_{CR}=41$ (Fig. 7). However, it was found that this value of V_{CR} also gave the best fit to the elastic-scattering data. It should be noted that, with this value of V_{CR}, the fitting procedure was rather insensitive to the values of V_{SR} (the real part of the spin-orbit potential) and V_{CI}, over the ranges $V_{SR}=5$ to 9.5 MeV, and $V_{CI}=3$ to 7 MeV.

VI. CONCLUSION

Some general conclusions may be drawn from the present experiment:

(1) In the region of 2 MeV, there are rapid variations in elastic scattering and polarization between elements of neighboring mass numbers. Smoothly varying sets of optical-model parameters are, therefore, inadequate

to describe the experimental results. This in not unexpected since, in three of the elements studied (Al, Si, and Fe), there is a resonance in the total cross section of a width comparable to the energy resolution of the present experiment.

(2) For each element, the best fit to both the scattering and the polarization was obtained with the same set of parameters. This is shown most strikingly in case of Al^{27}, where the opposite sign of the polarization, and the best fit to the elastic scattering, were both obtained with the same large change in V_{CR}. The analysis shows that there is a strong correlation between the fluctuations away from the optical model in the elastic scattering and in the associated polarization.

(3) The addition of compound elastic scattering improved the agreement between calculation and experiment for both scattering and polarization in all the cases studied, and for some of the curves, was essential to give any semblance of an optical-model fit.

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Inelastic $\pi^- - p$ Interactions in the Energy Region of 310 to 454 MeV*

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Differential cross sections for positive pions, protons, and neutrons resulting from inelastic $\pi^- - p$ collisions have been measured from 310- to 454-MeV incident-pion kinetic energy. The data were obtained with electronic counter systems, which measured the energy distribution of the final-state particle of interest at a series of fixed angles. The results have been interpreted in terms of the final states $\pi^+\pi^-n$, $\pi^0\pi^0n$, and $\pi^-\pi^0p$. The total cross sections for these three modes as a function of incident pion energy are in qualitative agreement with the predictions by Schnitzer. A preference is shown for his set of $\pi-\pi$ scattering lengths; $a_0=0.65$, $a_1=0.07$, and $a_2=-0.14\mu^{-1}$. The observed neutron distributions correspond to a strong preference for low c.m.-system neutron energies in both the $\pi^+\pi^-n$ and $\pi^0\pi^0n$ final states. The effect is not present in the observed proton distributions from the $\pi^-\pi^0p$ reaction, which suggests that it is due to a $I=0$, $\pi-\pi$ interaction. The π^+ data show the formation of the (3,3) isobar combination of the $\pi^- - n$ system in the $\pi^+\pi^-n$ final state. Analysis in terms of an isobar model indicates the predominance of $I=1/2$ incident state.

I. INTRODUCTION

We have performed a series of measurements to investigate the inelastic channels available to the $\pi^- - p$ system in the region between 310- and 454-MeV incident π^- kinetic energy. In the analysis of these measurements we have assumed that the single-pion-production channels listed below are the dominant inelastic reactions:

$$\pi^- + p \to \pi^+ + \pi^- + n \quad (\pi^+\pi^-n)$$
$$\pi^- + p \to \pi^- + \pi^0 + p \quad (\pi^-\pi^0p)$$
$$\pi^- + p \to \pi^0 + \pi^0 + n \quad (\pi^0\pi^0n).$$

Double-pion production has been neglected.

Three separate experiments were performed with an internal target of the Berkeley 184-in. synchrocyclotron as the source of pions. A magnetic beam-transport system momentum-analyzed and focused the π^- beam at a liquid-hydrogen target. In each experiment one of the three final-state particles was detected by an electronic-counter system. In the first experiment the final-state particle detected was a π^+, which is produced only in $\pi^+\pi^-n$. The following two experiments were concerned with the proton from $\pi^-\pi^0p$ and the neutrons from $\pi^+\pi^-n$ and $\pi^0\pi^0n$.

The emphasis of this paper is upon the results of the measurements. Consequently a description of the experimental methods and data analysis is deferred to the end of the paper (Sec. III). The reader is referred to Ref. 1 for detailed discussion of any aspects of the work reported here. In Sec. II the results of the three meas-

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[1] Barry C. Barish, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-10470, August 1962 (unpublished); Richard J. Kurz, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-10564, December 1962 (unpublished); Julius Solomon, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-10585, January 1963 (unpublished).