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Optical-Model Analyses of Scattering of 4.1-, 7-, and 14-Mev Neutrons by Complex Nuclei*

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Exact phase-shift calculations were carried out on the UNIVAC for the scattering of fast neutrons by complex nuclei. Both central and spin-orbit potentials are included. At each energy considered, a single set of parameters was found to give fairly good agreement with experimental data.

I. INTRODUCTION

In a previous report,[1] exact phase-shift calculations were carried out for the scattering of 14.6-Mev neutrons incident on Mg, Ca, Cd, and Bi. The potentials used at that time were the diffuse-boundary real central well (V_{CR}) and a Gaussian centered on the nuclear edge for the imaginary "central" well (V_{CI}). No spin-orbit terms were included. Since that time, many new experimental measurements have been made, especially for large-angle scattering, and the calculation has been extended to include spin-orbit potentials as well as the central potentials.

There are no experimental polarization data available at the energies considered in this report, so the single set of parameters was sought which fit the elastic, nonelastic, and total cross sections at each energy.

The potential used in this calculation is of the form

$$V=V_{CR}\rho(r)+iV_{CI}q(r)+V_{SR}\left(\frac{\hbar}{\mu c}\right)^2\frac{1}{r}\frac{d\rho(r)}{dr}\boldsymbol{\sigma}\cdot\mathbf{l},$$

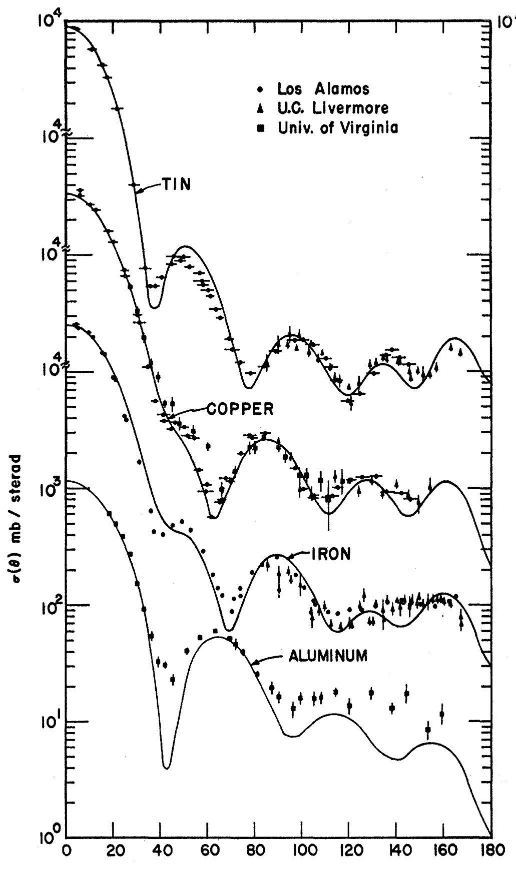

FIG. 1. Experimental[3] and theoretical differential cross sections for 14-Mev neutrons scattered from Sn, Cu, Fe, and Al. The experimental data presented are not completely corrected for multiple scattering nor have angular and energy resolution been taken into account. The data of Berko *et al.* (University of Virginia) have been normalized to the point at 18° for the heavy elements and 30° for the lighter elements.

TABLE I. Parameters adopted as giving the best fit to the neutron-scattering experimental data at 4.1, 7, and 14 Mev.

E (Mev)	V_{CR} (Mev)	V_{CI} (Mev)	V_{SR} (Mev)	a (10^{-13} cm)	b (10^{-13} cm)	r_0 (10^{-13} cm)
4.1	50	7	9.5	0.65	0.98	1.25
7	45.5	9.5	8.6	0.65	0.98	1.25
14	44	11	8.3	0.65	0.98	1.25

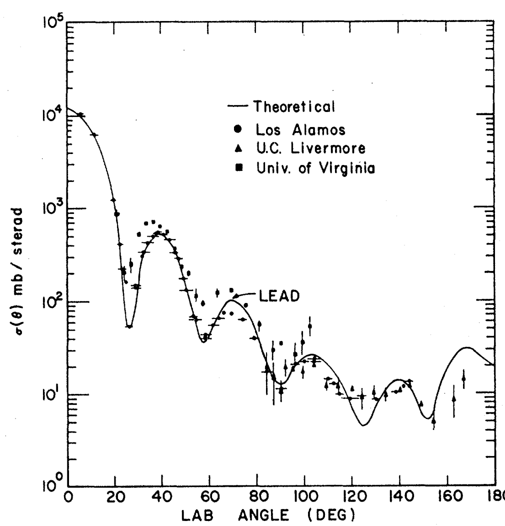

FIG. 2. Experimental[3] and theoretical cross sections for 14-Mev neutrons scattered from Pb. The data of Berko *et al.* have been normalized to the point at 18°.

* Work done under the auspices of the U. S. Atomic Energy Commission.

[1] Bjorklund, Fernbach, and Sherman, Phys. Rev. 101, 1832 (1956).

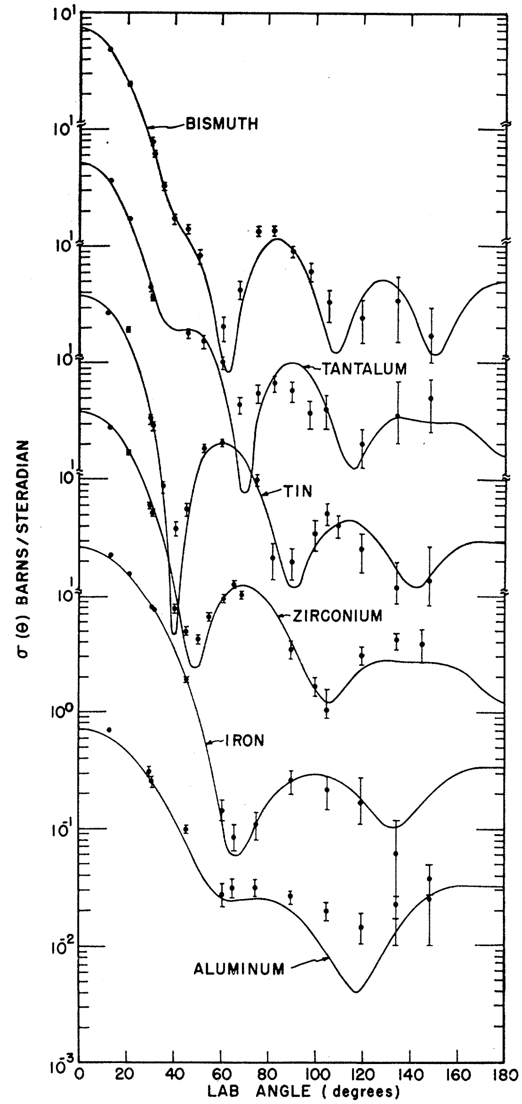

FIG. 3. Experimental[4] and theoretical differential cross sections for 7-Mev neutrons scattered from Al, Fe, Sn, Ta, and Pb.

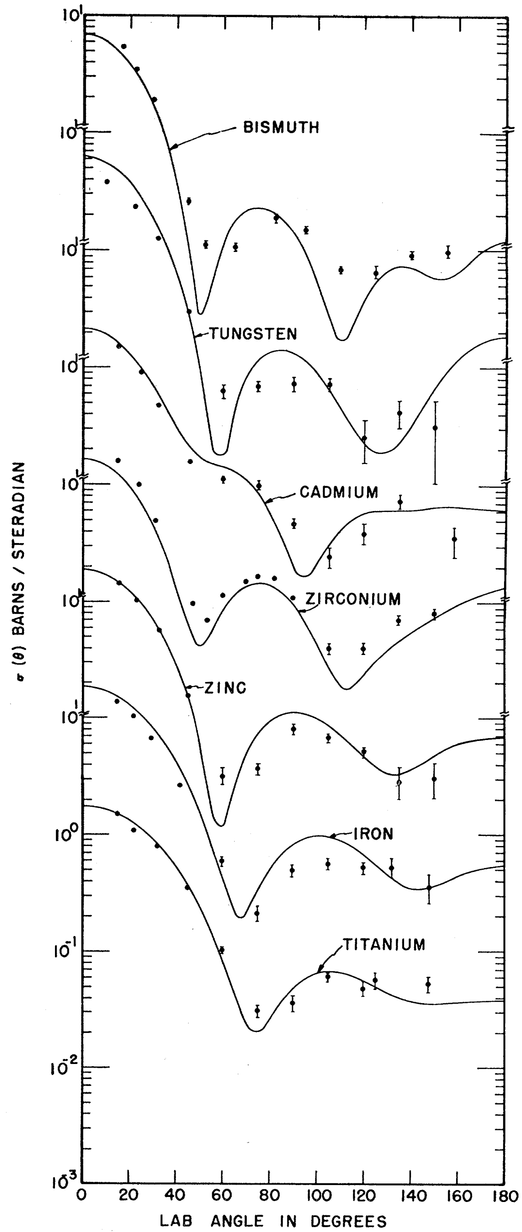

FIG. 4. Experimental[4] and theoretical differential cross sections for 4.1-Mev neutrons scattered from Al, Fe, Sn, and Pb.

where

$$\rho(r)=1/[1+\exp(r-R_0)/a],$$
$$q(r)=\exp[-(r-R_0)^2/b^2],$$
$$R_0=r_0A^{\frac{1}{3}}.$$

The notation is the same as that used by Riesenfeld and Watson.[2] An attempt was made to extrapolate their nucleon-nucleon phase-shift analyses to lower energies in order to obtain a set of optical-model parameters consistent with nucleon-nucleon scattering data. When one considers the differences between empirical data and Riesenfeld and Watson's calculated values at other energies, the extrapolated values are fairly good.

[2] W. B. Riesenfeld and K. M. Watson, Phys. Rev. **102**, 1157 (1956).

Most emphasis in this computation was placed on fitting the 14-Mev data. The parameters thus selected were then tried at the lower energies and the central potentials were varied to find again a best fit. No attempt was made to correct for compound elastic scattering, although it is obvious that some correction is necessary at 4.1 Mev. More computations are in progress at this and at lower energies, so that the parameters chosen to fit the data at this energy are subject to change.

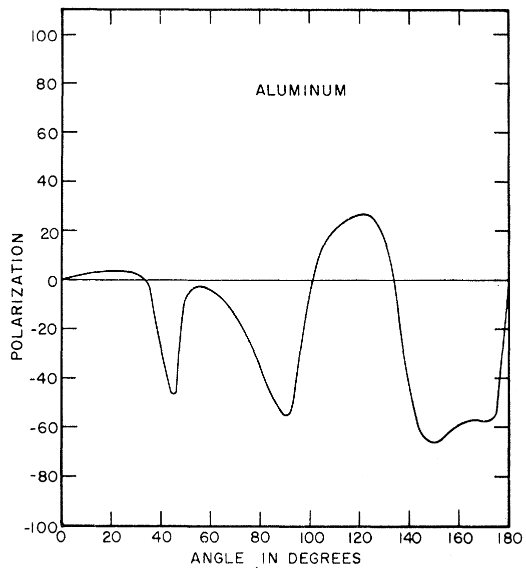

FIG. 5. Percent polarization (theoretical) of 14-Mev neutrons by Al.

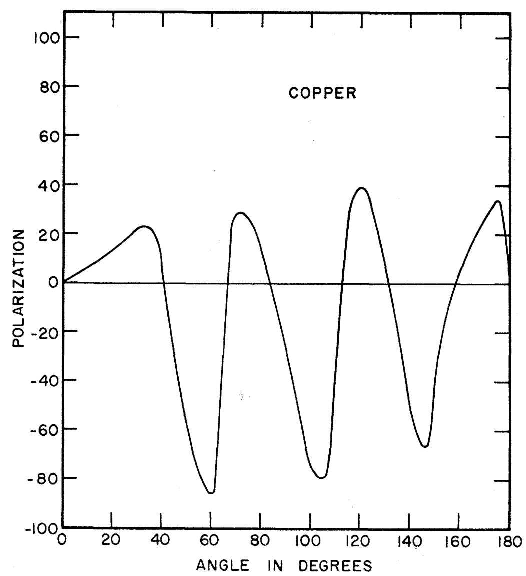

FIG. 6. Percent polarization (theoretical) of 14-Mev neutrons by Cu.

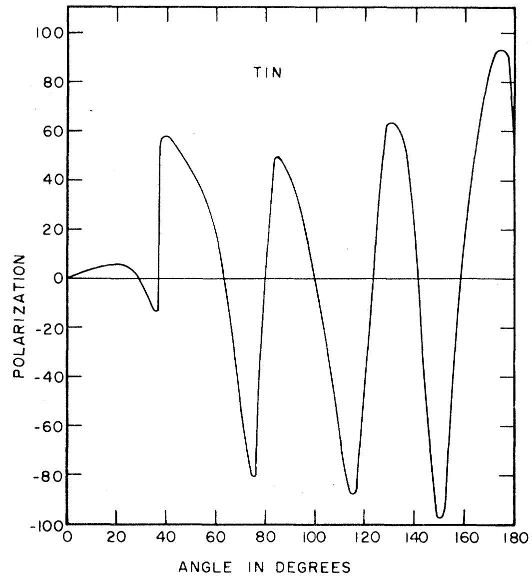

FIG. 7. Percent polarization (theoretical) of 14-Mev neutrons by Sn.

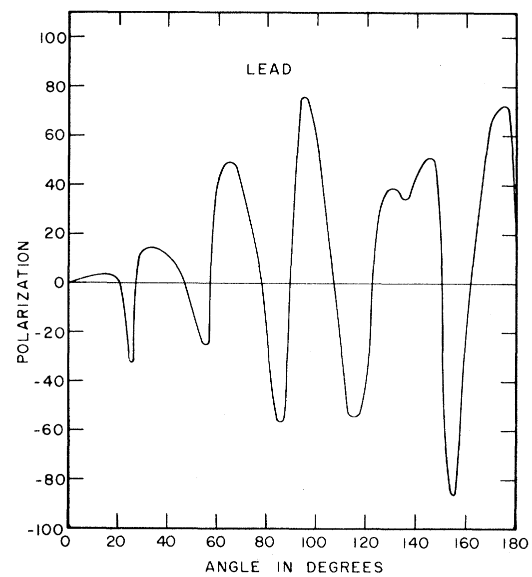

FIG. 8. Percent polarization (theoretical) of 14-Mev neutrons by Pb.

Table I shows the parameters finally selected to fit the data best. In this analysis, the most sensitive parameters were the combination of V_0, a, and r_0. As much as a 5% variation can be made in V_0 and 2% in r_0 without disturbing the fit greatly. The three parameters must be adjusted simultaneously, however, to bring about good agreement with the data. The least sensitive parameter is V_{SR}. This is because of the lack of polarization data to which V_{SR} can be adjusted. At other energies where polarization data are available it was found that V_{SR} is most sensitive—that small variations in V_{SR} result is small changes in $\sigma(\theta)$ but in large changes in $\rho(\theta)$.

Figures 1 and 2 show the theoretically calculated angular distribution and the experimental results obtained at various laboratories[3] for 14-Mev neutrons. Figures 3 and 4 show similar plots for 7- and 4.1-Mev

[3] The experimental data are those of Coon, Davis, Felthauser, and Nicodemus (Los Alamos); Whitehead, Groseclose, and Berko (University of Virginia); and Wong, Anderson, Gardner, and Nakada (University of California, Livermore). We wish to thank these authors for allowing us to use their data prior to publication of their results.

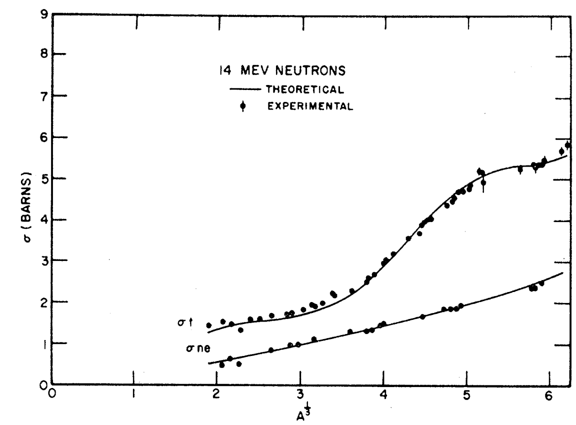

FIG. 9. Experimental[5] and theoretical total and nonelastic cross sections of 14-Mev neutrons as a function of $A^{\frac{1}{3}}$.

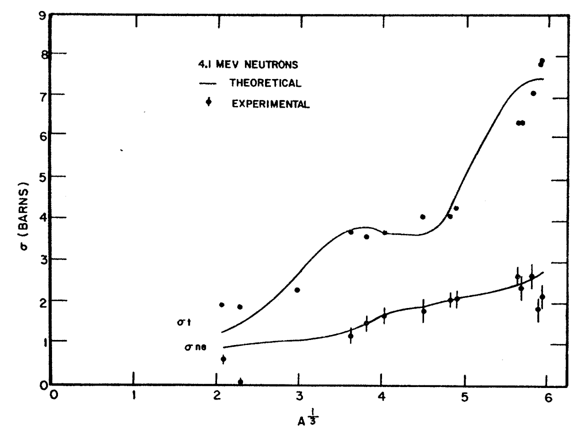

FIG. 11. Experimental[5] and theoretical total and nonelastic cross sections of 4.1-Mev neutrons as a function of $A^{\frac{1}{3}}$.

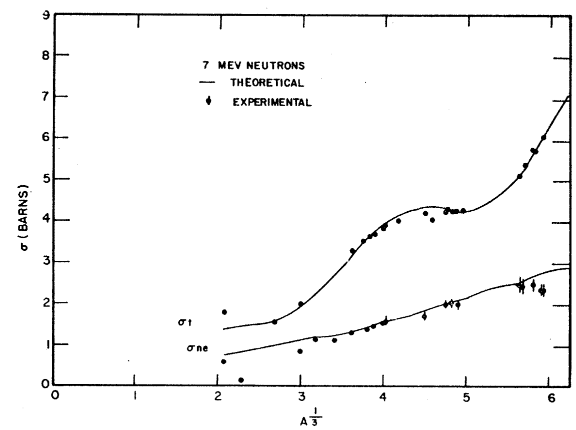

FIG. 10. Experimental[5] and theoretical total and nonelastic cross sections of 7-Mev neutrons as a function of $A^{\frac{1}{3}}$.

neutrons, respectively.[4] Figures 5–8 are illustrations of the percentage polarization one should expect for several elements at 14 Mev. As reported previously, the polarization is fairly small at small angles but does get considerably larger at the large angles. The peaks are broader for small A, since the number of times the polarization curve goes through zero depends on the number of maxima and minima in the scattering cross sections. Figures 9–11 show the nonelastic, and total cross sections as a function of $A^{\frac{1}{3}}$ at the three energies.[5] As expected, the agreement is much better for the higher energies. It should be mentioned that even at the lower energy, the nonelastic cross sections show better agreement with experimental data when the surface absorption potential is used rather than the diffuse-boundary absorption potential.

Until more data, such as polarization curves, are available, it is assumed that not much more can be done with the type of potential used for this computation to improve the results for heavy elements at 14 Mev. The computational effort is now being pushed to improve the lower-energy calculations as well as to find how the potentials must be varied to fit higher-energy data, both for neutrons and protons scattered from the heavy nuclei.

ACKNOWLEDGMENTS

We wish to thank Jean Yoshizuka and Carol Garcia for their assistance in preparing the figures.

[4] Experimental data are those of M. Walt and J. R. Beyster, Phys. Rev. **98**, 677 (1955); and Beyster, Walt, and Salmi, Phys. Rev. **104**, 1319 (1956).

[5] 14-Mev total cross sections are those of Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952); 14-Mev nonelastic cross sections are those of MacGregor, Ball, and Booth, University of California Radiation Laboratory Report UCRL-4790 (to be published); 7-Mev total cross sections are those of Bratenahl, Peterson, Stoering, and Wood [University of California, Livermore (to be published)]; other data are those of M. Walt and J. R. Beyster, reference 4, and Beyster, Walt, and Salmi, reference 4.