Determination of the Spin-Orbit Interaction for Neutron-Nucleus Scattering

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Accurate analyzing power data have been obtained for scattering of 10- and 14-MeV neutrons from ^{54}Fe and ^{65}Cu, with use of a new combination of techniques to produce pulsed, polarized neutron beams. Parametrization with the conventional optical model yields a spin-orbit interaction which is consistent with that observed for proton-nucleus scattering. This combined experimental and theoretical study represents the most sensitive test of similarities between proton and neutron spin-orbit potentials for medium-weight nuclei.

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Polarization data are of critical significance in determining the spin-orbit interaction in elastic scattering of nucleons from nuclei. A large quantity of accurate proton-nucleus polarization data exist for medium- and heavy-weight nuclei, especially for energies above 15 MeV. Direct interaction analyses, which frequently employ a standard nucleon-nucleus optical potential, have used these data to parametrize the spin-orbit term for proton-nucleus scattering. Some neutron polarization data exist for energies below 4 MeV, but contributions from compound-nucleus formation complicate the interpretation of the data with such models. Only a meager amount of neutron polarization data have been reported for energies above 4 MeV. Consequently, neutron-nucleus potentials usually incorporate spin-orbit parameters obtained from fitting proton data. For instance, frequently the proton spin-orbit potential obtained twelve years ago in a global analysis by Becchetti and Greenless[1] is employed in neutron calculations. In the present Letter, we report briefly on a breakthrough in neutron polarization measurements in the 7- to 18-MeV energy range; furthermore, we present some of the data along with optical-model calculations and list some of our early findings for the neutron spin-orbit term.

The scattering observable to be reported here is the analyzing power $A_y(\theta)$. Briefly, this quantity relates the differential cross section $\sigma_L(\theta)$ on the left-hand side of a reaction induced by a 100% transversely polarized "spin-up" incident beam to the differential cross section $\sigma_R(\theta)$ for an equal scattering angle θ on the right-hand side for the same spin-up incident beam. The analyzing power can then be defined as follows:

$$A_y(\theta) = \frac{\sigma_L(\theta) - \sigma_R(\theta)}{\sigma_L(\theta) + \sigma_R(\theta)}.$$

Values of $A_y(\theta)$ range from $+1.0$ to -1.0.

A *unique combination* of facilities has been developed at the Triangle Universities Nuclear Laboratory (TUNL) which makes possible accurate $A_y(\theta)$ measurements for neutrons. The first essential feature involves a well-established method for producing a polarized neutron beam through the bombardment of a deuterium gas target with about 200 nA of polarized deuterons. This polarization-transfer reaction, indicated as $^2\mathrm{H}(\vec{d}_{\mathrm{pol}}, \vec{n}_{\mathrm{pol}})^3\mathrm{He}_{\mathrm{g.s.}}$, produces a clean, intense neutron beam at 0° reaction angle with almost 90% of the vector polarization P_d of the incident deuteron beam.[2] For the present experiments, P_d is typically 0.62 which leads to P_n of about 0.56. The polarization transfer remains high over the deuteron energy range convenient with the tandem Van de Graaff accelerator at TUNL, that is, from $E_d = 4$ to 15 MeV. The reaction Q value of 3.3 MeV allows us to explore the neutron energy region between 7 and 18 MeV quite successfully. The fact that the cross section for $^2\mathrm{H}(\vec{d}_{\mathrm{pol}}, \vec{n}_{\mathrm{pol}})^3\mathrm{He}$ is strongly peaked at 0° is used to advantage in this method of polarized-neutron production. Another important advantage of the polarization-transfer source reaction is that false (instrumental) asymmetries are greatly reduced by flipping the neutron polarization vector by alternating the direction of the vector polarization of the deuteron beam at the ion source.

The second crucial feature of our method is the capability developed at TUNL to compress about 75% of the normal direct-current polarized deuteron beam into pulses 2 ns wide at the target.[3] This breakthrough, permitted by applying a ramp voltage to the anode of the ion source and incorporating a double-drift harmonic buncher, provides better than an order magnitude improvement of the polarized beam intensity over previous pulsed systems at tandem accelerator laboratories. Our pulse repetition rate is 4 MHz, an ideal rate for neutron time-of-flight spectroscopy in our energy region.

The third key ingredient is the existence at TUNL of a large neutron time-of-flight spectrometer. The facility contains two heavily shielded but movable detectors, a setup which is ideally suited for analyzing power measurements. For the $A_y(\theta)$ measurements reported here, these two detectors were always placed at equal angles on opposite sides of the incident beam axis at flight paths of 2.7 and 3.7 m, respectively, from the scatterer.

To date we have investigated neutron analyzing powers at 10 and 14 MeV for ^{40}Ca, ^{54}Fe, ^{58}Ni, ^{65}Cu, ^{116,120}Sn, and ^{208}Pb with the pulsed-beam system. In addition, we obtained results for the lighter nuclei ^{9}Be and ^{12}C at five and twelve energies, respectively. In the present paper we report the conclusions on the first completed data set of this project—elastic scattering from ^{54}Fe and ^{65}Cu. Elaborate Monte Carlo calculations which include geometrical and multiple-scattering effects have been performed for these data.

Previously published data for $A_y(\theta)$ for neutron scattering between 8 and 16 MeV are very sparse and have low accuracy; existing data for Cu(n,n) in the 14- to 16-MeV region[4] give little information about the shape of $A_y(\theta)$. Neutron data (of similar quality to those in Ref. 4) have been reported for energies between 8 and 24 MeV for only about six nuclei heavier than carbon. Our new results, which are shown in Figs. 1 and 2, provide a clear definition of the function $A_y(\theta)$.

Data at 10 and 14 MeV for $A_y(\theta)$, the differential cross section $\sigma(\theta)$, and the total cross section were fitted with calculations based on a spherical optical potential using the search code GENOA obtained from F. Perey of Oak Ridge National

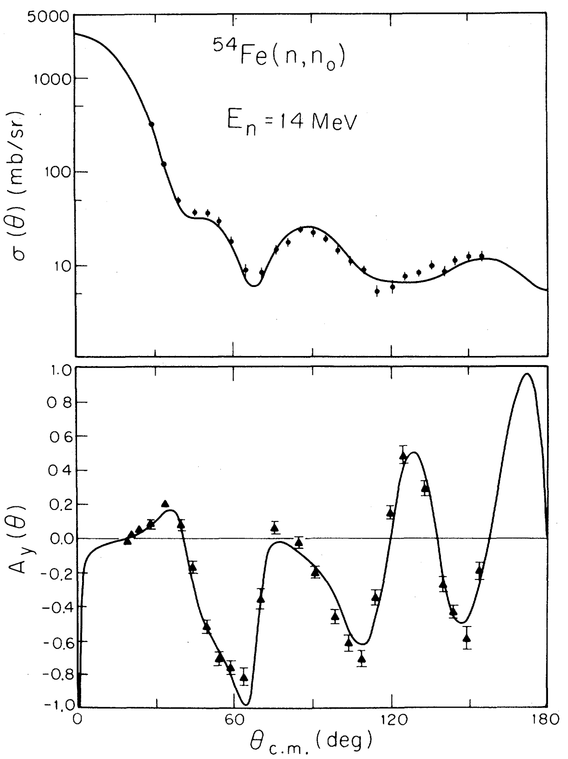

FIG. 1. Cross section and analyzing power for ^{54}Fe. The curve is the optical-model calculation using average geometry parameters.

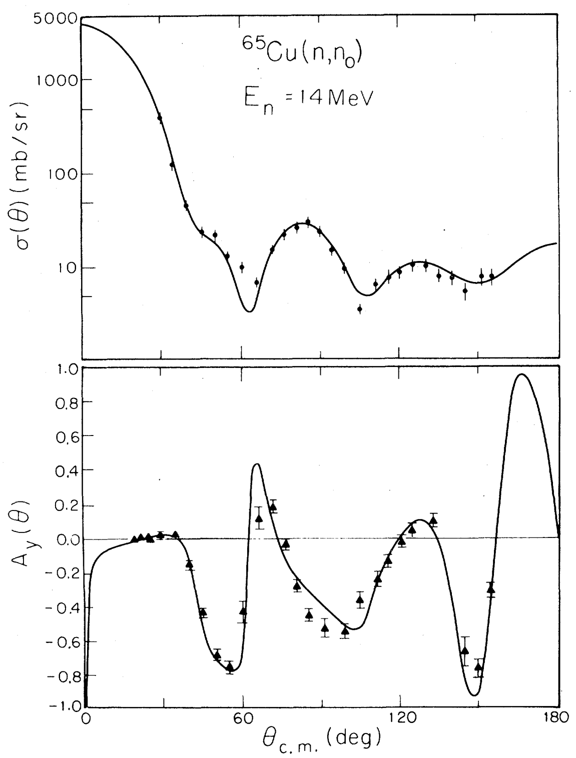

FIG. 2. Cross section and analyzing power for ^{65}Cu. The curve is the optical-model calculation using average geometry parameters.

Laboratory. The potential, which includes a standard Thomas-type spin-orbit interaction, is parametrized as follows:

$$V = -V(r) - iW(r) + U(r,l,s),$$

where

$$V(r) = V_R f(r, r_R, a_R) = V_R\left[1 + \exp\left(\frac{r - r_R A^{1/3}}{a_R}\right)\right]^{-1},$$

$$W(r) = W_V f(r, r_I, a_I) - 4a_I W_D \frac{df(r, r_I, a_I)}{dr},$$

$$U(r,l,s) = (V_{so} + iW_{so})\left(\frac{\hbar}{m_\pi c}\right)^2 (l\cdot\sigma)\frac{1}{r}\frac{df(r, r_{so}, a_{so})}{dr}.$$

To this standard spherical optical potential we added the Mott-Schwinger interaction between the neutron magnetic moment and the (moving) Coulomb field of the nucleus, since this electromagnetic spin-orbit interaction has been shown to affect calculation of the $A_y(\theta)$ distribution over a wide angular range.[5] We modified GENOA to include this effect in the Born approximation.[6]

Starting values for our optical-model parameter search were the global parameters which El-Kadi *et al.*[7] obtained previously at TUNL in a search on cross-section angular distributions and which concentrated primarily on ^{54,56}Fe and ^{63,65}Cu at 8, 10, 12, and 14 MeV. In our initial search all parameters were systematically varied; this provided a "best-fit" set for each of the four pairs of data sets. Then five averaged geometry parameters—central diffuseness a_R, central radius r_R, imaginary diffuseness a_I, imaginary radius r_I, and spin-orbit radius r_{so}—were obtained from the four best-fit parameter sets. The remaining parameters were permitted to vary in the second stage of the search procedure until χ^2 was minimized. In a final step, an imaginary spin-orbit term was included; this resulted in a 30% reduction in χ^2. Results of the search are shown in Table I and illustrated by the solid curves in Figs. 1 and 2. As an indication of how well the spin-orbit parameters are determined, a simple procedure was followed—each parameter was varied, while holding other parameters fixed, until χ^2 increased by a specific amount. The results indicate that while the radius probably is well confined, the other spin-orbit parameters are less well defined by the data set (polarization plus cross section).

To investigate differences between neutron and proton optical potentials, we compare our values in Table I with those reported in 1977 for proton scattering[8] from Fe and Ni between 17 and 25 MeV, energies comparable to those of our neutron experiments when one compensates for Coulomb effects. In Ref. 8, Van Hall *et al.* report average values of 5.5 MeV for the spin-orbit strength V_{so} and 0.54 fm for the spin-orbit diffuseness a_{so}. Corresponding to these, our average values for Fe and Cu are 5.4 MeV and 0.52 fm. That is, we find no systematic difference between our spin-orbit parameters for neutrons and the results of Van Hall *et al.* for protons. Although Van Hall *et al.* did not need an imaginary spin-orbit term, one was required in the analysis of Macintosh and Kobos[9] for (p,p) scattering around 30 MeV. Our small, positive values of W_{so} in Table I are consistent with their findings.

Reviewing the significant results of our spherical optical-model parametrization, we list the following: (1) for the first time, the spin-orbit part of the neutron-nucleus interaction has been well tested for medium-weight nuclei; (2) the spin-orbit radii and strengths are consistent with recent results for proton scattering; (3) the average spin-orbit diffuseness is 0.52 fm, consistent with Van Hall *et al.*[8] for protons but less than the 0.75 fm of the popular Becchetti-Greenlees set[1]; and (4) the present data favor a small positive imaginary spin-orbit strength.

In summary, a facility has been developed for

TABLE I. Results[a] of parameter search with the averaged geometry parameters.[b]

Isotope	E_n	V_R	W_V	W_D	V_{so}	W_{so}	a_{so}	χ^2/N_σ	χ^2/N_{A_y}
^{54}Fe	10	50.75	0.0	8.60	5.34	1.14	0.36	6.4	6.5
^{54}Fe	14	49.39	0.0	8.15	6.36	0.29	0.59	2.7	4.6
^{65}Cu	10	50.70	2.23	4.20	5.11	1.18	0.62	1.5	3.2
^{65}Cu	14	48.60	0.0	8.34	4.62	0.40	0.51	1.7	4.5

[a] Strengths in megaelectronvolts; radii and diffuseness in femtometers.

[b] Average geometry: $r_R = 1.181$, $a_R = 0.676$, $r_I = 1.265$, $a_I = 0.571$, $r_{so} = 1.025$.

obtaining accurate neutron analyzing power data, and a global study of the neutron-nucleus interaction which emphasizes the sensitivity to the spin-orbit term is underway at TUNL. The first analyses of high-accuracy neutron polarization data for the medium-weight nuclei ^{54}Fe and ^{65}Cu yielded spin-orbit parameters that are close to recent proton results. That is, no special geometry or strength is required for neutrons. Lastly, for completeness, but without displaying our data or calculations here, we report that our optical-model investigations for the light nuclei ^{9}Be, ^{12}C, and ^{40}Ca indicate that if the spin-orbit term is restricted to the conventional Thomas form factor, then the diffuseness takes on an unusually small value of 0.3 fm or less. A small spin-orbit diffuseness was suggested earlier for the neutron-nucleus potential by Roman,[10] who tried to interpret the significance of an unusually small diffuseness for ^{3}He elastic scattering from light nuclei. Our results for light nuclei concur with his proposal.

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