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Effects of Spin-Orbit Deformation in Inelastic Scattering at 0.8 GeV

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New differential cross section and analyzing-power data for 800-MeV $\vec{p}_{\mathrm{pol}}+{}^{12}\mathrm{C},{}^{116,124}\mathrm{Sn}$ inelastic scattering to the first 2^+ states are presented. A distorted-wave Born-approximation analysis which utilizes collective form factors and includes deformation of the spin-orbit potential is shown to provide a reasonable description of the analyzing-power data.

Distorted-wave Born-approximation (DWBA)[1] analyses of some of the available medium-energy (~1 GeV) proton-nucleus inelastic differential cross-section data were found generally to give good overall agreement for both shapes and magnitudes of the cross sections, using *spin-independent* collective form factors and deformation lengths consistent with averages of results of many low-energy determinations.[2-4] A recent investigation[5] of the sensitivity of the calculations to a spin-orbit contribution to the macroscopic collective form factor suggested considerable sensitivity of the predicted analyzing powers to deformation of the spin-orbit potential, but unfortunately, no inelastic analyzing-power data were available for comparison with the predictions. At lower energies, where such comparisons have been made, this sensitivity has been established.[6-12]

This Letter presents new angular distribution data ($d\sigma/d\Omega$) and the first inelastic analyzing power data [$A_y(\theta)$] obtained at Clinton P. Anderson Meson Physics Facility using the high-resolution spectrometer and the 800-MeV polarized proton beam. Also presented are the results of a theoretical analysis whose purpose is to investigate the importance of the spin-dependent inelastic collective form factor at medium energies. The data, shown in Fig. 1, along with the results of the theoretical analysis to be discussed, consist of analyzing powers and differential cross sections for 800 MeV $p_{\rm pol}$ + ^{12}C, $^{116, 124}$Sn to the first 2^+ state of each nucleus. The analyzing-power data were obtained during the polarized-proton survey experiment[13, 14] and poor energy resolution (~300 keV) and use of a restricted region of the spectrometer focal plane permitted extraction of the analyzing powers for these first excited states only. The ^{12}C differential cross-section data have been reported earlier.[2] The inelastic analyzing-power data are quite similar, in both shape and magnitude, to the elastic analyzing-power data, whose qualitative features are discussed in Ref. 13.

Conventional use of the DWBA to describe strong collective nuclear excitations involves the spin-independent inelastic form factor which is

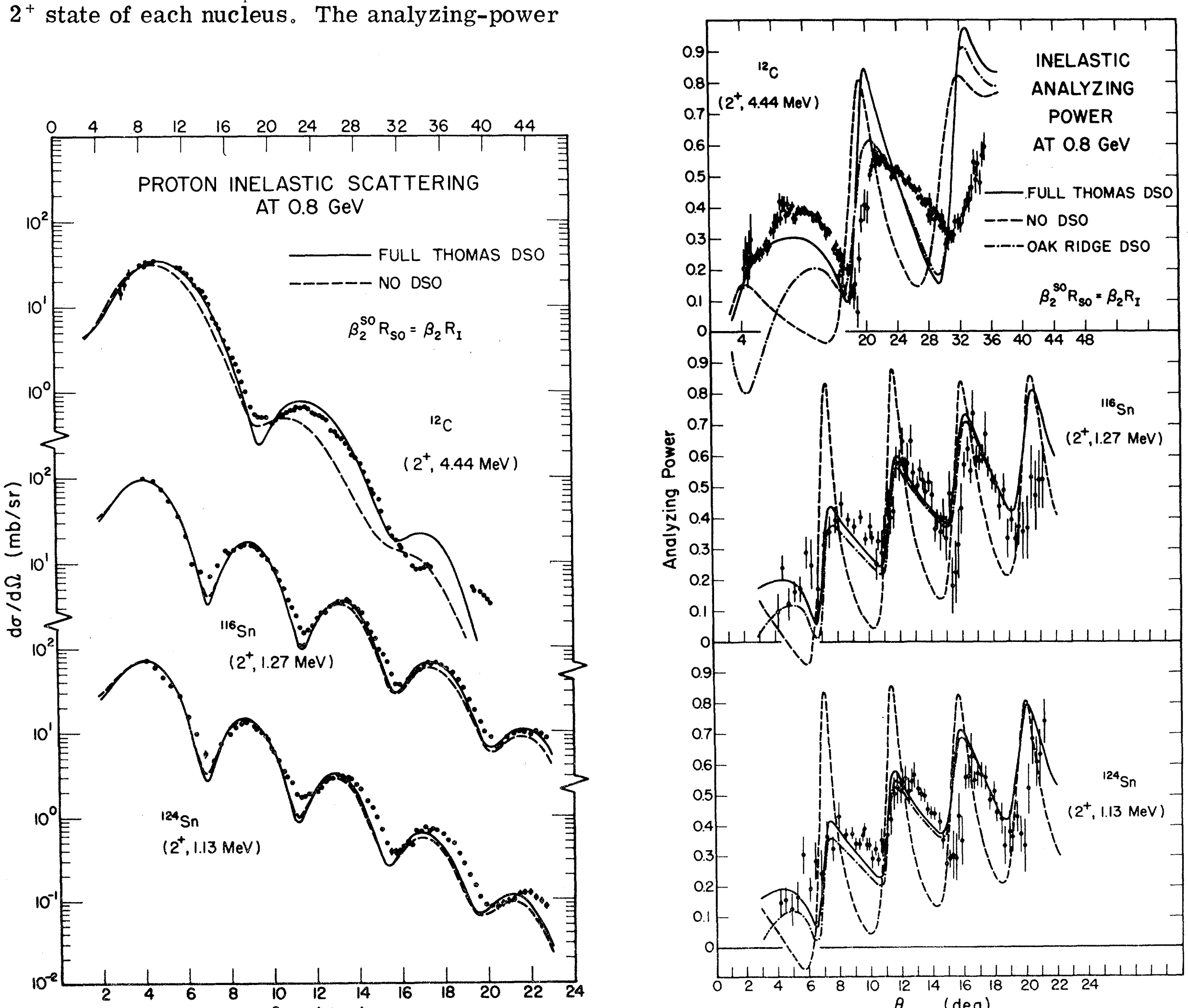

FIG. 1. Experimental and theoretical angular distributions and analyzing powers for the first 2^+ excited states in ^{12}C, ^{116}Sn and ^{124}Sn. Note that the upper center-of-mass angle scale applies to ^{12}C while the lower scale is for $^{116, 124}$Sn. The curves are discussed in the text.

inserted into the matrix element between initial and final distorted waves and is just the derivative of the spherical, central potential times an additional "deformation length" $\beta_l R_I$, where R_I is the half-radius of this potential.[1-12] Deformed potentials rather than deformed densities will be used here to allow comparisons with low-energy analyses.[6-12, 15-18] Within the framework of Kerman, McManus, and Thaler (KMT),[19] the spin-dependent part of the first-order optical potential arises from the two-nucleon amplitudes that are proportional to $(\vec{\sigma}_p + \vec{\sigma}_j)\cdot(\vec{k}_i \times \vec{k}_f)$, where p refers to the incident proton and j to the target nucleon. The resulting spin-orbit potential, $U_{s.o.}(\vec{r})$, is known as the "full Thomas form" (FTF) and is given by[7-9]

$$U_{s.o.}(\vec{r}) = \vec{\sigma}\cdot[\{\nabla f_{s.o.}(r, R(\hat{r}))\}\times(1/i)\nabla]. \qquad (1)$$

The quantity $f_{s.o.}(r, R(\hat{r}))$ is a convolution integral of the nuclear matter density with the Fourier transform of the spin-dependent part of the nucleon-nucleon scattering amplitudes, is in general complex,[14] and can be nonspherical, thus contributing to the inelastic transition matrix element. The diagonal and nondiagonal parts of this potential are obtained by expanding $R(\hat{r}) = R_{s.o.} + \alpha_{s.o.}(\hat{r})$, where $\alpha_{s.o.}(\hat{r}) \propto \beta_l^{s.o.} R_{s.o.} Y_l^{m*}(\hat{r})$ as given in Ref. 9. KMT theory and the collective model require $\beta_l^{s.o.} R_{s.o.} \approx \beta_l R_I$,[20] but $\beta_l^{s.o.}$ is often allowed to vary.[6-12] The resulting DWBA matrix element is given by Verhaar *et al.*[7] For many low-energy applications, an approximation to Eq. (1), known as the "Oak Ridge form" (ORF)[6,9] has been used. In order to test the validity of this approximation at medium energies, both the FTF and ORF were used for the calculations reported here.

The curves shown in Fig. 1 are the results of the calculations. The KMT spin-dependent microscopic optical potentials used for these calculations, and the fits to the elastic cross sections and analyzing powers, are presented in Refs. 2, 13, 14. The calculations were done using a version of the DWBA program VENUS[3,21] modified to include relativistic kinematics[3] and the above spin-dependent form factors. The spin-independent–potential deformation lengths $\beta_2 R_I$ which account for the magnitudes of the differential cross sections are 1.45, 0.74, and 0.63 fm for ^{12}C, ^{116}Sn, and ^{124}Sn, respectively, in good agreement with lower-energy results.[15-18]

The dashed curves shown in Fig. 1 result when the contribution of the deformed spin-orbit potential to the inelastic form factor in the transition matrix element is omitted. Use of the full Thomas form with $\beta_2^{s.o.} R_{s.o.} = \beta_2^{s.o.} R_I$ gives the solid curves, while the ORF, again with $\beta_2^{s.o.} R_{s.o.} = \beta_2 R_I$, produces the dash-dotted curves. The differences between the predicted differential cross sections using the two forms for the deformed spin-orbit potential are negligible, and only the FTF result is shown for the cross sections. As seen from Fig. 1, inclusion of the spin-orbit collectivity decreases the ratios of successive maxima of the predicted cross sections, as has been previously noted,[5] producing better agreement with the data in all three cases.

As seen from Fig. 1, the calculations with omission of spin-orbit collectivity (dashed curves) fail to account for the qualitative features of the analyzing powers. However, the predicted analyzing powers with either the FTF or ORF collectivity (solid and dash-dotted, respectively) give much better qualitative agreement with both the magnitudes and shapes of the analyzing powers. The predicted ^{12}C analyzing power is poor in an absolute sense, but is similar in quality to the fit obtained to the elastic analyzing power.[13] Beyond the second maxima, the analyzing powers predicted using the FTF and the ORF are quite similar, and from the small differences at the most forward angles no clear preference can be determined. At lower energies such comparisons clearly indicate the need for the FTF form.[6,9] Allowing $\beta_2^{s.o.} R_{s.o.} = 1.5\beta_2 R_I$ results in fits of similar quality to those shown in Fig. 1; however, a definite deterioration in the quality of fit results if $\beta_2^{s.o.} R_{s.o.} = 2.0\beta_2 R_I$.

In conclusion, new medium-energy proton inelastic cross-section and analyzing-power data have been presented and analyzed within the framework of the DWBA and the collective model using a deformed spin-orbit contribution to the inelastic transition matrix element. Central deformation parameters are consistent with those found from analyses of data at lower energies and the importance of the deformed spin-orbit potential is demonstrated. From these calculations it was found that $\beta_2^{s.o.} R_{s.o.} \simeq (1.0-1.5)\beta_2 R_I$ provides a reasonable description of the inelastic analyzing power for the three cases studied, as has been found in all but the very low-energy ($\gtrsim$ 20 MeV) analyses.[11,12]

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Giant-Resonance Studies with High-Energy Heavy Ions

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Evidence is presented for the excitation of giant multipole resonances in inelastic scattering of 315-MeV ^{16}O ions on ^{12}C, ^{58}Ni, and ^{208}Pb targets. Highly excited modes around 20 MeV of excitation energy in ^{208}Pb exhaust a large fraction of the energy-weighted isoscalar $E3$ and $E5$ sum-rule strengths.

For the study of energy dissipation processes in heavy-ion reactions it is important to understand the response function[1] of the nuclei involved in the collisions. It is natural to assume that in the initial reaction step the excitation of simple one-particle, one-hole states absorbs part of the kinetic energy of relative motion. Therefore, giant multipole resonances may also be involved[2] if, in the adiabatic limit, the collision times are of the same order of magnitude as the corresponding quantum transition times.[3] In addition, angular-momentum matching conditions in heavy-ion reactions allow large angular momentum transfers. While several low-energy, heavy-ion scattering experiments (≤10 MeV/nucleon)[4-6] have reported the observation of giant quadrupole structures in nuclei, it was the goal of the present experiment to improve these studies with a high-energy ^{16}O beam at 315 MeV on ^{12}C, ^{58}Ni, and ^{208}Pb, and to search for excitations of higher multipolarity, which have been reported so far only in electron scattering on ^{208}Pb.[7,8]

The experiments were performed at the Lawrence Berkeley Laboratory 88-in. cyclotron. A beam of 315-MeV $^{16}O^{6+}$ ions was scattered from self-supporting ^{208}Pb (1.03 mg/cm^2), ^{58}Ni (1.67 mg/cm^2), and ^{12}C (0.36 mg/cm^2) foils. The reaction products were identified in the focal plane of a magnetic quadrupole–single-dipole spectrometer, using a counter which determines the position ($B\rho$), energy loss (ΔE), and time of flight (TOF) of the reaction products. Position spectra of inelastically scattered ^{16}O particles on ^{208}Pb, ^{58}Ni, and ^{12}C targets are shown in Figs. 1(a)–1(c). Single-nucleon–transfer reactions were also investigated to assess the competition between

