ASYMMETRY IN THE INELASTIC SCATTERING OF 40-MeV POLARIZED PROTONS*

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The collective-model generalization of the optical potential in the distorted-waves (DW) method[1] has proved successful in the analysis[2] of cross sections[3] for the inelastic scattering of 40-MeV protons. However, it was expected that inelastic polarization or asymmetry measurements would furnish a more sensitive test of many aspects of this treatment. Moreover, a closer examination of this "macroscopic" approach could provide important clues for a more microscopic description[4] of the interaction and nuclear wave functions. We are now in the process of making asymmetry measurements for quadrupole and octupole excitations in several even-even nuclei, and this Letter reports the results for the first excited (2^+) states in ^{28}Si and ^{60}Ni. Our preliminary DW calculations with collective-model form factors indicate a preference for complex coupling[5] and for a deformation of the spin-orbit term in the optical potential.

The experimental arrangement is that reported previously,[6] with the addition of a sector magnet to provide energy analysis of the polarized beam. A 10-MeV-thick piece of calcium is bombarded with 50-MeV unpolarized protons from the Oak Ridge isochronous cyclotron (ORIC). The protons elastically scattered at 25.5° are magnetically analyzed and focused to a 4-mm-wide spot at the target. The resultant polarization is 28%, intensity 10^8 p/sec, and energy spread 500 keV full width at half-maximum. The scattering of the polarized beam is measured with an array of 32 NaI(Tl) counters, 16 on each side; and the over-all resolution is 700 keV. Probable errors for the inelastic data are almost entirely due to uncertainties in unfolding the inelastic group from the elastic peak.

The elastic cross-section and polarization data are shown in Fig. 1, along with the optical-model fits achieved with the parameters given in Table I. The potential used consists of the Coulomb terms plus

$$U(r) = -Vf(x_R) - i(W - 4W_D d/dx_I)f(x_I) + (\hbar/m_\pi c)^2(V_S + iW_S)\vec{\sigma}\cdot\vec{l}\,(1/r)(d/dr)f(x_S),$$

where $f(x_K) = [\exp(x_K)+1]^{-1}$, $x_K = (r - r_K A^{1/3}/a_K)$. For the calculations made to date, a value of r_S less than r_R and a value of r_I greater than r_R produce the best fits to the elastic polarization. While the parameters of Table I are the result of searching simultaneously for the best fits to both cross section and polarization, the fit to the polarization data was given greater emphasis.

The inelastic cross sections and asymmetries are shown in Fig. 2; the asymmetries are normalized to 100% beam polarization. The collective-model interaction for the DW calculation is obtained[1] by deforming the op-

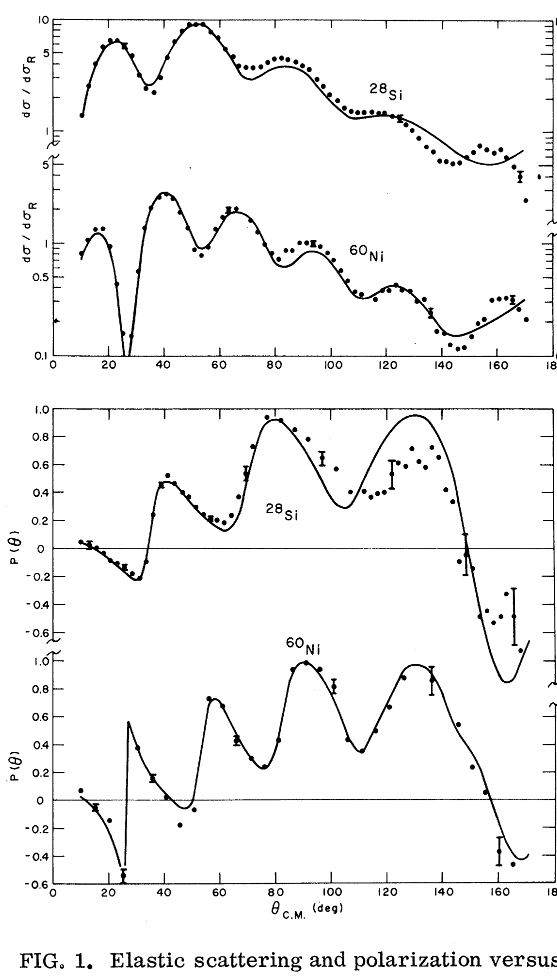

FIG. 1. Elastic scattering and polarization versus optical-model fits using parameters of Table I.

Table I. Optical-model parameters.

Nucleus	V (MeV)	W (MeV)	W_D (MeV)	V_S (MeV)	W_S (MeV)	r_R (F)	a_R (F)	r_I (F)	a_I (F)	r_S (F)	a_S (F)
^{28}Si	44.6	1.4	4.4	5.8	−0.4	1.13	0.73	1.41	0.54	1.01	0.63
^{60}Ni	52.9	5.5	2.8	4.7	−0.7	1.06	0.87	1.41	0.49	1.04	0.52

tical potential $U(r)$; and we have examined separately the results produced by deforming (i) only the real part of the central term, (ii) the real and imaginary parts of the central term, and (iii) the complete potential including the spin-orbit term (as discussed below). The result of deforming the central term is illustrated by the broken curves in Fig. 2 for ^{28}Si; the effect is very similar for ^{60}Ni. When both real and imaginary parts of the central term are included (complex coupling), the oscillations in the asymmetry are much more pronounced than those obtained by deforming only the real, central term (real coupling).

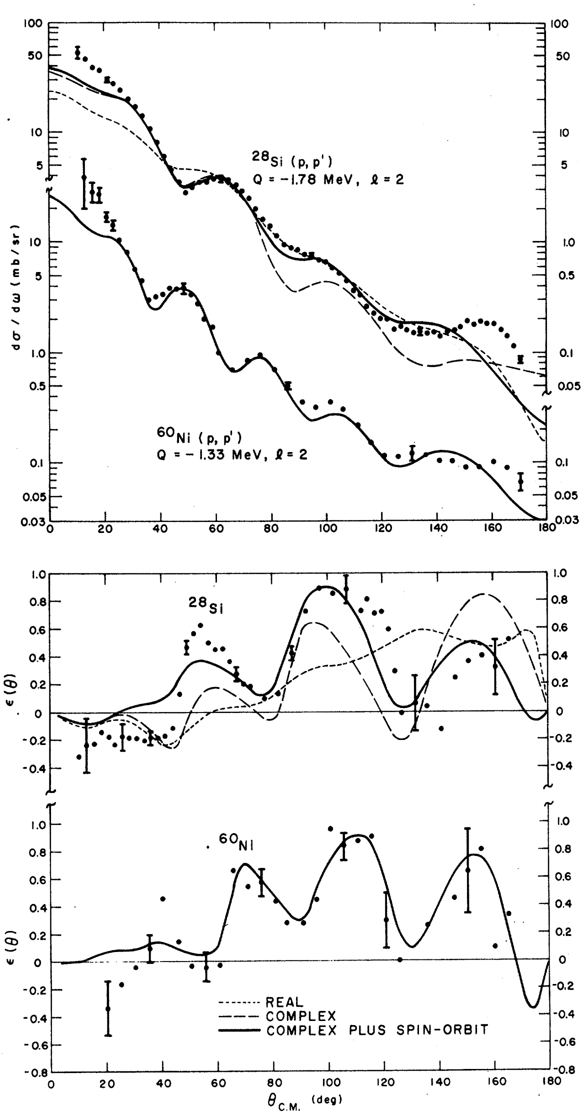

FIG. 2. Inelastic scattering and asymmetry. The full curves are DW calculations in which the complete optical potential is deformed, while the broken curves for Si use real and complex coupling with no spin-orbit deformation. All calculations use the optical parameters of Table I.

Within the spirit of the collective model, there is no a priori reason to assume that the spin-orbit interaction does not also follow the motion of a vibrating nucleus. However, it is not clear how to treat such a term; straightforward use of the Thomas prescription yields a complicated expression for this contribution to the nonspherical interaction. At this stage, we treat the spin-orbit contribution phenomenologically and expand only the radial gradient of $f(x_S)$:

$$V_{0L}^{\text{S.O.}} = -\tfrac{1}{2}(\hbar/m_\pi c)^2(\beta_L^{\text{S.O.}} r_S A^{1/3})(V_S + iW_S)$$
$$\times (1/r)(d^2/dr^2)f(x_S)[Y_L(\vec{\sigma}\cdot\vec{l}) + (\vec{\sigma}\cdot\vec{l})Y_L].$$

The solid lines in Fig. 2 are the result of calculations for ^{28}Si and ^{60}Ni which include this interaction (complex plus spin-orbit coupling). The spin-orbit contribution improves the overall agreement with both the observed cross sections and asymmetries. This is only apparent when the contribution from the imaginary, central term is retained, since otherwise the calculation (real plus spin-orbit coupling) fails to reproduce the strong oscillations observed in the asymmetry.

It is prudent to note that these calculations of inelastic asymmetry, and the effects produced by deforming the different terms in the potential, are quite sensitive to the values of the optical parameters used, through both the elastic distortion and the shape and extent of the collective-model form factors. This sensitivity emphasizes the need for a better understanding of the systematics and ambiguities of the optical potential for medium-energy protons. When the complete potential is deformed, the optical parameters (Table I) found so far to give the best fit to the elastic polarization also produce the best prediction of inelastic asymmetry.

All the curves in Fig. 2 use a central-well deformation parameter of $\beta_2 = 0.39$ for ^{28}Si and $\beta_2 = 0.22$ for ^{60}Ni. The deformation parameter of the spin-orbit term is 1.5 times the central-well value, which produces slightly better agreement with the asymmetry data for ^{28}Si. Both real and imaginary parts of the spin-orbit interaction are included, but since $|W_S| \ll V_S$, the imaginary part makes little difference. The curves also include Coulomb-excitation amplitudes,[1] which make little difference in either the asymmetry or the cross section. We find that for all of the calculations made, the predictions of inelastic asymmetry and inelastic polarization are very nearly identical.

In summary we find that, provided the imaginary and spin-orbit terms are included, the collective-model generalization of the optical potential gives a good account of the present inelastic asymmetry data at all but the most forward angles. It is quite possible that a more comprehensive treatment of the spin-dependent interaction will improve matters in this region, and such calculations are in progress.

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END TO THE COSMIC-RAY SPECTRUM?

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The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{22} eV. This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

The cause of the catastrophic cutoff is the intense isotropic radiation first detected by Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2 cm wavelength. It is not essential to the present argument that the origin of this radiation conform exactly to the primeval-fireball model outlined by Dicke, Peebles, Roll, and Wilkinson[5]; what matters is only that the radiation exists and pervades the observable universe. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions,