Complete Measurement of Polarization-Transfer Observables for the Reaction $^{12}C(p,p')^{12}C^*$ at 500 MeV

J. B. McClelland and J. M. Moss
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

B. Aas, A. Azizi, E. Bleszynski, M. Bleszynski, J. Geaga, G. Igo, A. Rahbar, J. B. Wagner, G. S. Weston, and C. Whitten, Jr.
Physics Department, University of California, Los Angeles, California 90024

and

K. Jones and S. Nanda
Physics Department, Rutgers University, New Brunswick, New Jersey 08903

and

M. Gazzaly and N. Hintz
Physics Department, University of Minnesota, Minneapolis, Minnesota 55455
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The first complete measurement of the polarization-transfer observables in the (p,p') reaction at intermediate energies is reported. Data are presented for the reaction $^{12}C(p,p')^{12}C$ to the 1^+, $T=0$ (12.71-MeV) and 1^+, $T=1$ (15.11-MeV) states at 500 MeV for laboratory scattering angles of 3.5°, 5.5°, 7.5°, and 12.0°. Linear combinations of these observables are shown to exhibit a very selective dependence on the isoscalar and isovector spin-dependent components of the nucleon-nucleon interaction.

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Inelastic proton scattering involves the full complexity of the nucleon-nucleon (NN) interaction. In particular, unnatural-parity transitions are expected to be particularly sensitive to the spin-dependent parts of the NN interaction.[1] In this Letter we report the first complete measurement of polarization-transfer (PT) observables in the excitation of two well-known unnatural-parity states in ^{12}C, the 1^+, $T=0$ (12.71 MeV) and 1^+, $T=1$ (15.11 MeV). The data are compared to distorted-wave impulse-approximation (DWIA) and Glauber-model calculations. Using a simplified reaction model, we show that the PT observables demonstrate a high selectivity and sensitivity to the spin-dependent amplitudes of the effective NN interaction in the small-momentum-transfer region covered by the data.

Beams of 500-MeV protons with initial polarization longitudinal (L) and normal to the reaction plane (N) and sideways ($S=N\times L$) were provided by the Clinton P. Anderson Meson Physics Facility (LAMPF). Protons inelastically scattered from natural carbon targets were momentum analyzed in the high-resolution spectrometer (HRS). For these measurements the focal-plane polarimeter (FPP) was employed to analyze the outgoing proton polarization. This apparatus has been used for elastic-scattering measurements reported recently[2]; and it is equally well suited to the present high-resolution inelastic measurements. Residing at the exit of the HRS, the FPP consists of eight planes of multiwire drift chambers (MWDC) plus associated trigger scintillators which constitute the standard focal-plane detector system. This system is followed by a four-inch carbon analyzer and eight more planes of larger MWDC's to detect the rescattered protons.

The FFP system maintains the energy resolution (~100 keV for these measurements) and angular resolution (~0.1°) of the HRS while reconstructing trajectories of the rescattered protons for all states on the focal plane, finally yielding the polarization of the scattered proton. A fast microprocessor is used to reject small-angle rescatterings and buffered CAMAC electronics are used to maintain high data rates at low duty cycles. The overall efficiency of the polarimeter is 10%–15%.

Analysis of both polarization components perpendicular to the momentum at the focal plane allows for measurement of all possible polarization-transfer observables at this energy because of the precession of the spin in the HRS dipoles. The outgoing sideways component (S', perpendicular to k' and in the reaction plane) is transported unprecessed to the focal plane and is determined by the vertical asymmetry. The longitudinal (L') and normal (N') components precess by $360° + 52°$ and are inferred from the horizontal asymmetry.

Several systematic checks of the data are possible when analyzing all states present at the focal plane. For most of the measurements, simultaneous analysis of the 0^+ (7.65 MeV) state in ^{12}C allowed for checking of several symmetry relations appropriate to $0^+ \to 0^+$ transitions. In most instances, the statistical accuracy of the checks was comparable to or better than that of the 1^+ states of interest. High-precision checks for elastic scattering,[2] as well as systematic checks of the FPP in general,[3] lead to the estimation that false asymmetries are less than 0.01. At the smallest scattering angle covered by these measurements the signal-to-background ratio for the 15.11-MeV state was better than 10:1; at the largest angle it was 1:10. This background was primarily broad nuclear states underlying the peaks of interest. Since this background is analyzed concurrently with the peaks of interest, the background subtraction did not pose a serious systematic problem and has been described previously for these states at 397 MeV.[4]

Data for the 1^+, $T=0$ (12.71 MeV) and 1^+, $T=1$ (15.11 MeV) states in ^{12}C at laboratory scattering angles of 3.5°, 5.5°, 7.5°, and 12° are shown in Figs. 1(a) and 1(b). The solid curve is a Glauber calculation of the PT observables with use of Cohen-Kurath (CK) wave functions and free NN amplitudes from Arndt's SP82 solution.[5] The dashed curve in Fig. 1 is a DWIA calculation with use of CK wave functions and a recent parametrization of the same free NN amplitudes in terms of Yukawa potentials.[6]

In order to determine the origin of the differences between the Glauber and DWIA predictions, a DWIA calculation (not shown in the figures) was done in which the $(LSJ)_{\text{target}} = (111)$ and (101) transition densities were excluded. Parity conservation prevents these $L=1$ components from contributing to the transition if the effective interaction is local (momentum independent). Thus they have no effect on the Glauber predictions and also do not enter the *direct* DWIA scattering amplitudes. However, these $L=1$ densities are sampled by the effective interaction operator ($\vec{\sigma} \times \vec{L}$), acting on the target nucleons, which enters

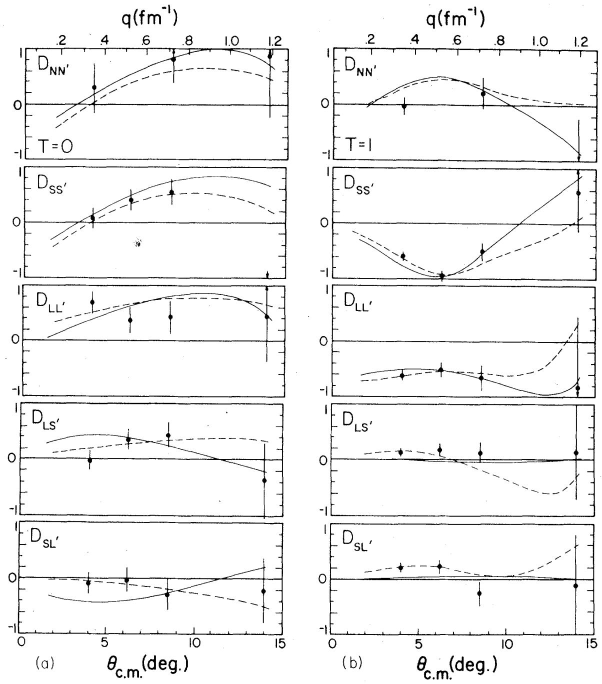

FIG. 1. Polarization transfer observables for (a) 1^+, $T=0$ (12.71 MeV), and (b) 1^+, $T=1$ (15.11 MeV) in reaction $^{12}C(p,p')^{12}C$ at 500 MeV. Shown are Glauber-model (solid curve) and DWIA (dashed curve) calculations.

the exchange scattering amplitudes.[7] With these densities excluded, the Glauber and DWIA results are very similar, the largest differences remaining between the two calculations being in $D_{LS'}$ and $D_{SL'}$.

Although complete calculations presented here have been done, some simple insights are offered by examining the expressions for the PT observables in the lowest order of the expansion of the (p,p') reaction amplitude in terms of the free NN amplitudes (the plane-wave impulse approximation or equivalently the single-collision approximation in the Glauber theory). The nucleon-nucleus scattering amplitude is

$$M_{fi}(\vec{q}) = \langle f | \hat{F}_{NN}(\vec{q}) e^{-i\vec{q}\cdot\vec{r}} | i \rangle, \tag{1}$$

where $|i\rangle$ and $|f\rangle$ are the initial and final states of the system characterized by the target spin, parity, isospin, and the projectile spin projections. $\hat{F}_{NN}(\vec{q})$ is the NN scattering operator which we parametrize as

$$\hat{F}_{NN}(\vec{q}) = \hat{A}(\vec{q}) + \hat{B}(\vec{q})(\hat{\sigma}_1 \cdot \vec{n})(\hat{\sigma}_2 \cdot \vec{n}) + \hat{C}(\vec{q})(\hat{\sigma}_1 \cdot \vec{n} + \hat{\sigma}_2 \cdot \vec{n}) + \hat{E}(\vec{q})(\hat{\sigma}_1 \cdot \vec{m})(\hat{\sigma}_2 \cdot \vec{m}) + \hat{F}(\vec{q})(\hat{\sigma}_1 \cdot \vec{p})(\hat{\sigma}_2 \cdot \vec{p}), \tag{2}$$

where

$$\vec{q}=\vec{k}'-\vec{k}, \quad \vec{n}=\vec{k}\times\vec{k}'/|\vec{k}\times\vec{k}'|, \quad \vec{m}=\vec{q}/|\vec{q}|, \quad \vec{p}=\vec{m}\times\vec{n} \tag{3}$$

and

$$\hat{A}(\vec{q})=A_0(\vec{q})+A_1(\vec{q})(\hat{\tau}_1\cdot\hat{\tau}_2), \text{ etc.} \tag{4}$$

$\hat{\sigma}_1(\hat{\tau}_1)$ and $\hat{\sigma}_2(\hat{\tau}_2)$ are the projectile- and target-nucleon Pauli (isospin) matrices, respectively, and $\vec{k}(\vec{k}')$ is the incoming (outgoing) momentum vector in the laboratory system.

Given the complete set of PT observables, it is possible to construct four functions D_K, $K=0$, X, Y, Z, which show particular selectivity to the specific components of the (p,p') collision matrix. These functions are shown in Figs. 2(a) and 2(b) for the $T=0$ and $T=1$ states and are related to the PT observables for unnatural-parity transitions by

$$\begin{aligned}
D_0^{\xi} &= \tfrac14[1+(D_{SS'}+D_{LL'})\cos\theta_L+D_{NN'}-(D_{LS'}-D_{SL'})\sin\theta_L]\approx[X_\xi^T]^2|C_\xi|^2/I_\xi,\\
D_X^{\xi} &= \tfrac14[1+D_{SS'}-D_{LL'}-D_{NN'}]\approx[X_\xi^L]^2|E_\xi|^2/I_\xi,\\
D_Y^{\xi} &= \tfrac14[1+(D_{SS'}+D_{LL'})\cos\theta_L+D_{NN'}+(D_{LS'}-D_{SL'})\sin\theta_L]\approx[X_\xi^T]^2|B_\xi|^2/I_\xi,\\
D_Z^{\xi} &= \tfrac14[1+D_{SS'}-D_{NN'}+D_{LL'}]\approx[X_\xi^T]^2|F_\xi|^2/I_\xi,
\end{aligned} \tag{5}$$

where

$$I_\xi=[X_\xi^T]^2[|C_\xi|^2+|B_\xi|^2+|F_\xi|^2]+2[X_\xi^L]^2|E_\xi|^2 \tag{6}$$

is the unpolarized cross section, and X_ξ^T and X_ξ^L are the transverse and longitudinal form factors defined as the reduced matrix elements of the axial transverse electric and axial longitudinal multipole operators[8]

$$\begin{aligned}
X_\xi^T &= \langle 1^+\xi||\hat{T}^{\mathrm{el}\,5}||0^+\ \xi=0\rangle,\\
X_\xi^L &= \langle 1^+\xi||\hat{L}^5||0^+\ \xi=0\rangle.
\end{aligned} \tag{7}$$

$\xi=0,1$ is the isospin of the final nuclear state and θ_L is the laboratory scattering angle. A more detailed discussion of the PT observables and the D_K functions is given in Moss[9] and Bleszynski, Bleszynski, and Whitten.[10] In the single-collision approximations the D_K functions reduce to the approximate forms of Eq. (5). For momentum transfers less than 0.7 fm^{-1} the agreement between the full Glauber (solid curve) or DWIA (dashed curve) and the approximate form (dotted curve) is to within the accuracy of the data. (Those functions where the two calculations are virtually the same are indicated with an asterisk.) It is seen from the approximate forms of Eq. (5) that each D_K function is proportional to the product of the modulus of a single spin-dependent amplitude of the NN interaction and a form factor. It is this second factor which contains the nuclear structure information. Furthermore, the normally dominant spin-independent part of the NN interaction does not enter in the D_K functions. Additional calculations have been done where only the dominant $l=0$ component of the wave function was kept. It is found that at small momentum transfers this reproduces results using the full CK wave function. Under these

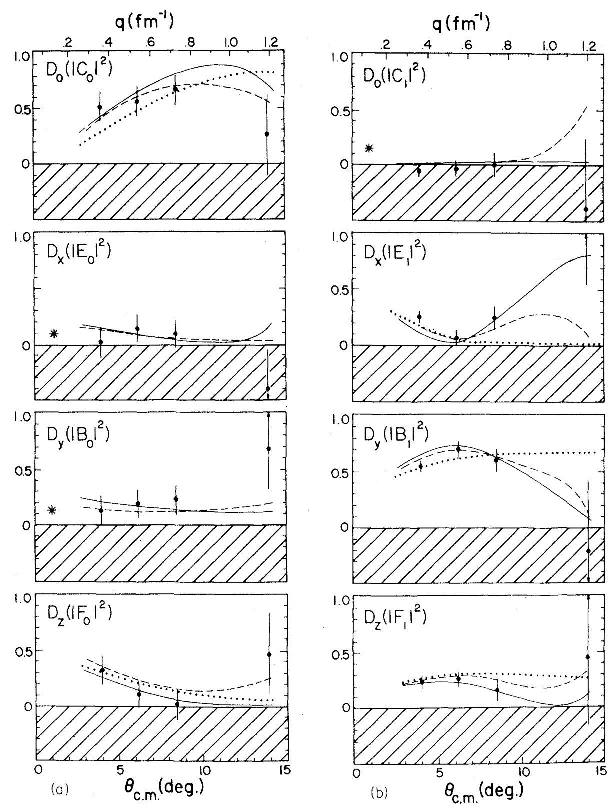

FIG. 2. D_K observables defined in Eq. (5) for (a) 1^+, $T=0$ (12.71 MeV), and (b) 1^+, $T=1$ (15.11 MeV) states. Shown are Glauber model (solid curve), DWIA (dashed curve), and the approximate forms of Eq. (5) (dotted curve).

conditions the two form factors given in Eq. (7) are equal and therefore cancel with the same factors in the cross section given by the approximate forms of Eq. (5). One therefore is left with relations between the D_K functions and a single spin-dependent NN amplitude, independent of any nuclear structure. In Fig. 2 the amplitude of the NN interaction to which a particular D_K function is proportional is shown in parentheses.

Our results relate to recent natural-parity inelastic- and elastic-scattering results. Effective interactions have been derived which incorporate nuclear matter effects in the local-density approximation. Typically large density-dependent effects are seen in the central spin-independent part of the force.[11] However, it is found that proton elastic data on ^{40}Ca at 500 MeV for the analyzing power A_y and spin rotation function Q require a phenomenological adjustment of the spin-orbit NN amplitude in order to improve agreement between theory and the data.[2,12] Our data for D_0, which is proportional to the spin-orbit strength in the single-collision approximation, are not precise enough to discriminate between the free NN spin-orbit values and those needed to fit the elastic-scattering data. We must conclude, in fact, that our measurements are in very good agreement with calculations based on free NN amplitudes at the 10% to 15% level. Improvements at the HRS facility should make it possible to increase our sensitivity significantly in future measurements.

We have demonstrated a new approach at intermediate energies to determine the effective nucleon-nucleon interaction for proton-nucleus reactions directly from PT observables. The approach presented here requires the complete measurement of polarization-transfer observables in order to study selectively the individual components of the full spin-dependent form of the nucleon-nucleon effective interaction. We have shown the first such complete set of measurements. As a result of high-efficiency and high-resolution polarimeters now available, further measurements will hopefully allow for a very sensitive and selective mapping of the effective interaction in nuclei and provide insights into the deficiencies of the theories.

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