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THE EXPERIMENTAL DETERMINATION OF THE EFFECTIVE NUCLEON-NUCLEON INTERACTION FOR P-NUCLEUS REACTIONS AT INTERMEDIATE ENERGIES

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Abstract: A complete measurement of the polarization transfer observables has been made for the first time in the (p,p′) reaction at intermediate energies. Measurements are reported for the $^{12}C(p,p')^{12}C$ reaction to the 1^+, T = 0(12.71 MeV) and 1^+, T = 1(15.11 MeV) states at 500 MeV at 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. To the extent of the validity of the single collision approximation, these amplitudes are compared directly to the free nucleon-nucleon amplitudes at small momentum transfers (<1 fm^{-1}).

1. Introduction

A great deal of effort is currently underway to assess the importance of medium-modified nucleon-nucleon (NN) amplitudes in interpreting proton-nucleus elastic and inelastic scattering data at intermediate energies[1,2]). The success achieved to date has been encouraging but the results often depend on theoretical interpretation or pure phenomenology. This is understandable since previous data included only cross sections and analyzing powers. There is a gross lack of sensitivity to the individual components of the NN interaction, especially the spin-dependent parts, in these types of measurements. In the case of elastic scattering or natural parity transitions the central part of the interaction dominates.

Polarization transfer measurements for unnatural parity states, however, offer selectivity and sensitivity to the individual pieces of the NN spin dependent interaction[3]). These measurements require high energies where the impulse approximation is expected to be valid, a high resolution spectrometer capable of resolving inelastic transitions, and a means of analyzing the polarization of the scattered protons. The first two requirements have been met for some time now but only recently have we been able to realize the third[4,5]).

We would like to report on the first such complete measurement of $D_{LL'}$, $D_{SS'}$, $D_{NN'}$, $D_{LS'}$, $D_{SL'}$, P, and A_y for the $^{12}C(p,p')^{12}C$ reaction to the 1^+, T = 0 (12.71 MeV) and 1^+, T = 1 (15.11 MeV) states at 500 MeV for momentum transfers of q < 1.2 fm^{-1}, and show that it is possible to construct four functions which are linear combinations of the polarization transfer observables which, in the limit of the single collision approximation, are each proportional to the strength of a single spin-dependent amplitude of the nucleon-nucleon interaction. In this fashion it is possible to compare the effective nucleon-nucleon spin-dependent amplitudes obtained from the proton-nucleus measurements with the free values.

2. Experimental Method

Beams of 500 MeV protons with initial polarization longitudinal (L), normal to the reaction plane (N), and sideways (S = NxL) 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[6]); and it is equally well suited to the present high resolution inelastic measurements.

Figure 1 shows the construction of the FPP residing at the exit of the HRS. It consists of eight planes of multi-wire 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 front end of the system maintains the energy resolution of the HRS (~100 keV), while the rear reconstructs 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%. It is the marriage of a high resolution spectrometer and a high efficiency polarimeter which allows the types of measurements which we report.

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 due to the precession of the spin in the 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 $360^\circ + 52^\circ$ 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 $0^+ \rightarrow 0^+$ 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[6]), as well as systematic checks of the FPP in general[5]), lead to the estimation that false asymmetries are less than 0.01.

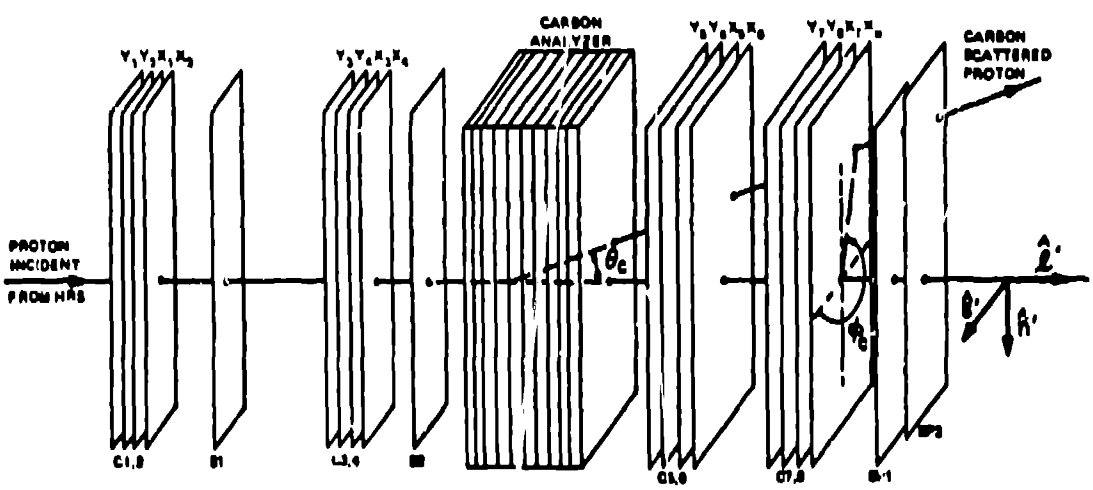

Fig. 1. Schematic of the HRS Focal Plane Polarimeter.

A new class of problems is encountered for inelastic scattering to discrete states involving background subtraction. For cases of poor peak to background, determination of the background polarization becomes quite important. The FPP is well suited to this task as it provides a measurement of the peak plus background polarization as well as the background polarization on either side of the peak. Figure 2 shows spectra of missing mass for three of the angles measured. The peak to background for the 15.11 MeV state decreases from 10:1 to 1:1 to 1:10 at 3.5°, 7.5° and 12°, respectively. The uncertainties introduced in the polarization transfer observables by the background correction were ~20% of the statistical uncertainty of the peak at the smallest angle and ~50% at the largest angle.

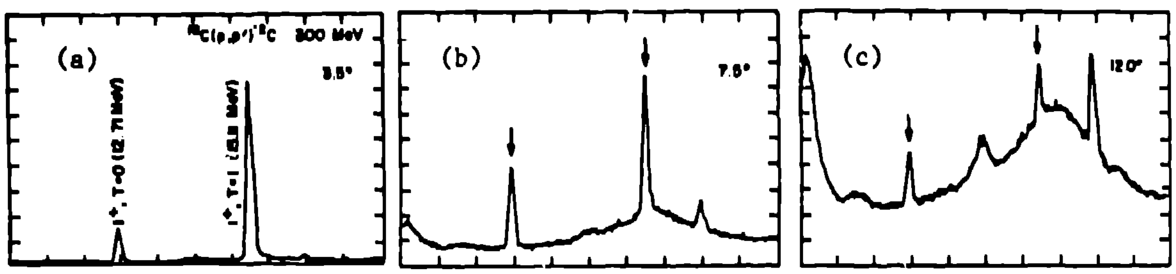

Fig. 2. Missing Mass Spectra at (a) 3.5°, (b) 7.5°, (c) 12°.

3. Results

Our preliminary data for the 1^+, T = 0 (12.71 MeV) and 1^+, T = 1 (15.11 MeV) states in ^{12}C are shown in Figs. 3a and 3b. In these figures we also show the functions $D_{ij'}$ defined as

$$D_{ij'} = Tr(\bar{F}\ \hat{\sigma}_i\ \bar{F}^+\ \hat{\sigma}_{j'})/Tr(\bar{F}\bar{F}^+) \qquad (1)$$

where $\bar{F}$ is the collision matrix for the reaction, $\hat{\sigma}_o = \hat{\sigma}_{o'} = 1$, $\hat{\sigma}_i$, i = S,N,L and $\hat{\sigma}_{j'}$, j' = S', N', L' are the cartesian components of the Pauli matrices of the incident and scattered proton. L(L') is parallel to the incident (scattered) momentum direction, N = N' is normal to the reaction plane and S(S') form a right-handed coordinate system with N and L (N' and L'). Tr denotes the trace with respect to the proton and nuclear spin projections.

In Figs. 4a and 4b we show the functions D_k for the T = 0 and T = 1 states related to the spin transfer observables $D_{ij'}$ by

$$D_o = \frac{1}{4}\left[1 + (D_{SS'} + D_{LL'})\cos\theta_L + D_{NN'} \quad (D_{LS'} - D_{SL'})\sin\theta_L\right]$$

$$D_x = \frac{1}{4}\left[1 + D_{SS'} - D_{LL'} - D_{NN'}\right] \qquad (2)$$

$$D_y = \frac{1}{4}\left[1 - (D_{SS'} + D_{LL'})\cos\theta_L + D_{NN'} + (D_{LS'} - D_{SL'})\sin\theta_L\right]$$

$$D_z = \frac{1}{4}\left[1 - D_{SS'} + D_{LL'} - D_{NN'}\right]$$

where θ_L is the laboratory scattering angle. These functions will be shown to be simply related to the NN amplitude in Sec. 4. The error bars reflect both statistical and systematic effects due to background subtraction.

4. Discussion

Shown on Figs. 3 and 4 are Glauber (solid curve) calculations of the polarization transfer observables using Cohen-Kurath wave functions and free N-N amplitudes from Arndt's SP82 solution.

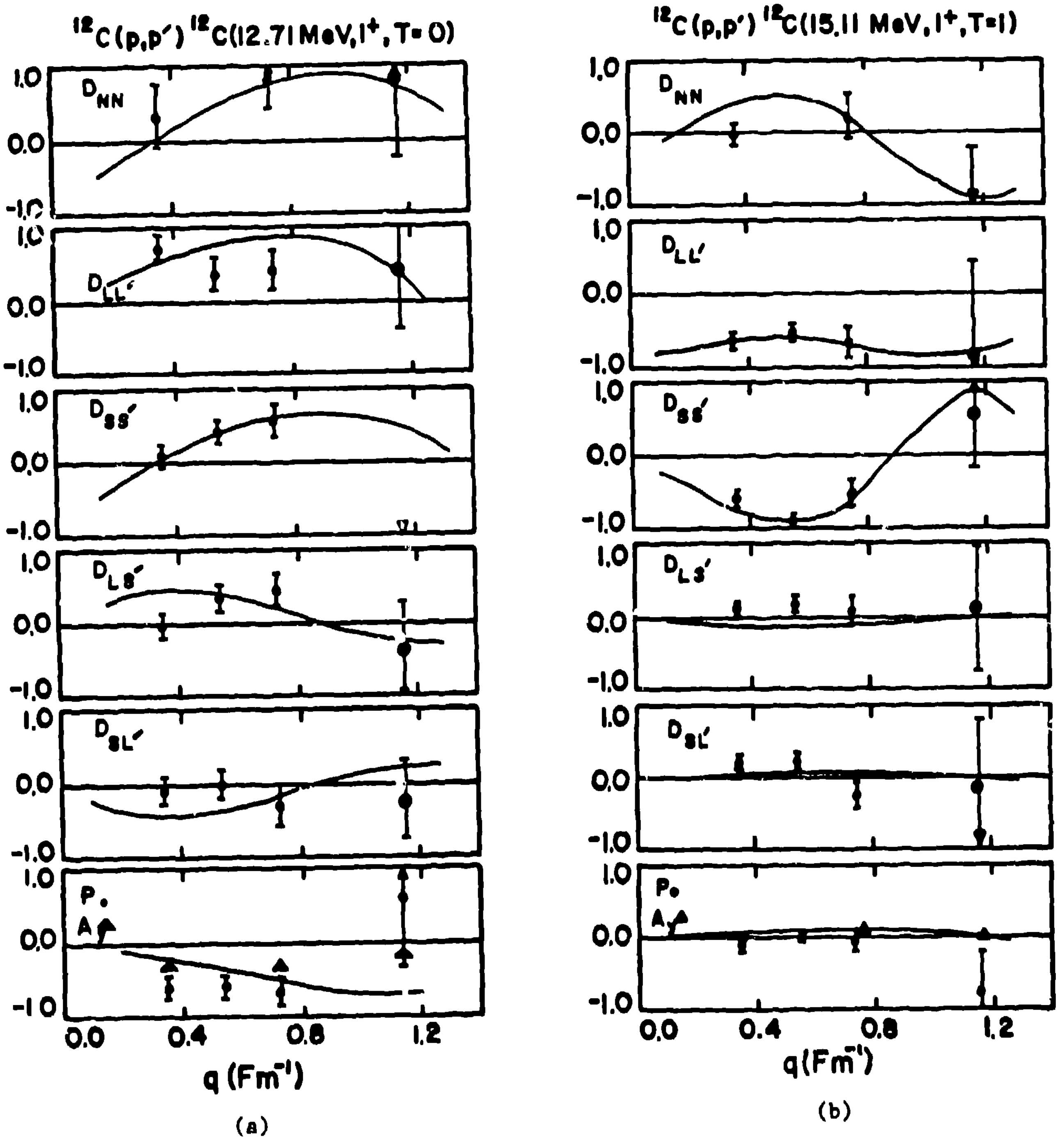

Fig. 3. Polarization transfer observables for (a) 1^+, T = 0 (12.71 MeV), and (b) 1^+, T = 1 (15.11 MeV) $^{12}C(p,p')^{12}C$ Reaction at 500 MeV.

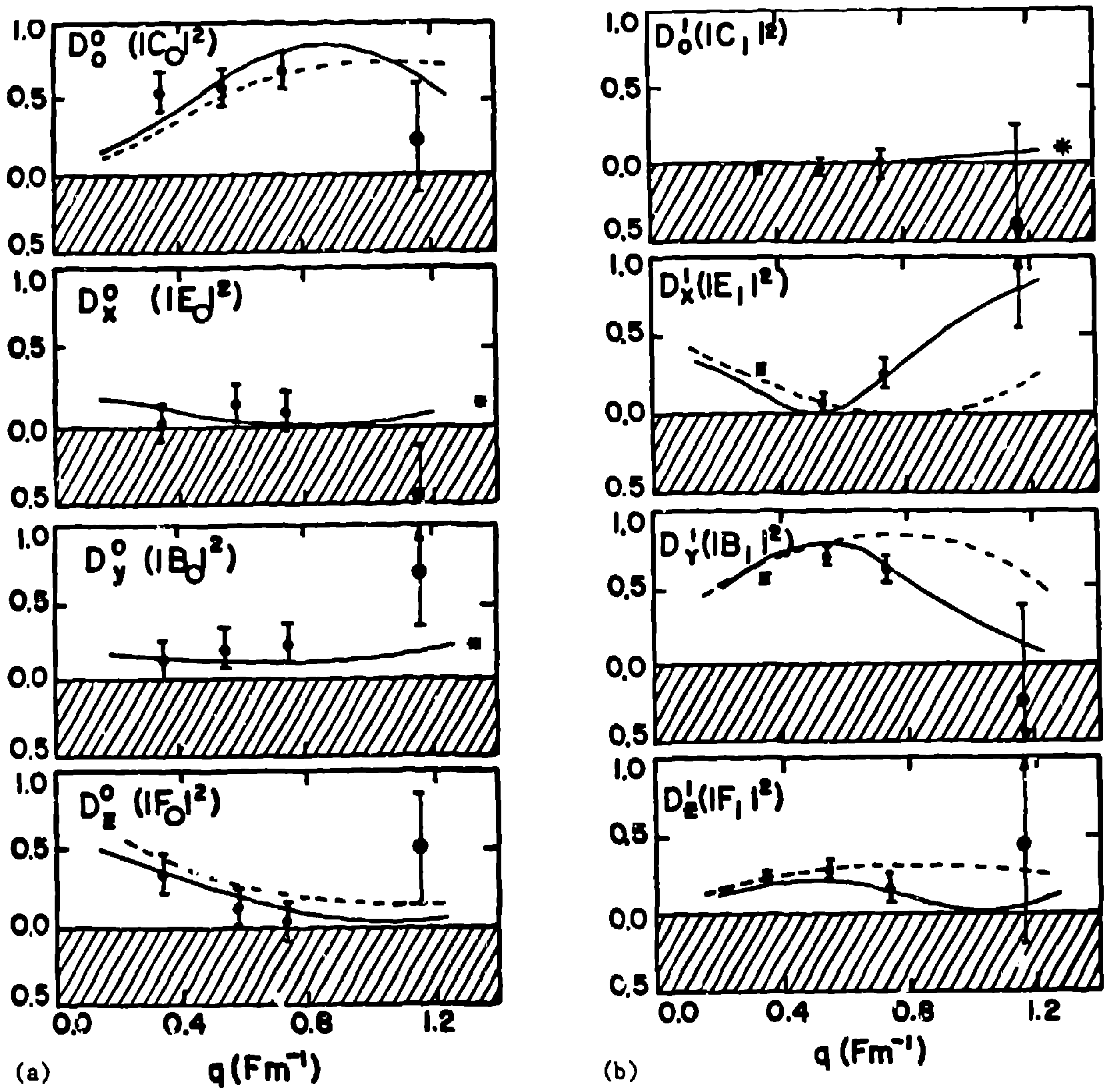

Fig. 4. D_k observables defined in Eq. (3) for (a) 1^+, T = 0 (12.71 MeV), and (b) 1^+, T = 1 (15.11 MeV) states. The solid curve is a full Glauber calculation; the dashed curve is the single collision approximation of Eqn. (10).

Several features of the data are noteworthy. As has been shown at 150 MeV[7]) and 400 MeV[8]), D_{NN} is close to zero at small momentum transfer indicative of a spin-flip transition. This is true for the 12.71 and 15.11 MeV states. $P \approx A_y$ in the case of the 15.11 but there is some evidence for $P - A_y$ for the 12.71 to be as large as -0.4 but with substantial error bars. This is similar to the differences seen at 150 MeV[9]) but opposite in sign. Glauber theory predicts this to be zero. There is also evidence for $D_{LS'} = -D_{SL'}$ as predicted in the adiabatic approximation[10]).

It is difficult to assess the implications of any agreement or disagreement without a simple model in which a direct correspondence is made between the observables and the ingredients of the theory. Although complete calculations can be done within the Glauber theory or DWIA frameworks, some insight is offered by the simple expressions for the observables developed in the single collision Glauber approximation or equivalently plane wave impulse approximation (PWIA).

The matrix elements of both of these approximations are given by

$$\tilde{M}(q) = \langle f | \tilde{F}_{NN}(q) e^{-i\vec{q}\cdot\vec{r}} | i \rangle \qquad (3)$$

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. $\bar{F}_{NN}(q)$ is the NN collision matrix which we parameterize as

$$\bar{F}_{NN}(q) = \bar{A}(q) + \bar{B}(q)(\hat{\sigma}_1 \cdot \hat{n})(\hat{\sigma}_2 \cdot \hat{n}) + \bar{C}(q)(\hat{\sigma}_1 \cdot \hat{n} + \hat{\sigma}_2 \cdot \hat{n})$$
$$+ \bar{E}(q)(\hat{\sigma}_1 \cdot \hat{q})(\hat{\sigma}_2 \cdot \hat{q}) + \bar{F}(q)(\hat{\sigma}_1 \cdot \hat{p})(\hat{\sigma}_2 \cdot \hat{p}) \tag{4}$$

where

$$\bar{q} = \bar{k}' - \bar{k}\ ,\ \bar{n} = \bar{k} \times \bar{k}'\ ,\ \hat{q} = \bar{q}/|\bar{q}|\ ,\ \hat{n} = \bar{n}/|\bar{n}|\ ,\ \hat{p} = \hat{q} \times \hat{n} \tag{5}$$

$\hat{\sigma}_1$ and $\hat{\sigma}_2$ are the projectile- and target-nucleon Pauli matrices respectively, and $k(k')$ is the incoming (outgoing) momentum vector. The components $\bar{A}(q)$, ...$\bar{F}(q)$ in Eq. (5) can be further decomposed into isoscalar and isovector parts by

$$\bar{A}(q) = A_0(q) + A_1(q)(\hat{\tau}_1 \cdot \hat{\tau}_2) \text{ etc.} \tag{6}$$

where $\hat{\tau}_1$ and $\hat{\tau}_2$ are the projectile- and target-nucleon isospin operators respectively.

The single collision approximation allows us to reduce the expressions for the spin transfer observables, $D_{ij'}$, into simple expressions for transitions to unnatural parity states given by[11]):

$$
\begin{aligned}
I_\xi D_{\hat{n}\hat{n}} &= [X_\xi^T]^2 [|C_\xi|^2 + |B_\xi|^2 - |F_\xi|^2] - [X_\xi^L]^2 |E_\xi|^2 \\
I_\xi D_{\hat{p}\hat{p}} &= [X_\xi^T]^2 [|C_\xi|^2 - |B_\xi|^2 + |F_\xi|^2] - [X_\xi^L]^2 |E_\xi|^2 \\
I_\xi D_{\hat{q}\hat{q}} &= [X_\xi^T]^2 [|C_\xi|^2 - |B_\xi|^2 - |F_\xi|] + [X_\xi^L]^2 |E_\xi|^2 \\
I_\xi D_{\hat{q}\hat{p}} &= -I_\xi D_{\hat{p}\hat{q}} = 2[X_\xi^T]^2 \,\mathrm{Im}\,(B_\xi C_\xi^*)
\end{aligned}
\tag{7}
$$

where

$$I_\xi = [X_\xi^T]^2 [|C_\xi|^2 + |B_\xi|^2 + |F_\xi|^2] + [X_\xi^L]^2 |E_\xi|^2 \tag{8}$$

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[12]):

$$X_\xi^T = \langle 1^+ \;\xi \,||\hat{T}^{5e\ell}||\, 0^+ \;\xi = 0\rangle \qquad (9)$$

$$X_\xi^L = \langle 1^+ \;\xi \,||\hat{L}^{5mag}\,||\, 0^+ \;\xi = 0\rangle$$

$\xi = 0,1$ is the isospin of the final nuclear state. A simple rotation transforms the $(\hat{q},\hat{n},\hat{p})$ system into $(\hat{S},\hat{N},\hat{L})$.

Within the context of the single collision approximation, the D_k functions defined in Eq. (2) reduce to the following simple expressions[3]:

$$D_o^\xi = \frac{[X_\xi^T]^2\,|C_\xi|^2}{I_\xi}$$

$$D_x^\xi = \frac{[X_\xi^L]^2\,|E_\xi|^2}{I_\xi} \qquad (10)$$

$$D_y^\xi = \frac{[X_\xi^T]^2\,|B_\xi|^2}{I_\xi}$$

$$D_z^\xi = \frac{[X_\xi^T]^2\,|F_\xi|^2}{I_\xi}\;.$$

The single collision approximate forms of the D_k functions are shown in Fig. 4 (dashed curve). Out to 0.7 fm^{-1} or better, the agreement between the full Glauber calculation (solid curve) and the approximate form is to within the accuracy of of the data. (Those functions where the two calculations are virtually the same are indicated with an asterisk). To this extent, it is possible to compare the magnitude of the individual components of the NN amplitudes with the data, since from Eqn. (10) it is seen that each D_k is proportional to the strength of a single spin-dependent amplitude of the NN interaction, so that each curve of Fig. 4 is sensitive to one and only one NN amplitude. In Fig. 4 the amplitude to which the particular D_k is proportional is shown in parentheses.

In the local density approximation, a large density dependent effect is seen in the central spin-independent part of the force. However, the central spin orbit is unchanged from its free values[1]). Phenomenologically it is found[2]) that a 50% increase in the central spin orbit force around 0.2 to 0.6 fm^{-1} is needed to fit elastic cross section and analyzing power data at 500 MeV. A similar result holds for the Q elastic data at 500 MeV[6]). Our data for D_o is only suggestive of such an effect. More precise measurements are needed. 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.

The data shown in Fig. 3 represent approximately 200 hours of data taking. It is therefore feasible to envision more precise measurements over several nuclear transitions to investigate the systematics of the effective NN interaction in proton nucleus scattering.

5. Conclusions

We believe we have demonstrated a new approach at intermediate energies to determine the effective nucleon-nucleon interaction for proton-nucleus reactions directly from polarization transfer observables. This impacts directly on the question of the validity of the impulse approximation at intermediate energies. Due to the high-efficiency, high-resolution polarimeters now available, these measurements are feasible and may provide the insight into the known deficiencies of the theories. We have shown the first such complete set of measurements. Further measurements will hopefully allow for a very definitive mapping of these effective NN interactions in nuclei.

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