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Observed relations between proton spin observables in natural parity transitions in ^{40}Ca$(p,p')^{40}$Ca and ^{208}Pb$(p,p')^{208}$Pb reactions at 500 MeV

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A set of proton spin observables has been measured for the inelastic transitions to the 3^- (3.73 MeV) and 5^- (4.48 MeV) states in the ^{40}Ca$(p,p')^{40}$Ca reaction and for the 3^- (2.61 MeV) state in the ^{208}Pb$(p,p')^{208}$Pb reaction at 497 MeV. The interval of laboratory scattering angles was 6 to 20° for ^{40}Ca and 2.5 to 14° for ^{208}Pb. Comparison of these observables reveals that they satisfy relations analogous to those valid in the elastic scattering of spin $\frac{1}{2}$ and spin 0 objects. The origin of these observed relations is explained.

[NUCLEAR REACTIONS Relations between spin observables in ^{40}Ca$(p,p')^{40}$Ca and ^{208}Pb$(p,p')^{208}$Pb at 500 MeV.]

Until recently, experiments on nuclear scattering of protons at intermediate energies[1] have been limited to the measurement of two observables, the differential cross section and the analyzing power. These measurements do not provide the complete information on the collision matrix describing a given process. Already the elastic scattering of protons from a spin zero nucleus is described by two complex amplitudes, and the measurement of a third observable, the spin rotation function[2] Q, is needed to determine the collision matrix up to a phase factor. The first such measurements were reported recently for the elastic scattering of protons from ^{40}Ca and ^{208}Pb at 500 MeV.[3,4]

Measurements of the proton spin observables in (p,p') reactions could provide rich information on the structure of excited nuclear states.[5] In contrast to elastic scattering of protons from a spin zero target, where only three independent observables exist, for a given (p,p') reaction eight independent spin observables can be measured if the target spins are not analyzed. These are the differential cross section and seven components of the proton depolarization tensor: $D_{0N'}(P)$, $D_{N0}(A_y)$, $D_{LS'}(A)$, $D_{SL'}(R')$, $D_{SS'}(R)$, $D_{LL'}(A')$, and $D_{NN'}(D)$.[6,7] (The alternate names of these parameters suggested by Wolfenstein are given in parentheses.) The latter observables relate the components of the polarization of the incident proton beam: p_S, p_N, p_L, and those of the scattered beam: $p_{S'}$, $p_{N'}$, $p_{L'}$, through

$$p_{S'} = [D_{SS'}p_S + D_{LS'}p_L]/(1+p_N D_{N0}) \ , \quad (1a)$$

$$p_{N'} = [D_{NN'}p_N + D_{0N'}]/(1+p_N D_{N0}) \ , \quad (1b)$$

$$p_{L'} = [D_{LS'}p_S + D_{LL'}p_L]/(1+p_N D_{N0}) \ . \quad (1c)$$

Here the indices S, N, L and S', N', L' refer to the axes of two right-handed Cartesian frames with L and L' pointing along the incident $\vec{k}_i$ and final $\vec{k}_f$ proton laboratory momenta, respectively, and the axis $N=N'$ is parallel to $\vec{k}_i \times \vec{k}_f$. The functions $D_{mm'}$ are

$$D_{mm'} = \mathrm{Tr}(\hat{F}\sigma_m \hat{F}^{+}\sigma_{m'})/\mathrm{Tr}(\hat{F}\hat{F}^{+}) \ , \tag{2}$$

where σ_m and $\sigma_{m'}$ are the components of the proton Pauli matrix with respect to S, N, L and S', N', L' axes, and $\hat{F}$ is the collision operator for the transition.

We present here the first results of the measurement of the observables $D_{LS'}$, $D_{SL'}$, $D_{SS'}$, $D_{LL'}$, and $D_{0N'}$ for the (p,p') transitions to the 3^-(3.73 MeV) and 5^-(4.48 MeV) states in ^{40}Ca and to the 3^-(2.61 MeV) state in ^{208}Pb at 497 MeV. The experiment was performed using the high resolution spectrometer and a newly installed focal plane polarimeter[8] at the Clinton P. Anderson Meson Physics Facility. The experimental details have been described previously.[3] The main purpose of this Communication is to report that for inelastic scattering the measured values of these observables obey relationships known to hold for elastic scattering, and to interpret this result.

As a consequence of the parity invariance of the interaction, the following relations are valid for the elastic scattering of a spin $\frac{1}{2}$ projectile from a spin zero object:

$$D_{LS'} = -D_{SL'} \quad (\text{equivalently } A=-R') \ , \tag{3a}$$

$$D_{0N'} = D_{N0'} \quad (P=A_y) \ , \tag{3b}$$

$$D_{SS'} = D_{LL'} \quad (R=A') \ , \tag{3c}$$

$$D_{NN'} = 1 \quad (D=1) \ . \tag{3d}$$

The data from our previous experiment on elastic scattering[3,9] are quite consistent with the above equations.

The analogous comparisons between the $D_{LS'}$ and $D_{SL'}$, as well as between $D_{SS'}$ and $D_{LL'}$ for the three inelastic transitions discussed here, reveal that Eqs. (3a) and (3c) are also well satisfied, as shown in Figs. 1 and 2. A comparison, not presented here, shows that our data for the polarization is in agreement with the data for the analyzing power for the 3^- and 5^- transitions in ^{40}Ca,[10] so that Eq. (3b) is also well satisfied.

The proper understanding of the origin of these observed relations between the proton spin observables is of considerable importance. In particular, from among Eqs. (3a)–(3d), one should distinguish between those relations which are related to the general symmetries of the reaction theory and those which are specific to the excitation mechanism of a given transition.

In order to connect the relations (3) with the properties of the components of the collision matrix $\hat{F}$ we

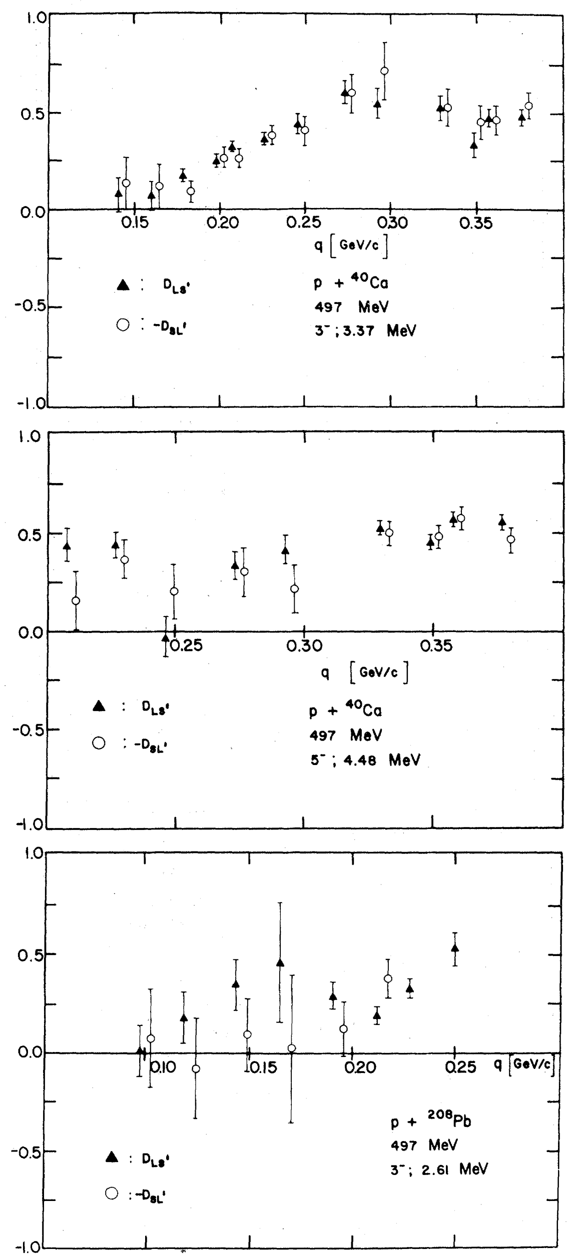

FIG. 1. Comparison between the observables $D_{LS'}$ (triangles) and $-D_{SL'}$ (circles). Originally the data were taken at the same angles. In figures the triangles are shifted with respect to the circles to make the drawings more transparent.

shall follow the approach of Ref. 5 and express $\hat{F}$ in a general form consistent with rotational invariance as a scalar product of two tensor operators acting in the projectile and target spin spaces:

$$\hat{F} = \hat{F}_0\sigma_0 + \hat{F}_x\sigma_x + \hat{F}_y\sigma_y + \hat{F}_z\sigma_z \ . \tag{4}$$

Here $\sigma_0 = \hat{1}$ and σ_x, σ_y, and σ_z are the components of the proton Pauli matrix in the right-handed coordinate frame with the z axis parallel to $\vec{k}_i + \vec{k}_f$ and the

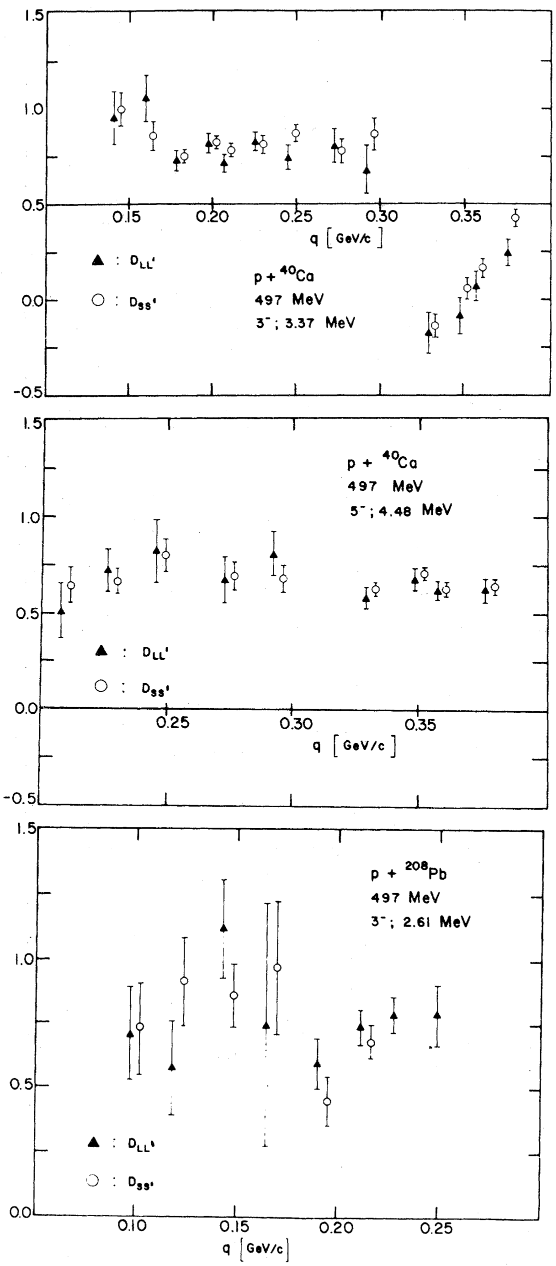

FIG. 2. Same as in Fig. 1 but for the observables $D_{LL'}$ and $D_{SS'}$.

y axis parallel to $\vec{k}_i \times \vec{k}_f$; and $\hat{F}_m$ are matrices connecting the spin spaces of the initial and excited nucleus. [In the particular case of the elastic scattering of a spin $\frac{1}{2}$ projectile from a spin zero nucleus, Eq. (4) reduces to the familiar form $\hat{F} = F_0\sigma_0 + F_y\sigma_y$, where F_0 and F_y are the central and spin orbit components of the collision matrix $\hat{F}$.] From the definitions of the observables $D_{mm'}$ [Eq. (2)] and Eq. (4), it follows, after somewhat lengthy algebra, that the quantities of interest are

$$D_{LS'} + D_{SL'} = 4\,\mathrm{Re}(h_{xz}) \ , \tag{5a}$$

$$D_{0N'} - D_{N0} = 4\,\mathrm{Im}(h_{xz}) \ , \tag{5b}$$

$$D_{SS'} - D_{LL'} = 2(h_{xx} - h_{zz}) \ , \tag{5c}$$

$$1 - D_{NN'} = 2(h_{xx} + h_{zz}) \ . \tag{5d}$$

Here h_{xx}, h_{zz}, and h_{xz} are the functions

$$h_{mn}(\vec{k}_i, \vec{k}_f) = \mathrm{Tr}'(\hat{F}_m \hat{F}_n^+)/\mathrm{Tr}(\hat{F}\hat{F}^+) \ , \tag{6}$$

and Tr′ denotes the trace with respect to the nuclear spin projections. The structure of Eqs. (5a)–(5d) is such that the relations (3a) and (3b) will be satisfied provided that

$$h_{xz} = 0 \ , \tag{7}$$

in other words, if there is no interference between the matrix elements of $\hat{F}_x$ and $\hat{F}_z$. On the other hand, our finding that Eq. (3c) is approximately valid means that either $\hat{F}_x$ and $\hat{F}_z$ are both very small (compared to $\hat{F}_0$ and $\hat{F}_y$) or that the functions h_{xx} and h_{zz} are approximately equal.

A simple general condition has recently been found under which Eq. (7) and consequently Eqs. (3a) and (3b) are valid for (p,p') reactions.[11] The only assumption (apart from the parity, time reversal, and rotational invariance) needed in any reaction theory to get $h_{xz} = 0$ is adiabaticity (target excitation energy is small compared to the incident projectile energy). Thus the relations (3a) and (3b) have a general character and do not provide any information on the structure of the excited states. They hold for all (natural and unnatural parity) transitions at high energies to the extent that the adiabatic approximation is valid.

On the other hand, the relation (3c) turns out to be valid only approximately for the natural parity transitions discussed here. Its origin can be explained by the analysis of the matrix elements of the operators $\hat{F}_0$, $\hat{F}_x$, $\hat{F}_y$, and $\hat{F}_z$, which is discussed in detail in Ref. 5. In the single collision (impulse) approximation, the matrix elements of the operators $\hat{F}_m$, $m = 0,x,y,z$, between the initial $|J_i = 0, M_i = 0, T_i = 0\rangle$ and final $|J_f = J, M_f = M, T_f = T\rangle$ nuclear states are

$$\langle J^\pi, M, T|\hat{F}_0|0^+, 0, 0, \rangle = A\,\alpha_T(q) c_{JM}^{(0)} \langle J^\pi T||\hat{M}_{JT}(q)||0^+0\rangle + A\,\gamma_T(q) c_{JM}^{(-)} \langle J^\pi T||\hat{T}_{JT}^{\mathrm{mag5}}(q)||0^+0\rangle \ , \tag{8a}$$

$$\langle J^\pi, M, T|\hat{F}_x|0^+, 0, 0\rangle = 0 \ , \tag{8b}$$

$$\langle J^\pi, M, T|\hat{F}_y|0^+, 0, 0\rangle = iA\,\gamma_T(q) c_{JM}^{(0)} \langle J^\pi T||\hat{M}_{JT}(q)||0^+0\rangle + iA\,\beta_T(q) c_{JM}^{(-)} \langle J^\pi T||\hat{T}_{JT}^{\mathrm{mag5}}(q)||0^+0\rangle \ , \tag{8c}$$

$$\langle J^\pi, M, T|\hat{F}_z|0^+, 0, 0\rangle = A\,\epsilon_T(q) c_{JM}^{(+)} \langle J^\pi T||\hat{T}_{JT}^{\mathrm{mag5}}(q)||0^+0\rangle \ . \tag{8d}$$

Here A is the target mass number, and α_T, β_T, γ_T, and ϵ_T are the conventional isoscalar components of the NN amplitude.

The constants $c_{JM}^{(\alpha)}$, $\alpha=0$, $+$, and $-$, are given by

$$c_{JM}^{(0)} = i^J[4\pi(2J+1)]^{1/2} d_{M0}^J(\pi/2) \ ,$$

$$c_{JM}^{(\pm)} = \tfrac{1}{2} i^J[4\pi(2J+1)]^{1/2}[d_{M1}^J(\pi/2) \pm d_{M-1}^J(\pi/2)] \ ,$$

where $d_{MM'}^J$ are the Wigner rotation matrices, and $\langle J^\pi T || \hat{M}_{JT}(q) || 0^+, 0\rangle$ and $\langle J^\pi T || \hat{T}_{JT}^{\text{mag5}} || 0^+ 0\rangle$ are the reduced matrix elements of the Coulombic and axial transverse magnetic multipole operators, defined as in Ref. 12, and J, M, and T denote the spin, spin projection, and isospin of the excited nuclear state. Thus, in the single collision approximation,[13]

$$h_{xx} = 0 \ , \tag{9}$$

and from the above equations we find that

$$D_{SS'} - D_{LL'} = -2h_{zz} = \frac{-R(q)|\epsilon_T|^2/(|\alpha_T|^2+|\gamma_T|^2)}{1+R(q)(|\gamma_T|^2+|\beta_T|^2+|\epsilon_T|^2)/(|\alpha_T|^2+|\gamma_T|^2)} \ , \tag{10}$$

where

$$R(q) = \frac{1}{2}\left|\frac{\langle J^\pi T || \hat{T}_{JT}^{\text{mag5}}(q) || 0^+ 0\rangle}{\langle J^\pi T || \hat{M}_{JT}(q) || 0^+ 0\rangle}\right|^2 \ . \tag{11}$$

Thus the approximate equality between $D_{SS'}$ and $D_{LL'}$ can be understood as a consequence of the fact that $\hat{F}_z$ of the collision matrix is small compared with $\hat{F}_0$ and $\hat{F}_y$. From Eqs. (8) it is seen that the matrix elements of $\hat{F}_z$ are proportional to the product of the spin-spin interaction component $\epsilon_T(q)$ of the NN amplitude and the axial multipole magnetic form factor, while the matrix elements of $\hat{F}_0$ and $\hat{F}_y$ contain terms proportional to the products of the Coulombic form factor and the central $\alpha_T(q)$ and the spin orbit $\gamma_T(q)$ components of the NN amplitude. From Eq. (10) we see that the quantity $D_{SS'} - D_{LL'}$ is proportional to the ratio $R(q)$ of the two relevant form factors (which is expected to be small for the collective natural parity transitions) and the ratio

$$\frac{|\epsilon_T(q)|^2}{|\alpha_T(q)|^2 + |\gamma_T(q)|^2} \ ,$$

which is small in the interval of momentum transfers considered here at 500 MeV.[14]

More accurate determination of the parameters $D_{SS'}$ and $D_{LL'}$ might reveal some deviations from the equality (3c). Also, precise determination of the quantity $D_{NN'}$, which was not measured in our experiment, should provide additional information on the strength of the axial magnetic transition density.

In summary, the data exhibited for ^{40}Ca and ^{208}Pb follow the relations (3a), (3b), and (3c). We have shown that the relations (3a) and (3b) are true, in general, for both natural and unnatural parity inelastic transitions, whenever the adiabatic approximation is valid. (Note, however, that knock-on exchange contributions may violate this approximation.) The relation (3c), on the other hand, is specific to the transitions measured here. It depends on the small relative strength of the spin dependent excitations in natural parity transitions and on the relative weakness of the spin-spin force. It should be mentioned finally that, due to the vanishing of the $\hat{F}_x$ component of the collision matrix for natural parity transitions, relations (3a) and (3b) are more trivial for natural parity transitions than for the unnatural parity transitions where both $\hat{F}_x$ and $\hat{F}_z$ are important.[5]

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