INELASTIC SCATTERING

SIMULTANEOUS MEASUREMENTS OF $(\vec{p},\vec{p}\,')$ AND $(\vec{p},p'\gamma)$ OBSERVABLES FOR THE 15.11 MeV, 1^+, T=1 STATE IN ^{12}C AT 200 MeV

S.P. Wells, S.W. Wissink, A.D. Bacher, G.P.A. Berg, A. Betker, S.M. Bowyer,
S. Chang, C. Foster, W. Franklin, J. Liu, W. Schmitt, and E.J. Stephenson
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

J. Beene, F. Bertrand, M. Halbert, D. Horen, P. Mueller,
D. Olive, D. Stracener, and R. Varner
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

J. Lisantti
Centenary College of Louisiana, Shreveport, Louisiana 71134

K. Hicks
Ohio University, Athens, Ohio 45701

Studies of $(\vec{p},\vec{p}\,')$ spin observables have provided much valuable information about the NN interaction inside the nuclear medium.[1] There are, however, only eight independent quantities that can be determined in singles $(\vec{p},\vec{p}\,')$ measurements. For transitions to discrete final states of non-zero spin J, additional information on the scattering amplitude can be obtained by studying the polarization state of the recoil nucleus. This can be done via measurements of the angular correlation between the scattered proton and the particle(s) emitted in the nuclear deexcitation, as in reactions of the type $(\vec{p},p'\gamma)$ in which the polarizations of the outgoing proton and photon are not detected. Such measurements are now technically quite feasible. Of particular interest are studies of transitions with simple spin sequences, such as $0^+ \rightarrow 1^+$; in this case, it has been recently shown[2] that certain $(\vec{p},p'\gamma)$ measurements, when combined with the complete set of $(\vec{p},\vec{p}\,')$ observables discussed above, provide sufficient information to specify completely the scattering amplitude in a model-independent manner. For IUCF experiment E354, we therefore proposed to carry out simultaneous measurements of the $(\vec{p},\vec{p}\,')$ spin-transfer observables and the $(\vec{p},p'\gamma)$ coincident observables for excitation of the 15.11 MeV, 1^+, T=1 state in ^{12}C at a proton bombarding energy of 200 MeV, using the K600 spectrometer and its associated focal plane polarimeter (FPP) to detect the scattered protons, and a system of BaF$_2$ detectors[3] surrounding the K600 target to detect the coincident γ–rays.

Because eleven quantities must be determined to describe the scattering amplitude fully for a $0^+ \rightarrow 1^+$ transition, one sees that $(\vec{p},p'\gamma)$ observables can provide information that is not accessible in $(\vec{p},\vec{p}\,')$ singles measurements. In general, the scattering amplitude for $(p,p\,')$ transitions can be divided into two parts: terms which couple the proton spin to unit vectors that lie in the reaction plane; and terms in which the proton spin couples to the unit vector normal to the scattering plane. It is the relative phases between these two sets of terms that can not be determined via $(\vec{p},\vec{p}\,')$ measurements alone. A bit of algebra reveals[2] that if the coincident γ–rays are detected at some angle out of the reaction plane, yet not normal to it, then the photon polarization tensor will have negative parity. In this case, the sideways and longitudinal analyzing powers D_{0S} and D_{0L} (or A_x and A_z, respectively), which must vanish identically in singles measurements if parity is conserved, may be non-zero in $(\vec{p},p'\gamma)$ studies. Contained in these asymmetries are the relative phases just discussed. By placing three of the BaF_2 arrays at an angle of 45° out of the scattering plane, we were thus able to map out the angular distribution of these previously unmeasured asymmetries.

Because $0^+ \rightarrow 1^+$ transitions are of unnatural parity, they occur predominantly without an orbital angular momentum change, or $\Delta L = 0$. As such, the differential cross sections for exciting these states are very forward-peaked. To obtain appreciable yields for these studies, it was therefore necessary to detect the inelastically scattered protons at small angles in the laboratory frame. Moreover, because the BaF_2 detectors were positioned close to the target chamber, it was also necessary to deposit the unscattered beam in a well-shielded beam dump far downstream from the target. To meet both of these requirements, we utilized the septum magnet system of the K600 spectrometer.[4] In this mode of operation, we were able to detect cleanly the coincident γ–rays associated with protons scattered at laboratory angles as small as $\theta_p \approx 5°$.

In April 1993, we were given 28 shifts of beam to carry out measurements of $(\vec{p},\vec{p}\,')$ singles spin-observables and $(\vec{p},p'\gamma)$ coincident observables for the 1^+ states in ^{12}C at 200 MeV. Measurements were made at proton scattering angles of $\theta_p = 5°$, $8°$, $11°$, and $15°$. An additional 9 shifts of beam of the same energy were given to us in October 1993 to improve the statistical accuracy of some observables for the two largest scattering angles. At each of the angles studied, data were taken with three of the BaF_2 arrays arranged in two different geometric configurations; the fourth array was always positioned directly above the target. The two configurations allowed for a larger number of $(\vec{p},p'\gamma)$ observables to be investigated, though each set of measurements placed different constraints on the orientation of the incident beam polarization vector.

For the first set of observables, which required that the incident proton beam be polarized vertically (normal to the scattering plane), the three BaF_2 arrays were positioned *in* the scattering plane at angles of $\theta_{lab} = 60°$, $100°$, and $140°$ on beam right, with the front face of each array 56 cm from the center of the target. Due to the large charged-particle flux emitted at forward angles from the 93.8 mg/cm^2 thick ^{nat}C target, it was necessary to cover the front face of the BaF_2 array at 60° with 3.6 cm of aluminum, which was sufficient to stop protons of energies up to ~100 MeV. In this configuration, we made measurements of the singles observables $d\sigma/d\Omega_p$, A_y, P, and $D_{NN'}$, and simultaneously measured the coincident double-differential cross section $d^2\sigma/d\Omega_\gamma d\Omega_p$ and coincident asymmetry $A_y(\hat{k})$ as a function of photon angle in the scattering plane. (Here $\hat{k}$ is the momentum direction of the emitted photon.) We also measured a coincident cross section and asymmetry using the BaF_2 array placed directly above the target. In this case, both observables can be expressed, in a model-independent way, in terms of the normal-component $(\vec{p},\vec{p}\,')$ spin-transfer coefficients.[2] In particular, the coincident asymmetry (*i.e.*, the relative change in the coincident cross section caused by reversing the direction of the incident beam spin), measured when the photon is emitted along the normal to the scattering plane, takes the form[2]

$$A_y(\hat{n}) = -\frac{(P - A_y)}{(1 - D_{NN'})} \ . \tag{1}$$

Since we were simultaneously measuring these normal-component singles observables in the FPP, we thus obtained a valuable internal consistency check on the data. Shown in Fig. 1 are the measured values of the coincident yield asymmetry as described above, plotted as a function of the center-of-mass proton scattering angle, θ_{cm}. Also shown is the particular combination of $(\vec{p}, \vec{p}\,')$ observables presented in Eq. 1, deduced from the FPP yields. The excellent agreement seen between these two completely independent determinations of the same physical quantity gives us confidence that our measurements of both $(\vec{p}, \vec{p}\,')$ and $(\vec{p}, p'\gamma)$ observables are reasonable and consistent.

For the second set of observables, we used an incident proton beam which had its polarization vector rotated (via the high-energy beamline spin-precession solenoids) *into* the scattering plane. We chose to make measurements with the incident proton polarization in three different orientations, at in-plane angles of $\Phi = 53°$, $117°$, and $169°$ with respect to the incident beam direction. With these polarization directions, we were able to determine

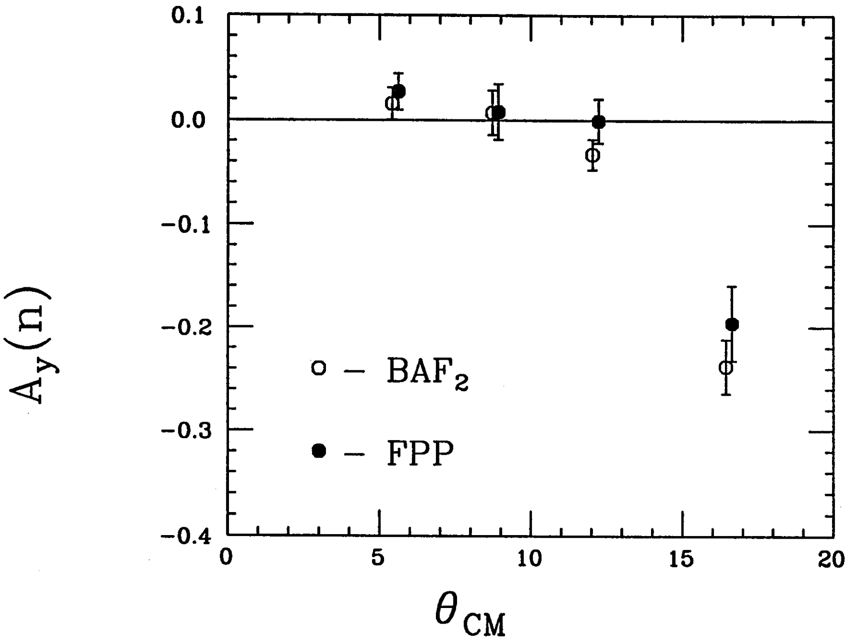

Figure 1. The normal-component coincident asymmetry plotted versus θ_{cm}. The open circles represent the coincident yield asymmetry directly measured by the BaF$_2$ array positioned along the normal to the reaction plane, while the closed circles represent a combination of singles observables (see Eq. 1 in the text) measured with the FPP. The two data sets are displaced slightly in angle for plotting clarity.

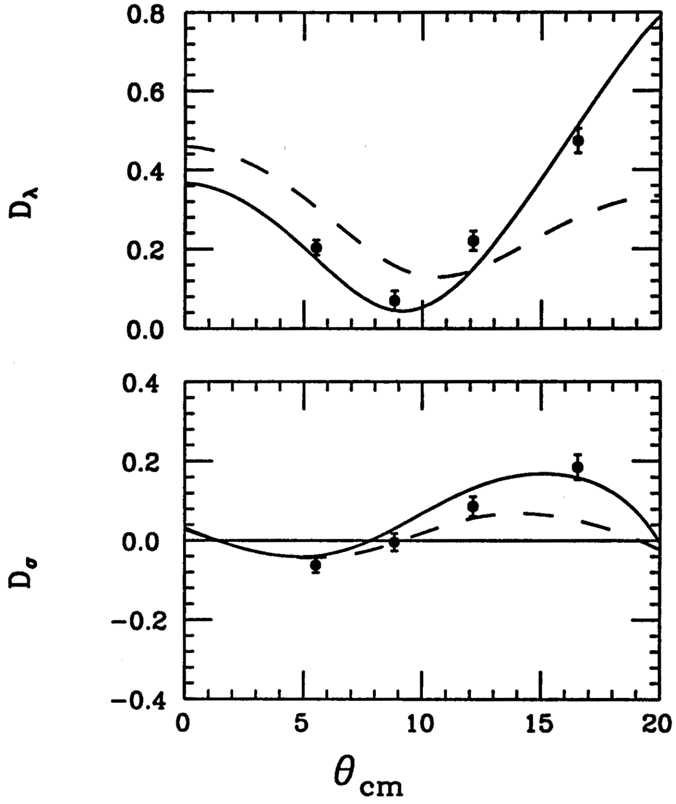

Figure 2. Two linear combinations of the in-plane singles spin-transfer coefficients (see Eq. 2 in text) plotted versus θ_{cm}. Solid lines represent calculations done in a relativistic formalism (DREX), and dashed lines a nonrelativistic formalism (DW81).

two linear combinations of the four in-plane spin-transfer coefficients using the FPP,

$$D_\lambda = D_{LL'}\ \sin\alpha + D_{LS'}\ \cos\alpha$$

$$D_\sigma = D_{SL'}\ \sin\alpha + D_{SS'}\ \cos\alpha \tag{2}$$

where $\alpha = 264°$ is the angle of spin precession experienced by the scattered proton flux in the dipole field of the K600 spectrometer. In Fig. 2 we show our data for these observables, plotted as a function of θ_{cm}. Also included on this plot are two distorted-wave impulse approximation (DWIA) calculations,[5] performed using either a relativistic (DREX) or nonrelativistic (DW81) formalism. The large differences seen between the two predictions, relative to the size of the uncertainties in the data, suggest the extent to which these measurements may help pinpoint weaknesses present in the underlying theory, or in approximations made in carrying out the particular calculations.

For this second data set, with the incident polarization vector horizontal, we supported the three BaF_2 arrays at an angle of 45° out of the scattering plane. In this case, the BaF_2 arrays were positioned on beam right at angles (projected into the scattering plane) of $\theta_{lab} = 41°$, 88.3°, and 140°. Due to space limitations, we were forced to place the centers of the arrays at distances of 79 cm, 66 cm, and 66 cm from the target, respectively. In this configuration, the BaF_2 arrays were used to map out an angular distribution of the coincident yield asymmetries to determine the sideways and longitudinal analyzing powers D_{0S} and D_{0L} discussed earlier. The use of three different incident beam polarization

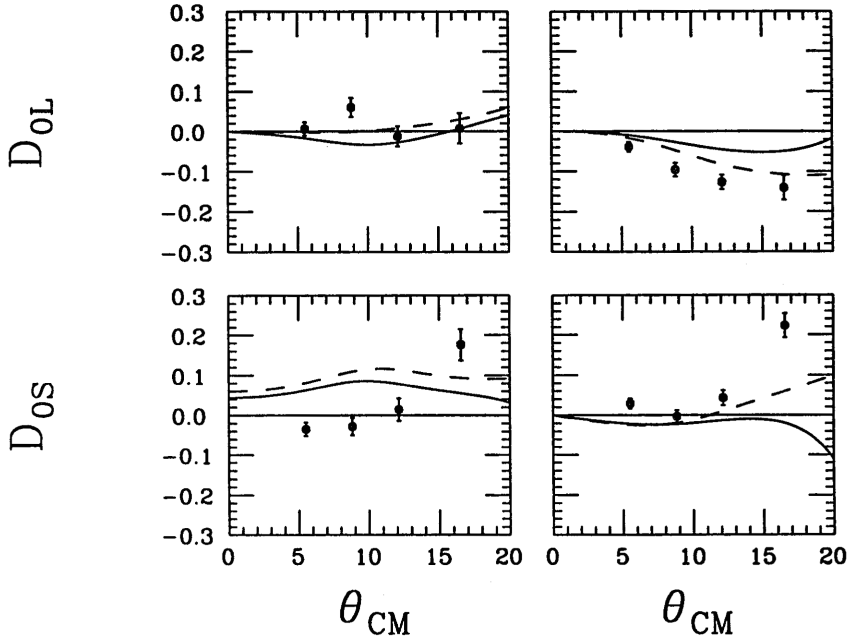

Figure 3. The four observables that describe the 45° out-of-plane coincident asymmetry, plotted versus θ_{cm}. The physical interpretations of the various coefficients are described in the text.

orientations allowed us to separate the sideways and longitudinal pieces, and also provided another check of internal consistency, in that only two orientations were actually needed. This is because the asymmetry can have only a simple sinusoidal dependence on both the incident proton spin orientation and the direction of the emitted photon; therefore just four coefficients are necessary to describe the asymmetry completely along a cone 45° out of the scattering plane. Shown in Fig. 3 are these coefficients plotted as a function of θ_{cm}. These observables represent the asymmetry that would be measured if the beam were polarized purely along the longitudinal or sideways directions (upper or lower graphs, respectively) and if the photon was emitted in the average-momentum ($\hat{K}$) or momentum-transfer ($\hat{q}$) planes (left or right graphs, respectively). The calculations shown are the same as those displayed in Fig. 2.

Final analysis of the data for these and other observables is almost complete. We are just beginning our investigations into the possibility of converting these sets of observables into a complete description of the scattering amplitude at each of the four angles studied.

1. See, for example, H. Bagheai, *et al.*, Phys. Rev. Lett. **69**, 2054 (1992), and references therein.
2. J. Piekarewicz, *et al.*, Phys. Rev. C **41**, 2277 (1990).
3. M. Thoennessen, J.R. Beene, F.E. Bertrand, and J.L. Blankenship, Oak Ridge Nat'l. Lab. Prog. Rep. (1989).
4. G.P.A. Berg, *et al.*, IUCF Sci. and Tech. Rep., p. 220 (1993).
5. J. Piekarewicz, private communication.