Spin-Dependent Observables for the $^{12}C(p,p'\gamma)$ Reaction at 400 MeV

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Protons scattered inelastically from ^{12}C were detected at laboratory angles between 6° and 13° in coincidence with γ rays from deexcitation of the 1^+ $T=1$ state in the recoil nucleus. Coincident cross sections for γ rays emitted normal to the reaction plane and angular correlations for γ rays emitted in the proton scattering plane at angles between 90° and 270° are presented and compared with predictions from both nonrelativistic and relativistic models of proton-nucleus scattering calculated in the impulse approximation. These data display a clear preference for the relativistic-model prediction.

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The proton-nucleus interaction can be described economically at intermediate energies with the impulse approximation.[1] To describe elastic scattering in this approximation, one needs only the nucleon-nucleon (NN) phase shifts and a description of the nuclear density (usually taken to be the charge density measured by electron scattering or a self-consistent Hartree-Fock density). The impulse approximation is expected to do well between incident proton energies of 200 and 500 MeV where the NN interaction is weakest. For inelastic proton-nucleus scattering, the nuclear structure of the excited state is also required; this can be tested independently with inelastic electron scattering in most cases where application of the impulse approximation is not so successful.

Both relativistic models (with use of the Dirac equation) and nonrelativistic models (with use of the Schrödinger equation) have had reasonable success in describing elastic scattering.[2] With the advent of the focal-plane polarimeter,[3] measurements of the spin rotation parameter have shown a preference for the relativistic model[4,5] above incident proton energies of 290 MeV. For inelastic scattering at 500 MeV, neither model is favored for a complete set of spin observables.[6] In many cases, inelastic data (to states that do not show a "collective" nature) at other energies between 200 and 800 MeV are not described well by either model.[7-9] In order to resolve this theoretical problem, alternative experimental techniques were sought that could provide observables which are sensitive to different parts of the proton-nucleus interaction. The data presented here are the first application of the $(p,p'\gamma)$ reaction above 150 MeV to measure observables which clearly discriminate between relativistic and nonrelativistic descriptions of inelastic proton-nucleus scattering. Detection of the decay γ ray gives angular correlations which are sensitive to the spin of the residual nucleus. Previous studies of the $(p_{\text{pol}},p'\gamma)$ reaction[10] have been done at 150 MeV and below, where the impulse approximation is poorer.

The measurements made use of the medium-resolution spectrometer[11] (MRS) at the TRIUMF facility with 400-MeV protons incident on a 94.7-mg/cm^2 graphite target. Eight bismuth germanate detectors were put in lead shielding and placed at angles between 90° and 270° in the scattering plane at a distance of 35.5 cm from the target. γ rays were detected in coincidence with scattered protons in the medium-resolution spectrometer at laboratory angles of 6°, 7°, 9°, 11°, and 13°. Half of the bismuth germanates were 7.6 cm diam and half were 10.2 cm diam; all were 7.6 cm long. One BaF_2 detector (7.6 cm diam and 7.6 cm long) was placed normal to the scattering plane at a distance of 10.2 cm from the target. The high duty cycle of the TRIUMF cyclotron with beam pulses of 2–3 ns duration, repeating every 43 ns, gave high coincidence data rates with typical reals:randoms ratios of 3:1. A threshold of 1.2 MeV was set on the γ-ray detectors, and strong coincidences were observed with protons at excitation energies of 4.44 and 15.1 MeV corresponding to the 2^+ $T=0$ and 1^+ $T=1$ states in ^{12}C. Spectra of γ rays in coincidence with these states were compared with Monte Carlo calculations,[12] which gave an excellent prediction of both the shape (at a resolution of 2 MeV) and the absolute efficiency (as determined from the detector solid angles with the isotropic γ ray emitted for the 3.56 MeV 0^+ to ground-state transition in ^{6}Li). The physical background from a wide $E2$ resonance under the 1^+ state in the proton energy spectra was suppressed by a factor of about 10 (before subtraction of randoms) by the γ-ray coincidence. This allowed a clean determination of the peak areas with the 200-keV resolution obtained with the medium-resolution spectrometer. Proton-arm singles data, tagged with a bit set in a coincidence register with a known prescale factor, were taken simultaneously with the coincidence data. The singles cross sections were found to be consistent within errors (4% relative and 6% absolute) with previously published values.[7,13]

The in-plane angular correlation for a γ ray emitted by deexcitation of the residual nucleus from a 1^+ to a 0^+ state has the general form[14]

$$d\sigma/d\Omega_p d\Omega_\gamma = A(\theta_p) + B(\theta_p)\cos(2\theta_\gamma) + C(\theta_p)\sin(2\theta_\gamma), \quad (1)$$

where θ_γ is measured in the laboratory frame with respect to the beam axis, and θ_p is the scattered proton angle in the center-of-mass frame. The three constants corresponding to the isotropic, symmetric, and antisymmetric terms can be obtained from the impulse approximation.[15,16] Following Shepard and Rost,[8] the general form for the 0^+ to 1^+ transition amplitude as determined by parity and rotational invariance is

$$\begin{aligned} T_{M=q} &= C_q\sigma_p + D_q\sigma_q, \\ T_{M=p} &= C_p\sigma_p + D_p\sigma_q, \\ T_{M=n} &= A_n\mathbf{1} + B_n\sigma_n, \end{aligned} \quad (2)$$

where $\mathbf{q} = \mathbf{k}_f - \mathbf{k}_i$, $\mathbf{p} = \frac{1}{2}(\mathbf{k}_i + \mathbf{k}_f)$, and $\mathbf{n} = \mathbf{p}\times\mathbf{q}$ in terms of the initial and final projectile momenta $\mathbf{k}_i$ and $\mathbf{k}_f$. The T_i are operators in the projectile spin space for residual nucleus substates with projection $M=0$ along the direction $i = \hat{\mathbf{q}}$, $\hat{\mathbf{p}}$, or $\hat{\mathbf{n}}$. The projectile spin operators are $\sigma_q = \boldsymbol{\sigma}\cdot\hat{\mathbf{q}}$, etc. Then the in-plane angular-correlation coefficients of Eq. (1) are given in terms of the coefficients of Eq. (2) by[15]

$$\begin{aligned} A(\theta_p) &= |A_n|^2 + |B_n|^2 + \tfrac{1}{2}[|C_p|^2 + |D_p|^2 + |C_q|^2 + |D_q|^2], \\ B(\theta_p) &= |C_q|^2 + |D_q|^2 - |C_p|^2 - |D_p|^2, \\ C(\theta_p) &= -2\,\mathrm{Re}(C_pC_q^* + D_pD_q^*). \end{aligned} \quad (3)$$

The computer codes[9,17] DREX and DW81 were used to calculate the transition amplitude for the relativistic and nonrelativistic models, respectively. From the transition amplitude, the in-plane coincident angular correlations were calculated with the program ACOR[18] for the 1^+ $T=1$ state. The same nuclear structure amplitudes, as given by Cohen and Kurath,[19] were input to both DREX and DW81. The NN scattering t matrix was parametrized by the meson-exchange representation of Horowitz[20] for DREX, and by the summed-Yukawa representation of Franey and Love[21] for DW81. Both representations are fitted to the SP84 NN phase-shift solutions of Arndt and Roper.[22] Both calculations used "consistent" distorted waves, where the same effective interaction was used for the inelastic transition as for the elastic-scattering optical potentials. The elastic calculations have been previously published[23] and give an excellent prediction of the data. The *input* to both calculations is essentially identical, and the main difference between them is the off-shell representation of the NN t matrix.

The angular correlations for the present measurements are shown in Fig. 1 along with a best-fit solution to the general form expected from Eq. (1). The errors shown do not include an overall normalization error of 8% common to all angles. The value of $A(\theta_p)$ will reflect this uncertainty, but the ratios B/A and C/A will be unaffected. The data show almost a 180° shift in phase between 6.7° and 13.3°. The values of the isotropic,

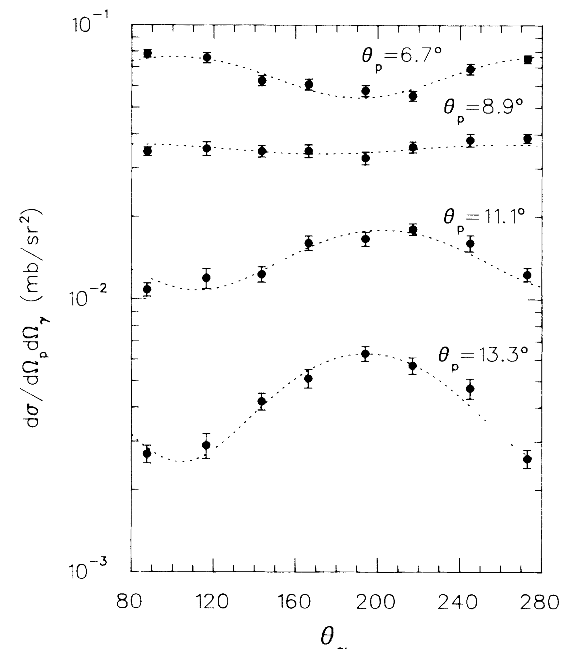

FIG. 1. γ-ray angular correlations for different coincident proton angles for the 15.1 MeV 1^+ $T=1$ state in ^{12}C at an incident proton energy of 400 MeV. The differential cross sections and the scattered proton angles θ_p are given in the center-of-mass frame vs the laboratory γ-ray angle. The dotted lines are fits to the general form given in Eq. (1).

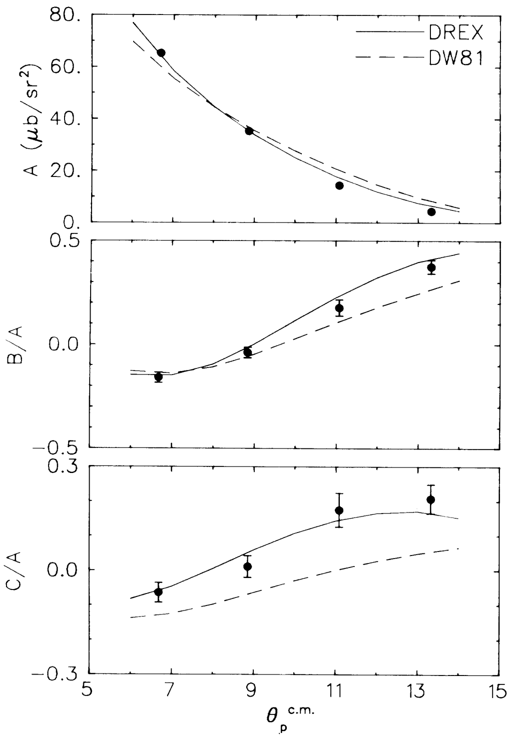

FIG. 2. The isotropic term $A(\theta_p)$ (top), the symmetric term $B(\theta_p)/A(\theta_p)$ (middle), and the antisymmetric term $C(\theta_p)/A(\theta_p)$ (bottom) of Eq. (1) for the 15.1 MeV 1^+ $T=1$ state in ^{12}C plotted as a function of proton angle. The solid points represent the coefficients for the fits (and fitting errors) of Fig. 1, the solid curve is the prediction from the relativistic model, and the dashed curve is the prediction from the nonrelativistic model. The cross sections in the top figure do not include an overall normalization error of 8%.

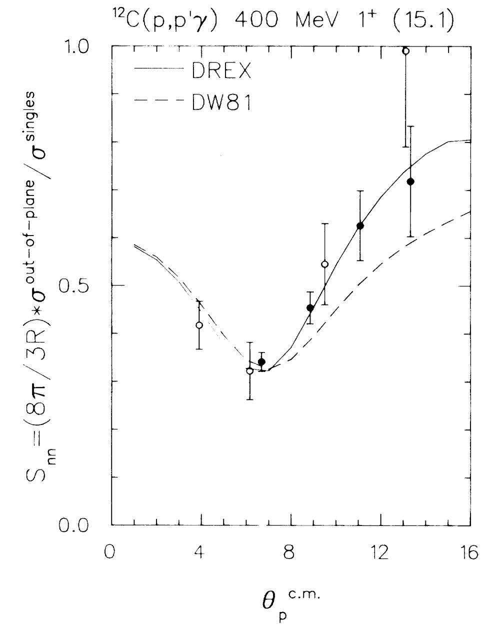

FIG. 3. The spin-flip probability (S_{nn}) as determined from the coincidence cross sections for γ rays emitted normal to the reaction plane and from the singles cross section. The solid points are from the present measurements, and the open points are from the focal-plane polarimeter data of Ref. 26.

symmetric, and antisymmetric terms, as determined by these fits are shown in Fig. 2, along with fitting errors. The small (approximately 1%) correction for the finite angular size of the γ-ray detectors[24] has been ignored. Also shown in Fig. 2 are the coefficients of Eq. (1) as predicted by DREX and DW81. For all coefficients, the relativistic model is favored. It is important to point out that both calculations have no adjustable parameters, and should be considered to be predictions. If plane waves rather than distorted waves are used, the A coefficient is overestimated by a factor of 2 to 3, and the calculations for the B and C coefficients at all proton angles retain the shape given by the distorted-wave calculations at $\theta_p=7°$ (i.e., the lower two curves in Fig. 2 would be virtually flat with the values given by the 7° point) for both DW81 and DREX. This implies that the effect seen here is mainly due to distortions (from the optical potentials), which are better described by the large vector and scalar potentials of the relativistic model.

The coincident cross section for γ rays emitted normal to the reaction plane is related to the spin-flip probability by[10,15]

$$S_{nn}\left(\frac{d\sigma}{d\Omega}\right)^{\text{singles}}=\frac{8\pi}{3R}\left(\frac{d^2\sigma}{d^2\Omega}\right)^{\hat{n}\text{-coinc}}, \tag{4}$$

where R is the branching ratio for γ decay of the excited state (0.96 for the 15.1-MeV state[25] in ^{12}C). These data are shown in Fig. 3. As for the in-plane cross sections, the relativistic model is clearly favored. Plane-wave calculations give a constant value of $S_{nn}\simeq 0.4$ from 7° to 16° for both DW81 and DREX, showing the importance of the relativistic description of distortions. It is worth noting that the large scalar potential in the relativistic model results in a reduced effective mass of the nucleon inside the nucleus (as shown in relativistic Hartree calculations[27]), and hence an enhancement of the lower components of the nuclear structure wave functions.[9]

In conclusion, both the in-plane angular-correlation observables and the out-of-plane cross sections associated with the $(p,p'\gamma)$ reaction display a preference for the relativistic model, in contrast to previous $(p_{\text{pol}},p'_{\text{pol}})$ data at intermediate energies where there is not a clear preference for either model. As more data become available from the $(p,p'\gamma)$ reaction, more can be learned about why the relativistic impulse approximation for the proton-nucleus interaction does well for the observables of the present measurements. This knowledge, in turn, should lead to improvements in the predictive power of the calculations.

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