Polarization and Analyzing-Power Differences in the Excitation of 1^+ States in ^{12}C at 150 MeV

T. A. Carey, J. M. Moss, and S. J. Seestrom-Morris
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

A. D. Bacher, D. W. Miller, H. Nann, C. Olmer, P. Schwandt, and E. J. Stephenson
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

and

W. G. Love
Physics Department, University of Georgia, Athens, Georgia 30601
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Significant differences between the polarization, P, and analyzing power, A, have been measured in the reaction $^{12}C(p,p')^{12}C(1^+$ states) at $E_p = 150$ MeV. It is shown that $P-A$ is different from zero primarily because of that part of the tensor exchange amplitude associated with the transferred quanta, $lsj = 111$, to the nucleus. This amplitude determines a combination of transition density matrix elements for the 15.11-MeV state that is largely undetermined from other experiments.

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The polarization (P) and analyzing power (A) are equal for elastic nucleon scattering to the extent that time-reversal symmetry holds.[1] For inelastic scattering, on the other hand, there is no general symmetry that relates P to A. There are, however, limiting cases where one expects $P = A$. Satchler[2] has shown that in the adiabatic limit ($Q \ll E_p$, where Q and E_p are respectively the reaction Q value and beam energy), and in the absence of exchange interactions, differences between P and A arise only from interference terms between spin transfer ($s = 1$) and spin nontransfer ($s = 0$) processes. Recently Amado[3] has presented a more detailed treatment of the difference between P and A in inelastic scattering. One result of this work is that $P = A$ in the limit that $Q = 0$.

The expression of the quantity $P - A$ in terms of the partial differential cross sections, σ_{ij}, for scattering from an initial state with spin projection i to a final state with projection j, normal to the scattering plane, is

$$P - A = 2(\sigma_{-+} - \sigma_{+-})/\sum_{ij} \sigma_{ij}.$$

In general one expects σ_{-+} and σ_{+-} to be large only when spin transfer is important in the inelastic reaction. This situation does not occur in a majority of strong inelastic transitions where collective spin-independent phenomena dominate. Hence it is not surprising that differences between P and A have been observed only rarely.[4]

In this Letter we present data for inelastic-proton transitions to the 1^+ states of ^{12}C (12.71 and 15.11 MeV) at $E_p = 150$ MeV which show large differences between P and A. We show evidence that these differences arise mainly from the nonlocal/exchange character of the effective nucleon-nucleon interaction, particularly from the tensor component. The exchange terms provide information about nuclear transition densities that are unobtainable from electron-scattering and not easily obtainable from pion-scattering experiments.

Beams of 150-MeV polarized protons were provided by the Indiana University Cyclotron Facility (IUCF). In order to measure P and other observables for inelastic proton scattering, we constructed a carbon polarimeter which mounts directly behind the focal-plane array of the quadrupole-dipole-dipole-multipole (QDDM) magnetic spectrometer.[5] The polarimeter target consists of a 0.25-in-thick scintillator mounted directly in front of a 20-MeV-thick block of natural graphite. Double scattering is detected by a right and left pair of detector telescopes each consisting of a 0.25-in-thick plastic scintillator and a $3 \times 3 \times 6$ in^3 NaI(Tl) crystal in which the protons stop. The polarimeter is operated in coincidence with the normal QDDM focal-plane detectors.[5] Thus the polarimeter-gated energy spectrum appears as a 600-keV-wide band of excitation energy with the peak of primary interest located at the center (corresponding to the center of the polarimeter target). Analyzing powers are measured simultaneously with polarimeter quantities by scaling down and storing singles focal-plane spectra.

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Detailed characteristics of the polarimeter as well as its alignment and operation will be described in a forthcoming publication.[6] At $E_p = 150$ MeV the measured analyzing power is 0.37 with a scattering efficiency of 0.6%. Systematic errors are believed to be less than 0.02 in the measured final polarization. The error bars presented here are a combination of statistical errors plus uncertainties arising from the choice of continuum background subtracted from the two 1^+ states.

Figures 1 and 2 show data for the $T = 1$ and $T = 0$ 1^+ states in terms of $P - A$. It is apparent that large deviations from zero are seen for both states. The inset in Fig. 1 is the product of $d\sigma/d\Omega$ and $P - A$, using the cross-section data from Comfort *et al.*[7] Also shown are distorted-wave impulse-approximation (DWIA) calculations employing the Cohen-Kurath[8] (CK) wave functions and the Love[9] interaction (Sussex tensor). The calculations were performed with a modified version of the code DWBA-70.[10] The optical potential was extrapolated from the 122-MeV potential of Comfort *et al.*[11]

Although nonzero Q values remove the equality of P and A in the direct DWIA amplitude they typically have similar shapes unless one is close to a diffraction minimum. A much more interesting difference between P and A arises from the nonlocal/exchange nature of the nucleon-nucleon interaction which produces an effective coupling

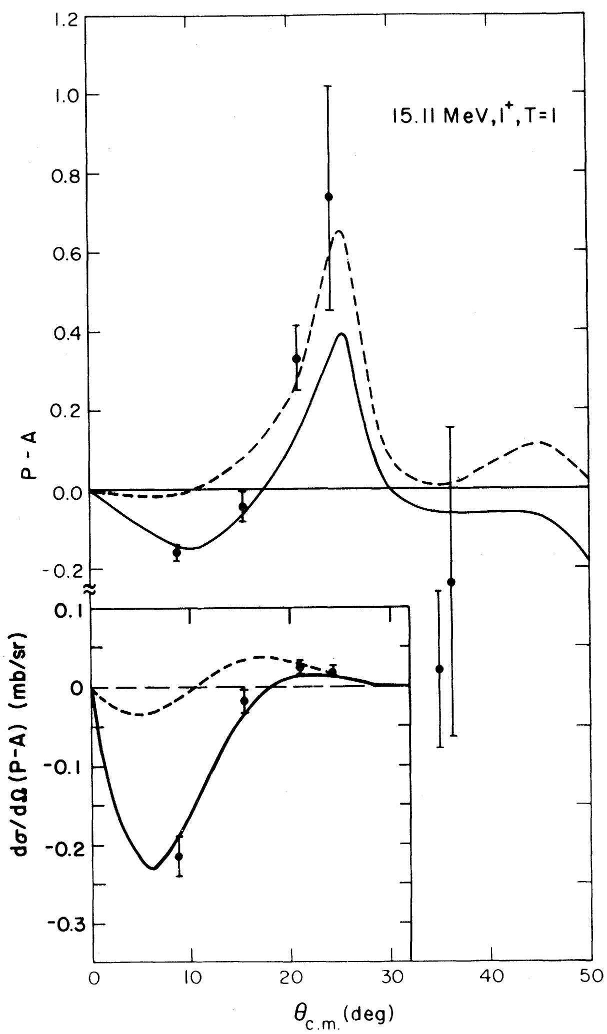

FIG. 1. Polarization minus analyzing power. The curves are DWIA calculations described in the text. The inset at the lower left is $P-A$ times the differential cross section.

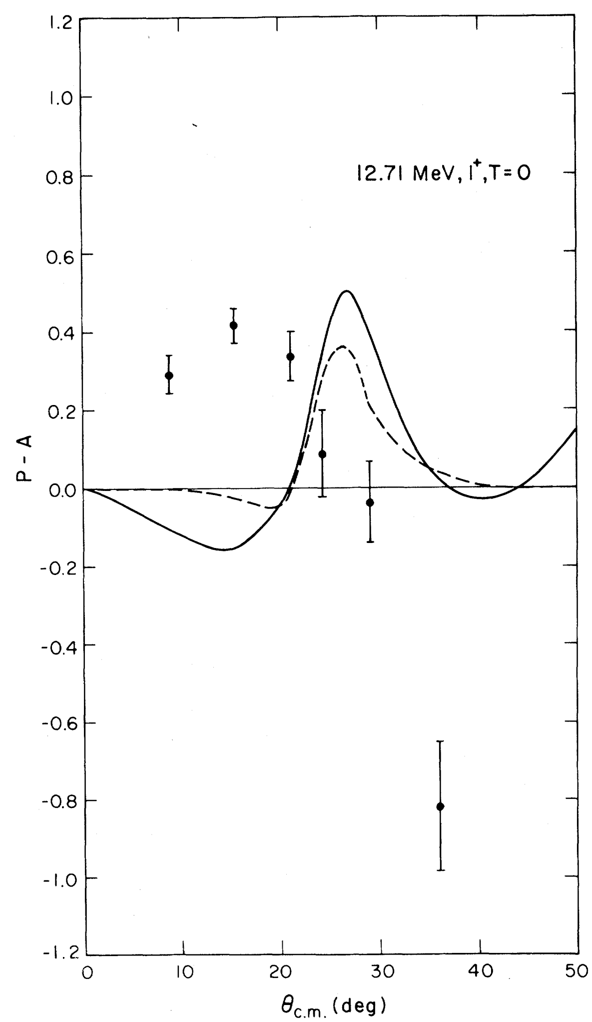

FIG. 2. Polarization minus analyzing power. The solid curve is a DWIA calculation using the Cohen-Kurath wave functions. The dashed curve is a similar calculation with the $lsj = 111$ term removed.

between the currents of the projectile and target nucleons. This results in calculated values of P that differ in sign from A. This difference in sign arises from spin, orbital, and total angular transfer $lsj=111$ to the nucleus[12] and is dominated by the tensor interaction.[13] The CK wave functions predict this term to be spectroscopically dominant for both 1^+ states.

The effects of tensor exchange are readily seen in Fig. 1 where DWIA calculations are shown in which $lsj=111$ term has been removed from the CK transition density for the 15.11-MeV state (dashed curve). The full CK calculations show much better agreement with the small-angle data. This region is most significant since the differential cross section is large and well described by the DWIA. The nonvanishing value of $P-A$ comes almost entirely from tensor exchange. The maximum near $\theta_{c.m.}=25°$ occurs at the minimum of the cross section. The magnitude of $P-A$ at this point is less significant because of its extreme sensitivity to slight changes in optical-potential distortions. A more meaningful comparison of the product of experiment and calculation is in terms of the product of $P-A$ and $d\sigma/d\Omega$ (Fig. 1, inset). Here it is even more apparent that the full CK calculation is required to reproduce the data.

The sensitivity of $P-A$ to the $lsj=111$ amplitude is especially significant because this term determines an important feature of the transition density matrix which is poorly known at present.[13,14] Dubach and Haxton[14] pointed out recently that an analysis of electromagnetic and beta-decay data for the 15.11-MeV state and its analogs leaves the sum of the density matrix elements $[p_{3/2}^{-1}p_{1/2}+p_{1/2}^{-1}p_{3/2}]$ almost undetermined. The $lsj=111$ term depends entirely on this sum, and hence $P-A$ is a direct measure of its strength. The CK result, -0.73, is in good agreement with the present measurements.

The same analysis may, in prinicple, be applied to the 12.71-MeV state. The central spin-dependent interaction, V_σ, is believed to be small[15] and at $E_p=150$ MeV the cross section of the 12.71-MeV state is dominated by the tensor-exchange amplitudes. Unfortunately neither $P-A$ nor the differential cross section[11] is well described by the calculations. Removing the $lsj=111$ term (dashed curve, Fig. 2) reduces $P-A$ at small angles (and reduces the differential cross section substantially) as expected. The large values of $P-A$ observed experimentally suggest that the 111 term is important but that the isoscalar impulse-approximation interaction is inadequate. More precise information therefore cannot be extracted for the 12.71-MeV state at this time.

In summary, we have measured significant differences between the polarization and analyzing power in the (p,p') excitation of the 1^+ states of ^{12}C at $E_p=150$ MeV. At forward angles we have shown that $P-A$ is substantially different from zero only when the $lsj=111$ amplitude, arising primarily from tensor exchange, is important. Using DWIA calculations of $P-A$ we have exploited the relation between the $lsj=111$ amplitude and the sum of density matrix elements $[p_{3/2}^{-1}p_{1/2}+p_{1/2}^{-1}p_{3/2}]$ to determine the latter quantity. This aspect of the density matrix is undetermined by electromagnetic experiments and is poorly fixed by beta-decay experiments involving the 15.11-MeV state and its analogs. The same information is derivable in principle for the 12.71-MeV state. At present, however, ambiguities in the $s=1$, isoscalar interaction prevent one from drawing firm conclusions about the transition density.

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