$P - A$ in the $^{48}Ca(p,n)^{48}Sc$ reaction at 135 MeV

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(Received 30 September 1991)

The polarization (P) and the analyzing power (A) were measured for the $^{48}Ca(p,n)^{48}Sc$ reaction at 135 MeV. Of special interest is the difference ($P - A$) in these two quantities for the transitions to the two 1^+ states at 2.52 and 16.8 MeV. Because of the difference in the predominant one-particle–one-hole configurations for these two states, viz., $(f_{7/2},f_{7/2}^{-1})$ and $(f_{5/2},f_{7/2}^{-1})$, respectively, qualitative differences in $P - A$ are predicted based on nonlocal exchange contributions. The experimental results agree qualitatively with these predicted differences, but there are significant quantitative differences indicating that other effects contribute as well.

PACS number(s): 25.40.Ep, 21.30.+y, 24.70.+s, 27.40.+z

I. INTRODUCTION AND BACKGROUND

For elastic nucleon scattering, time-reversal invariance requires that the polarization (P) be equal to the analyzing power (A). For inelastic scattering, there is no such requirement [1]; for example, it is known that higher-order terms in nucleon-nucleus scattering can make P not equal A [2], and that the reaction Q value can affect $P - A$ [3]. The Dirac impulse approximation also gives rise to certain exchange currents that can yield nonzero $P - A$ [4]. Love and Comfort [1] showed that Q-value effects are probably small, but that nonlocal (velocity-dependent) contributions to the nucleon-nucleon effective interaction can give rise to relatively large values of $P - A$ within a single-scattering approximation. They specifically isolate one source of such nonlocal contributions that arises from exchange terms and would be expected to be most important for unnatural-parity transitions. This paper presents experimental evidence in qualitative support of this prediction, although there are significant quantitative differences indicating that other effects are present also.

Previously, two experiments were performed to measure $P - A$ for the $0^+ \rightarrow 1^+$, unnatural-parity transitions in the $^{12}C(p,p')$ reaction [5,6]. Carey *et al.* [5] performed an experiment at 150 MeV at the Indiana University Cyclotron Facility (IUCF) and observed differences as large as 0.4 between P and A for the transitions to both the $T=0$, 12.71 MeV, and the $T=1$, 15.11 MeV, 1^+ states. These large $P - A$ values were ascribed primarily to an effective coupling between the currents of the projectile and target nucleons, which is dominated by the exchange contributions arising from the tensor force as discussed by Love and Comfort [1]. Distorted-wave impulse-approximation (DWIA) calculations were able to describe the $P - A$ measurements for the $T=1$, 15.11 MeV transition, but were not able to describe the $T=0$, 12.71 MeV transition very well. The transition to the 12.71 MeV, 1^+ state presents serious problems for description by the DWIA even for the cross-section angular distribution [1]. The problem with this latter transition is believed to be either that the nuclear structure is not known well or that the $\Delta T=0$, $\Delta S=1$ part of the nucleon-nucleon (N-N) effective interaction is represented poorly [7]. Hicks *et al.* [6] studied the same transitions at 400 MeV and observed smaller $P - A$ values than those reported for 150 MeV, consistent with the interpretation that the P and A differences arise primarily from exchange contributions that are expected to be smaller at the higher energy. Hicks *et al.* found that the transitions are described reasonably well by both relativistic and nonrelativistic DWIA calculations; however, because the effect is smaller, the measurements do not provide as sensitive a test of the nonlocal contributions.

We performed an experiment at the IUCF to measure the polarization (P) and analyzing power ($A \equiv A_y$) for the $^{48}Ca(p,n)^{48}Sc$ reaction at 135 MeV. These measurements extend our earlier cross-section [8], analyzing-power [9], and spin-transfer [10] measurements for this reaction at this energy. Although we extracted P and A for all strong transitions, the transitions of most interest are to the 1^+ states at 2.52 and 16.8 MeV with $T=3$ and $T=4$, respectively. For reasons described below, these transitions provide essentially ideal tests of the proposed nonlocal, exchange term as a source of $P - A$ contributions.

First of all, ^{48}Ca is understood to be a relatively good closed-shell nucleus; thus, the strong transitions induced by the impulsive (p,n) reaction are to predominantly one-particle–one-hole (1p-1h) states [8]. Indeed, DWIA calculations with shell-model wave functions are able to

describe reasonably well all of the observables measured for the strong transitions [8–10], i.e., the basic shapes of the angular distributions of cross sections and various spin observables are reproduced qualitatively, even though these shapes vary considerably for the different transitions. The shell-model calculations and these earlier studies indicate that the two 1^+ transitions of interest are predominantly $(f_{7/2},f_{7/2}^{-1})$ for the 2.52 MeV state and $(f_{5/2},f_{7/2}^{-1})$ for the 16.8 MeV state [8].

Secondly, the difference in the dominant 1p-1h structures of these two 1^+ excitations is expected to affect $P-A$ strongly. Love and Comfort show [1] that for transitions of this type, within a single shell, one of the nonvanishing form factors required for $P\neq A$ is specified by the matrix element of the operator $\langle i\mathbf{L}\times\boldsymbol{\sigma}\rangle$. In terms of the $\langle\sigma\rangle$ operator, they show that this matrix element becomes

$$\langle j'\|i\mathbf{L}\times\boldsymbol{\sigma}\|j\rangle=(j-j')j_>\langle j'\|\sigma\|j\rangle\ , \tag{1}$$

where j and j' are the total angular momenta for initial and final single particle orbitals and $j_>$ is the greater of j and j'. From this expression, we see that this matrix element will vanish for $j=j'$, so that *no* contribution to $P-A$ is expected for the 1^+ state at 2.52 MeV with the predominant 1p-1h configuration, $(f_{7/2},f_{7/2}^{-1})$. In contrast, a significant contribution is expected for the predominantly $(f_{5/2},f_{7/2}^{-1})$ 1^+ state at 16.8 MeV. More generally, the operator of Eq. (1) is referred to as the "induced tensor" term in β decay and is expected to be a significant contributor to $0^+\rightarrow 1^+$ unnatural-parity transitions involving spin-orbit partners.

Love and Comfort note that the various contributions leading to $P\neq A$ can be modeled in the DWIA explicitly through the nonlocality present in the exchange terms [1]. Thus, so-called "standard" DWIA calculations will provide a prediction of the difference in P and A based on the nonlocalities in the assumed nucleon-nucleon effective interaction. We performed such DWIA calculations with the code DW81 [11] using the N-N effective interaction of Franey and Love [12]. The calculations use the empirical global optical-model parameters of Schwandt *et al.* [13]. (We note that the observable $P-A$ was shown [1] to be considerably less sensitive to optical-model distortion than is P, A, or $P+A$.) The results of these calculations support the arguments presented above; the calculations indicate relatively small differences between P and A for the low-lying 1^+ state, but relatively large differences for the 1^+ state at 16.8 MeV. In fact, the *signs* of P and A are predicted to be opposite over the entire angular range for the high-lying excitation. These differences are not due to Q-value effects; the same basic signatures are seen if the Q values for the two transitions are interchanged. The differences predicted for these two transitions are qualitatively clear, and the measurements should be able to confirm or deny these predictions.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with the neutron time-of-flight beam-swinger facility at the IUCF [14]. This experiment used the improved polarized ion source, which provided intensities of 400 to 600 nA of protons with a typical polarization of 72%. Because we used polarized beam throughout the experiment, we were able to measure P and A (and also the polarization-transfer coefficient D_{nn}) simultaneously, thereby eliminating certain possible sources of systematic false asymmetry.

The neutron polarimeter was located along the 0° swinger line at a flight path of 37 m from the target. The overall time resolution was about 800 ps, and includes contributions from the beam burst width (~350 ps), beam energy spread (~200 ps), energy loss in the target (~250 ps), the intrinsic time resolution of the neutron detectors (~350 ps), and the neutron transit time across the neutron detectors (~500 ps). This time resolution provides an energy resolution of about 1.0 MeV. The neutron polarimeter, described previously by Watson *et al.* [15], uses three BC-517L liquid scintillator neutron analyzers together with six plastic scintillator "side" detectors. The neutron spin polarization was measured using the scattering of the neutrons from the hydrogen in the front detectors. The front detectors were 12.7 cm wide by 1 m high by 10.2 cm thick. The side detectors were 25.4 cm wide by 1 m high by 10.2 cm thick. The mean flight path between the front and side detectors was 1 m, with an opening angle of 22.5°. This angle was chosen because it provides the maximum figure of merit, defined to be the product of the cross section (σ) times the square of the analyzing power (A_y) for neutron scattering off hydrogen [15]. The analyzing power for neutron scattering by hydrogen at the energy of interest (~125 MeV) is known to be ~0.50 [15]. The effective analyzing power of the polarimeter was measured using the 0^+ to 0^+ isobaric-analog-state (IAS) transition in the $^{14}C(p,n)^{14}N$ reaction and found to be 0.36 ± 0.02. This calibration was entirely similar to that described in more detail earlier in Ref. [15]. The false asymmetry was checked at 0°, where both P and A must vanish. Using the strong transitions in the $^{48}Ca(p,n)^{48}Sc$ reaction, the false asymmetry was measured to be 0.016 ± 0.011; because the polarimeter was not moved to obtain the measurements at other angles, we assumed that the false asymmetry was constant. All measurements were corrected for this small false asymmetry.

III. RESULTS

Figure 1 shows the experimental results from the cross section (σ), and the products of cross section times the polarization (σP) and the analyzing power (σA), as a function of excitation energy for the $^{48}Ca(p,n)^{48}Sc$ reaction at 5.0° (laboratory). Such σP and σA plots are a useful way to see the effect of the polarization and analyzing power in the spectrum without over emphasizing weak transitions. The main features of the reaction are indicated in the cross-section plot, including the two 1^+ states of interest at 2.52 and 16.8 MeV, the 0^+ IAS at 6.67 MeV, and the 1^+ Gamow-Teller giant resonance (GTGR) at ~10 MeV. Note that up to about 10 MeV, both P and A are negative. Above 10 MeV, A swings positive, while P becomes only slightly positive above about 20 MeV. Above about 30 MeV, in the continuum, both P and A

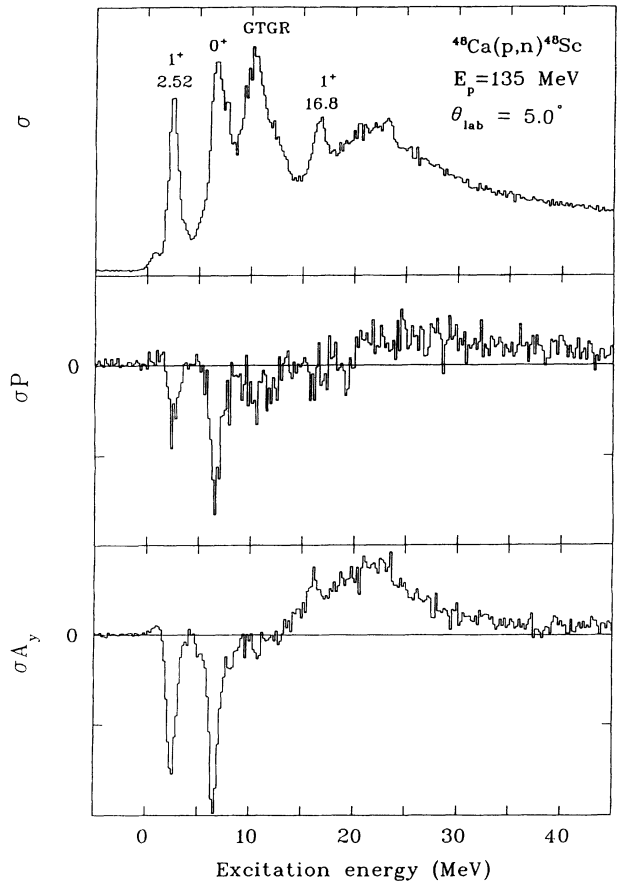

FIG. 1. Experimental results for σ, σP, and σA for the $^{48}Ca(p,n)^{48}Sc$ reaction at 135 MeV and 5.0°. The ordinate scales are in arbitrary units.

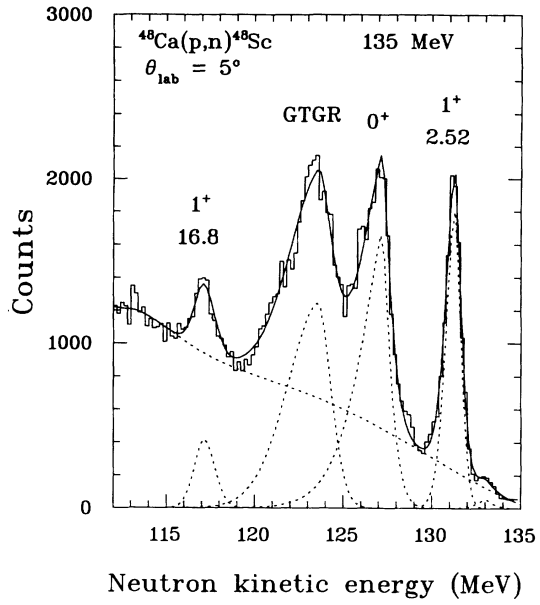

FIG. 2. Fit to the neutron energy spectrum at 5°. This spectrum corresponds to proton beam spin "up" and neutron scattering to the "right."

are about the same, viz., slightly positive. These characteristics are consistent with the qualitative discussion presented above together with the interpretation that the low-energy portion of the spectrum is dominated by $(f_{7/2},f_{7/2}^{-1})$ 1p-1h strength, that the part between about 10 and 30 MeV is dominated by $(f_{5/2},f_{7/2}^{-1})$ 1p-1h strength, and finally in the continuum quasifree scattering dominates and is expected to yield $P \approx A$. The qualitative change in σA from negative at low-excitation energies to positive around 20 MeV is really quite striking.

In order to extract the angular distributions for P, A, and $P - A$ for the 1^+ states at 2.52 and 16.8 MeV, it was necessary to fit the spectra at each angle. Four spectra need to be considered for each angle; these spectra correspond to the four combinations of the proton beam spin ("up" or "down") together with the neutron scattering ("left" or "right"). The fit to one of these four spectra is shown in Fig. 2. The peaks observed in the spectra were fitted with asymmetric Gaussian distributions on top of a smooth broad Lorentzian background. These fits were unambiguous for the 2.52 MeV state, seen at low excitation energy with a relatively small background. The fits to the 16.8 MeV state were on top of a large background, which included contributions both from nearby giant resonances (viz., the GTGR at ~10 MeV and the giant dipole resonance at ~23 MeV) and from the nuclear continuum. As shown in Fig. 2, the fit to the 16.8 MeV state appears reliable. (Note that the large statistical fluctuations seen in Fig. 1 arise from adding and subtracting the four separate spectra to form P, A, and $P - A$.) The results of the fits to the four spectra were then combined to obtain P, A, and $P - A$ for the 2.52 and 16.8 MeV states. The uncertainties in the extracted areas were dominated by the fitting uncertainties and were taken from the error matrix of the fitting code [17]. These uncertainties were combined in quadrature to obtain the final uncertainty for each transition at each angle for each observable.

Figure 3 compares the experimental angular distributions for P, A, and $P - A$ for the 2.52 and 16.8 MeV, 1^+ transitions with the DWIA predictions discussed above. We see that the results agree clearly with the qualitative expectations discussed earlier; namely, the 2.52 MeV, 1^+ transition has the same sign for both P and A as the angle increases, whereas the signs of P and A are opposite for the 16.8 MeV, 1^+ transition.

From Fig. 3, one sees that the DWIA predictions describe the qualitative behavior of $P(\theta)$ and $A(\theta)$ reasonably well, although the magnitudes of the calculations generally underestimate the measurements. The $P - A$ results are clearly positive for the 2.52 MeV transition and negative for the 16.8 MeV transition; the DWIA calculations reproduce these results qualitatively, but are not in good agreement quantatively. It is important to keep in mind that both P and A are interference observables; thus $P - A$ is actually measuring the difference between two interference observables and is in effect a second-order interference observable. It is encouraging that the DWIA calculations reproduce the qualitative results observed; the quantitative disagreements indicate

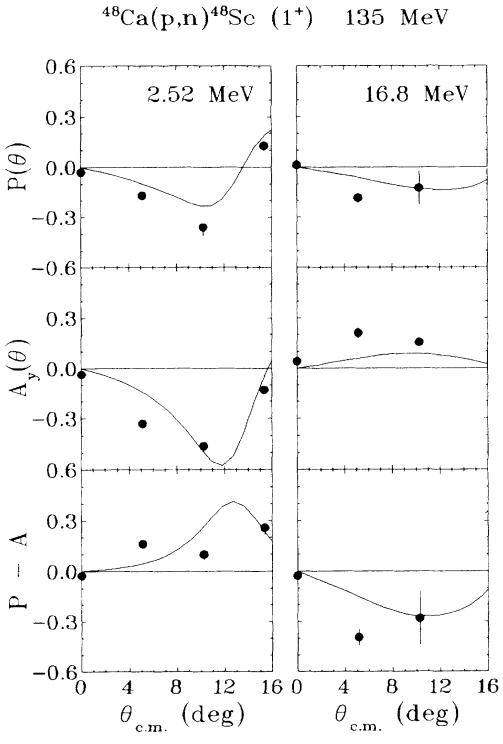

FIG. 3. P, A_y, and $P-A$ angular distributions for the ^{48}Ca(p,n)^{48}Sc reaction at 135 MeV to the 1^+ states at 2.52 and 16.8 MeV. The curves represent DWIA calculations (see text).

that not all of the various effects which contribute to P and A (the optical distortions, exchange effects, etc.) are modeled exactly. The sensitivity of such calculations to the various ingredients was discussed in more detail in Ref. [9]. Basically, one finds that the DWIA calculations of analyzing power and polarization are sensitive to all of the major ingredients, viz., the optical-model parameters, the N-N interaction, exchange effects, and the nuclear structure; however, one finds that "reasonable" changes in these ingredients do not change the qualitative results. Only unreasonable changes can change the calculated shapes significantly. Thus, the general agreement between the calculated and measured shapes (which can be very different for different transitions, see Ref. [9]) indicates that the DWIA is basically correct. The quantitative differences indicate that some of the ingredients are not perfectly correct, and that there is need for improvement.

In addition to calculations using the "standard" DWIA, we performed also density-dependent DWIA calculations (DD-DWIA) for these transitions. These calculations were performed using the density-dependent G-matrix interaction of Nakayama and Love [18], which is derived from the one-boson-exchange potentials of the Bonn collaboration [19]. The calculations were performed with the density-dependent option in DW81 [11]. Similar calculations for 0^+ to 0^+ isobaric-analog-state (IAS) transitions were reported previously [20]. Although the earlier DD-DWIA calculations were able to describe the IAS cross sections significantly better than standard DWIA calculations, we find that the density-dependent calculations do not describe P, A, and $P-A$ for the ^{48}Ca(p,n)^{48}Sc (1^+) transitions considered here as well as the conventional DWIA calculations. In general, the DD-DWIA calculations predict significantly smaller values for both P and A than observed experimentally and are quite unreliable for the difference $P-A$.

It would be interesting to consider also relativistic, Dirac-model DWIA calculations. Such calculations have been shown to sometimes provide improved agreement for spin observables at higher energies [6,21]; however, these calculations usually do not show improvement over standard DWIA calculations below 200 MeV and are beyond the scope of the present work.

IV. CONCLUSIONS

In conclusion, we see that the P, A, and $P-A$ results for the ^{48}Ca(p,n)^{48}Sc reaction agree with the qualitative expectations of the effect of the "induced-tensor"-like contributions to differences in P and A. The experimental angular distributions are described qualitatively well by "standard" DWIA calculations which model, in part, nonlocal contributions to exchange processes that can yield P and A differences. These results, with the clear differences between the two 1^+ transitions, provide evidence for the existence of such contributions in the nucleon-nucleon effective interaction. The lack of good quantitative agreement between the DWIA calculations and the measurements indicates that not all the ingredients in the DWIA are modeled correctly. These results should provide sensitive tests of improved calculations.

This work was supported in part by the National Science Foundation.

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