Brief Reports

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j dependence of the vector analyzing power in the $^{40}Ca(\vec{d},p)^{41}Ca$ reaction at 4 MeV

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The vector analyzing power for the $^{40}Ca(\vec{d},p)^{41}Ca$ reaction has been measured at 4.0 MeV. Data for transitions to a number of states in ^{41}Ca are compared with the results of distorted-wave Born approximation calculations. The *j* dependence of the vector analyzing power is shown to persist in spite of the low bombarding energy and the presence of compound nucleus formation. The data for the 3.61 MeV state lead to a spin assignment of $j^{\pi}=\frac{1}{2}^{-}$. The present results support the conclusion that this state is a close doublet.

[NUCLEAR REACTIONS $^{40}Ca(\vec{d},p)$, $E_d=4.0$ MeV; measured vector analyzing power $iT_{11}(\theta)$ for transitions to states in ^{41}Ca at $E_x=0.0$, 1.94, 3.61, 3.94 MeV. DWBA analysis.]

The *j* dependence of the vector analyzing power iT_{11} in direct reactions is the basis of a well-established technique for determining the spins of nuclear states. If the final state is populated by the transfer of a single nucleon, the orbital angular momentum transferred, *l*, can be determined from the measured angular distribution of the differential cross section. Comparison of the measured angular distribution of iT_{11} with either distorted-wave Born approximation (DWBA) calculations or with data for a similar state of known spin then indicates which of the two possible values of *j* is the correct one.

Most measurements of this type have been made at incident beam energies that are sufficiently high ($\gtrsim 10$ MeV) to insure that the reaction proceeds primarily by direct transfer. In this paper we present data for the vector analyzing power in the $^{40}Ca(\vec{d},p)^{41}Ca$ reaction at a deuteron energy of 4.0 MeV. At this low energy the reaction cross section fluctuates strongly with energy, indicating the presence of significant compound effects.[1-3] Our measurements nevertheless show that the *j* dependence of the vector analyzing power is still pronounced.

Previous measurements[4] demonstrated a pronounced *j* dependence of iT_{11} for the strong transitions in $^{40}Ca(\vec{d},p)$ at beam energies as low as 5 MeV. Our results are not only at a lower energy, but also include data for the relatively weak transition to the 3.61 MeV state for which compound nucleus formation and coupled-channels effects might be particularly troublesome.

Our measurements were made by bombarding a 1 mg/cm^2 self-supporting natural Ca foil with 4.0 MeV vector-polarized deuterons from the Wisconsin Lamb-shift polarized ion source[5] and tandem accelerator. The reaction products were detected by an array of four solid state detectors on one side of the beam. The energy resolution was typically 60 keV. A pulse-height spectrum is shown in Fig. 1. A ^{4}He polarimeter was used to continuously measure the beam polarization.

The ground state peaks in the pulse-height spectra were cleanly separated from other features (see Fig. 1). For the other transitions a peak-fitting program was used to obtain the individual peak sums. In each of these cases the contribution to the yield from nearby peaks was a small fraction of the yield from the transition in question. Peaks resulting from ^{12}C contamination of the target were included in the fits when they occurred close to peaks of interest. The overall quality of the fits was good. The analyzing power data for the transitions to the ground state and excited states at 1.94, 3.61, and 3.94 MeV are shown in Fig. 2. The

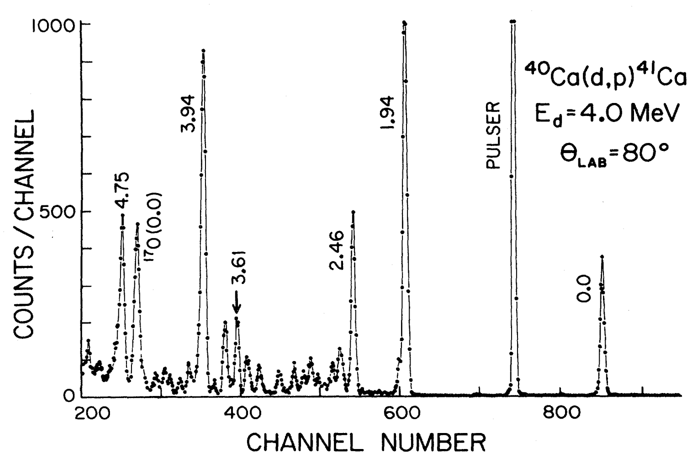

FIG. 1. Pulse-height spectrum for the $^{40}Ca(d,p)^{41}Ca$ reaction at $\theta_{lab}=80°$.

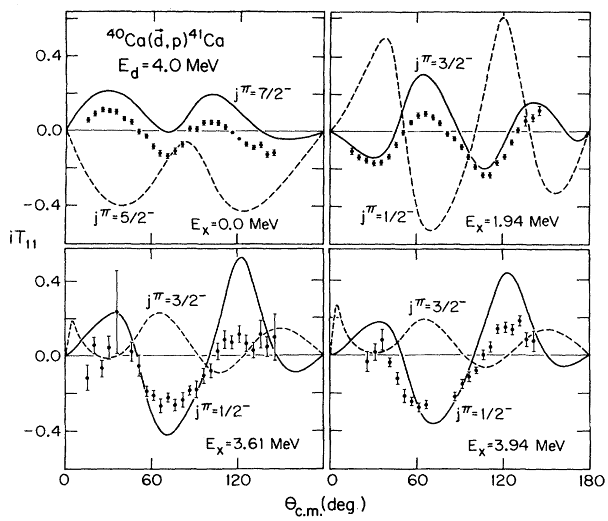

FIG. 2. Measurements of the vector analyzing power for the $^{40}Ca(\vec{d},p)$ reaction at 4 MeV leading to four states in ^{41}Ca. The solid curves are DWBA calculations corresponding to the correct spin assignments for the states. The dashed curves are the corresponding calculations for the alternative spin assignments.

error bars shown include the uncertainties associated with the peak-fitting procedure.

The measurements were compared with the results of zero-range DWBA calculations performed with the program DWUCK2.[6] Examples of the results of the DWBA calculations are shown in Fig. 2. In each case the value of l was already known and the calculations were done for the two permitted values of j, namely, $j=l\pm\frac{1}{2}$. These calculations included finite-range corrections, but did not include the effects of the deuteron D state. The proton optical potential parameters were calculated according to the prescription of Becchetti and Greenlees.[7] The parameters of the deuteron optical potential were obtained by extrapolating the $^{40}Ca+d$ potential of Schwandt and Haeberli[8] to 4 MeV. The parameters of Ref. 8 vary smoothly with energy in the range from 5 to 34 MeV, so the extrapolation is probably reliable. Other potentials, including those of Refs. 9 and 10, were no more successful in reproducing the data.

As shown in Fig. 2, the calculations corresponding to our spin assignments (solid curves) reproduce the general features of the analyzing power data. The calculations corresponding to the alternative choices (dashed curves), on the other hand, are almost completely out of phase with the measurements. The j dependence of iT_{11} is therefore still pronounced in spite of the low energy and presence of compound effects. In particular, the data for the $j^\pi=\frac{1}{2}^-$ states at 3.61 and 3.94 MeV are similar to each other but are opposite in sign to those for the $j^\pi=\frac{3}{2}^-$ state at 1.94 MeV. The spin assignments for the ground state and for the states at 1.94 and 3.94 MeV agree with the well-established values for these states.[11]

The 3.61 MeV state is actually a very close doublet consisting of a $j^\pi=\frac{1}{2}^-$ state at $E_x=3613.5\pm0.2$ keV and a $j^\pi=\frac{7}{2}^+$ state at $E_x=3613.0\pm0.6$ keV.[11] Early attempts to assign a spin to the unresolved transition observed in the $^{40}Ca(d,p)^{41}$ reaction gave inconsistent results. Measurements of iT_{11} for this reaction at 11 MeV led to an assignment[12] of $j^\pi=\frac{1}{2}^-$. The results of several experiments[13–16] involving observations of the γ decay of this state, however, appeared to rule out a $j^\pi=\frac{1}{2}^-$ assignment. In particular, when the $^{40}Ca(d,p\gamma)$ reaction was initiated with 3 or 4 MeV deuterons and the protons were detected at angles of at least 140°, a decay branch from the 3.61 MeV state to the $j^\pi=\frac{7}{2}^-$ ground state was observed and the angular distribution of these γ rays was anisotropic. This situation was clarified by an additional $(d,p\gamma)$ experiment[17] in which the beam energy was 11 MeV (as in the iT_{11} measurements) and the protons were detected near 0°. In this case the γ decay was characteristic of that from a $j^\pi=\frac{1}{2}^-$ state, in agreement with the polarization experiment. Apparently one member of the doublet (with $j^\pi=\frac{1}{2}^-$) is populated when the beam energy in the (d,p) reaction is *high* and the protons are emitted at *forward* angles, and the other component is populated when the beam energy is *low* and the protons are emitted at *backward* angles. The present data show that the important difference between the two types of observations is not the bombarding energy, but the reaction angle of the protons, since these data were obtained at a low bombarding energy (4 MeV) and include forward reaction angles, but are characteristic of $j^\pi=\frac{1}{2}^-$.

The failure of the DWBA calculations to reproduce the details of the analyzing power data in this case might be blamed on several factors. First, there is clearly a significant compound-nuclear contribution to the process that is ignored in the DWBA calculations. Stephenson and Haeberli[18] have shown, however, that for the $^{46}Ti(d,p)^{47}Ti$ reaction at 6 MeV the Ericson fluctuations in iT_{11} are far smaller than the discrepancies between the data and the corresponding DWBA calculations. Although the present data may have a greater compound-nuclear contribution because the reaction involves both a lower mass number and a lower beam energy, compound effects are probably not primarily responsible for the discrepancies between the data and the calculations. Coupled-channels effects, on the other hand, may play a major role. In particular, Mukherjee and Shyam[10] have shown that coupled-channels and DWBA calculations for the analyzing power in the $^{40}Ca(\vec{d},p)$ reaction at 5 MeV give quite different results. Although these authors stress that the purpose of their work was not to fit data, the coupled-channels calculations appear to be in better agreement with the experimental results for the transitions to the 1.94 and 3.94 MeV states at a bombarding energy of 5 MeV. They also conclude that breakup effects and the D state of the deuteron may be responsible for the substantial discrepancies that remain between theory and experiment.

The present results demonstrate that the j dependence of the vector analyzing power continues to be a valuable spectroscopic tool even at low bombarding energies. The j dependence is clearly evident in the data, and the gross features of the iT_{11} angular distributions are reproduced by DWBA calculations.

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