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Proton partial decay widths from the intermediate structure in ^{41}Sc

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Proton partial decay widths were measured from four of the members of the intermediate structure in ^{41}Sc at $E_x=7.2$ MeV, using analyzing powers and spin-flip correlations to ascertain the relative $p_{1/2}$ and $p_{3/2}$ contributions to the structure. Two of the resonances at $E_x=7.27$ and 7.44 MeV, respectively, are rather pure configurations of a $p_{1/2}$ proton coupled to the 3^-, 3.73 MeV excited state in ^{40}Ca whereas at least one of the resonances at $E_x=7.37$ MeV has some $p_{3/2}$ proton coupling to the same 3^- state in ^{40}Ca.

[NUCLEAR REACTIONS ^{40}Ca(p,p'), measured $\sigma(\theta)$ at four energies. ^{40}Ca($\vec{p}$,$p'\gamma$), measured analyzing powers, spin-flip correlations, and spin-flip asymmetries. Calculated partial proton decay widths.]

I. INTRODUCTION

A 2p-1h intermediate structure in ^{41}Sc, first suggested as a possibility by Bolsterli, Gibbs, Kerman, and Young,[1] was identified in 1974 by Mittig, Cassagnou, Cindro, Papineau, and Seth.[2] They observed a cluster of some seven resonances in ^{41}Sc, centered at an excitation energy of 7.2 MeV, which preferentially decayed to the 3^- (3.73 MeV) 1p-1h state in ^{40}Ca. In addition, most members of the structure appeared to have $J^\pi=\frac{5}{2}^+$ which led Mittig *et al.* to propose that the structure was the coupling of the $p_{1/2}$ single-particle state in ^{41}Sc to the 3^- collective state in ^{40}Ca. Detailed (p,$p'\gamma$) angular correlation data over the seven members of the structure were measured by two groups,[3,4] independently assigning $J^\pi=\frac{5}{2}^+$ to all but one member of the structure. Although this doorway state appears primarily in the 3^- exit channel, there was sufficient strength in the elastic channel for one of the groups[3] to corroborate the spin assignments by analyzing power measurements in the elastic channel.

The center of gravity of the intermediate structure at an excitation of 7.2 MeV, is essentially the sum of the excitation energies of the 3^- state in ^{40}Ca (3.73 MeV) and the $p_{1/2}$ single-particle state (3.46 MeV) in ^{41}Sc. This simple weak-coupling picture lends credence to the assignment of the structure as a $p_{1/2}$ proton coupled to the 3^- state in ^{40}Ca. However, weak-coupling calculations[5] have indicated that the (2p-1h) state may be a mixture of $(3^-\otimes p_{1/2})^J$ and $(3^-\otimes p_{3/2})^J$ configurations. It is the purpose of this paper to report on experiments of analyzing-power and spin-flip-correlation measurements in the inelastic decay channel to the 3^- state in ^{40}Ca of the various members of the structure. These measurements are sensitive to both the l value and J value of the emitted protons, and hence, can aid in determining the relative strength of the $p_{1/2}$ and $p_{3/2}$ protons coupled to the 3^- state in ^{40}Ca.

II. EXPERIMENTAL PROCEDURE

The experiments were performed using the polarized proton beam from the Ohio State University 7 MV Van de Graaff accelerator. A 40 nA proton beam with a typical transverse polarization p_y of 0.65 was incident on the Ca target. The inelastic scattered protons were detected by four pairs of symmetrically located surface barrier detectors. The spectra were collected in the eight-fold channel PACE-ADC input to an IBM 1800 on-line computer. After recording spectra for the eight detectors for a fixed charge, the scattering chamber was rotated by 180° precisely about the beam momentum axis, according to the proper spin-flip criteria of Ohlsen and Keaton,[6] so that the four pairs of detectors were interchanged. The beam polarization was measured by ($p-\alpha$) scattering before and after each chamber rotation and was found to vary no more than $\pm 1\%$ over a 24-h period.

Spin-flip angular correlation asymmetries were measured only for the two most prominent resonances at $E_p = 6.18$ and 6.28 MeV, respectively. The target chamber used for the correlation measurements was essentially the same as that used in the inelastic analyzing power measurements except that a new lid was fabricated to hold a 7.6×7.6 cm NaI(Tl) detector. The γ-ray detector was mounted perpendicular to the reaction plane in a proper spin-flip geometry. Both the proton and γ-ray signals were examined and corrected for pulse pileup. Corrections were made for accidental coincidences by measuring coincidences between the decay γ rays and the elastic proton peak.

The Ca target was prepared by the evaporation of natural calcium onto a thin carbon backing. In order to prevent the calcium from oxidizing, a thin layer of gold was evaporated on both sides of the Ca target. By measuring the elastic scattering from the gold layers, we were able to determine that the incident protons lost approximately 20 keV in the Ca target at a laboratory energy of 6.2 MeV. For a given energy, the inelastic analyzing powers and spin-flip asymmetries were measured for at least 12 angles between 45° and 160°. A complete set of data was obtained at two energies, $E_p = 6.18$ and 6.28 MeV, respectively, and the inelastic analyzing powers were measured at two additional energies, $E_p = 6.045$ and 6.365 MeV.

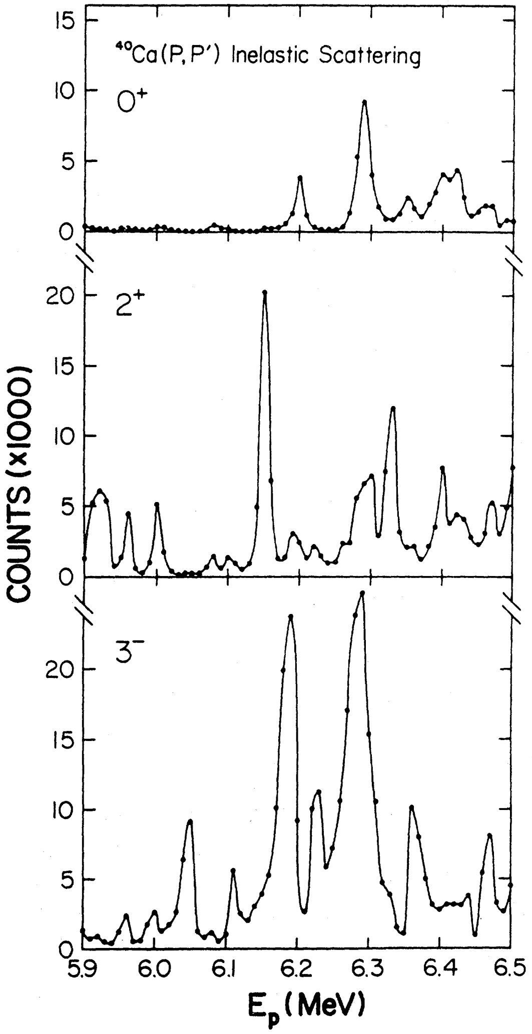

FIG. 1. Inelastic proton yields to the first three excited states in ^{40}Ca. The solid lines are not theoretical fits but serve mainly to guide the eye.

III. EXPERIMENTAL RESULTS

The yield of inelastically scattered protons leaving the residual nucleus ^{40}Ca in its first three excited states is shown in Fig. 1. There are seven resonances centered at $E_p = 6.2$ MeV ($E_x = 7.2$ MeV), which preferentially decay to the 3^- excited state in ^{40}Ca. The analyzing power and spin-flip correlation measurements were taken at the peaks of the resonances located at $E_p = 6.045$, 6.18, 6.28, and 6.36 MeV, respectively. Absolute differential cross sections were obtained both by comparison with the

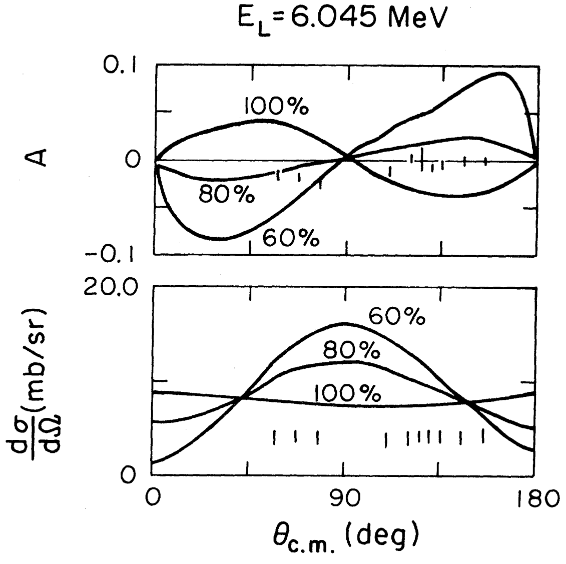

FIG. 2. The analyzing power and cross sections for the ^{40}Ca($\vec{p}$,p')^{40}Ca* (3.73 MeV) reaction taken at the peak of the $E_p = 6.045$ MeV resonance in ^{41}Sc. The solid curves represent calculations containing various percentages of $p_{1/2}$ to $p_{3/2}$ proton decay.

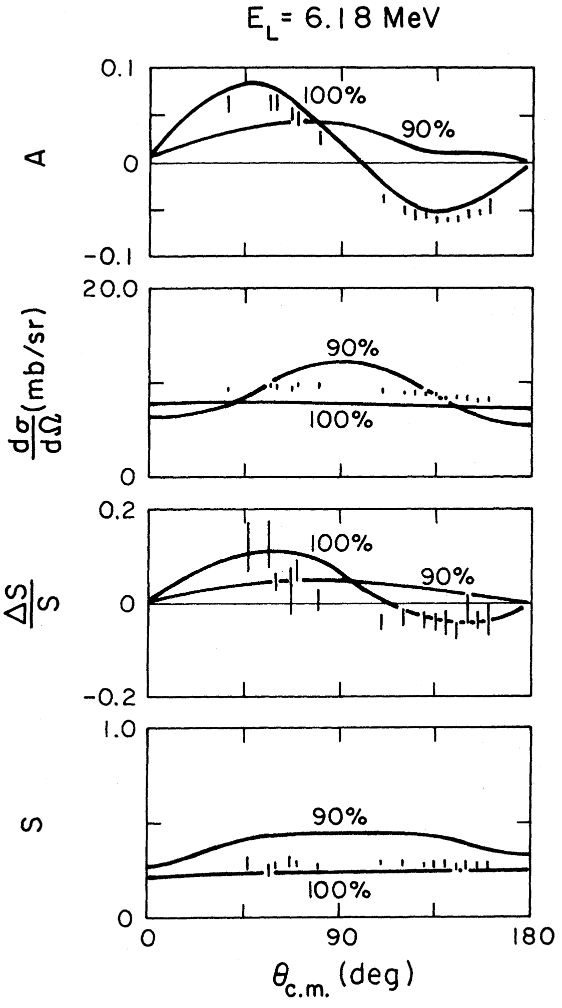

FIG. 3. Analyzing power, cross section, spin-flip asymmetry, and spin-flip cross section measurements taken at the peak of the $E_p=6.18$ MeV resonance in ^{41}Sc. The solid curves represent calculations containing various percentages of $p_{1/2}$ to $p_{3/2}$ proton decay.

cross section measurements of Mittig *et al.* and by summing the events in the symmetrically-placed particle detectors.

The results of the analyzing power, spin-flip correlation, and differential cross section measurements are shown in Figs. 2–5. The quantity $\Delta S/S$ is proportional to the left-right asymmetry in the number of proton-γ coincidences and is calculated as

$$\frac{\Delta S}{S}=\frac{1}{|P_B|}\,\frac{(N_1^+N_2^-)^{1/2}-(N_2^+N_1^-)^{1/2}}{(N_1^+N_2^-)^{1/2}+(N_2^+N_1^-)^{1/2}}\,,$$

where P_B is the incident beam polarization and N_1^+ is equal to the number of coincidences between the (left) particle detector No. 1 and the γ detector, and

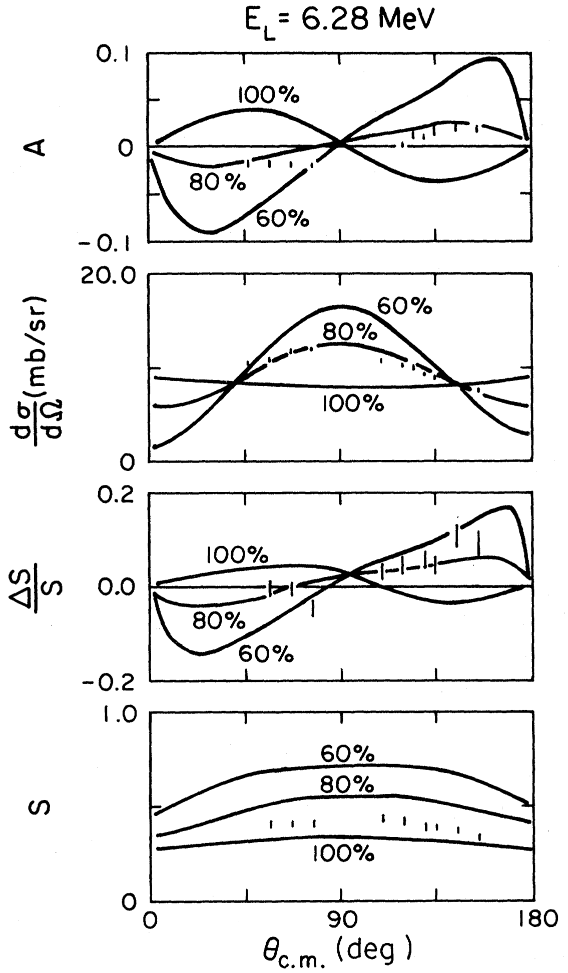

FIG. 4. Same as Fig. 3, but taken at the peak of the $E_p=6.28$ MeV resonance.

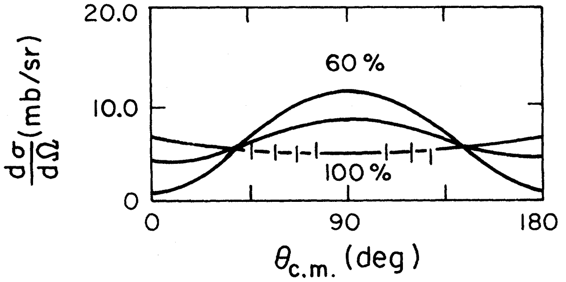

FIG. 5. Same as Fig. 2, but taken at the peak of the $E_p=6.36$ MeV resonance.

N_2^+ is the number of coincidences between the (right) particle detector No. 2, while the chamber is upright. N_1^- is the number of coincidences between the (right) particle detector No. 1 and the γ detector and N_2^- is the number of coincidences between the (left) particle detector No. 2 and the γ detector while the chamber is inverted. The spin-flip probability S is proportional to the sum of the coincidences with both the left and right particle detectors. Using the definition of Schmidt *et al.*,[7] the spin-flip probability is computed as

$$S(\theta)=\frac{8\pi}{5}\frac{N_{\text{coin}}(\theta)}{N_{\text{inel}}(\theta)E_\gamma d\Omega_\gamma},$$

where N_{coin} and N_{inel} are the number of coincidences and the number of inelastic protons measured at a given angle θ, and $E_\gamma\, d\Omega_\gamma$ are the efficiency and solid angle of the NaI detector. The correction for the finite size of the NaI detector was found to be small ($\leq$ 1%). All of the measurements were corrected for pulse pileup and the correlations were also corrected for accidental events.

The theoretical fits shown in the figures were calculated using a modified version[8] of the DWBA computer code DWUCK. The optical model parameters used in Ref. 3 to calculate fits to the elastic analyzing power measurements were used in this analysis as well. The deformation parameter $\beta(3^-)$ was set equal to 0.34, in agreement with values reported in the literature.[9] The total and elastic widths used in this analysis were those obtained from the analysis of the elastic data.

The existence of analyzing powers in the inelastic decay channels of the various resonances to the 3^- excited state in ^{40}Ca can result from interference in the partial decay amplitudes from the resonant states as well as direct-resonant interference. The differential cross section was assumed to contain both a resonant term and a direct term and was calculated as

$$\frac{d\sigma(\theta)}{d\Omega}=\frac{1}{2}\sum_{mm_bm_a}|A(\text{DWBA})+A(\text{RES})|^2,$$

where $A(\text{DWBA})+A(\text{RES})$ are the direct and resonant amplitudes, and m, m_b and m_a are the z components of transferred angular momentum, z components of scattered particle, and z components of the incident particle, respectively. For the spin-flip correlation calculations, the z axis was chosen perpendicular to the scattering plane.

The partial decay amplitudes, Γ, and mixing phases, ϕ_j, in the calculations were varied until a visual "best fit" was obtained. The decay of the resonances at $E_p=6.18$ and 6.365 MeV was found to be an almost pure $p_{1/2}$ transition. The resonance at 6.28 MeV showed components of both $p_{1/2}$ and $p_{3/2}$ decay. It is difficult to draw any conclusions from the decay of the resonance at 6.045 MeV. The analyzing power results indicate some $p_{3/2}$ component in the decay channel but the shape of the differential cross section suggests almost pure $p_{1/2}$ decay. The results of the analysis are summarized in Table I, where the uncertainties in each of the decay strengths are noted.

IV. DISCUSSION

The results of these and other measurements lead to the conclusion that the ("simple") intermediate structure state at an excitation energy of 7.2 MeV in ^{41}Sc is of a rather pure configuration in which a $2p$ proton is weakly coupled to the 3^- core state in ^{40}Ca. In addition, the angular correlation results

TABLE I. Summary of resonance parameters including inelastic decay widths.

E_{res} (MeV)	J^π	Γ_{tot} (keV)	Γ_p (keV)	$\Gamma_{p'(p_{1/2})}$	$\Gamma_{p'(p_{3/2})}$	$\phi_{1/2}$ (deg)	$\phi_{3/2}$ (deg)	$\%p_{1/2}$	$\%p_{3/2}$
6.045	$\frac{5}{2}^+$	22	21						
6.18	$\frac{5}{2}^+$	16	8	5±2	0±1	15±5	0±5	100% ±5%	0% ±5%
6.225		30	10						
6.285	$\frac{5}{2}^+$	40	18	10±3	2±1	0±5	0±5	80% ±10%	20% ±10%
6.365	$\frac{5}{2}^+$	12	3	(4)	(0)	(15)	(0)	(100%)	(0%)

TABLE II. Comparison of experimental results and theoretical predictions for levels in the vicinity of the intermediate structure in ^{41}Sc at $E_x = 7.2$ MeV.

$\mid 3^- \otimes 2p_{1/2}\rangle$	$\mid 3^- \otimes 2p_{3/2}\rangle$	J^π	E_p	E_x (MeV)	E_x (MeV)	J^π	$\mid 3^- \otimes 2p_{1/2}\rangle$	$\mid 3^- \otimes 2p_{1/2}\rangle$
					7.7	$\frac{5}{2}^+$	85%	15%
		$\frac{5}{2}^+$	6.40	7.49				
		$\frac{5}{2}^+$	6.35	7.44				
80%	20%	$\frac{5}{2}^+$	6.28	7.37				
100%		$\frac{5}{2}^+$	6.18	7.27				
		$\frac{5}{2}^+$	6.10	7.19	7.21	$\frac{5}{2}^+$	100%	
		$\frac{5}{2}^+$	6.04	7.13				
					4.9	$\frac{5}{2}^+$	15%	85%
Levels determined experimentally					Theoretical predictions			

and the analyzing power results indicate that the particle is predominantly the $p_{1/2}$ particle with only a weak contribution due to the $p_{3/2}$ particle. The structure thus satisfies the criteria of an intermediate structure state, as predicted by Bolsterli *et al.* in that: (a) the components of the simple 2p-1h state preferentially decay to the 1p-1h 3^- state in ^{40}Ca; (b) the $J^\pi = \frac{5}{2}^+$ of the members of the state have spin and parity determined by the coupling of the $2p$ particle to the 3^- core; and (c) the distribution of partial widths is well represented by a Lorentzian shape with a spreading width $\Gamma^\downarrow$ of 200 keV.

The presence of some $(p_{3/2} \otimes 3^-)$ strength in the intermediate structure is not unexpected. The weak-coupling calculations by Hoffman-Pinther indicate the presence of both the $p_{1/2}$ and $p_{3/2}$ protons coupled to the 3^- core in approximately the same excitation region in ^{41}Sc. The calculations included an interaction term of the form

$$-\xi \bar{J}_c \cdot \bar{j}_p - \eta \bar{Q}_c \cdot \bar{Q}_p \ ,$$

where $\bar{J}_c$ and $\bar{Q}_c$, and $\bar{j}_p$ and $\bar{Q}_p$ are the spin and quadrupole moment operators of the 3^- core and $2p$ proton, respectively, and ξ and η are adjustable strengths. The quadrupole term was evaluated using a value of 17.34 f^2 for the $\langle 3^- \| Q \| 3^- \rangle$ term extracted from the experimental quadrupole moment of the 3^- state of ^{40}Ca. No radial matrix elements were used for the single particle factor since it can be included in η for this case. Amplitudes were calculated for $(3^- \otimes p_{3/2^-})_{5/2^+}$ and $(3^- \otimes p_{1/2^-})_{5/2^+}$ terms leading to the prediction of two mixed states at excitation energies of 4.9 and 7.7 MeV, respectively. These predictions are shown in Table II. The agreement of the predicted $p_{1/2}$ and $p_{3/2}$ strengths of the calculated state at 7.7 MeV with that of the measured values of the 7.37 MeV ($E_p = 6.28$ MeV) state may be fortuitous since there is evidence that some weak $p_{3/2}$ component exists in some of the other fine-structure states, such as the state at $E_p = 6.045$ MeV.

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