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Excitation of two-particle – one-hole high-spin states in the ^{45}Sc$(p,n)^{45}$Ti reaction at 136 MeV

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The ^{45}Sc$(p,n)^{45}$Ti reaction was studied at 135 MeV with a beam-swinger system. Neutron kinetic energies were measured by the time-of-flight technique, with neutron detectors located in three detector stations at 0°, 24°, and 45° with respect to the undeflected beam. Flight paths of 131.0, 131.1, and 81.3 m were used. The overall timing resolution was about 825 ps, providing energy resolutions of 320 keV in the first two stations and 520 keV in the third. The wide-angle spectra are dominated by a complex at $E_x = 4.3$ MeV. The angular distribution for this complex is fitted well by a distorted-wave impulse approximation calculation for an assumed $J^\pi = \frac{17}{2}^-, \frac{19}{2}^-$ $(\pi f^2_{7/2}, \nu f^{-1}_{7/2})$ doublet. The spectra and angular distribution are consistent with (p,π^-) excitations of the same states and are in good agreement with a full $1f$-$2p$ shell-model calculation. The $\frac{17}{2}^-, \frac{19}{2}^-$ strength predicted by distorted-wave impulse approximation calculations using these shell-model wave functions is in good agreement with the experimental measurements.

I. INTRODUCTION

The (p,π^-) reaction near threshold has been shown to preferentially excite 2p-1h high-spin states. Strong excitation of such states was observed in many nuclei in experiments performed at the Indiana University Cyclotron Facility (IUCF).[1–4] The selectivity of this reaction for exciting states of the highest possible spin is dramatic and the reaction provides an excellent probe for mapping out the distribution of strength for high-spin orbitals. Although there does exist a simple model for the (p,π^-) reaction mechanism,[5] it is a plane-wave model and can predict only relative strengths, so that absolute spectroscopic information is unavailable. It would be highly desirable to excite these same states with another reaction that might be able to yield absolute spectroscopic information. To this end, we have used the ^{45}Sc$(p,n)^{45}$Ti reaction at 136 MeV to excite the same states observed earlier with the ^{45}Ca$(p,\pi^-)^{45}$Ti reaction.[6] Because the (p,n) reaction is known to be described reasonably well by the distorted-wave impulse approximation (DWIA), absolute spectroscopic information can be obtained for these 2p-1h high-spin states in the same way that it is for 1p-1h "stretched states" observed in many nuclei [where comparison can be made with (p,p') and (e,e') excitations].[7]

In order to excite a 2p-1h state in the (p,n) reaction, which creates a proton particle and a neutron hole, it is necessary to find a target that already has an odd proton in the orbital of interest, with which the created particle and hole can couple to form the 2p-1h state. This requirement is difficult to satisfy, in general, but is available for the ^{45}Sc$(p,n)^{45}$Ti reaction, which can create the same states as does the ^{44}Ca$(p,\pi^-)^{45}$Ti reaction. In the simple shell model, ^{45}Sc has four neutrons and one proton in the $f_{7/2}$ orbital. The (p,n) reaction converts one of these neutrons into a proton forming two proton particles and one neutron hole in the $f_{7/2}$ orbital. The highest spin state allowed is thus $\frac{19}{2}^-$ (the $\frac{21}{2}^-$ state is not allowed by the Pauli exclusion principle). As described below, the $\frac{19}{2}^-$ state is observed to be excited by the (p,n) reaction and the extracted angular distribution is compared with a DWIA calculation using large-basis, shell-model wave functions.

II. EXPERIMENTAL PROCEDURE

The experiment was performed at the Indiana University Cyclotron Facility with the beam-swinger system. The experimental arrangement and data-reduction procedures were similar to those described previously.[8] Neutron kinetic energies were measured by the time-of-flight (TOF) technique. A beam of 136 MeV protons was obtained from the cyclotron in narrow beam bursts typically 350 ps long, separated by 132.7 ns. Neutrons were detected in three detector stations at 0°, 24°, and 45° with respect to the undeflected proton beam. The flight paths were 131.0, 131.1, and 81.3 m, respectively. The neutron detectors were rectangular bars of fast plastic scintillator 10.2 cm thick. Three separate detectors each with a scintillator bar 1.02 m long by 0.51 m high were combined for a total frontal area of 1.55 m^2 in the 0° and 24° stations. Two detectors were used in the 45° station; both with a scintillator bar 1.52 m long by 0.76 m high, for a combined frontal area of 2.31 m^2. Each neutron detector had tapered plexiglass light pipes attached on the two ends of the scintillator bar, coupled to 12.76 cm diam phototubes. Timing signals were derived from each end and combined in a mean-timer circuit[9] to provide the net timing signal from each detector. Overall time resolutions of about 825 ps were obtained, including contributions from the beam burst width (~350 ps) and energy spread (~400 ps), energy loss in the target (~460 ps), neutron transit times across the 10.2 cm thickness of the detectors (~530 ps), and the intrinsic time dispersion of each detector (~300 ps). This overall time resolution provided an energy resolution of about 320 keV in the first two detector stations and about 520 keV in the widest-angle station. The large-volume neutron detectors were described in more detail previously.[10] Protons from the target were rejected by anticoincidence detectors in front of each neutron detector array. Cosmic rays were vetoed by anticoincidence detectors on top as well as the ones at the front of each array.

The target was a 37.7(±0.8) mg/cm^2 self-supporting foil of ^{45}Sc. Time-of-flight spectra were obtained at 15 angles between 0° and 63°. Spectra from each detector were recorded at many pulse-height thresholds ranging from 25 to 90 MeV equivalent-electron energy (MeV *ee*). Calibration of the pulse-height response of each of the detectors was performed with a ^{228}Th gamma source and a calibrated fast amplifier. The values of the cross sections extracted for several different thresholds (from 40 to 70 MeV *ee*) were found to be the same within statistics.

III. DATA REDUCTION

Excitation-energy spectra were obtained from the measured TOF spectra using the known flight path and a calibration of the time-to-amplitude converter. The observed gamma flash from the target provided an absolute reference point. Because of the long flight paths, the gamma flash observed is actually from a later beam burst (because the gammas have about twice the velocity of the neutrons of interest). Because the time between beam bursts is known accurately (132.67 ns), this effect could be taken into account. This procedure was checked using the known ^{12}C$(p,n)^{12}$N(g.s.) reaction. Absolute neutron kinetic energies (and therefore excitation energies) are believed to be accurate to ±0.1 MeV.

Yields for transitions in the ^{45}Sc$(p,n)^{45}$Ti reaction were obtained by peak fitting of the TOF spectra. The spectra were fitted with an improved version of the peak-fitting code of Bevington.[11] Examples of peak fitting of similar neutron TOF spectra were presented earlier for the (p,n) reaction on ^{48}Ca and ^{26}Mg.[8,12] The TOF spectra were subdivided into regions where groups of peaks and a polynomial background could be fitted simultaneously. Cross sections were obtained by combining the yields with the measured geometrical parameters, the beam integration, and the target thickness. The neutron detector efficiencies were obtained from a Monte Carlo computer code,[13] which was tested extensively at these energies.[14,15] The overall absolute cross sections so obtained were checked by remeasuring the known ^{12}C$(p,n)^{12}$N(g.s.) and ^{7}Li$(p,n)^{7}$Be (0.00+0.43 MeV) cross sections.[14,15] The experimental procedure and data reduction are similar to that described in more detail in Ref. 8. The uncertainty in the overall scale factor is dominated by the uncertainty in the detector efficiencies and is estimated to be ±12%.

IV. RESULTS AND DISCUSSION

The excitation-energy spectra for the ^{45}Sc$(p,n)^{45}$Ti reaction are dominated at wide angles by a single peak at $E_x = 4.3$ MeV. The excitation-energy spectrum at 45° is shown in Fig. 1. The spectrum is very similar to that for the ^{44}Ca$(p,\pi^-)^{45}$Ti reaction reported by Throwe *et al.*[6] The angular distribution for the (p,n) peak is shown in Fig. 2. The angular distribution, although peaked at a wide angle as expected for a high-spin state, cannot be fitted well by a DWIA calculation for a $\frac{19}{2}^-$ excitation alone. As shown, if we assume that there is also an unresolved $\frac{17}{2}^-$ state in the peak shown in Fig. 1, then the sum of the two DWIA calculations can describe the angular distribution well.

Note that the normalization factors required to make the DWIA calculations fit the experimental angular distribution are nearly unity (viz., 0.9). The DWIA calculations were performed with the computer code DW81 (Ref. 16) using the global optical-model parameters of Schwandt *et al.*[17] and the nucleon-nucleon effective interaction of Franey and Love.[18] The calculations use one-body transition densities (OBTD's) obtained from a full $1f$-$2p$ shell-model calculation.

The shell-model calculations were performed with the Oxford–Buenos Aires Shell Model Code (OXBASH).[19] The two-body matrix elements were obtained partly from those of Van Hees and Glaudemans,[20] and Koops and Glaudemans.[21] The rest of the matrix elements were obtained from a modified surface delta interaction (MSDI) calculation by Brown.[22] Hereafter we refer to this set of matrix elements as the VGKB interaction. The single-particle energies for the $1f$-$2p$ states were taken from Van Hees and Glaudemans[20] with one modification as described below. The calculation considers five particles in the $1f$-$2p$ shell with no restrictions (i.e., a full $1f$-$2p$

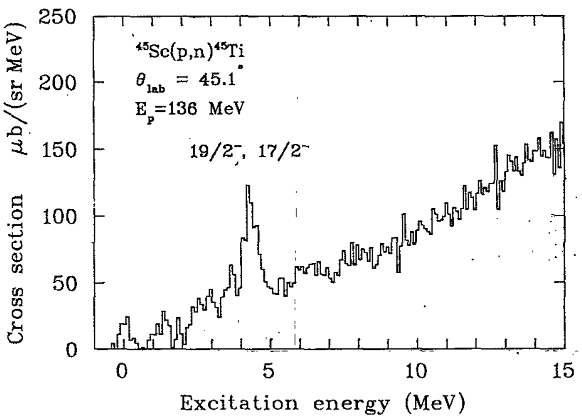

FIG. 1. Excitation-energy spectrum for the ^{45}Sc$(p,n)^{45}$Ti reaction at 136 MeV and 45°.

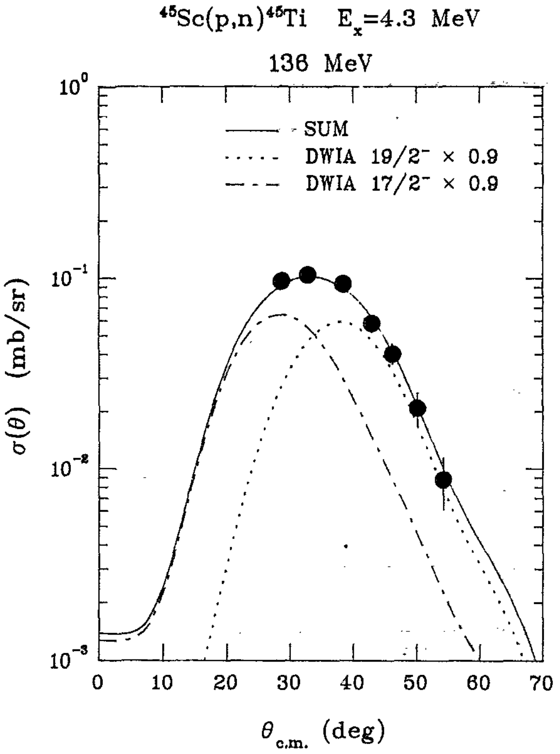

FIG. 2. The angular distribution for the $E_x=4.3$ complex in the ^{45}Sc$(p,n)^{45}$Ti reaction at 136 MeV. DWIA calculations for the $\frac{19}{2}^-$ and $\frac{17}{2}^-$ excitations using full $1f$-$2p$ shell-model calculation wave functions are shown (see text).

model-space calculation). The $A=45$ systems are among a few cases in the $1f$-$2p$ shell model space for which full f-p shell-model calculations are possible.

The effective interaction of Van Hees and Glaudemans (VG) gives reasonable agreement over the mass region $A=41-55$ (Rapaport *et al.*[23]). Their model space included the excitation of one $f_{7/2}$ nucleon to the $p_{3/2}$, $f_{7/2}$, or $p_{1/2}$ orbital as well as pure $f_{7/2}$ configurations. The Koop and Glaudemans matrix elements (KG) were obtained for full $(p_{3/2},f_{5/2},p_{1/2})$ model-space calculations. The single-particle energies adopted here are essentially the same as that of Van Hees and Glaudemans except that the $f_{7/2}$-$f_{5/2}$ splitting was increased by 2 MeV. This modification probably is required because the original interaction was fitted to known states in $A=52-55$ nuclei and the spacing could be different in the $A=45$ region. This interaction and the same modified single-particle energies were adopted in earlier shell-model calculations for $A=48$ systems.[24] In that work, the comparison of the calculated distribution of 1^+ states with the experimental 0° spectrum for the ^{48}Ca$(p,n)^{48}$Sc was remarkably good.

As a test of the two-body interactions and single-particle energies for $A=45$, we performed calculations for energy levels in ^{45}Ca, ^{45}Sc, and ^{45}Ti. It was possible to identify some twenty-three states with known experimental values. These states extend up to about 5 MeV of excitation and include J^π values from $\frac{3}{2}^-$ to $\frac{19}{2}^-$. The agreement is very good with an average deviation of 298 keV. We note that there are some known positive parity "intruder" levels in these nuclei. These states, as well as some negative parity states that can be made by 2p-2h core excitations, will not be predicted by this model space. Unfortunately inclusion of the $d_{3/2}$ subshell in the calculation is not possible at this time. In general, because of core polarization, one does not expect impressive agreement of calculated and measured energy levels in nuclei with only a few particles outside a closed core. The good agreement between theoretical and experimental energy levels observed here suggests that core configuration admixtures in this case have small effects on the wave functions; furthermore, it shows also that the $f_{7/2}^2$ two-body matrix elements originally developed for a truncated basis are good in this basis as well. We conclude that it is quite reasonable to use the combined $1f$-$2p$ matrix elements in our full basis shell-model calculations.

The shell-model calculations for this work predict a $\frac{19}{2}^-$ state at $E_x=4.6$ MeV in ^{45}Ti, which is within 0.3 MeV of the state we observe at large angles (viz., at 4.3 MeV). This same calculation also predicts a $\frac{17}{2}^-$ state at 4.2 MeV, which is within 0.4 MeV of the predicted $\frac{19}{2}^-$ state; if these two states are actually this close in energy (or closer), we could not resolve them in this experiment. Furthermore, the absence of another peak that could be a candidate for a $\frac{17}{2}^-$ state in the spectra suggests that this state probably is in the 4.3 MeV complex. Above all, the $\frac{17}{2}^-$ and $\frac{19}{2}^-$ states are known in ^{45}Sc, and are only 0.12 MeV apart; viz., the $\frac{17}{2}^-$ is at 3.570 MeV and the $\frac{19}{2}^-$ is at 3.693 MeV.[25] It is not expected that the energy difference (or splitting) of these states in ^{45}Ti is very different than it is in ^{45}Sc. Based on these arguments, it is likely that the 4.3 MeV complex is in fact a $\frac{19}{2}^-$, $\frac{17}{2}^-$ doublet.

The simple reaction model developed by Brown for the ^{45}Ca$(p,\pi^-)^{45}$Ti reaction predicts that the $\frac{17}{2}^-$ state would be suppressed severely. The observed (p,π^-) spectrum appears to be consistent with this prediction.[6] The observed (p,n) spectrum is compared with the theoretically predicted spectrum in Fig. 3. The predictions are DWIA calculations that use the $1f$-$2p$ shell-model wave functions. The spectrum is for 45° where the $\frac{19}{2}^-$ state is predicted to dominate (see the angular distribution of Fig. 2). The (p,n) spectrum is seen to be in reasonable agreement with the theoretical predictions.

It is worthwhile to compare the spectroscopic strength obtained from the ^{45}Sc$(p,n)^{45}$Ti reaction with that obtained for the ^{48}Ca$(p,n)^{48}$Sc reaction to the 7^+, "$0\hbar\omega$," 1p-1h stretched state. This result is a good example of a relatively pure 1p-1h excitation with the (p,n) reaction and was reported earlier.[24] The earlier analysis yielded a spectroscopic strength (i.e., a DWIA normalization factor) Z^2 (DWIA)$=0.60$. In this analysis, the same two-body interaction (VGKB) and single-particle energies were used in the OXBASH calculations; however, a severely truncated configuration space $[(f_{7/2})^8+(f_{7/2})^7(p_{3/2},f_{5/2},p_{1/2})^1]$ was assumed for the $A=48$ nuclear systems calculations. In order to see the effects

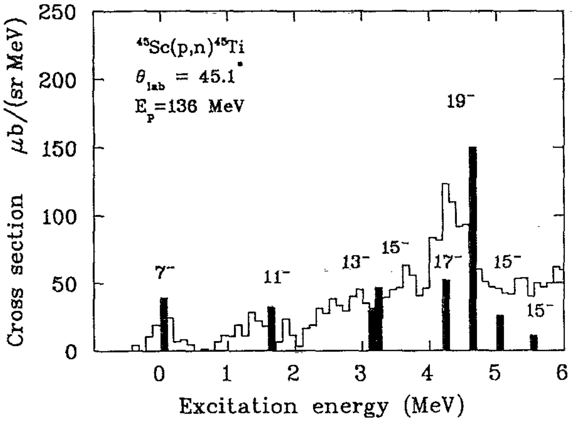

FIG. 3. Comparison of the predicted and observed (p,n) spectra at 45° for the excitation of 2p-1h states in ^{45}Ti. (States are labeled by their $2J^{\pi}$ values.)

of the truncation of the model space on the wave functions, we performed new shell-model calculations using the VGKB effective interaction in an extended configuration space that includes up to 3p-3h excitations in the $1f$-$2p$ model space for the ^{48}Ca and ^{48}Sc systems. When OBTD's obtained from these new wave functions are used in a DWIA calculation for the ^{48}Ca$(p,n)^{48}$Sc (7^+) reaction, the normalization factor required to fit the experimental angular distribution is increased to 0.91. This increase is due to the increased configuration mixings, which were restricted in the original model-space calculation. The total strength is distributed among 1617 7^+ states in the extended model space, whereas the total number of 7^+ states in the limited model space is only 25. These observations indicate that structure effects are important and that most of the stretched-state strength may be accounted for when realistic wave functions are used.

V. CONCLUSIONS

In summary, the (p,n) reaction is observed to excite the $\frac{19}{2}^-$, 2p-1h stretched state in ^{45}Ti observed also in the (p,π^-) reaction on ^{44}Ca. The excitations observed in the two reactions appear to be consistent with each other, although, in contrast to the (p,π^-) reaction, the (p,n) reaction does not suppress the nearby $\frac{17}{2}^-$ state. The (p,n) reaction provides an angular distribution that can be fitted with DWIA calculations. It is found that if these DWIA calculations use realistic structure wave functions from a full $1f$-$2p$ shell-model calculation, the calculations of both the angular distributions and the absolute strengths are in good agreement with the experimental results.

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