Study of the $Ca^{48}(He^3, p)Sc^{50}$ Reaction*

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The $Ca^{48}(He^3, p)Sc^{50}$ reaction was studied with a magnetic spectrograph at a bombarding energy of 12 MeV. Energy levels of Sc^{50} were obtained. Spins and parities for these levels were assigned on the basis of a comparison between the experimental and calculated angular distributions. Distorted-wave Born-approximation theory and the shell-model wave functions due to Kuo and Brown were used to calculate the angular distributions.

I. INTRODUCTION

THE nuclear structure of Sc^{50} is particularly interesting because it has, in the simplest shell-model picture, one proton and one neutron outside the doubly magic Ca^{48} core. However, very little has been previously reported about this nucleus. It is known[1] that the ground state has spin and parity 5^+ and the metastable state at 258 keV has spin 2^+. Shida *et al.*[2] found another state at 330 keV in the study of the β decay of Ca^{50} and tentatively assigned 1^+ to it. Recently, Chase *et al.*[3] and Miyano *et al.*[4] reinvestigated the decay of Ca^{50} and assigned spin 1^+ to a state at 1.85 MeV, which decays to the states at 330 and 258 keV. From the consideration of the branching ratio, Chase *et al.*[3] suggested a 3^+ assignment to the state at 330 keV. Shell-model calculations for Sc^{50} have been done by several authors.[5–8] All of these calculations predict low-lying 5^+, 2^+, 3^+, and 4^+ states whose main configuration is $(\pi f_{7/2}\nu p_{3/2})$. It is the purpose of this paper to obtain more information on the Sc^{50} nucleus by using a two-nucleon stripping reaction. With such a reaction, different amplitudes contributing to a given transition add coherently and therefore the cross section is very sensitive to small admixtures. A preliminary report of the present study has been given previously.[9]

II. EXPERIMENTAL PROCEDURES AND RESULTS

The $Ca^{48}(He^3, p)Sc^{50}$ reaction was studied with a broad-range magnetic spectrograph and the 12-MeV He^3 beam from the Argonne tandem Van de Graaff. Some of the data were read from the nuclear emulsions with an automatic plate-counting machine.[10] Metallic calcium targets about 50 $\mu g/cm^2$ thick and enriched to 98% in Ca^{48} were used. Absolute differential cross sections were obtained by comparing the (He^3, p) yield with the yield of elastic scattering on Ca^{48}. The elastic-scattering cross section was obtained from optical-model calculations with the parameters described below.

A typical proton spectrum is shown in Fig. 1. States in Sc^{50} observed in this experiment are listed in Table I. The ground-state Q value was measured to be 7.965 ± 0.015 MeV. Angular distributions of proton groups measured for the lower excited states are shown in Fig. 2. The differential cross section of the 0^+ $T=5$ analog of the Ca^{50} ground state was measured to be 0.3 ± 0.1 and 0.08 ± 0.03 mb/sr at 7° and 45° scattering angles. This state had been observed by Nolen *et al.*[11] at 11.195 MeV excitation.

III. DISCUSSION

The low-energy portion of the level scheme of Sc^{50} is shown in Fig. 3, in which the level energies obtained in the present experiment are compared with those calculated by Kuo and Brown[7] and with those from calculation E of Hughes and Soga.[8] The Sc^{50} level scheme observed here experimentally is very similar to the two theoretical ones—at least below 3 MeV. There are four states below 900 keV and three levels around 2 MeV.

The ground state and the first-excited state are known[1] to be 5^+ and 2^+. The 1.85-MeV state was assigned to be 1^+ by Chase *et al.*[3] and by Miyano *et al.*[4] The energies of these known states are very well reproduced by the calculations (Fig. 3). The second excited state at 330 keV is most likely 3^+ from a simple comparison between the experimental and theoretical energies (Fig. 3). Further support for this 3^+ assignment is as follows. The angular distribution (Fig. 2) meas-

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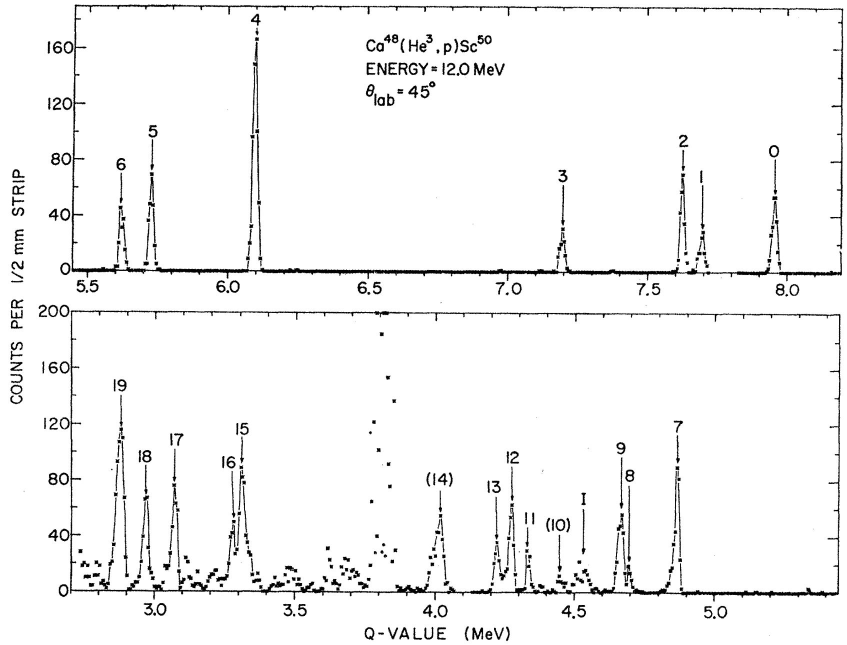

FIG. 1. Proton spectrum from the $Ca^{48}(He^3, p)Sc^{50}$ reaction.

ured for the 330-keV state is not forward peaked as the angular distributions of the 1854- and 3090-keV states are. This apparent absence of a strong $l=0$ component in the angular distribution for this state argues against the 1^+ assignment[2] and favors the 3^+ assignment suggested by Chase *et al.*,[3] since a low-lying 1^+ state is expected to have relatively large $(p_{3/2})^2$ and $(p_{3/2}p_{1/2})$ components and should therefore be strongly excited by an $l=0$ transfer. The 756-keV state was not observed[3,4] in the study of the β decay of Ca^{50}. Comparison with the theoretical calculation shows that this state is most likely 4^+. The calculations also predict that there should be a doublet of spins 4^+ and 3^+ at about 2.3 MeV. There apparently is an $l=2$ component in the angular distribution for the 2227-keV state since the shape of the

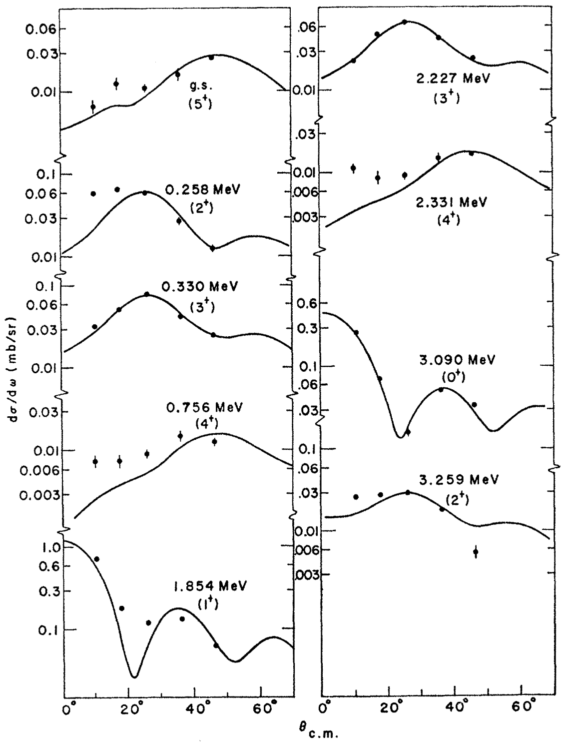

FIG. 2. Angular distributions of proton groups leading to the lowest nine states in Sc^{50}. The solid lines are the DWBA calculations.

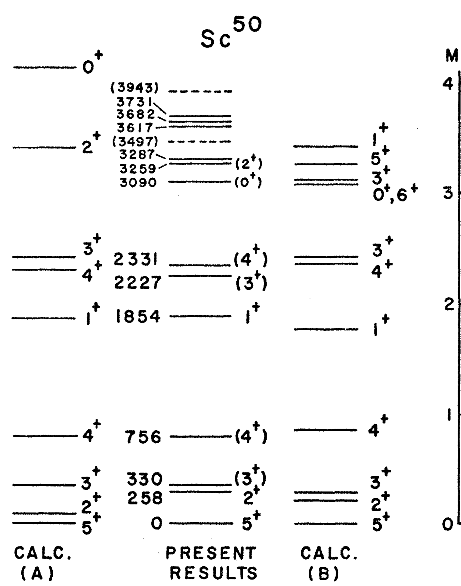

FIG. 3. Low-energy portion of the energy levels of Sc^{50}. (A) Is the spectrum calculated by Kuo and Brown (Ref. 7) and (B) shows calculation E of Hughes and Soga (Ref. 8).

TABLE I. Levels of Sc^{50} observed in the present experiment, and the results of Chase *et al.* (Ref. 3). The experimental cross sections are compared with those calculated on the assumption of a pure $(\pi f_{7/2}\nu p_{3/2})$ configuration and with those obtained by use of the wave functions of Kuo and Brown (Ref. 7)

	Excitation energies (keV)		Spin assignments		$\sigma_{expt}/\sigma_{calc}$	
Level no.	Present work	Chase *et al.*	Chase *et al.*	Present work	Pure $(\pi f_{7/2}\nu p_{3/2})$[a]	Kuo and Brown[b]
0	0	0	5^+	5^+	0.93	0.76
1	258±5	257	2^+	2^+	1.1	1.1
2	330±5	329	(3^+)	(3^+)	4.3	1.3
3	756±8			(4^+)	0.92	0.95
4	1 854±5	1848	(1^+)	1^+		5.0
5	2 227±5			(3^+)		3.0
6	2 331±8			(4^+)		1.1
7	3 090±5			(0^+)		3.6
8	3.259±7			(2^+)		6.6
9	3 287±5					
10	(3 497)±15					
11	3 617±15					
12	3 682±5					
13	3 731±10					
14	(3 943)±10					
15	4 640±7					
16	(4 675)±15					
17	4 879±7					
18	4 980±7					
19	5 073±10					
20	11 195±20			(0^+)		~8

[a] The normalization constants that best fit the four lowest states are $D_0^2=20.8$ for the singlet state and $D_1^2=8.0$ for the triplet.

[b] The normalization constants that best fit the four lowest states are $D_0^2=D_1^2=10.0$.

angular distribution is similar to those for the first and the second excited states. This excludes a 4^+ assignment for the 2227-keV state. Therefore, if the doublet calculated at 2.3 MeV corresponds to states experimentally observed at 2227 and 2331 keV, the order of the spins is probably reversed.

Angular distributions were calculated with the distorted-wave Born-approximation (DWBA) theory of two-nucleon stripping reactions and shell-model wave functions.[12] These calculated results were compared with the experimental angular distributions to see whether the spin assignments made above could be confirmed. The calculations were done with Woods-Saxon single-particle wave functions expanded in terms of oscillator wave functions. The Woods-Saxon well parameters were $r_0=r_c=1.2$ F, $a=0.65$ F, and $\lambda_{so}=25$. The binding energies were those to separate a neutron and a proton from the ground state of Sc^{50}. The optical-potential parameters used are given in Table II. These potentials were chosen from a number of optical potentials on the basis of the fit to the 0^+ state, which is the calculation most sensitive to the optical-model parameters. The He^3 parameters are those Rapaport and Dorenbusch[13] obtained from the analysis of the elastic scattering of 13-MeV He^3 particles on Ca^{48}. The proton parameters were taken from the work of Satchler.[14] The wave functions of Kuo and Brown were used for Sc^{50}. Besides those levels considered before, levels observed at 3090 and 3259 keV were tentatively assumed to correspond to the 0^+ and 2^+ states, respectively, predicted in this region. The solid lines in Fig. 2 are the predictions of the DWBA calculations. The general shapes of the angular distributions are reproduced by the theory, and support the correspondence of levels assumed above.

The ratios of experimental cross sections to the cross

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TABLE II. Optical-model parameters used in the calculations.

	V_0 (MeV)	W (MeV)	r_0 (F)	r_c (F)	a (F)	V_{so} (MeV)	r_0' (F)	a' (F)	W' (MeV)
He^3	146.9	23.46	1.24	1.40	0.686	···	1.601	0.676	···
p	55.4	3.0	1.12	1.2	0.75	6.4	1.33	0.58	21.6

sections calculated by use of the Kuo-Brown wave functions are given in column 7 of Table I. In addition, in order to show the effect of the mixed-configuration wave functions, the ratios for the four lowest states ($J^\pi = 2^+, \cdots, 5^+$) were calculated on the basis of a pure ($\pi f_{7/2} \nu p_{3/2}$) configuration and are listed in column 6. In each case the normalization constants D_0^2 for the singlet state and D_1^2 for the triplet state of the transferred pair were chosen to best describe these lowest four states, and are given in the table.

If one assumes a pure ($\pi f_{7/2} \nu p_{3/2}$) description for these states, the calculated cross section for the lowest 3^+ state is roughly a quarter of the experimental value, although the relative cross sections for the other three states are well reproduced. The Kuo-Brown wave functions, however, enhance the theoretical cross section for the lowest 3^+ state more than for the other three states, thereby producing better agreement with the data. This preference for the 3^+ state is due to the fact that the ($\pi f_{7/2} \nu p_{3/2}$) configuration constitutes only 86% of the lowest 3^+ wave function but $>94\%$ of the wave functions of the other three states. As in other two-nucleon-transfer analyses, these results show that small admixtures in the wave functions can produce significant changes in cross section. Table I shows that the mixed-configuration wave functions produce agreement within 30% for the lowest four states.

When the calculations for the higher states are based on the normalization constants obtained from the four lowest states, the theoretical cross sections for all except the 2.331-MeV state (assumed to be 4^+) are significantly smaller than those measured experimentally. The most disturbing $\sigma_{\rm expt}/\sigma_{\rm calc}$ ratios in Table I are those for 0^+ and 1^+ states. There are several possible sources for this discrepancy. In the following we discuss some of these.

(a) One may first of all look at the theoretical Kuo-Brown wave functions in order to see what modifications would be needed to give agreement with experimental cross sections. For the upper 2^+, 3^+, and 4^+ states, significant cancellation between the various components of the wave function occur. Therefore, one would expect that relatively small changes in the wave function could increase the calculated cross sections appreciably and bring it into agreement with experiment. However, for the 0^+ and 1^+ states even the most coherent combination within the configurations used by Kuo and Brown can account for only about half the observed discrepancy.

(b) Of course it is possible to include additional configurations, not considered by Kuo and Brown, and add them coherently to increase the calculated cross section. That there are such configurations which should be included can be seen from the fact that many more states are seen above 3-MeV excitation than are predicted by the calculation.

(c) Another possibility is that the target state in Ca^{48} contains appreciable core excitation; such admixtures could have a large effect on the cross sections. Recently, Peterson[15] published some data which he interpreted as tentative evidence for such admixtures. However, this result is contradicted by several careful measurements[16,17] which can be used to set a much lower limit than Peterson's on the core excitation in Ca^{48}.

(d) After these discrepancies were observed, we also obtained a cross section for the 0^+ state at 11.195-MeV excitation, which is the $T=5$ analog of the Ca^{50} ground state. Using a DWBA calculation which includes the difference in binding, we get $\sigma_{\rm expt}/\sigma_{\rm calc} \approx 8$, indicating that all $l=0$ transitions have too small a calculated cross section. It has been mentioned that in the calculations the $l=0$ transitions were the most sensitive in shape to the choice of DWBA parameters. In absolute cross section this sensitivity can lead to an uncertainty which could be at most a factor of 2.

We conclude that the source of the relatively large discrepancy in the cross sections is not completely understood and should be the subject of further investigation.

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