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Level Structure of Sc^{48} from the $Ca^{48}(He^3, t)$ Reaction*

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The Ca^{48} $(He^3, t)Sc^{48}$ reaction was studied with a magnetic spectrograph at a bombarding energy of 15 MeV. Energy levels of Sc^{48} were obtained and compared with the results of previous work. From consideration of cross sections, angular distributions, and previous spin and parity assignments, eight levels of Sc^{48} are tentatively assigned to the $(\pi f_{7/2}{}^1)(\nu f_{7/2}{}^{-1})$ configuration—namely, those with $J^\pi=0^+$, $E_x=6.680$; 1^+, 2.525; 2^+, 1.145; 3^+, 0.624; 4^+, 0.253; 5^+, 0.133; 6^+, 0; and 7^+, 1.096 MeV. These states are populated roughly an order of magnitude more strongly than the other states in Sc^{48}.

I. INTRODUCTION

The energy levels of Sc^{48} are of particular interest from the point of view of the shell model, and have been investigated by various authors. Elwyn *et al.*,[1] Ferguson and Paul,[2] Chasman *et al.*,[3] McMurray *et al.*,[4] and McDonald *et al.*[5] studied the $Ca^{48}(p, n)Sc^{48}$ reaction to obtain the energy levels in Sc^{48}. Chasman *et al.*[3] and Dubois[6] measured γ rays in the $Ca^{48}(p, n\gamma)Sc^{48}$ reaction and proposed possible spin values of some excited states in Sc^{48}. Ricci[7] investigated the analog resonances observed in the $Ca^{48}+p$ reaction and measured gamma rays following the neutron decay of these resonances. Nolen *et al.*[8] located the analog state in Sc^{48} at 6.68 MeV. This state is the 0^+ state of the $(\pi f_{7/2}{}^1)(\nu f_{7/2}{}^{-1})$ configuration. Ohnuma *et al.*,[9] who used a magnetic spectrograph, analyzed triton groups from the $Ca^{48}(He^3, t)Sc^{48}$ reaction at 15 MeV and found a previously unknown level at 1.097 MeV in addition to a level at 1.14 MeV which had been observed in the $(p, n\gamma)$ work. From the study of the $Ti^{50}(d, \alpha)Sc^{48}$ reaction, Grotowski *et al.*[10] discussed the configurations of the low-lying states of Sc^{48}. In the recent work of Wallen *et al.*,[11] this reaction has been reinvestigated with good energy resolution, and angular distributions of many alpha groups have been obtained. These experiments show the existence of a possible 7^+ state at 1.09 MeV, which must be the lower member of the doublet found in the (He^3, t) experiment. Investigation of the (He^3, t) reaction at higher energy (30.2 MeV) but with poorer resolution[12] confirmed the existence of the doublet at 1.1 MeV.

Single-particle-transfer reactions usually give the most direct information concerning the wave functions of nuclei involved. The only single-particle-transfer reactions available for the study of Sc^{48} are proton pickup reactions from Ti^{49}. Schwartz[13] measured angular distributions from the $Ti^{49}(t, \alpha)Sc^{48}$ reaction. In addition to the $l=3$ transitions to the lowest four states of Sc^{48}, he found two more $l=3$ transitions to states at 1.17 MeV and 2.70 MeV. The cross section to the latter was roughly a third of those to the first three states and was as strong as that to the third excited state. The $Ti^{49}(d, He^3)Sc^{48}$ reaction was first studied by Yntema and Satchler,[14] and was recently repeated by Ohnuma and Yntema.[15] In the latter experiment the resolution was better than that in Ref. 14, but was still barely adequate to extract the spectroscopic factors for the lowest four states. However, cross sections to these levels seem to be in disagreement with the results of the (t, α) experiment. Furthermore, the (d, He^3) reaction failed to populate the 2.7-MeV state strongly.

Shell-model calculations for Sc^{48} have been performed by several authors, who usually assumed pure $f_{7/2}$ configuration. McCullen, Bayman, and Zamick[16] obtained effective-interaction matrices in the $f_{7/2}$ shell from the energy levels of Ca^{42}, Sc^{42}, and Ti^{50}, and calculated

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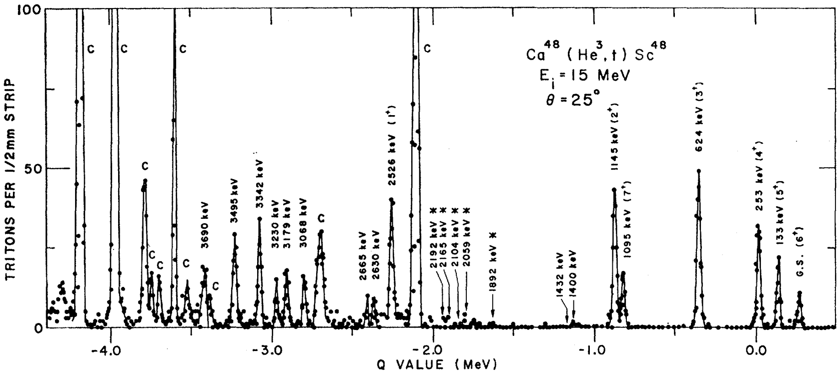

FIG. 1. Triton spectrum from the $Ca^{48}(He^3, t)Sc^{48}$ reaction. The location of five levels observed below 2.2-MeV excitation in other reactions but not in the present study are shown and marked with asterisks.

various properties of $f_{7/2}$ nuclei, including level energies of Sc^{48}. Unfortunately, the energy levels of Sc^{42} were not well known at that time and therefore they had to assume spin assignments for most of the states. Positions of 1^+, 3^+, and 5^+ states in Sc^{42} later turned out to be incorrect, although the calculated results were in general agreement with experiment. As long as one assumes pure $f_{7/2}$ configuration for both Sc^{42} and Sc^{48}, the level energies of these two nuclei are related to each other by the so-called Pandya transformation.[17] Schwartz,[13] taking known energies of states in these two nuclei and assuming some additional ones, made use of the Pandya transformation in a least-squares fit to these energies and obtained energies for the unknown states of the $(f_{7/2})^2$ configuration. In this calculation, the 2^+ state in Sc^{48} was predicted to be around 600 keV, and the 1.17- and 2.70-MeV states found in the (t, α) experiment were assigned to be the 7^+ and 1^+ states, respectively. However no evidence of this new level around 600 keV has been found since Schwartz's prediction. Ball[18] and Ohnuma *et al.*[9] did similar calculations with slightly different assumptions and placed the 2^+ state around 1.1 MeV. Meanwhile Schwartz *et al.*[19] studied the $Ca^{40}(He^3, p)Sc^{42}$ and $Ca^{42}(He^3, t)Sc^{42}$ reactions with a magnetic spectrograph and found all states that were thought to belong to the $f_{7/2}$ configuration. Using this information, Wong[20] calculated the energy levels of Sc^{48} by use of the Pandya transformation and found that the 2^+ state should occur around 600 keV. Ball[18] and Wong[20] also calculated absolute and relative spectroscopic factors, respectively, in the proton pickup reactions from Ti^{49} on the assumption that the ground state of Ti^{49} has a pure $f_{7/2}$ configuration. Calculated spectroscopic factors are in qualitative agreement with the (d, He^3) results,[15] while the experimental (t, α) cross sections[13] for reactions to the assumed 4^+ state and 1^+ state are found to be too large.

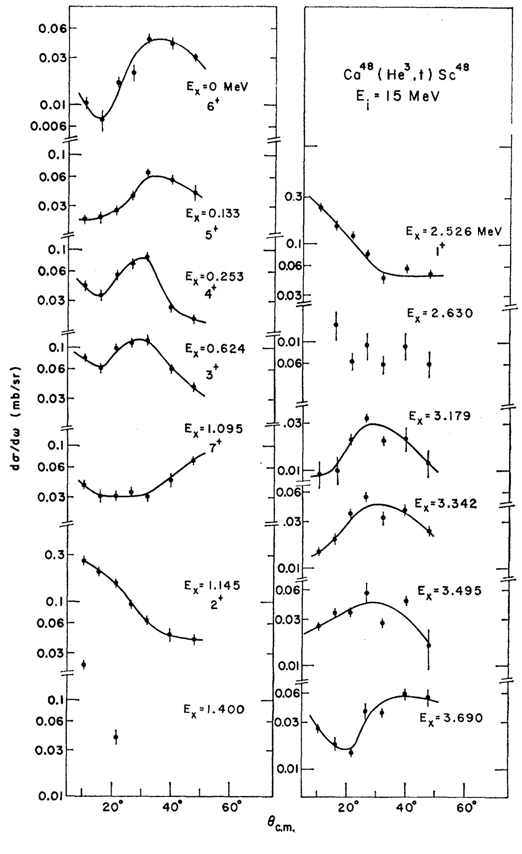

FIG. 2. Angular distributions of triton groups for the states relatively strongly excited in the $Ca^{48}(He^3, t)Sc^{48}$ reaction. The solid lines are only to guide the eye.

All the above calculations were based on the assumption of a pure $(f_{7/2})^2$ configuration. Recently, Moinester *et al.*[21] analyzed the energy levels of all available particle-particle, hole-hole, and particle-hole multiplets formed of doubly closed shells. They used a multipole expansion of the total interaction energy and, where possible, all multipole terms of one nucleus were compared with

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TABLE I. States in Sc^{48}, as observed in various experiments. In addition to those

Ref. 1 (p, n) E (keV)[a]	Ref. 2 (p, n) E (keV)[a]	Ref. 3 (p, n) E (keV)	Ref. 3 $(p, n\gamma)$ E (keV)	J^π	Ref. 4 (p, n) E (keV)	Ref. 5 (p, n) E (keV)	Ref. 6 $(p, n\gamma)$ E (keV)	J^π	Ref. 7 $(p, n\gamma)$ E (keV)	J^π	Ref. 9 (He^3, t) E (keV)	J^π
			0	(6^+)			0	(6^+)	0	6^+	0	(6^+)
131		131	131±2	(5^+)	151±20	131±7	131±1	(5^+)	131	5^+	132±3	(5^+)
243±5		245±20	253±2	(4^+)	237±20	258±7	252±2	(4^+)	253	4^+	256±3	(4^+)
616±8	598±35	631±20	624±3	(3^+)	628±6	624±5	623±2	(3^+)	623	3^+	625±3	(3^+)
	714±35											
	851±35											
											1097±3	(7^+)
1116±15	1127±35	1140±20	1144±3	(1, 2)	1139±7	1140±5	(1123)	(2^+)	1143	1^+	1150±3	(2^+)
1361±20	1372±35	1405±20	1406±3	(1, 2)	1397±7	1403±7			1403	2^+		
		1592±20										
	1925±35	1877±20			1883±6	1892±5						
						2059±5						
		2077±20			2080±7							
						2104±4						
						(2165±4)						
		2188±20			2175±5							
			2192±3	(4)		2192±4						
	2259±35	2270±20	2276±3	(2)	2267±6	2276±4						
						(2303±5)						
					2380±5	2392±4						
	2494±35	2502±20	2519±5	(0, 1)	2508±4	2518±4						
					2548±4	2560±4						
					2630±10	2639±5						
	2670±35				2661±10	2669±4						
					About 35 levels up to 4.3 MeV							

[a] Shifted as described in Ref. 3.

those of the conjugate nucleus. If the multipole coefficients for a given pair are the same, this is equivalent to the Pandya transformation being valid. The only exception is that the monopole term (centroid shift) is usually ignored in the Pandya relation. Good agreement was found between monopole terms for the Cl^{38}-K^{40} pair but not for the Sc^{42}-Sc^{48} pair. This would imply that one or both of this latter pair of nuclei must contain considerable amounts of configuration admixtures. In that case, it is meaningless to compare the energy levels of these two nuclei in a simple way.

From the stripping and pickup experiments on Ca^{40} and Ca^{48}, it has been recognized[22] that these nuclei are not perfect closed-shell nuclei. The amount of the core excitation in the ground states of these nuclei is not without question because of difficulties in obtaining reliable absolute spectroscopic factors,[23] but there seem to be indications[24] that Ca^{48} is a better closed-shell nucleus than Ca^{40}.

Work on (He^3, t) reactions on nuclei in this region, but at higher incident energies than those in the present work, have recently been reported by a number of authors.[12,19,25] Although there have been attempts to fit the "quasielastic" (He^3, t) angular distributions with theoretical calculations, there have not yet been any

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listed here, the analog state is known to lie at 6.68 MeV (Ref. 8).

Ref. 10		Ref. 11		Ref. 12		Ref. 13		Ref. 14		Ref. 15			This work	
(d,α)		(d,α)		(He^3,t)		(t,α)		(d,He^3)		(d,He^3)			(He^3,t)	
E (MeV)	J^π	E (keV)	J^π	E (MeV)	J^π	E (keV)	l	E (MeV)	l	E (MeV)	l	c^2S	E (keV)	J^π
				0	6^+	0	3	0	3	0	3	0.42	0	(6^+)
0.14±0.04	(5^+)	131±1	(5^+)	0.13±0.03	5^+					0.13	3	0.63	133±2	(5^+)
		254±2		0.25±0.03	4^+	230	3			0.26	3	0.34	253±2	(4^+)
						388±20	2							
0.60±0.04		624±1	(3^+)	0.62±0.03	3^+	610±20	3			0.62	3	0.26	624±4	(3^+)
								0.77	2					
1.06±0.04	(7^+)	1097±1	(7^+)	1.08±0.03	(2^+)								1095±5	(7^+)
		1143±3		1.14±0.03	7^+	1170±20	3						1145±5	(2^+)
		1406±1						1.40	2				1400±10	
		1892±2				1872±20	2						(1432±15)	
										1.89	(0+2)			
								2.01	0					
2.03±0.04						2100±20	0			2.10	(0+2)			
		2104±1				2140±20	2							
		2165±1												
						2360±20	0							
						2530±20	0						2526±5	(1^+)
		2520±2		2.51±0.03	1^+									
		2560±3												
													2630±10	
		(2617±3)											2665±10	
						2700±20	3							
		2894±4												
		2988±2		3.04±0.03	(5^+)								3068±5	
		3069±2											3179±10	
													3230±7	
				3.32±0.03	3^+								3342±7	
				3.47±0.03	4^+								3495±7	
				3.67±0.03	(2^+)								3690±10	
				4.27±0.03	1^+								4265±10	
				6.42±0.03										

reliable predictions for the (He^3,t) angular distributions for reactions to states with $T_<$. Therefore instead of studying the details of the measured angular distributions, we have merely compared them with those from previous work and used them as a guide to conjecture.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The present work, which is a continuation of that reported in Ref. 9, was undertaken in the hope of clarifying the situation by providing additional information on the energy levels of Sc^{48}. The $Ca^{48}(He^3,t)Sc^{48}$ reaction was studied with a broad-range magnetic spectrograph and the 15-MeV He^3 beam from the Argonne tandem Van de Graaff. The targets were metallic calcium about 50 $\mu g/cm^2$ thick and enriched to 98% in Ca^{48}. Some of the nuclear emulsions were scanned by an automatic track-counting machine.[26] Angular distributions were measured between 10° and 45° to obtain a crude idea of the spins of the final states.

A typical triton spectrum is shown in Fig. 1. Table I lists the excitation energies of the Sc^{48} states observed in the present experiment and compares them with the results of other experiments. Figure 2 shows the angular distributions of triton groups measured for the states that were relatively strongly excited. Figure 3 is an energy level diagram for Sc^{48}.

III. DISCUSSION

Spin and parity assignments 6^+, 5^+, 4^+, and 3^+ to the states at 0, 0.13, 0.25, and 0.62 MeV in Sc^{48}, respectively, were first suggested by Chasman *et al.*[3] All existing experimental data seem to confirm these assignments although there still is no direct measurement of spins. The angular distributions obtained here also support these assignments. The angular distributions for the ground state and the first excited state are very similar to each other. Both have maxima at about 35° and fall

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[26] J. R. Erskine and R. H. Vonderohe, Bull. Am. Phys. Soc. **13**, 700 (1968); Nucl. Instr. Methods (to be published).

TABLE II. Comparison of experimental assignments of $(f_{7/2})^2$ energies in Sc^{42} and Sc^{48} with a least-squares fit. All energies in MeV.

J	Sc^{42} Observed energies	Sc^{42} Fitted energies	Sc^{42} Difference	Sc^{48} Observed energies	Sc^{48} Fitted energies	Sc^{48} Difference
0	0.000	0.061	−0.061	6.680	6.695	−0.015
1	0.615	0.558	0.057	2.520	2.553	−0.033
2	1.593	1.702	−0.109	1.145	0.889	0.256
3	1.498	1.549	−0.051	0.624	0.645	−0.021
4	2.800	2.742	0.056	0.253	0.213	0.040
5	1.518	1.729	−0.211	0.133	0.179	−0.046
6	3.200	3.026	0.174	0.000	0.037	−0.037
7	0.625	0.481	0.144	1.096	1.240	−0.144

off at smaller angles. Bruge *et al.*[12] observed a maximum around 25°–30° in the angular distributions for these two states at 30.2 MeV. The shift of the maxima is roughly equal to that expected from momentum-transfer considerations. These angular distributions are also similar to the one obtained by Schwartz *et al.*[19] for the 5^+ state at 1518 keV in Sc^{42} from the Ca^{42}(He^3, t) reaction at 26 MeV, for which they found a maximum at about 30°. Therefore the angular distributions are consistent with the spin assignments 6^+ and 5^+ for the ground state and the first excited state, respectively. The angular distributions for the 253- and 624-keV states obtained here are again similar to each other, and are shifted by several degrees from those obtained[12] for the same states at 30.2 MeV and that for the 3^+ state at 1498 keV in Sc^{42}. Therefore the 4^+ and 3^+ assignments to the 253- and 624-keV states are compatible with the (He^3, t) angular distributions. If these assignments are correct, our results seem to support the statement of Bruge *et al.*[12] that the $l=J+1$ component is favored in the (He^3, t) reaction.

The angular distribution for the 1.095-MeV state suggests that this state has a high spin, possibly higher than 6, because the maximum appears at larger angles than in the angular distribution for the ground state. Thus the 7^+ assignment suggested in previous work[9,10] is plausible. The 1.14-MeV state was assigned to be $J=1$ or 2 in Ref. 3. The forward peaking of the present angular distribution for this state suggests that it has a low spin. A comparatively weak $l=3$ transition to this state was seen in the Ti$^{49}(t,\alpha)$Sc^{48} reaction. We therefore conclude that it is most likely that the 1.14-MeV state is the 2^+ state of primarily $(f_{7/2})^2$ configuration, as suggested in our previous work.[9] This conclusion contradicts the result of Bruge *et al.*,[12] who assigned 7^+ to the 1.14-MeV level and 2^+ to the 1.08-MeV level.

The angular distributions for the 1.400- and 2.526-MeV states are forward peaked. The cross sections are very small for the 1.400-MeV state, and it was not seen in the work of Bruge *et al.*[12] The forward-peaked angular distribution is expected, since spin 1 or 2 was assigned to the 1.40-MeV state in Ref. 3, and spin 2 in Ref. 7. The fact that the cross section is an order of magnitude smaller than those for reactions to the other low-lying states might suggest that this state is not one with the configuration $(\pi f_{7/2}{}^1)(\nu f_{7/2}{}^{-1})$. The state at 2.526 MeV, on the other hand, has as large a cross section as the other low-lying states. Therefore this state could be a candidate for the 1^+ state of the $(\pi f_{7/2}{}^1)(\nu f_{7/2}{}^{-1})$ configuration which is expected in this energy region.[9,13,18,20] This assignment is also supported by the fact that the gamma decay of the 6.680-MeV 0^+ state proceeds predominantly to this state.[27]

If the above conjectures are correct, all of the states of the $(\pi f_{7/2}{}^1)(\nu f_{7/2}{}^{-1})$ configuration in Sc^{48} are identified here. They are: 0^+, 6.680 MeV; 1^+, 2.526 MeV; 2^+, 1.145 MeV; 3^+, 0.624 MeV; 4^+, 0.253 MeV; 5^+, 0.133 MeV; 6^+, 0 MeV; and 7^+, 1.095 MeV. These energies

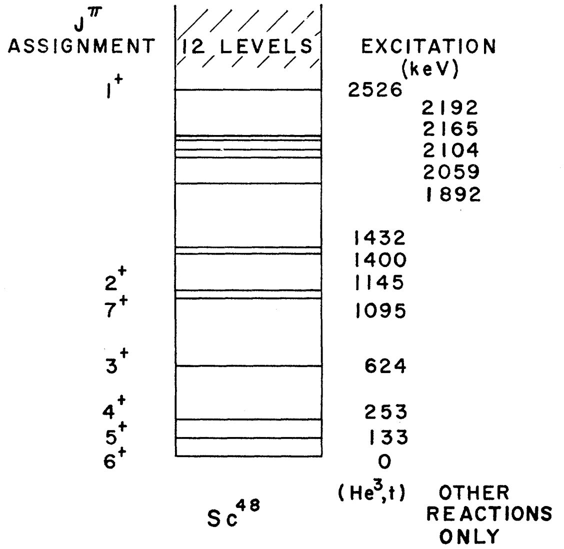

FIG. 3. Level scheme of Sc^{48} below about 2.7 MeV. Energies are those obtained here for states observed in the present experiment, and are weighted averages of various measurements shown in Table I for the others.

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[27] K. W. Jones and A. Schwarzschild (private communication).

were used in the calculation of multipole coefficients by Moinester *et al.*[21] As mentioned before, their results show a significant difference between the monopole coefficients for Sc^{42} and Sc^{48}. Although the above assignments have to be checked by further experiments, it seems evident that there are considerable admixtures in either Sc^{42} or Sc^{48} or in both, since the calculated monopole coefficients are rather insensitive to the positions of individual levels.

The large discrepancy in the expected 2^+ energy is not as serious as it seems. We have made a least-squares fit to the known states in Sc^{42} and Sc^{48} making use of the Pandya transformation

$$E_{\mathrm{ph}}{}^{J}=C-\sum_{J'}(2J'+1)W(\tfrac{7}{2}\tfrac{7}{2}\tfrac{7}{2}\tfrac{7}{2};J'J)E_{\mathrm{pp}}{}^{J'}.$$

A total of nine parameters (8 value of $E_{\mathrm{pp}}{}^{J'}$ and C) were fitted to the 16 experimental energies. The resultant fitted energies are compared with the observed ones in Table II and, while it is clear that the 2^+ state in Sc^{48} deviates more than other states, the difference in this deviation is not excessive. The rms deviation is 125 keV. The ~500-keV discrepancy in the average two-body energies derived from Sc^{48} and Sc^{42} was discussed by Moinester *et al.*[21] and admixtures in Sc^{42} were suspected. It would seem quite possible that such admixtures would cause more than just a centroid shift and some of the other discrepancies may well have their source in such admixture. Shell-model calculations[28,29] predict large admixtures in the 1^+, 3^+, and 5^+ states of Sc^{42} and this may be the source of some of the deviations. Results, as yet somewhat contradictory, are becoming available on the $(f_{7/2})^2$ spectrum[12,25,30] in Co^{54}, and when this spectrum is understood one can perform some further interesting comparisons.[31]

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Investigation of ^{46}Sc by the Reaction $^{47}Ti(d,\,^3He)^{46}Sc$

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Angular distributions from the $^{47}Ti(d,\,^3He)^{46}Sc$ and $^{48}Ti(d,\,^3He)^{46}Sc$ reactions have been measured with a deuteron beam energy of 17 MeV. The ^3He particles were magnetically analyzed by position-sensitive counters and photographic emulsions mounted in an Enge split-pole spectrograph with typical experimental resolutions of 8-10 keV full width at half-maximum. With the use of distorted-wave Born-approximation calculations for $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$, and $2p$ pickup, l_p values and spectroscopic factors were deduced. The results verify a finite ($\approx$0.2 protons) occupation in the $2p$ orbitals. In addition, the $1f_{7/2}$ orbit appears in slight excess and $1d_{3/2}$ is slightly deficient in its shell-model value of protons. By comparison with other studies in ^{46}Sc, it is concluded that the similar average binding energies for $\pi f_{7/2}\nu(f_{7/2}{}^5)_{7/2}$, $\pi f_{7/2}\nu(f_{7/2}{}^5)_{5/2}$, and $\pi(d_{3/2}{}^{-1})(f_{7/2}{}^2)_0\nu(f_{7/2}{}^5)_{5/2}$ configurations are primarily responsible for the high level density and large configuration mixing in the 0–1-MeV excitation in ^{46}Sc. In the 1–2-MeV region, the $\pi(s_{1/2}{}^{-1})(f_{7/2}{}^2)_0\nu(f_{7/2}{}^5)_{5/2}$, $\pi d_{3/2}{}^{-1}(f_{7/2}{}^2)_0\nu(f_{7/2}{}^5)_{7/2}$, $\pi d_{3/2}{}^{-1}(f_{7/2}{}^2)_0\nu d_{3/2}{}^{-1}(f_{7/2}{}^6)_0$, and $\pi f_{7/2}\nu(f_{7/2}{}^4)_0 2p^1$ configurations dominate the spectrum.

I. INTRODUCTION

In previous investigations of ^{46}Sc, it has been evident that the level density of low-lying states and the shell-model configuration mixing is quite large in this odd-odd $f_{7/2}$-shell nucleus.[1–4] Due to the presence of both positive- and negative-parity states in the first MeV of excitation in ^{46}Sc, it is especially important that the levels be studied in as many different ways as possible. Thus, the proton pickup reaction study in this work supplements previous (d,p),[1] (d,α),[4] and (n,γ)[2,3] work. Furthermore, the high level density demands high-resolution techniques which were not available in the earlier $(d,\,^3He)$ work of Yntema and Satchler.[5] In fact, no individual levels in ^{46}Sc were resolved in this earlier attempt.

Nevertheless, several isotopes of scandium were investigated in $(d,\,^3He)$ studies of Ref. 5 and it was

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