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Nuclear Structure of Sc^{44}. I. The $Ca^{44}(He^3, t)Sc^{44}$ Reaction*

J. C. Manthuruthil and F. W. Prosser, Jr.†
Aerospace Research Laboratories, Wright Patterson Air Force Base, Ohio 45433

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The $Ca^{44}(He^3,t)Sc^{44}$ reaction has been studied, at an incident energy of $E_{He^{3++}}=25$ MeV, with a magnetic spectrograph. A total of 52 levels in Sc^{44} have been identified below an excitation energy of 3.35 MeV. 10 of the observed levels have not been previously reported. Angular distributions have been measured for most of the levels and analyzed by means of the distorted-wave Born approximation. Definite L-transfer values and spin assignments have been made to many levels. As a result, eight states predicted by a recent $(fp)^4$ calculation have been identified. In addition, four of the states predicted by a calculation with a single $d_{3/2}$ hole have been tentatively identified. The isobaric analog of the Ca^{44} ground state was located at an excitation energy of 2781± 5 keV, in good agreement with previous results.

I. INTRODUCTION

This is part of a continuing study of $f_{7/2}$ shell nuclei. We present here information on Sc^{44} from a study of the $Ca^{44}(He^3, t)Sc^{44}$ reaction. In the study[1] of Sc^{43}, it was found that an adequate description of the low-lying states could not be made with particles in $(fp)^3$ configurations. The best description seemed to be a model due to Johnstone and coworkers.[2] In this model, the normal negative-parity states were described as those arising from a mixture of $(fp)^3$ states and five-particle–two-hole deformed states. The positive-parity states were described as four-particle–one-hole deformed states. It appeared, therefore, to be interesting to see whether a similar model could be applied to the Sc^{44} nucleus. The results presented here, hopefully, will stimulate such calculations.

This nucleus has been studied by many types of experiments. Kashy,[3] using the $Sc^{45}(p, d)Sc^{44}$ reaction, reported 10 levels below 1.6 MeV. The $K^{41}(\alpha, n)Sc^{44}$ reaction[4] and the $Ti^{46}(d, \alpha)Sc^{44}$ reaction[5] have also been studied. More recently, Schwartz[6] investigated the $Ca^{43}(He^3, d)Sc^{44}$ reaction with high resolution and located about 83 levels below an excitation energy of 5.7 MeV. He was able to make l-value assignments on the basis of angular-distribution measurements. More l-value and some spin assignments have been made from the $Ca^{42}(He^3, p)Sc^{44}$ reaction[7] and from the $Sc^{45}(d, t)Sc^{44}$ reaction.[8] Very recently, high-resolution studies of the $Ti^{46}(d, \alpha)Sc^{44}$, the $Ca^{43}(p, \gamma)Sc^{44}$, and $Sc^{45}(He^3, \alpha)Sc^{44}$ reactions[9-11] have also been reported.

The spins and parities of the ground state (g.s.) and the isomeric state at 271 keV were determined to be 2^+ and 6^+, respectively, with the atomic beam beam magnetic resonance method.[12] The excitation of the first excited state at 68 keV and the second at 146 keV have not been reported to occur by any of the single-particle-transfer reactions. These two states were seen in the $Ti^{46}(d, \alpha)Sc^{44}$ reaction,[5] at 3.0- to 4.3-MeV incident energy, and in the (p, n) reaction,[13] probably through compound-nucleus processes. The recent (d, α) reaction studies,[9] at 19-MeV incident energy, showed only weak population of these two levels.

The first and second excited states are populated in the radioactive decay of Ti^{44}. Ristinen and Sunyar,[14] on the basis of their measurements of internal-conversion coefficients, angular correlations, lifetimes, and the reported logft value, assigned $J^\pi = 1^+$ to both these states. Subsequent perturbed angular-correlation measurements[15] have confirmed their spin assignment for the first excited state, but without a parity assignment. Since both of these studies were made, the logft value used by these authors was shown to be incorrect by new mass determinations[16, 17] of Ti^{44}. The logft value for the decay to the second excited state at 146 keV was shown to be 6.5, instead of 4.4, and a new limit of log$ft > 8.6$ was found for the decay to the first excited state at 68 keV. These new values weaken the arguments used in the assignment of 1^+ to both these states. The primary reason for the present (He^3, t) experiment was to study these two states in order to determine their spin and parity. Unfortunately, they were found to be very weakly populated in this reaction, as will be seen later.

Recently studies of (He^3, t) reactions with $J=0$ targets have shown that there is a striking similarity in the shape of the angular distributions leading to states of same J^π. These transitions appear to proceed primarily via the higher-orbital-angular-momentum transfer L when two are permitted by the spin and parity of the final state. The similarity of angular distributions was shown[18] to be a general feature of the (He^3, t) reactions for a mass range of 19 to 54. It was also shown[19] that this does not depend on the bombarding energy or Q value of the reaction. A part of the explanation of the anomalous features of the (He^3, t) reaction appears to lie in the influence of the tensor interaction.[20,21] [For a further discussion on (He^3, t) systematics, see the recent article by Comfort and Schiffer.[22]] Therefore, (He^3, t) reactions are proving to be a very useful spectroscopic tool, since spin-parity assignments can be made to those levels populated by this reaction with little ambiguity.

From a theoretical standpoint, the experimental study of Sc^{44} is necessary for comparison with various model predictions. The positive-parity spectrum has been calculated by McGrory and Halbert[23] by allowing four particles in the complete (fp) shell. The negative-parity spectrum has been calculated by Johnstone[24] by coupling a $d_{3/2}$ hole to the low-lying states in Ti^{45}. In Sec. IV, we compare these calculations with the available experimental results.

II. EXPERIMENTAL PROCEDURE

The measurements were carried out at the Argonne National Laboratory with a 25-MeV He^{3++} beam from the tandem Van de Graaff accelerator The targets consisted of about 50 $\mu g/cm^2$ of calcium, enriched to 99% in Ca^{44}, evaporated on to 20-$\mu g/cm^2$ carbon backings. The targets were prepared by reducing enriched $CaCo_3$ in a hot tantalum filament and evaporating the residual calcium onto the carbon backing. The targets were withdrawn directly from the evaporator through a vacuum lock into an evacuated vessel which was then attached to the scattering chamber. In this way the targets were always kept at a pressure less than 10 μ of mercury.

The tritons were detected on photographic plates placed in the focal plane of an Enge split-pole spectrograph.[25] Angular distributions were taken over the laboratory range of 10 to 70° in 6° intervals. Exposures at different angles were normalized to the yield of the elastically scattered He^3 from Ca^{44} detected in a monitor counter at 30°.

The plates were developed at Argonne National Laboratories and were counted by Deuterons Inc.[26] While in general the higher-energy portion of the spectra appeared to consist of relatively isolated peaks, the energy and intensity of the various triton groups at each angle were determined by a computerized analysis of these spectra using the code SAMPO.[27] The energy variation with angle, of all triton groups with sufficient intensity to be identified, agreed with the kinematics of the $Ca^{44}(He^3, t)Sc^{44}$ reaction, so all were assigned to this reaction. (The 25-MeV bombarding energy was chosen to prevent particles from other He^3-induced reactions on Ca^{44} and on C^{12} and Ca^{40} from occurring in the momentum range of the tritons. The primary potential source of background was elastic scattering from Ca followed by conversion of He^{3++} to He^{3+} and these particles were stopped by a 20-mil Mylar foil in front of the track plates.)

III. ANALYSIS AND RESULTS

A triton spectrum obtained at 16° is shown in Fig. 1. This particular spectrum was obtained

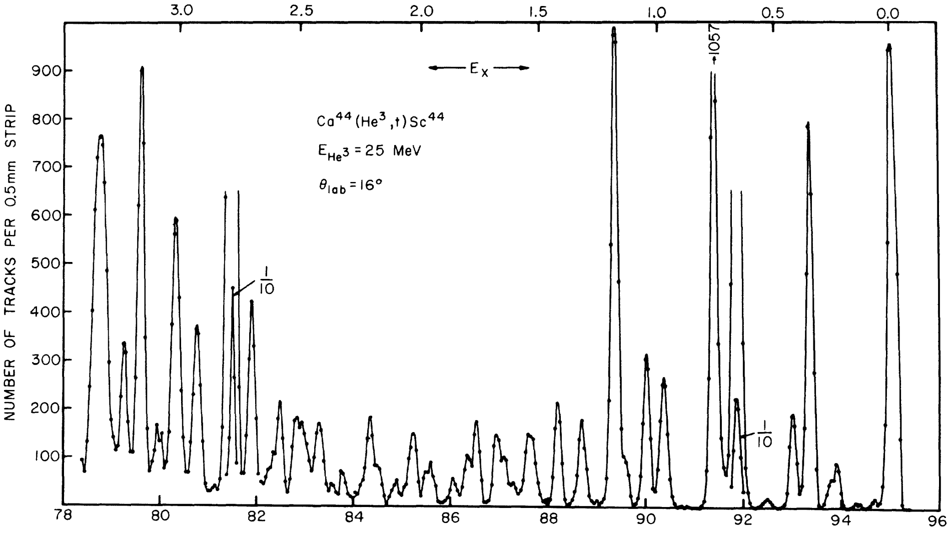

FIG. 1. A triton spectrum obtained at 16° with an exposure twice as long as that normal for the angular-distribution runs. The excitation energies in Sc^{44} (in MeV) are given at the top of the figure.

with an exposure twice as long as that normal for the angular distributions. Many states were seen which have not been previously observed in other reactions. The first two excited states are only weakly populated, as can be seen in the figure, so we were not able to obtain angular distributions for these states. The analog of the Ca^{44} g.s. (0^+) appears at 2.781 MeV and is strongly excited by this reaction. The energy that we obtain for this state, 2781 ± 5 keV, is in agreement with previous results.[28]

The angular distributions obtained for states observed in this experiment are shown in Figs. 2–5, along with distorted-wave Born-approximation (DWBA) fits made using the code DWUCK.[29] The interaction between He^3 and Ca^{44}, and between t

TABLE I. Optical-model parameters used with DWUCK. The notation is standard. The He^3 parameters are those determined by Bock *et al.* (Ref. 30) and were used without modification for the triton. The nucleon form factors were calculated with a Yukawa potential with a range parameter of 1.0 fm^{-1}. The quantity λ is the normalization factor in the Thomas spin-orbit term.

Particle	V (MeV)	W (MeV)	r_0 (fm)	a (fm)	r'_0 (fm)	a' (fm)	r_c (fm)	λ
He^3, t	165	20.2	1.14	0.723	1.6	0.81	1.3	
p, n	a		1.25	0.65			1.25	25

[a] Adjusted by the program to give the correct binding energy of each level.

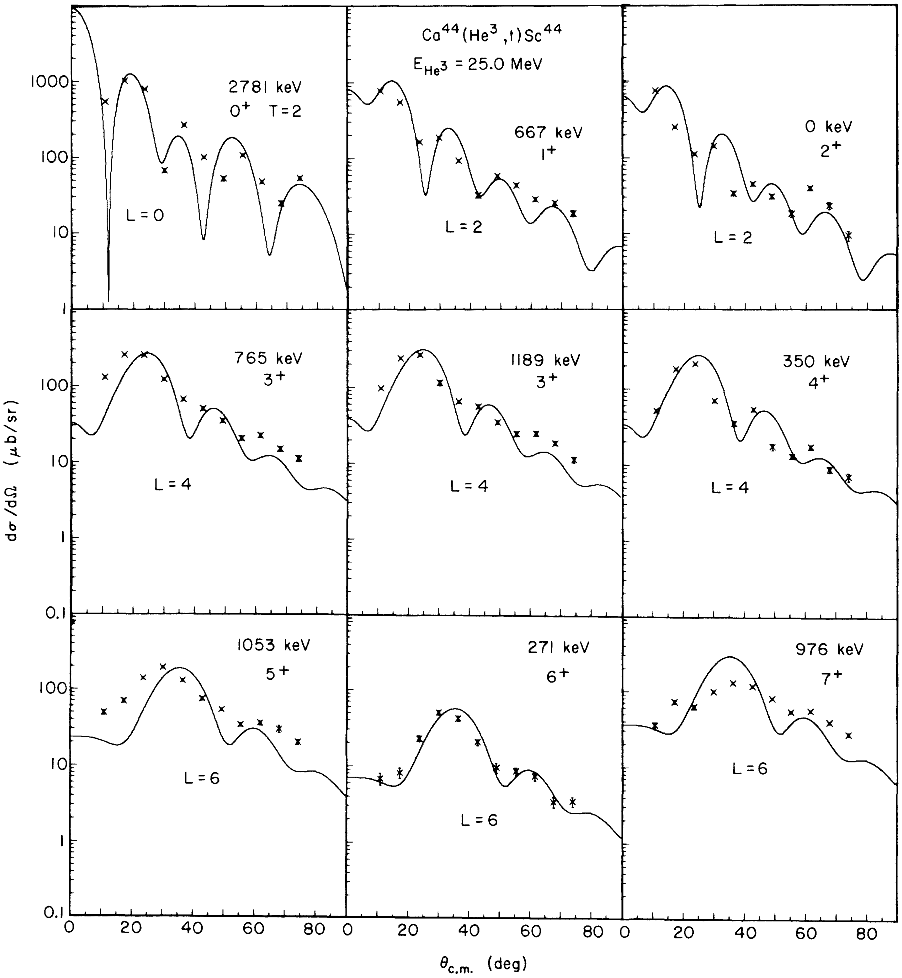

FIG. 2. Angular distributions obtained in the $Ca^{44}(He^3,t)Sc^{44}$ reaction. The solid curves are DWBA fits with the indicated L-transfer values, normalized to give the best apparent fit to the observed distributions. The error bars represent only the statistical errors in the data. (Since this figure, and those following, were drawn, a $1\frac{1}{2}°$ error in the location of the monitor detector in the Argonne spectrograph scattering chamber has been found, so that the indicated cross-section scales should be multiplied by a factor of 0.95.) The states shown in this figure are those believed to be predominantly of the $(f_{7/2})^4$ configuration.

and Sc^{44}, was of the Woods-Saxon form, with the parameters[30] shown in Table I for the real and imaginary volume terms. The He^3 and t interactions were taken to be identical in form. Table I also lists the parameters used for the bound-state wave functions, with real and spin-orbit volume terms. Nucleon form factors were calculated with a central Yukawa microscopic interaction with a range of 1.0 fm. The bound-state wave function assumed that the proton was captured into a $1f_{7/2}$ orbit and the picked-up neutron was from a $1f_{7/2}$ orbit for positive-parity final states and from a $1d_{3/2}$ orbit for negative parity. A systematic angular displacement between theory and experiment is evident, except for the $T=2$, $J^{\pi}=0^+$ state. This feature of the (He^3, t) reaction has been thoroughly documented[31] and cannot be explained by reasonable adjustment of the fitting parameters. We will discuss first those states which are believed to represent the dominant $(f_{7/2})^4$ configuration and then the other observed states.

A. $(f_{7/2})^4$ States

As a basis for the assignment of these states, we have assumed the values of $J^{\pi}=2^+$, 6^+, and 0^+ for the g.s., 271-, and 2781-keV state, respectively.[12, 28] The best fits we obtain of $L=2$, 6, and 0 for these states (Fig. 2) agree with these assignments. Then, on the basis of the strength of these states and of the yields to the states at 667 and 1052 keV, for $L=2$ and 6, respectively, the latter may reasonably be assigned to $J=L-1$ or 1^+ and 5^+, as indicated in Fig. 2. Part of the $(f_{7/2})^4$ $J=1$ strength may be in the 745-keV state, to be discussed below and also assigned $L=2$. The state at 974 keV is the only one observed with reasonable strength that has its first maximum at a larger angle than that for an $L=6$ assignment; hence it is assigned as the $J^{\pi}=7^+$ state.

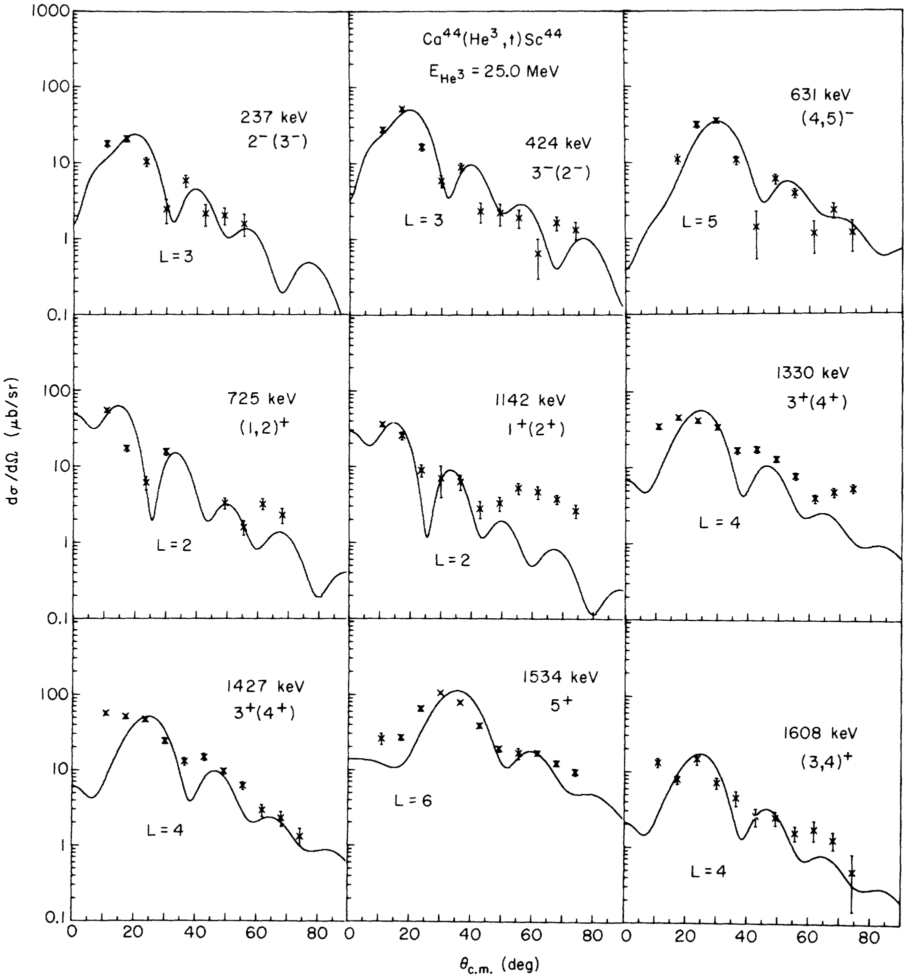

FIG. 3. Angular distributions obtained in the $Ca^{44}(He^3,t)Sc^{44}$ reaction. See the caption of Fig. 2 for explanation, except for the inferred configurations of these states.

Only the $L=4$ states to be assigned to this configuration remain. We obtain best fits for $L=4$ for the states at 350, 763, and 1186 keV (Fig. 2), all of which have reasonably large cross sections. Model calculations[23] suggest that the 4^+ state should lie significantly lower than the 3^+ state. Since our angular distribution for the 350-keV state shows more well-defined minima, we have assigned $J^\pi = 4^+$ for this state in agreement with the model predictions and 3^+ for the states at 763 and 1186 keV. These assignments are also in agreement with results from the Ti^{46}(d, α)Sc^{44} reaction.[9]

The assignment of these states to the dominant $(f_{7/2})^4$ spectrum on the basis of positive parity and relative strength is in agreement with the results of other particle-transfer reactions, as indicated in Table II and the references cited there. The choice of J for these states is also within the ranges established by these other reactions.

Higher-lying positive-parity states have also been found in the present and other investigations. While these probably contain a portion of the $(f_{7/2})^4$ configuration, their lower cross sections suggest that they have appreciable contributions from (fp) configurations.

B. States from Other Configurations

The remaining states will be discussed in order of excitation energy. Except where noted in the discussion below, our assignments agree in parity and lie within the range of J established by other particle-transfer reactions, as shown in Table II.

236 keV. An $L=3$ fit is best. This agrees with the observed γ-ray decays, in that decays to this state do not occur from the known positive-parity states.[10] Our preference is for a $J^\pi = 2^-$ assignment, in agreement with Wallen,[9] although the

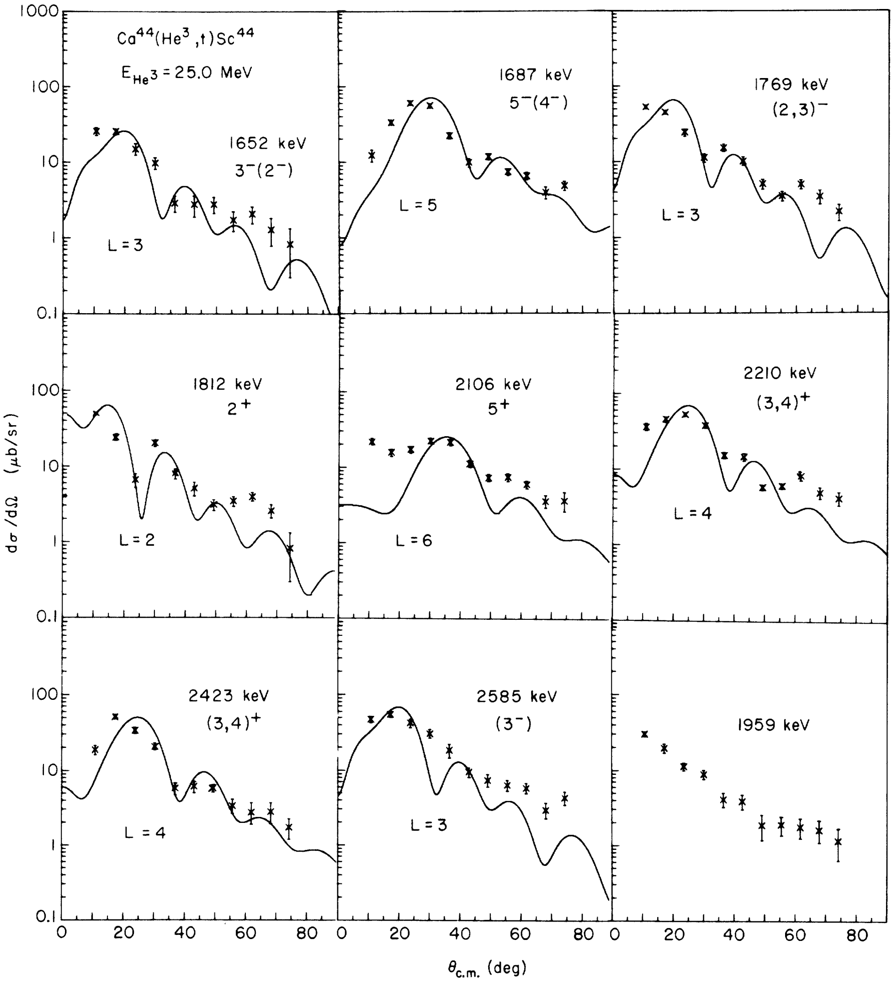

FIG. 4. Angular distributions obtained in the Ca^{44}(He^3,t)Sc^{44} reaction. See the caption of Fig. 2 for explanation, except for the inferred configurations of these states. No good DWBA fit was found for the 1959-keV state.

alternative 3^- assignment cannot be excluded.

425 keV. Again an $L=3$ fit is best and in agreement with the γ-ray decay pattern.[10] The relatively deep minima suggest that the preferred assignment is $J=L=3$; however, $J^\pi=2^-$ cannot be excluded.

632 keV. Here $L=5$ gives the best fit. The other evidence is ambiguous. The γ-ray decay is entirely to the 4^+ state at 350 keV rather than to the 6^+ state at 271 keV.[10] The study of the $Ca^{43}(He^3, d)Sc^{44}$ reaction assigns $l_p=0$ to a state at 632 keV.[6] Both of these results favor an assignment of 4^-; however, neither excludes an assignment of 5^- which is preferred from the present good fit in the (He^3, t) reaction. The conclusion must remain $J^\pi=(4,5)^-$.

745 keV. The angular distribution is best fit by $L=2$. The γ-ray decay is to the g.s. in good agreement with either 1^+ or 2^+. This state is not strongly excited in other transfer reactions (Table II). Our preference for this state is $J^\pi=1^+$, with an admixture of the $(f_{7/2})^4$ configuration which reduces the strength of the 667-keV state; but a 2^+ assignment cannot be excluded.

1142 keV. The best fit to the observed angular distribution is $L=2$ (Fig. 3). No γ-ray decay has been observed. A state near this excitation energy has been observed only in the $Ti^{46}(d, \alpha)Sc^{44}$ reaction, with the assignment (1^+).[9] The poorly defined minima we observe also suggest $J=L-1$. Thus the assignment is 1^+ (2^+).

1325 keV. The best fit is $L=4$. This agrees with the (d, α) result[9] and the observed γ-ray decay to the g.s., 350- and 667-keV state,[10] all of which have positive parity. The shallow minima in the observed angular distribution of the (He^3, t) reaction and the preferred 1^+ assignment for the 667-keV state provide the basis for a strong preference for a 3^+ assignment.

1427 keV. The results for a state at about this energy are ambiguous. Several reactions listed in

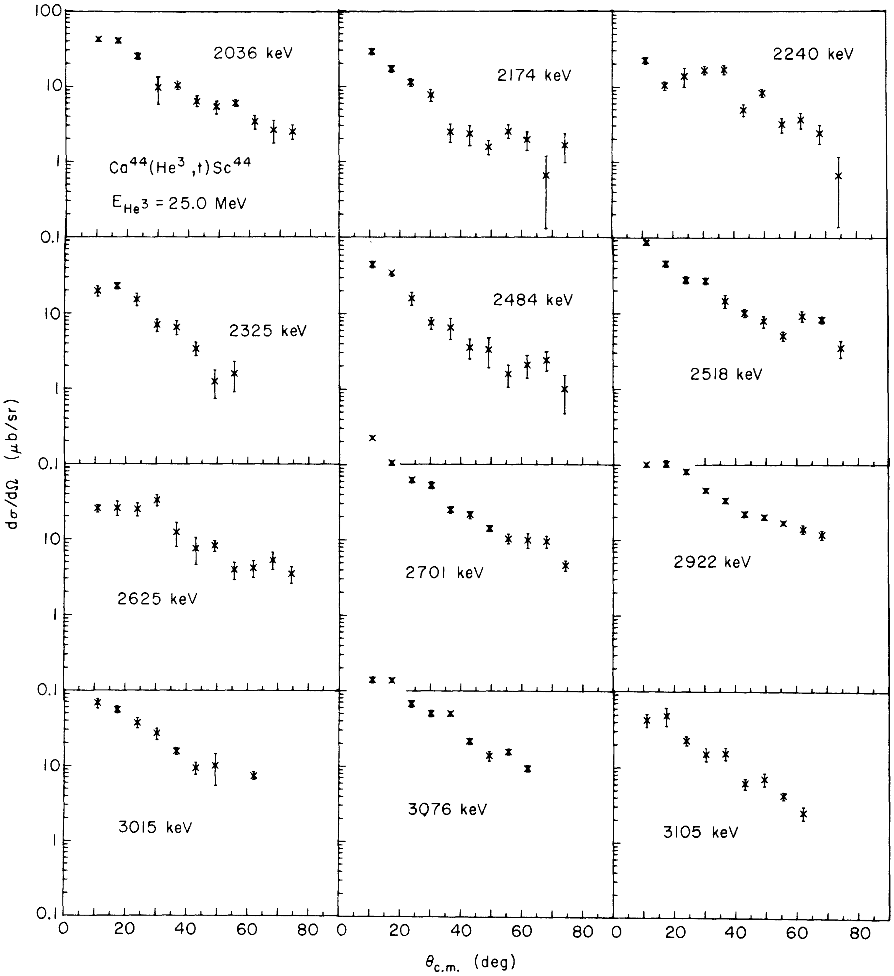

FIG. 5. Angular distributions observed in the $Ca^{44}(He^3,t)Sc^{44}$ reaction for which DWBA fits could not be made. See the caption of Fig. 2 for other details.

TABLE II. Summary of present results and comparison with previous results. Only l values are listed for other reactions for convenience, although a few specific J^π assignments have been made. Matching of energy levels observed by different reactions is subject to some uncertainty, particularly above 1.5 MeV. It has been based on comparison of trends in the relative energy scales and, where possible, on compatibility of l and/or J^π assignments. The agreement in excitation energies between the present work and the (p,γ) results is excellent, so that the discrepancy between the values, 725 and 745 keV, may indicate the existence of two distinct states in this region. The column labeled E (FINAL) is our best estimate, based on available data and subject to the above considerations. The final column, J^π (FINAL), is based on the discussion given in the text.

$Sc^{45}(p,d)$ (Ref. 3) E(keV)	l	$Ca^{43}(He^3,d)$ (Ref. 6) E(keV)	l	$Ca^{42}(He^3,p)$ (Ref. 7) E(keV)	l	$Sc^{45}(d,t)$ (Ref. 8) E(keV)	l	$Sc^{45}(He^3,\alpha)$ (Ref. 11) E(keV)	l	$Ca^{44}(He^3,t)$ Present work E(keV)	L	J^π	$Ca^{43}(p,\gamma)$ (Ref. 10) E(keV)	E(keV) (FINAL)	J^π (FINAL)
g.s.	3	g.s.	3	g.s.	2	g.s.	3	g.s.	3	g.s.	2	2^+		g.s.	2^+
										70 ± 5				67.85 ± 0.03 [a]	(1^-)
										150 ± 5				146.25 ± 0.04 [a]	
										237 ± 5	3	$2^-(3^-)$	236 ± 1	236 ± 1	$2^-(3^-)$
266 ± 9	3	274 ± 6	3			271 ± 5	3	269 ± 20	3	271 ± 5	6	6^+	270.6 ± 1.0	270.6 ± 1.0	6^+
344 ± 10	3	354 ± 9	1 + 3	360 ± 20	4	353 ± 5	1 + 3	344 ± 10	3	350 ± 5	4	4^+	350 ± 1	350 ± 1	4^+
		429 ± 13	1 + 3			427 ± 8	2			424 ± 5	3	$3^-(2^-)$	425 ± 1	425 ± 1	$3^-(2^-)$
										533 ± 8			532 ± 1	532 ± 1	
		637 ± 6	0			632 ± 6	2			631 ± 5	5	$(4, 5)^-$	632 ± 1	632 ± 1	$(4, 5)^-$
646 ± 12	3	671 ± 10	3	680 ± 20	0 + 2	669 ± 5	3	654 ± 20	3	667 ± 5	2	1^+	667 ± 1	667 ± 1	1^+
										725 ± 15	(2)	$(1, 2)^+$	745 ± 1	745 ± 1	$(1, 2)^+$
748 ± 15	3	760 ± 7	1 + 3			765 ± 5	3	756 ± 20	3	765 ± 5	4	3^+	763 ± 1	763 ± 1	3^+
													830 ± 1	830 ± 1	
													874 ± 1	874 ± 1	
952 ± 12	3	980 ± 10	3			971 ± 4	3	976 ± 20	3	976 ± 5	6	7^+		974 ± 5	7^+
				980 ± 20	2 + 4								986 ± 1	986 ± 1	3^+
						1012 ± 10	0, 0 + 2						1007 ± 1	1007 ± 1	$(2-5)^-$
1025 ± 20													1027 ± 1	1027 ± 1	
		1058 ± 12	1 + 3	1070 ± 20	4	1056 ± 5	1 + 3	1043 ± 20	3	1053 ± 5	6	5^+	1052 ± 1	1052 ± 1	5^+
													1106 ± 2	1106 ± 2	
										1142 ± 5	2	$1^+(2^+)$		1142 ± 5	$1^+(2^+)$
1165 ± 17		1197 ± 8	1 + 3	1160 ± 20		1187 ± 7	1 + 3	1181 ± 20	3	1189 ± 5	4	3^+	1186 ± 2	1186 ± 2	3^+
				1210 ± 20									1197 ± 2	1197 ± 2	
										1303 ± 10				1303 ± 10	
										1330 ± 5	4	$3^+(4^+)$	1325 ± 2	1325 ± 2	$3^+(4^+)$
1410 ± 20	(2)	1433 ± 18	1 + 3			1415 ± 10	2	1424 ± 20	(2)	1427 ± 5	4	$3^+(4^+)$	1427 ± 2	1427 ± 2	$3^+(4^+)$
1510 ± 20		1512 ± 9	1 + 3										1507 ± 2	1507 ± 2	$(1-6)^+$
		1537 ± 11	1 + 3	1550 ± 20		1534 ± 5	1 + 3	1531 ± 20	(2), (3)	1534 ± 5	6	5^+	1532 ± 2	1532 ± 2	5^+
						1560 ± 5	0 + 2			1561 ± 10			1567 ± 2	1567 ± 2	$(2-5)^-$
		1598 ± 13	1 + 3										1595 ± 2	1595 ± 2	$(1-6)^+$
				1610 ± 20						1608 ± 8	4	$(3, 4)^+$		1608 ± 8	$(3, 4)^+$
		1653 ± 12	1			1654 ± 10	0			1652 ± 5	3	$3^-(2^-)$		1652 ± 5	$3^-(2^-)$

TABLE II (*Continued*)

$Sc^{45}(p, d)$		$Ca^{43}(He^3, d)$		$Ca^{42}(He^3, p)$		$Sc^{45}(d, t)$		$Sc^{45}(He^3, \alpha)$		$Ca^{44}(He^3, t)$			$Ca^{43}(p, \gamma)$		
(Ref. 3)		(Ref. 6)		(Ref. 7)		(Ref. 8)		(Ref. 11)		Present work			(Ref. 10)	E(keV)	J^π
E(keV)	l	E(keV)	l	E(keV)	l	E(keV)	l	E(keV)	l	E(keV)	L	J^π	E(keV)	(FINAL)	(FINAL)
1660 ± 20	(2)	1683 ± 9	2	1700 ± 20		1688 ± 6	2	1682 ± 20	3	1687 ± 5	5	$5^-(4^-)$	1681 ± 2	1681 ± 2	$5^-(4^-)$
		1773 ± 13	1, 3	1790 ± 20		1768 ± 10	2			1769 ± 5	(3)	$(2^-, 3^-)$	1767 ± 2	1767 ± 2	$(2^-, 3^-)$
										1812 ± 5	2	(2^+)	1811 ± 2	1811 ± 2	(2^+)
		1865 ± 8	1							1866 ± 5			1866 ± 2	1866 ± 2	$(1-6)^+$
		1903 ± 11											1903 ± 2	1903 ± 2	
		1956 ± 10	1							1959 ± 10				1958 ± 10	$(1-6)^+$
						1988 ± 5	0			1984 ± 10				1986 ± 5	$(2-5)^-$
		2035 ± 10	1+3			2038 ± 8	0+2			2036 ± 10			2031 ± 2	2031 ± 2	
		2104 ± 6	1+3			2108 ± 5	2	2110 ± 20	(2), (3)	2106 ± 5	6	$(5, 6)^+$	2104 ± 2	2104 ± 2	5^+
													2115 ± 2	2115 ± 2	
		2173 ± 11	1+3			2186 ± 10	2			2174 ± 5			2179 ± 2	2179 ± 2	
						2213 ± 5	0+2	2210 ± 20	(2)	2210 ± 5	(4)	$(3, 4)^+$		2211 ± 5	$(3, 4)^+$
		2250 ± 14	3			2243 ± 10	2			2240 ± 5				2240 ± 5	$(0-7)^-$
		2295 ± 9	1+3										2291 ± 2	2291 ± 2	$(1-6)^+$
		2334 ± 5				2333 ± 10	2			2325 ± 8			2333 ± 2	2333 ± 2	$(0-7)^-$
		2382 ± 5								2374 ± 10				2380 ± 5	
		2427 ± 10	1+3							2423 ± 5	(4)	$(3, 4)^+$	2424 ± 2	2424 ± 2	$(3, 4)^+$
		2476 ± 10	1+3											2476 ± 10	$(1-6)^+$
						2492 ± 5	0+2			2484 ± 5				2488 ± 5	$(2-5)^-$
		2525 ± 11				2526 ± 10				2518 ± 10			2524 ± 3	2524 ± 3	$(0-7)^-$
		2556 ± 10												2556 ± 10	
		2591 ± 10	1+3			2586 ± 5	0	2584 ± 20	(0)	2585 ± 10	(3)	$(2, 3)^-$	2582 ± 3	2582 ± 3	(3^-)
		2617 ± 10				2622 ± 8	0+2			2625 ± 10			2615 ± 3	2615 ± 3	$(2-5)^-$
		2632 ± 11				2643 ± 10							2634 ± 3	2634 ± 3	
		2684 ± 10						2696 ± 20						2690 ± 10	
		2712 ± 8	1+3							2701 ± 5			2703 ± 3	2703 ± 3	$(1-6)^+$
						2751 ± 10	0+2							2751 ± 10	$(2-5)^-$
													2769 ± 3	2769 ± 3	
		2796 ± 5	3	2790 ± 20	0	2784 ± 10	3	2763 ± 20		2781 ± 5	0	0^+		2781 ± 5	0^+
										2854 ± 10				2854 ± 10	
		2878 ± 9												2878 ± 9	
						2912 ± 10	1+3	2907 ± 20		2922 ± 10			2915 ± 3	2915 ± 3	$(1-6)^+$
		2931 ± 10	1+3	2930 ± 20	2									2931 ± 10	$(1, 2, 3)^+$
						2989 ± 10	0+2						2980 ± 3	2980 ± 3	$(2-5)^-$
										2991 ± 10			2999 ± 3	2999 ± 3	
		3010 ± 11				3011 ± 10	0+2	3004 ± 20	2	3015 ± 10				3012 ± 10	$(2-5)^-$

TABLE II *(Continued)*

$Sc^{45}(p, d)$ (Ref. 3) E(keV)	l	$Ca^{43}(He^3, d)$ (Ref. 6) E(keV)	l	$Ca^{42}(He^3, p)$ (Ref. 7) E(keV)	l	$Sc^{45}(d, t)$ (Ref. 8) E(keV)	l	$Sc^{45}(He^3, \alpha)$ (Ref. 11) E(keV)	l	$Ca^{44}(He^3, t)$ Present work E(keV)	L	J^π	$Ca^{43}(p, \gamma)$ (Ref. 10) E(keV)	E(keV) (FINAL)	J^π (FINAL)
		3035 ± 10												3035 ± 10	
		3049 ± 10												3049 ± 10	
		3071 ± 8	1, 3							3076 ± 10				3073 ± 8	$(1-6)^+$
		3097 ± 10	1, 3							3105 ± 10				3101 ± 10	$(1-6)^+$
		3152 ± 10	1, 3	3160 ± 20	0 + 2					3152 ± 10				3152 ± 10	1^+
		3176 ± 8												3176 ± 8	
		3204 ± 7								3220 ± 10				3210 ± 10	
		3281 ± 15	1, 3	3280 ± 20						3292 ± 10				3287 ± 10	$(1-6)^+$
										3326 ± 20				3326 ± 10	
		3370 ± 14	1, 3											3370 ± 14	$(1-6)^+$

[a] Reference 14.

Table II and the (d, α) reaction[9] find a state of negative parity near this energy. Other studies, including the present with a preferred $L=4$ assignment, indicate positive parity. The observed γ-ray decay[10] is predominantly to the 3^+, 763-keV state, and to other positive-parity states including the g.s. On this basis, an assignment of 3^+ is preferred, with 4^+ not excluded.

1532 keV. An excellent $L=6$ fit is obtained for the angular distribution for this state. Approximately equal decays are observed to the 6^+, 271-keV state and the 4^+, 350-keV state.[10] Thus, the preference is for a 5^+ assignment. This is in agreement with the (d, α) results.[9]

1608 keV. The best fit is with $L=4$. No other information is available. On the basis of the shallow minima in the observed angular distribution, a 3^+ assignment is slightly preferred over the alternative 4^+.

1652 keV. Again there is disagreement about the parity of a state at this energy, as indicated in Table II. The (He^3, t) angular distribution is best fitted by an $L=3$ assignment. This, together with the $l=0$ assignment in the (d, t) reaction,[8] provides a preference for a $J^\pi=3^-$ assignment.

1681 keV. A very good fit is obtained to the (He^3, t) angular distribution for $L=5$. This is in good agreement with other particle-transfer reactions (Table II), but not with γ-ray decay data,[10] which show decays to positive-parity levels from a state at this energy. A 5^- assignment is preferred, but 4^- is not excluded.

1767 keV. The preferred $L=3$ assignment is in agreement with the (d, t) data,[8] but in disagreement with the (He^3, d) data[6] and with the decay to positive-parity states shown in the γ-ray data.[10] There are probably two states in this vicinity, one of which has $J^\pi=(2, 3)^-$.

1811 keV. A good fit is obtained with $L=2$. The predominant γ-ray decay is to the 4^+, 350-keV state, with decays to other positive-parity states. Hence, the preferred value is for $J^\pi=2^+$.

2104 keV. The best fit is obtained with $L=6$. Table II shows that there is not agreement as to the parity of a state at this energy. The γ-ray decays from a state at this energy are predominantly to positive-parity states, the strongest being to the 4^+, 350-keV state.[10] Hence a $J^\pi=5^+$ assignment is preferred.

2211 keV. A good $L=4$ fit is obtained for the (He^3, t) reaction, in disagreement with the other reactions shown in Table II. While there are probably two states, at least, near this energy, the one we observe must have $J^\pi=(3, 4)^+$.

2424 keV. A good $L=4$ fit is obtained. No other evidence is available to choose between $J^\pi=3^+$ or 4^+. The observed γ-ray decays from a state in this vicinity are to negative-parity states, indicating the possible presence of two or more states here.

2582 keV. There is again disagreement as to the parity of a state at this energy. An $L=3$ assignment is indicated by the (He^3, t) data, but rather weakly. Hence the $J^\pi = (3^-)$ assignment is tentative. This agrees with the $(3^-, 4^-)$ assignment from (d, t) and (He^3, d) reactions, but not with the $l_p = (1+3)$ from the (He^3, d) reaction.

C. Other States

Angular distributions which could not be assigned to definite L-transfer values are shown at the end of Fig. 4 and in Fig. 5. Remaining assignments of J^π in Table II are based on evidence from other particle-transfer reactions and on γ-ray decay systematics. These latter assignments will be discussed further.[10]

IV. DISCUSSION

There have been about 16 levels identified below 1 MeV, and 40 levels below 2 MeV, in Sc^{44}. It is quite a challenge to account for all these levels in any model. Most likely, these levels have dominant configurations of the type $(fp)^4$, $(fp)^5\,(sd)^{-1}$, and $(fp)^6\,(sd)^{-2}$. Three- and four-hole states are also possible; however, it is expected that they lie at higher excitation energies, if Sc^{44} has reasonable similarity to Sc^{43}. Recently, complete $(fp)^4$ calculations have been reported by McGrory and Halbert.[23] Negative-parity states have also been calculated by Johnstone[24] by coupling a $d_{3/2}$ hole to Ti^{45}. We will first discuss the positive-parity states.

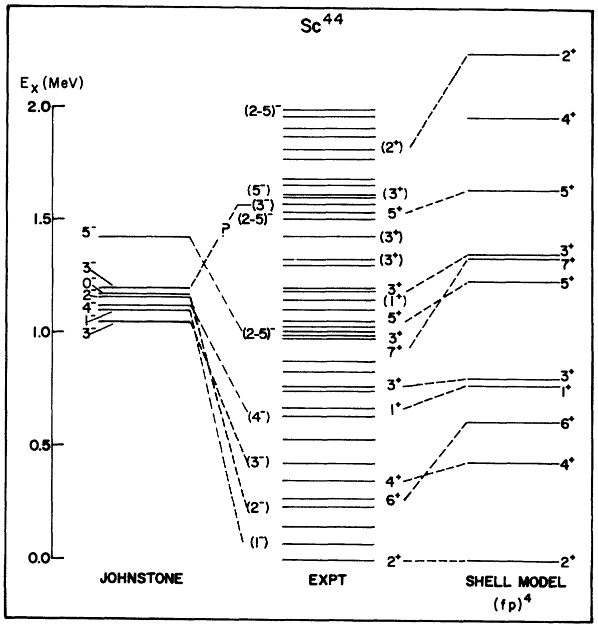

FIG. 6. The energy-level diagram of Sc^{44} below 2 MeV with spin and parity assignments along with the predictions of the theoretical calculations. The assignments shown in parentheses are tentative; alternatives are shown in Table II and discussed in the text. The $(fp)^4$ calculations are those due to McGrory and Halbert (Ref. 23), where they assumed an inert Ca^{40} core with active particles distributed over the four f-p shell orbits. The Johnstone calculations (Ref. 24) were done by coupling a $d_{3/2}$ hole to Ti^{45} core.

The positive-parity states were calculated by assuming an inert Ca^{40} core with active particles distributed over the four f-p shell orbits. The effective interaction used is that due to Kuo and Brown, with some modifications. The result of this calculation is given in Fig. 6, along with the experimental results. There are nine states predicted in this model below 2 MeV. By a comparison of (He^3, d) and (He^3, α) strengths and the J^π determination from the present experiments, these nine states are identified with the corresponding experimentally observed states. The calculated levels lie within approximately 100 to 350 keV of the observed levels. In addition, the (He^3, d) and (He^3, α) strengths to these levels are in good agreement with experimental results. We can thus identify the "spherical" states in Sc^{44}. However, this leaves approximately 30 states below 2 MeV to be accounted for and some of these states are undoubtedly negative-parity states. The others are most likely 6p-2h positive-parity states, similar to the two-hole states found in Sc^{43}. Such a calculation would be very desirable.

Johnstone[2] calculated the Sc^{43} hole spectrum by allowing a proton hole in any of the $(2s, 1d)$ shell Nilsson orbitals. The particle and hole orbitals were determined by a restricted Hartree-Fock calculation, using various two-particle interactions (Kuo-Brown, Serber, etc.). One result of this calculation was that the lowest $K=\frac{3}{2}$ band remained almost pure, suggesting that this band can be described in terms of a $d_{3/2}$ hole, with very little $s_{1/2}$ or $d_{5/2}$ admixture. However, the situation is much less satisfactory in the case of $K=\frac{1}{2}$ band states. When the $s_{1/2}$ hole energy is taken from the K^{39} spectrum, the lowest $\frac{1}{2}^+$ state came at an energy of 2 MeV for all reasonable choices of interactions. This is to be compared with the observed energy of 0.856 MeV for the lowest $\frac{1}{2}^+$ state in Sc^{43}. A decrease of the $s_{1/2}$-$d_{3/2}$ separation gives better agreement for the energy, but leads to incorrect values for the interband transition rates. Therefore, Johnstone[24] has calculated only the $d_{3/2}$ hole spectrum in Sc^{44} by coupling the hole to the Ti^{45} levels. The results of this calculation are given in Fig. 6, along with the experimental results. He predicts many states, and has given seven states which lie within 500 keV of the lowest predicted state. The lowest state has $J^{\pi}=3^{-}$ and is calculated to lie at an excitation energy of 1.05 MeV. In the present experiment, we have identified five possible negative-parity states. Most probably, all these states can be identified with the predicted states. We have very tentatively identified some of these states in Fig. 6. The energies appear to be in error since the lowest 2^{-} state appears at 236 keV, whereas the predicted 2^{-} state lies at 1150 keV. This may not be surprising since it is not a sufficiently good approximation to regard these negative-parity states as proton holes, because the neutron hole states lie close enough to mix appreciably. The neutron hole states are expected to lie at about 1.75 MeV.[32] The $Sc^{45}(p, d)Sc^{44}$ work seems to confirm this, since it gives neutron holes starting well below 2 MeV. A calculation allowing mixing of the two types of hole states would push down the lowest odd-parity levels well below 1 MeV. Such a calculation would be required before a better comparison can be made.

As a result of the new mass value[16, 17] of Ti^{44}, the log*ft* value for electron capture to the 68-keV state of Sc^{44} is >8.6. If the spin of this state is 1, as reported in the literature,[14, 15] then the parity is almost certainly negative. A state at 1007 keV has been reported to have a $J^{\pi}=(2-5)^{-}$ from the (d, t) work.[8] This state could be identified with the 4^{-} state. There are no suitable candidates for the 0^{-} state from the available results and additional work is required to locate it.

The identification of the negative-parity states as belonging to the $K=0^{-}$ band predicted by Johnstone is to be regarded only as very tentative. The states identified here have very small or no cross section for the (He^3, d) reaction in agreement with the predictions of the model. An unambiguous identification of these states is going to be difficult, since the best reaction to use would be $Ti^{45}(d, He^3)Sc^{44}$ and Ti^{45} is unstable. Therefore, their identification will depend primarily on their electromagnetic decay properties. Since a state of the form $(f_{7/2})^5(d_{3/2})^{-1}$ cannot decay to states of $(f_{7/2})^4$ configuration by $E1$ radiation, and $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ contributions may be expected to be small for states below 1 MeV, $E1$ transitions should be more than usually inhibited as in the case of other scandium isotopes. The primary decay mode should be by $M1$ transitions between states of the same dominant configuration when $\Delta J=0, \pm1$, otherwise, long lifetimes and measurable $M2/E1$ mixtures should occur. A study[10] of the $Ca^{43}(p,\gamma)Sc^{44}$ reaction is in progress to determine these decay properties.

Many other negative-parity states have been identified with the (d, t) reaction (see Table II). Since most of these must arise from $(s_{1/2})^{-1}$ or $(d_{5/2})^{-1}$ configurations, the calculation of these states is highly desirable.

V. CONCLUSION

In the present work, we have located 52 levels below 3.3-MeV excitation energy; 10 of these levels are reported here for the first time. Angular-distribution measurements were made for most of the observed states. Definite spin and parity assignments have been made for seven levels, with probable assignments for an additional seven levels. As a result of these spin-parity assignments, the "spherical" states, based on $(fp)^4$ configurations, have been identified. In addition, some of the deformed $d_{3/2}$-hole states belonging to the $K=0^{-}$ band have been identified. There are many unassigned states remaining. Among these, some negative-parity states are probably those due to an $s_{1/2}$ hole coupled to the Ti^{45} core. Sc^{44} appears to be similar to Sc^{43}, in the sense that there is a coexistence of spherical $(fp)^n$ and deformed $(fp)^{n+1}(d_{3/2})^{-1}$ states. We have also identified the isobaric analog of the Ca^{44} g.s., at an energy of 2781 ± 5 keV, in agreement with the previous results. In addition, we have confirmed the angular shift between the DWBA and the measured angular distributions reported previously for all states except the analog state.

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†NRC-OAR Senior Postdoctoral Research Associate. Permanent address: University of Kansas, Lawrence, Kansas 66044.

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^{157}Sm, a New Isotope*

N. A. Morcos, D. E. Adams, W. D. James, and P. K. Kuroda
Department of Chemistry, University of Arkansas, Fayetteville, Arkansas 72701

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Irradiation of enriched ^{160}Gd with fast neutrons was found to produce a new radioactivity which was assigned to the (n, α) product ^{157}Sm. The following radiation characteristics were observed to belong to ^{157}Sm: half-life 83± 2 sec, γ-ray energy 121.5± 0.5 keV, and maximum β^--ray energy 2.83± 0.05 MeV.

INTRODUCTION

Wille and Fink[1] observed a 0.5-min activity in Gd (14-MeV n). They tentatively assigned this half-life decay to ^{157}Sm, since they did not observe (with a scintillation detector) the 75-keV first member of the ground rotational band expected in ^{160}Gd from the decay of ^{160}Eu, although an assignment of this activity to ^{160}Eu, is not ruled out on the basis of cross section.[2] A Q_{β^-} energy of 2.79 MeV is estimated for ^{157}Sm from the decay energy systematics tabulation of Viola and Swant.[3] The decay of the ^{160}Gd (n,p) product ^{160}Eu has been assigned a β^- decay half-life of ~2.5 min.[4] The β^--decay Q value of ^{160}Eu is estimated[3] to be ~4.4 MeV.

In the present investigation, a new 83 ± 2-sec β^-- and γ-ray activity was observed from the fast-neutron bombardment of enriched ^{160}Gd metal, and was assigned to ^{157}Sm based on its decay characteristics as described in the results and discussion section.

EXPERIMENTAL

The radioactive sources were produced by fast neutron bombardment of 216-mg smaple of Gd