tively. We feel that the burden of evidence favors the 2^+ assignment. We find $J=1$ for the 344-keV level, in agreement with Refs. 1 and 14, but not with Ref. 2, who argue $J=(0 \text{ or } 2)$ on the strength of population of this level by (d,t) and the weakness of its population by (d,α). The 362-keV level is confirmed as $J=3$. The 663-keV level we find to be spin 1, again in agreement with Refs. 1 and 14, but in disagreement with Ref. 2, who find uniquely $J=3$ for this level. These results are summarized in Table I.

This work shows that the method-I technique of Litherland and Ferguson can be profitably applied to the investigation of closely spaced low-lying levels when Ge(Li) detectors are employed. In particular, the (p,n) reaction on even-even medium-weight nuclei provides an abundance of such subjects, and this technique should be of great value in the future.

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Levels of Sc^{44} from the $Sc^{45}(d,t)Sc^{44}$ Reaction*

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Energy levels in Sc^{44} have been studied using the $Sc^{45}(d,t)Sc^{44}$ reaction at 19.5-MeV incident energy. Thirty-six levels in Sc^{44} below an excitation energy of 3.2 MeV were observed. Angular distributions were measured, and compared with the distorted-wave Born-approximation theory to obtain transferred l values and spectroscopic factors. A considerable amount of $l=1$ strength was found, indicating the presence of $2p$ neutrons in the ground state of Sc^{45}. A recent shell-model calculation using an $(f_{7/2})^4$ configuration shows qualitative agreement with experiment.

I. INTRODUCTION

In recent years, nuclear structure of $f_{7/2}$ nuclei has been the subject of many experimental and theoretical studies. Over-all properties of $f_{7/2}$ nuclei can be at least qualitatively explained using the shell model.[1] Among $f_{7/2}$ nuclei Sc^{44} is very interesting, its first three excited states apparently belonging neither to simple s-d hole nor $f_{7/2}$ configurations despite Sc^{44} having only four nucleons outside the Ca^{40} core. It is thus pertinent to obtain detailed experimental information about Sc^{44} to see to what extent nuclear models apply.

Many direct-reaction experiments have been done to obtain nuclear wave-function information in this region. For Sc^{44}, neutron pickup from Sc^{45} was studied first by Kashy,[2] using the $Sc^{45}(p,d)Sc^{44}$ reaction, and more recently by Bainum *et al.*[3] with

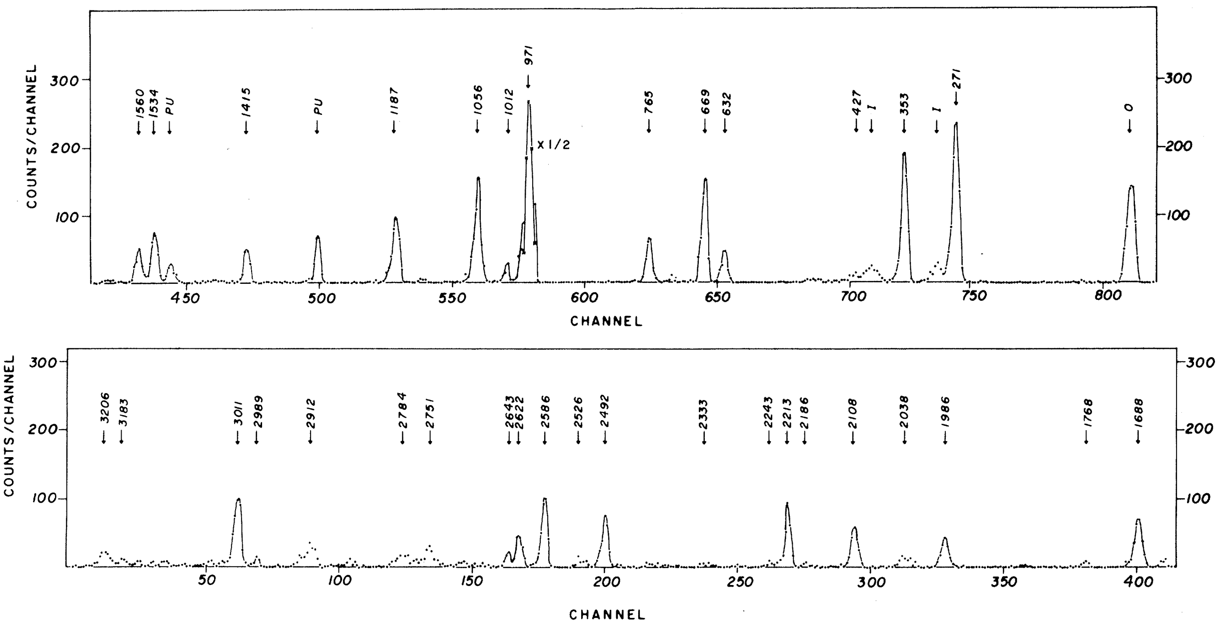

FIG. 1. A triton spectrum obtained at 25°, composed from several overlapping runs taken with three position-sensitive detectors. Those peaks marked with I are due to target impurities, those with PU to deuteron pileup.

the $Sc^{45}(He^3,\alpha)Sc^{44}$ reaction. The proton transfer reaction $Ca^{43}(He^3,d)Sc^{44}$ has been investigated by Schwartz.[4] In addition, the $Ca^{44}(He^3,t)Sc^{44}$,[5] $Ca^{42}(\alpha,d)Sc^{44}$,[6] and $Ti^{46}(d,\alpha)Sc^{44}$[7] reactions are being studied in the John H. Williams Laboratory of Nuclear Physics, University of Minnesota.

In the present work, neutron pickup from Sc^{45} is investigated using the $Sc^{45}(d,t)Sc^{44}$ reaction aided by a high-resolution magnetic spectrometer. The results are analyzed in terms of distorted-wave Born-approximation (DWBA) theory. Since the residual nucleus Sc^{44} is odd-odd, its level density is high, requiring a good-resolution particle detection system for investigation of its level scheme. For Van de Graaff experiments where incident beam energies are limited, Q values favor (d,t) over (p,d) reactions [the Q value for $Sc^{45}(d,t)$ is -5.062 MeV while that for $Sc^{45}(p,d)$ is -9.095 MeV]. In addition, l assignments in (d,t) are easier than in (He^3,α) work, where sometimes different l values have very similar structure. Also, extracted values of absolute spectroscopic factors are more reliable in (d,t) than in (He^3,α), where the normalization factor is not as well known.

Use of a counter telescope in the (p,d) work of Kashy did not allow resolution of some states. Furthermore, because of the low incident energy he could study states only up to about 1 MeV. The recent (He^3,α) work of Bainum *et al.*[3] is subject to the aforementioned difficulties for this reaction, and does not show as high a resolution as the present experiment. In the following paragraphs, (d,t) results are reported and compared in detail with existing Sc^{44} information.

II. EXPERIMENTAL PROCEDURE

The experiment was performed using a 19.5-MeV deuteron beam from the University of Minnesota tandem Van de Graaff; the reaction products were analyzed by a split-pole magnetic spectrometer.[8] An array of three position-sensitive detectors of 700-μ effective thickness placed in the spectrometer focal plane was used to detect and

TABLE I. Optical-model parameters used in the DWBA analysis.

Particle	V_0 (MeV)	r_0 (F)	a (F)	W (MeV)	W_D (MeV)	r_I (F)	a_I (F)	V_{so} (MeV)
d	105	1.02	0.80	···	15	1.42	0.65	6
t	152	1.24	0.651	22	···	1.49	0.808	···
n	···[a]	1.25	0.65	···	···	···	···	$\lambda=25$

[a]Adusted to give the transferred neutron a binding energy of Q + 6.258 MeV.

identify the particles. Evaporated, self-supporting and carbon-backed metallic foils were used as targets. The target thickness typically was 80 $\mu g/cm^2$; the over-all resolution was 15 keV. Angular distributions were measured between 10 and 50° in 2.5° steps for most of the states below 3 MeV in excitation.

III. RESULTS AND ANALYSIS

A typical triton spectrum obtained at 25° is shown in Fig. 1. There, peaks due to target impurities are marked I; those to deuteron pileup are marked PU. Between the ground state and the 270-keV level, study of Ti^{44} electron-capture decay[9] and $Ti^{46}(d,\alpha)Sc^{44}$ data[10] reveal three states. These were carefully looked for but none was seen in the

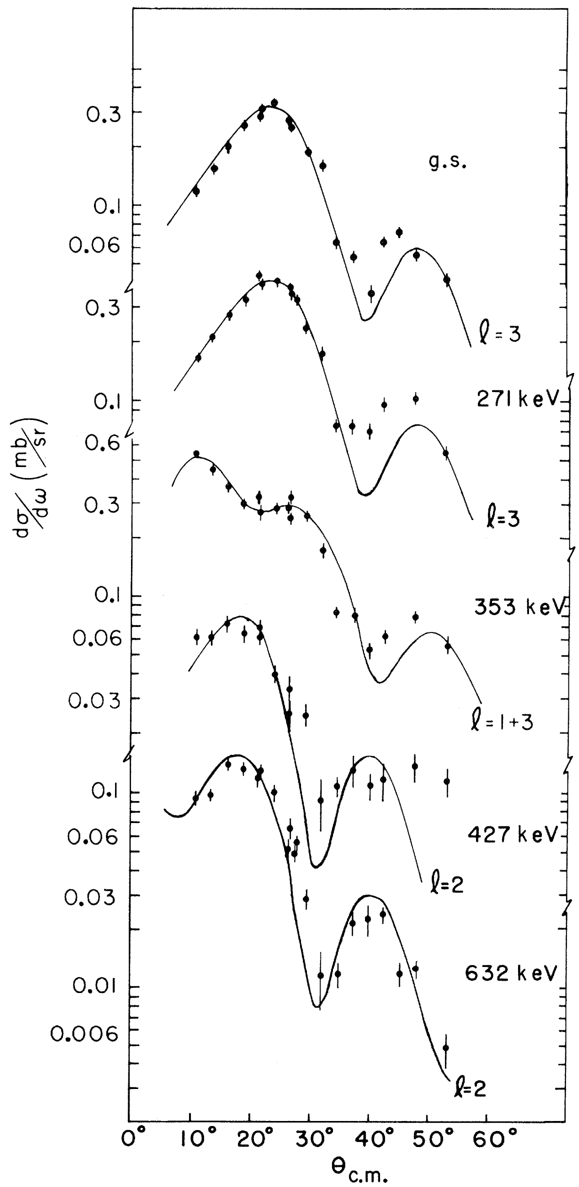

FIG. 2. Angular distributions obtained for the $Sc^{45}(d,t)$-Sc^{44} reaction. The solid curves are DWBA calculations for the indicated l values.

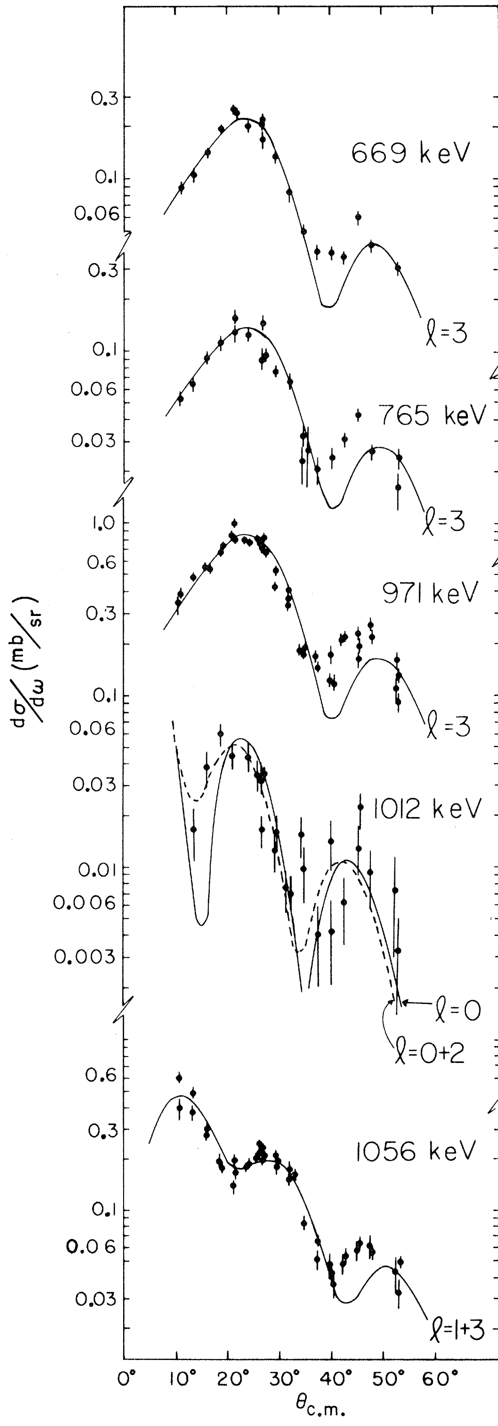

FIG. 3. Experimental angular distributions with best DWBA fits.

present reaction. This will be discussed later in this paper.

The analog state in Sc^{44} was found at 2.80 MeV by Nolen *et al.*[11] Schwartz located it at 2796 ± 5 keV from the $Ca^{43}(He^3, d)Sc^{44}$ reaction,[4] while Bainum *et al.* observed[3] an $l = 3$ transition in their (He^3, α) experiment to a state at 2763 ± 15 keV and designated it the analog state. In this region we saw states at 2751 ± 10 keV and 2784 ± 10 keV; they appear unresolved in the work of Bainum *et al.*[3]

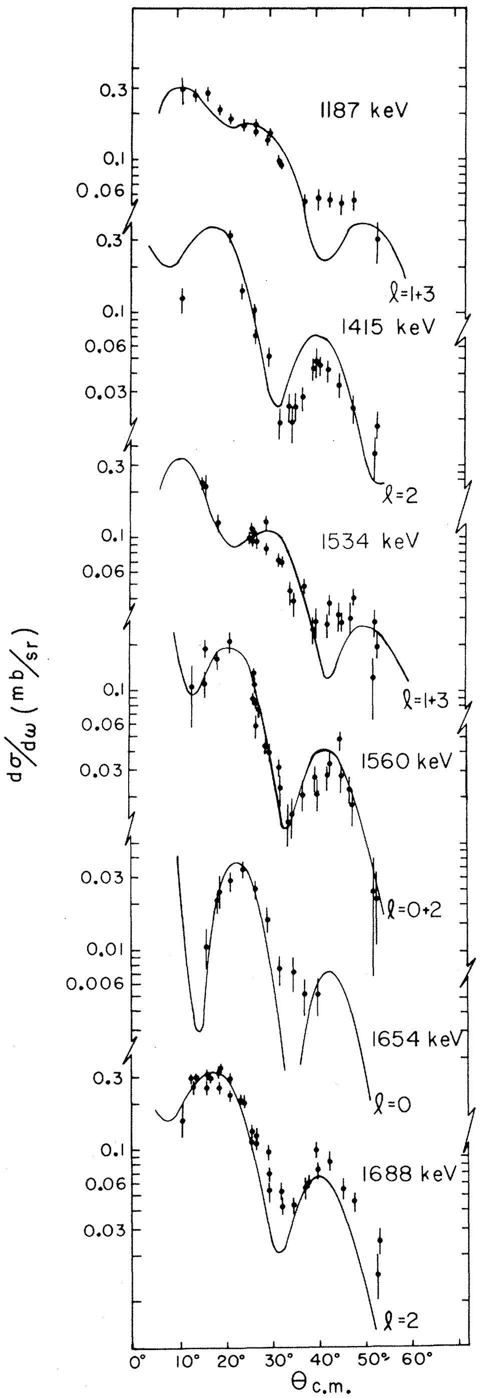

FIG. 4. Experimental angular distributions with best DWBA fits.

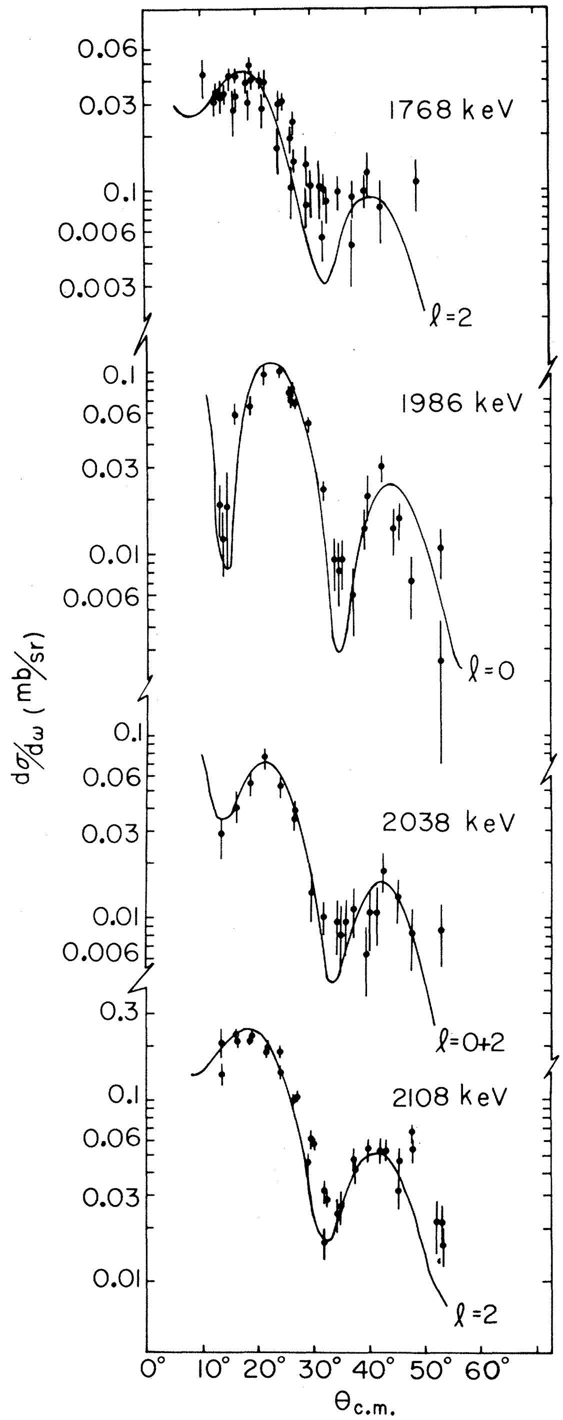

FIG. 5. Experimental angular distributions with best DWBA fits.

The higher member of the doublet is assigned as the analog state from its angular distribution as described below.

Angular distributions for the states observed in this experiment are shown in Figs. 2–8 along with DWBA fits made using the code DWUCK.[12] The optical-model parameters used are listed in Table I. The deuteron parameters are those obtained[13] from analysis of deuteron elastic scattering between 12 and 23 MeV on Ti^{50} and Fe^{54}, while the triton parameters are those obtained by Haefele, Flynn, and Blair[14] from 15-MeV triton elastic data on Cr^{52}. The zero-range local approximation without a low-

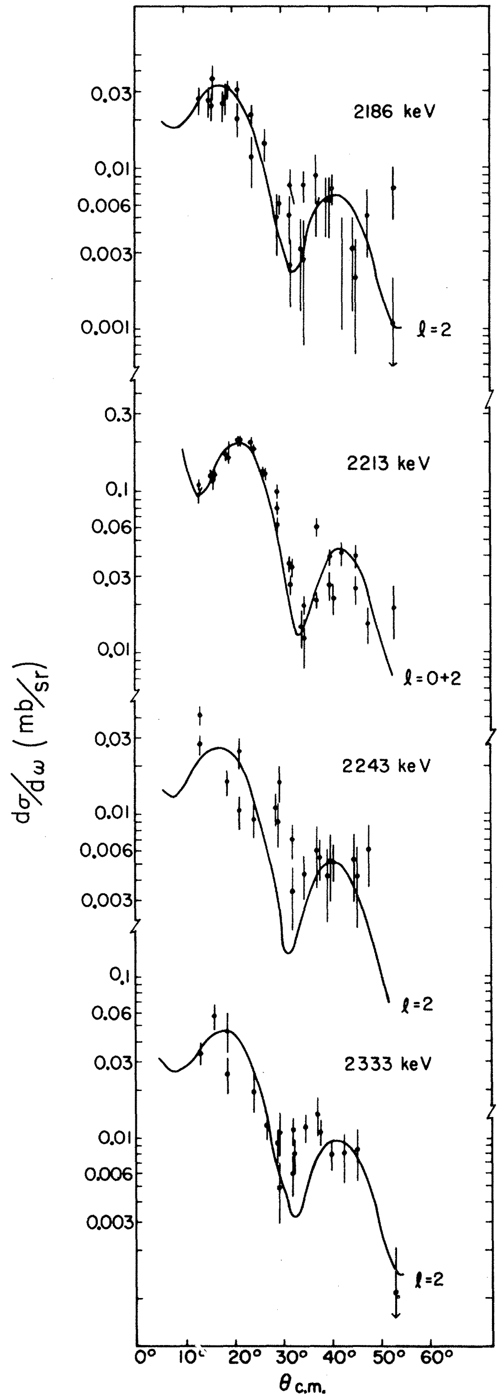

FIG. 6. Experimental angular distributions with best DWBA fits.

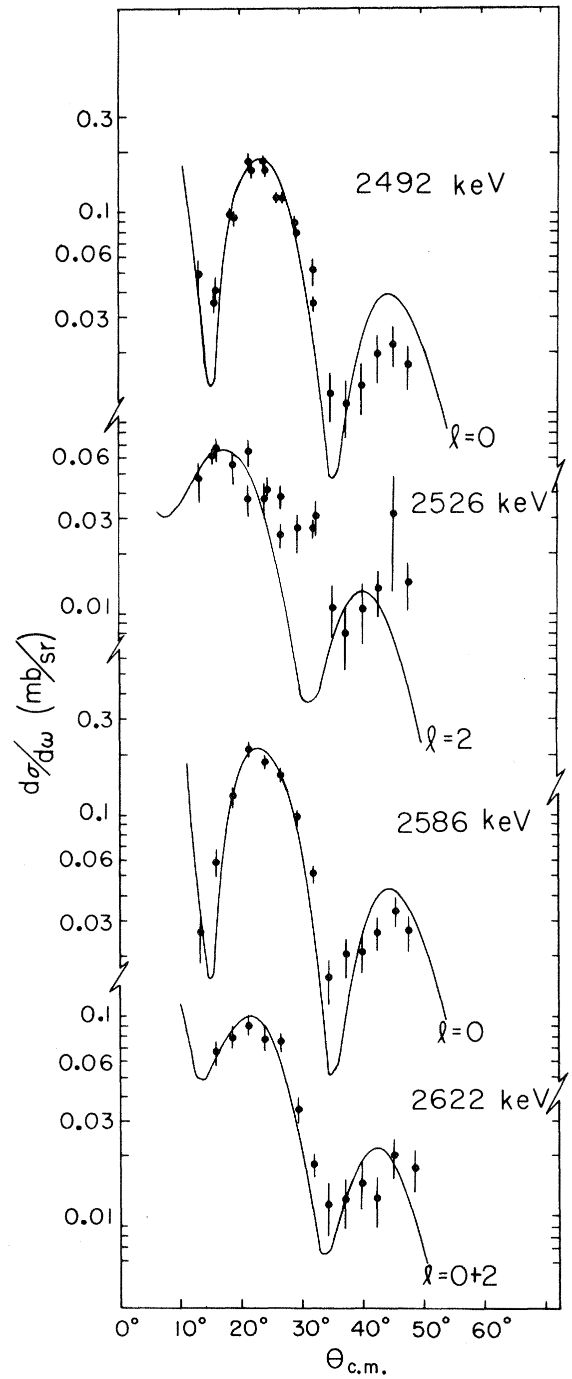

FIG. 7. Experimental angular distributions with best DWBA fits.

er cutoff was employed throughout the analysis. A normalization factor of 3.33 was used[15] to extract spectroscopic factors.

As seen clearly in the figures, angular distributions for some states reported to be $l=3$ in other neutron pickup reactions (Table II) cannot be fitted by pure $l=3$, their cross sections going up at small angles. A small $l=1$ admixture accounts for the large cross sections at small angles allowing reasonable fits to the experimental angular distributions. This indicates the presence of $2p$ neutrons in the ground state of Sc^{45}. This is not surprising, since admixtures of $2p$ neutrons are observed[16] in the ground state of most Ca and Ti isotopes. The $l=1$ mixture in the angular distributions serves to limit the range of final-state spin values.

In Table II the present results are summarized and compared with the other available neutron pickup reaction data on Sc^{45} and the $Ca^{43}(He^3,d)Sc^{44}$ experiment; a level scheme compiled by Endt and Van der Leun[17] is also included in Table II. All $l=3$ transitions are assumed to be $j=\frac{7}{2}$, and all $l=1$ and $l=2$ to be $j=\frac{3}{2}$ in order to calculate the (d,t) spectroscopic factors. Sums of spectroscopic factors obtained in this experiment are given in Table III together with values expected from the extreme single-particle shell model.

IV. DISCUSSION

Owing primarily to better resolution and lower background, we observed many weak transitions not previously reported. Agreement of the (p,d) and (He^3,α) work with the present experiment is otherwise good.

The sum of all $l=3$ and $l=1$ spectroscopic factors is 4.3, agreeing with the sum rule limit of 4.0 from the simple shell-model picture. Sums of $l=2$ and $l=0$ spectroscopic factors are both smaller than the sum rule limit, but we looked only up to 3.2 MeV, and there undoubtedly are higher excited states contributing s-d hole strength.

Schematic representation of the experimentally determined spectroscopic factors is shown in Fig. 9 together with the shell-model predictions for $l=3$ spectroscopic factors from a recent calculation[18] based on a pure $f_{7/2}$ configuration and using recent experimental information on Sc^{42} energy levels. The theory thus predicts only $l=3$ spectroscopic factors; they are in qualitative agreement with experiment as shown in Fig. 9 and Table IV.

The theoretical spectroscopic factors for the 0-keV (2^+), 360-keV (6^+), and 1240-keV (7^+) levels are in good agreement with the experimental ones for the ground state (2^+), the 270-keV level (6^+), and the 971-keV state (7^+), respectively. The theory places a 1^+ state at 440 keV, and 4^+ and 3^+ states at 700 and 760 keV, respectively. Below 1 MeV we, in fact, see three positive-parity states in addition to the three mentioned above. They occur at 353, 669, and 765 keV, the latter two being excited by pure $l=3$, and the 353-keV level containing an $l=1$ component as well. [Schwartz interpreted the angular distribution to the weakly ex-

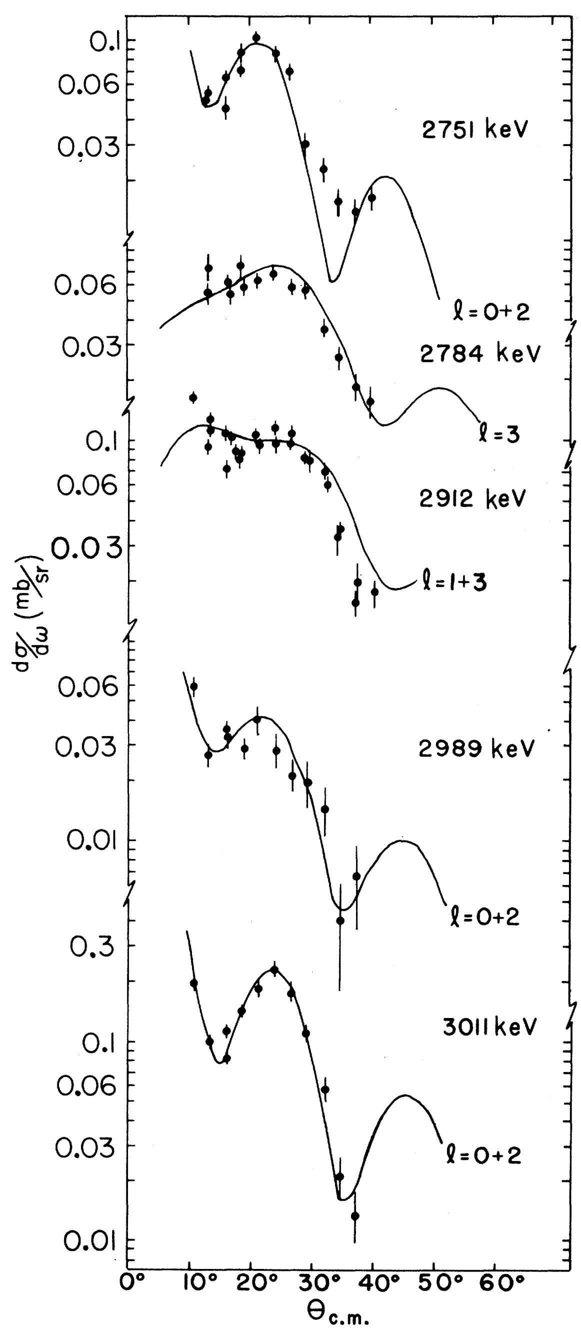

FIG. 8. Experimental angular distributions with best DWBA fits.

TABLE II. Summary and comparison of the present results with other experiments. [Only relevant results are shown for $Ca^{43}(He^3,d)Sc^{44}$ data.]

Ref. 17		Ref. 2 $Sc^{45}(p,d)Sc^{44}$			Ref. 3 $Sc^{45}(He^3,\alpha)Sc^{44}$			Present work $Sc^{45}(d,t)Sc^{44}$			Ref. 4 $Ca^{43}(He^3,d)Sc^{44}$		
E (keV)	J^π	E (MeV)	l	C^2S	E (keV)	l	C^2S	E (keV)	l	C^2S	E (keV)	l	C^2S
0	2^+	0	3	0.30	0	3	0.42	0	3	0.35	0	3	0.28
67.85±0.03													
146.25±0.04													
239±12													
270.6±0.6	6^+	0.266±0.009	3	0.47	269±20	3	0.60	271±5	3	0.48	274±6	3	0.73
349±8	+	0.344±0.010	3	0.38	344±20	3	0.43	353±5	1+3	0.03+0.35	354±9	1+3	0.023+0.450
426±12								427±8	2	0.06	429±13	1+3	0.004+0.084
533±12											521±11		
633±12								632±5	2	0.13	637±6	0	0.04
646±12	+	0.646±0.012	3	0.32	654±20	3	0.38	669±5	3	0.32	671±10	3	0.15
670±12													
758±9	+	0.748±0.015	3	0.22	756±20	3	0.17	765±5	3	0.20	760±7	1+3	0.055+0.166
829±12													
952±15	$(7)^+$	0.952±0.015	3	1.36	976±20	3	1.66	971±4	3	1.29	980±10	3	1.62
								1012±10	(0)	0.02			
									(0+2)	0.01+0.03			
1025±20		1.025±0.02			1043±20	3	0.28	1056±5	1+3	0.04+0.25	1058±12	1+3	0.170+0.340
1144±12													
1165±17		1.165±0.017			1181±20	3	0.28	1187±7	1+3	0.03+0.26	1197±8	1+3	0.024+0.490
1192±12													
1277±20													
1346±12													
1423±10		1.41±0.02	(2)		1424±20	(2)	0.24	1415±10	2	0.41	1433±18	1+3	0.010+0.070
											1512±9	1+3	0.020+0.141
1510±20		1.51±0.02			1531±20	(2)	0.54	1534±5	1+3	0.04+0.15	1537±11	1+3	0.038+0.756
						(3)	0.30						
								1560±5	0+2	0.05+0.12			
								1654±10	0	0.01			
1660±20		1.66 ±0.02	(2)		1682±20	2	0.39	1688±6	2	0.41			
								1768±10	2	0.06			
								1986±5	0	0.05	many levels		
								2038±8	0+2	0.02+0.05			
					2110±20	(3)	0.18	2108±5	2	0.38			
								2186±10	2	0.05			
					2210±20	(2)	0.24	2213±5	0+2	0.07+0.17			
								2243±10	2	0.04			
								2333±10	2	0.08			
								2492±5	0	0.12			
								2526±10	2	0.12			
					2584±20			2586±5	0	0.14			
								2622±8	0+2	0.04+0.10			
								2643±10					
					2696±20								
								2751±10	0+2	0.05+0.10			
					2763±20	3	0.12	2784±10	3	0.22	2796±5	3	0.11
					2907±20			2912±10	1+3	0.01+0.30	2931±10	1+3	0.076+0.23
								2989±10	0+2	0.02+0.07			
					3004±20	2	0.25	3011±10	0+2	0.15+0.15			
								3183±15					
								3206±10					

TABLE III. Sums of spectroscopic factors compared with sum-rule limits from the extreme single-particle shell model.

Orbit	$\sum c^2S$ Experimental	Sum rule
$f_{7/2}$	4.17	4.0
$p_{3/2}$	0.15	0
$d_{3/2}$	2.53	4.0
$s_{1/2}$	0.75	2.0

cited 429-keV state as an $l=1$ and $l=3$ mixture, but our (d,t) angular distribution to this level indicates it as a negative-parity state excited by $l=2$.] A 1^+ assignment to the 353-keV level is thus eliminated as corroborated by Schwartz, who also saw this as an $l=1$ and $l=3$ mixture, and so the 440-keV state from the calculation may not be identified with this state. On the other hand, a 1^+ assignment to the 669-keV level is consistent with the $Ca^{42}(He^3,p)Sc^{44}$ experiment[19] where this state is seen excited by $L=0$ and agrees with Schwartz who also saw it as pure $l=3$ in his (He^3,d) experiment. A recent study of the $Ca^{44}(He^3,t)Sc^{44}$ [5] and $Ti^{46}(d,\alpha)Sc^{44}$ [7] reactions also supports a 1^+ assignment to the 0.67-MeV level. In addition, angular distributions from these reactions favor 4^+ and 3^+ for the 0.35- and 0.76-MeV levels, respectively. The latter state being strongly excited in the $Ca^{42}(\alpha,d)Sc^{44}$ reaction[6] further supports the assignment.

We find four positive-parity states above 1 MeV, besides the analog state, all of which are excited by mixtures of $l=1$ and $l=3$. (Bainum *et al.* assigned[3] a possible $l=3$ to the 2110-keV state; the angular distribution obtained here favors an $l=2$ assignment.) There is no direct correspondence between these states and the calculation. The calculation shows[18] a 1^+ state with considerable $l=3$ strength at about 2.3 MeV, and a 3^+ state with $c^2S(l=3)$ about 0.05 at 2.2 MeV; no candidates for them are found in this experiment. Schwartz observed an $l=3$ transition to the 2250-keV state and tentatively assigned it to be a $(1^+,6^+)$ state from the $(f_{7/2})^4$ configuration. A state at 2243 keV is seen weakly excited in the present (d,t) experiment. Although an $l=2$ DWBA curve gives the best fit to its angular distribution, a mixture of $l=1$ and $l=3$ cannot be excluded, because of poor statistics – in which case $c^2S(l=3)=0.01$ and $c^2S(l=1)=0.004$. In any event this state cannot be the 1^+ state the theory predicts, since pure $l=3$ does not fit it.

Bainum *et al.* found[3] an $l=3$ transition to a state at 2.763 MeV, assigning it to be the analog ground state. In this region we found states at 2.751 and 2.784 MeV. The angular distribution of the former can be fitted by an $l=0$, $l=2$ mixture, while that of the latter by pure $l=3$. Therefore the 2.784-MeV level must be the analog state; its energy is in agreement with the 2.796 ± 0.005-MeV value obtained by Schwartz from the $Ca^{43}(He^3,d)Sc^{44}$ reaction[4] and the 2.786 ± 0.006 MeV value obtained by Becchetti, Dehnhard, and Dzubay[20] in their $Ca^{44}(He^3,t)$ experiment. The shell-model calculation yields 2.97 MeV. The weighted average of the three experimental values is 2.790 ± 0.004 MeV, resulting in a Coulomb energy difference for the Ca^{44}-Sc^{44} pair of 7.219 ± 0.011 MeV. The calculated spectroscopic factor for the analog state is 0.18, in reasonable agreement with the experimental value of 0.22.

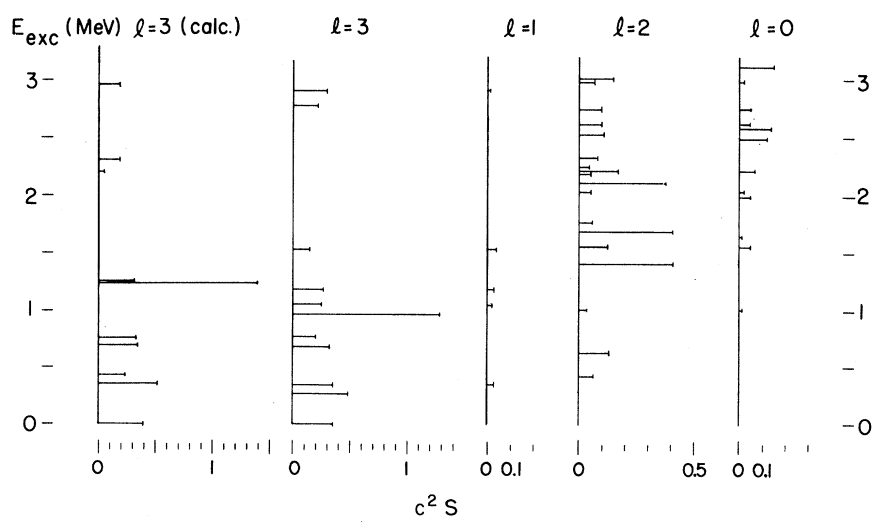

FIG. 9. Schematic representation of the experimentally determined spectroscopic factors. Shell-model prediction for $l=3$ spectroscopic factors obtained from Ref. 18 are also shown for comparison.

TABLE IV. Comparison of the experimental $l=3$ spectroscopic factors with the shell-model calculation taken from Ref. 18.

Experiment			Calculation		
E (MeV)	J^{π}	c^2S	E (MeV)	J^{π}	c^2S
0	2^+	0.35	0	2^+	0.391
0.271	6^+	0.48	0.358	6^+	0.505
0.353	(4^+)	0.35	0.696	4^+	0.342
0.669	1^+	0.32	0.438	1^+	0.225
0.765	(3^+)	0.20	0.762	3^+	0.315
0.971	7^+	1.29	1.238	7^+	1.392
1.056	(5^+)	0.25	1.252	5^+	0.303
1.187		0.26			
1.534		0.15			
			2.049	5^+	0
			2.188	6^+	0.012
			2.209	3^+	0.048
			2.310	1^+	0.184
			2.361	4^+	0
			2.557	2^+	0
2.784	0^+	0.22	2.966	0^+	0.184
2.912		0.30			
			3.111	3^+	0.014
$\sum c^2S$		4.17	$\sum c^2S$		3.915

Starting at about 1.4 MeV we saw many s-d neutron-hole states, while Schwartz observed many proton-particle levels in his (He^3,d) experiment. Bansal and French[21] give simple formulas to estimate the center of gravity of hole states in $f_{7/2}$ nuclei assuming Ca^{40} to be a good core. Using the parameters given in their paper one gets about 1.8 MeV for the center of gravity of the $d_{3/2}$ hole states in Sc^{44}, and about 3.4 MeV for that of the $s_{1/2}$ hole states. To make a quantitative comparison, the spins and transferred j values of the hole states must be known. One also has to see most of the hole strength. Considering that a fair amount of the hole component is missing in the present experiment, and transferred j values are not always known, the predicted positions of the center of gravity seem in reasonable agreement with the strength distribution, as shown in Fig. 9.

The lowest hole state observed in this experiment is at 427 keV, considerably higher than those in the neighboring Sc isotopes and in Sc^{46}. The lowest hole state is at 152 keV in Sc^{43}, at 12 keV in Sc^{45}, and at 143 keV in Sc^{46}. Very low energies of first hole states in Sc^{43} and Sc^{45} and a somewhat higher energy for that of Sc^{44} reflect the odd-even effect predicted by Bansal and French.

It is interesting that the first three excited states in Sc^{44} are not excited in any single-particle transfer reaction. These states were seen by Bjerregaard *et al.*[10] in the $Ti^{46}(d,\alpha)Sc^{44}$ reaction with 3- to 4.3-MeV incident energy, likely through a compound process. Recent study of the same reaction at higher incident energy (19 MeV)[7] shows that states at 0.14 and 0.24 MeV are excited, but only weakly. In the $Ca^{44}(He^3,t)Sc^{44}$ reaction at 29 MeV the 0.24-MeV level is very weakly excited.[5] The 68-keV level is not seen in either of these experiments. These three states thus prove difficult to excite in other direct reactions. The first two excited states were assigned[9] to be 1^+ from the study of electron-capture decay of Ti^{44}. Since then, further experimental information on Ti^{44} has been accumulated, and now it seems established that the mass of Ti^{44} is larger than was previously thought. The recent $Ca^{40}(\alpha,\gamma)Ti^{44}$ experiment of Simpson *et al.*[22] determined the Q value for electron-capture decay of Ti^{44} as 272 ± 15 keV, about 110 keV larger than the old value. This results in $\log ft$ values for electron capture to the first and second excited states of 8.6 and 6.5, respectively.[22] Therefore it is likely that the first excited state has negative parity; the parity of the second may still be positive. Even if both have negative parity, the interpretation of these levels is not elementary. Simple hole or particle states would have been seen in pickup or stripping reactions. To be only very weakly excited in single- and two-nucleon transfer reactions as well as in (He^3,t), these states must have very complicated configurations. There remain questions as to why such states appear at very low energy and why they are not mixed with simple configurations.

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Angular Distribution of Particles Evaporated in Nuclear Reactions*

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A method for the evaluation of the average angular distribution, over a range of energy, of particles evaporated in succession from a compound nucleus is presented. The method is applied to the analysis of the angular distribution in the reaction $Fe^{56}(\alpha,p)Co^{59}$ and the reaction $Cu^{63}(C^{12},p)Se^{74}$. The analysis indicated that nuclei at high excitation have rigid moments of inertia.

I. INTRODUCTION

In the present paper a new method for the calculation of the angular distribution of particles evaporated in reactions proceeding via a compound nucleus is discussed. The method is particularly applicable to the study of angular distributions for reactions in which states in the continuum decay into a wide energy range of final highly excited states. The method suggested in this paper offers an alternative to the method developed by Douglas and Macdonald.[1] Douglas and Macdonald generalize the theory of angular distribution between discrete levels to make it applicable to transitions to the levels in the continuum. The method described in this paper consists of a straightforward application of ideas related to the concepts of the compound nucleus and reciprocity to the study of angular distributions. The present method has the advantage of yielding simple forms for the angular distribution which do not require the knowledge of W and Z Racah coefficients. This simplicity stems from the fact that one calculates the average angular distribution over a wide range of final states. The present method has the additional advantage of being applicable to the evaluation of the angular distribution in reactions in which many particles are evaporated in succession.

It is shown that the calculated angular distribution is very sensitive to the value of the spin cutoff parameter. Therefore, a comparison between the measured value and calculated value of the angular distribution offers a very convenient tool for the determination of the spin cutoff parameter. In particular, the analysis of angular distribution based on the present method suggests that nuclei at high excitation have rigid moments of inertia.

One expects intuitively that the spin and polarization of the compound nucleus affects the angular distribution of the emitted particles. Ericson and Strutinsky[2] and Ericson[3,4] derived expressions for the angular distribution, in the classical limit, for particles emitted from compound nuclei. In most of their considerations the spin of the compound nu-