and $l=3$ transitions in the $Ni^{62}(t,He^4)Co^{61}$ reaction, for well depths $V_s=4$ and 8 MeV. The calculation also included a spin dependence in the bound-state well. The predicted distributions were nearly identical to those obtained for spinless particles. This behavior is somewhat surprising in view of the very definite $\mathbf{\delta}\cdot\mathbf{L}$ dependence predicted for the (He^4,p) reaction[36] and for the (p,He^4) reaction.[37] It is possible that the geometry of the spin-orbit potential well differs from that of the real potential well for highly absorbed particles such as tritons.

ACKNOWLEDGMENTS

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Stripping Analysis of the $Sc^{45}(d,p)Sc^{46}$ Reaction*

J. Rapaport,† A. Sperduto, and W. W. Buechner

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

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The $Sc^{45}(d,p)Sc^{46}$ reaction has been studied with a multiple-gap magnetic spectrograph and the MIT-ONR electrostatic accelerator. Eighty-four energy levels were observed, and angular distributions of the corresponding proton groups were analyzed up to an excitation energy of 4.0 MeV. Eighty-five additional energy levels in Sc^{46} were observed between 4.0 and 6.0 MeV where the level density is seen to increase rapidly with excitation energy. Some unresolved particle groups are estimated to have separations of a few keV. The ground-state Q value was measured to be 6.541 ± 0.008 MeV. The angular distributions were measured in 7.5-deg intervals between 7.5 and 172.5 deg. The assignments of the captured-neutron angular-momentum l_n were based on the position of the first maximum as predicted by a distorted-wave Born-approximation theoretical calculation. The transition strengths for the groups, for which l_n assignments were made, were determined from the measured differential cross sections and the predictions of the distorted-wave, deuteron-stripping analysis.

I. INTRODUCTION

INVESTIGATIONS of energy levels in Sc^{46} have in the past been restricted mainly to two modes of excitation: the (n,γ) and (d,p) reactions on the mono-isotopic element Sc^{45}. More recently, with the use of both higher bombarding energies and He^3-induced reactions,[1] it has been possible to study Sc^{46}, as well as other unstable scandium isotopes, by means of reactions involving the stable neighboring nuclei of calcium and titanium.

The earliest measurements of high-energy neutron-capture gamma rays were made by Bartholomew and Kinsey.[2] Eight gamma rays with energies between 6.35 and 8.85 MeV were measured, and if they are assumed to correspond to direct transitions from the capture state, then several states in Sc^{46} may be predicted. Groshev *et al.*[3] have extended these measurements to lower energy gamma rays (1.1 MeV) and report an additional 16 gamma rays associated with transitions in Sc^{46}.

The isomeric level at 142 keV in Sc^{46} has been known from the early work of Goldhaber and Muehlhause[4] from range measurements of internal-conversion electrons following the bombardment of Sc^{45} with slow neutrons.

Improved high resolution and coincidence techniques in gamma-ray spectroscopy have been used recently to study the decay characteristics of cascade gamma rays following direct transitions from the neutron capture state in Sc^{45}. Neill *et al.*,[5] using slow neutrons from the

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† Part of this work was done at MIT, while the author was on leave of absence from the Instituto de Física y Matemáticas, Universidad de Chile, Santiago, Chile.

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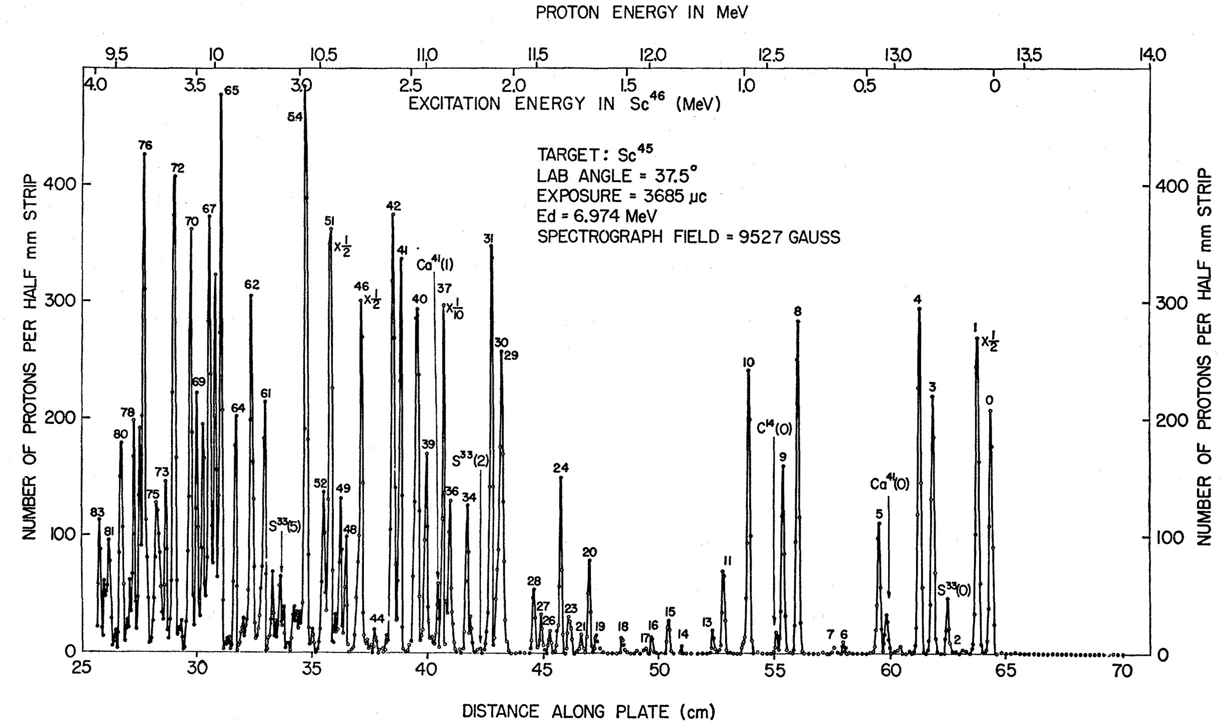

FIG. 1. Measured proton spectrum at laboratory angle 37.5 deg. The number of proton tracks in a 0.5-mm strip across the exposed zone is plotted against position along the photographic emulsion. Proton groups arising from levels in Sc^{46}, identified by their kinematics, are labeled with numbers. Prominent contaminant groups arising from sulfur, calcium, and carbon are also identified.

MIT reactor and a 6-m bent-crystal spectrometer, have measured gamma rays up to an energy of 350 keV. More recently, Bolotin[6] made coincidence studies of the low-energy gamma-ray transitions following neutron capture in Sc^{45} and inferred certain additional properties of low-lying levels in Sc^{46} (below 0.7 MeV) which are either weakly excited or not observed in the deuteron-stripping reaction. Further comments and comparison with the present (d,p) work will be made in Sec. IIIA.

In the first study of the (d,p) reaction on Sc^{45}, Davidson[7] reported two proton groups from range measurements with Q values of 6.78 and 4.48 MeV, corresponding to transitions to the ground state and a level at 2.30 MeV, respectively. A more nearly complete investigation of the proton spectra from the $Sc^{45}(d,p)Sc^{46}$ reaction was next made in this Laboratory by Mazari,[8] using the MIT single-gap spectrograph. The positions of 54 levels up to 3.941 MeV were reported. Still more recently, Bjerregaard *et al.*[9] reported 25 levels in Sc^{46} up to 2.114-MeV excitation from the $Sc^{45}(d,p)Sc^{46}$ reaction and twelve levels up to an excitation of 1.124 MeV from the $Ti^{48}(d,\alpha)Sc^{46}$ reaction.

The present more extensive investigation was undertaken to study the angular distributions of the proton groups from the $Sc^{45}(d,p)Sc^{46}$ reaction as part of a shell-model analysis of the $N=25$ nuclei (Ca^{45}, Sc^{46}, and Ti^{47}). Measurements of the excitation energies of 165 levels up to 5.976-MeV excitation have been made, and the angular distributions of the first 84 proton groups have been analyzed. The results are discussed in terms of the simple shell-model point of view. Since the ground state of Sc^{45} has spin and parity $J^\pi=\frac{7}{2}^-$, this simple model predicts eight levels with $l_n=3$ arising from coupling a neutron to the Sc^{45} ground state. This grouping is observed in the first 1 MeV of excitation in Sc^{46}.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental arrangement was the same as that described in a recent publication.[10] Metallic scandium (Sc^{45}), a mono-isotopic element, was vacuum evaporated onto a thin carbon film that was supported with a thin Formvar backing on a 1-in. diam circular frame. The target thickness, 42 $\mu g/cm^2$, was determined by Rutherford scattering of 2-MeV deuterons at 90 deg. Also, a target-mass analysis was made by using 3.0-MeV deuterons. With a 450 μC exposure, the elastically scat-

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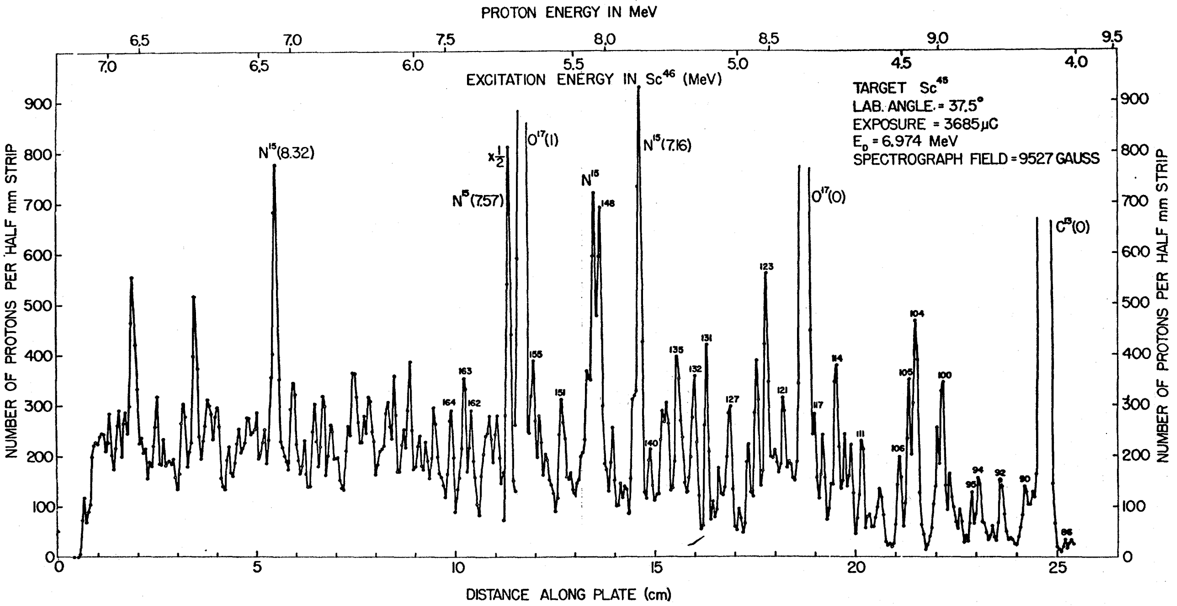

FIG. 2. Extension of the proton spectrum to the lower end of the focal surface of the spectrograph. Levels in Sc^{46} are labeled with numbers. Prominent contaminant groups arising from carbon, oxygen, and nitrogen are also identified.

tered deuterons were observed at 90 deg with respect to the incident beam. The following contaminants were identified: ytterbium, yttrium, calcium, sulfur, oxygen, nitrogen, and carbon. The material from which the target was made was obtained from Johnson, Matthey, and Company, L.td., England, and the estimate that was given for the ytterbium and yttrium impurities was less than 0.001%.

The $Sc^{45}(d,p)Sc^{46}$ reactions were investigated using 7.0-MeV incident deuterons. The exact bombarding energy was determined from measurements of proton groups arising from the $S^{32}(d,p)S^{33}$ and $Ca^{40}(d,p)Ca^{41}$ ground-state transitions for which the Q values are well known. With this resultant value of incident energy and the known spectrograph calibration, the Q value calculated for the $Sc^{45}(d,p)Sc^{46}$ reaction is 6.538 ± 0.008 MeV. This value is in excellent agreement with a previous measurement of 6.541 MeV [8] made in this Laboratory using the single-gap spectrograph. Because of the larger uncertainties in the calibration of the multiple-gap spectrograph, the Q values for those levels in Sc^{46} that were also observed by Mazari *et al.*[8] are quoted here. However, several additional levels are reported in this work that were not observed in the earlier investigation. The Q values quoted in these cases were determined either by interpolation using the known states from Ref. 8 or by reference to known contaminant Q values in the appropriate region of excitation and at the appropriate angles of observation.

Figure 1 shows part of a typical spectrum of protons recorded at an angle of 37.5 deg with respect to the beam direction; the range in proton energy corresponds to excitation energies in Sc^{46} from the ground state up to 4 MeV. Figure 2 shows an extension of this spectrum to the lower end of the focal surface of the spectrograph. A total of 168 levels in Sc^{46} were identified up to 6-MeV excitation energy. The resolution $\Delta E/E$ over the whole range was approximately 0.1%, which corresponds approximately to a half-width of ≤ 12 keV for the proton groups.

Figures 3, 4, and 5 show the observed angular distributions up to 4.0-MeV excitation energy. The solid line is a smooth curve connecting the experimental points. Up to 1 MeV of excitation energy, eight levels exhibit $l_n = 3$ stripping patterns with the strongest one at 51-keV excitation energy. The 140-keV isomeric state has a very low intensity and did not show a stripping pattern. The strongest $l_n = 1$ distribution is seen at an excitation energy of 2.334 MeV. At an excitation energy of 2.780 MeV, there is a state that shows the strongest $l_n = 0$ angular distribution.

Of the 84 angular distributions that were analyzed up to 4.0 MeV, 15 did not show typical stripping patterns. Of the remaining levels, nine were given $l_n = 3$ assignments; 50 were given $l_n = 1$ assignments; and ten, $l_n = 0$ assignments.

In Table I are listed the Q values and excitation energies for all the levels up to 4.0-MeV excitation energy in Sc^{46}. The maximum differential cross sections are listed in the fourth column. The error in the absolute cross-section values is estimated to be 12% from the combined errors in the target-thickness measurement and the counting of the proton tracks. For cross-section values less than 0.1 mb/sr, an additional statistical factor has to be added. The assignment of the orbital angular momentum l_n of the captured neutron

TABLE I. Summary of results for the levels of Sc^{46} formed through the $Sc^{45}(d,p)Sc^{46}$ reaction. $E_d=7.0$ MeV.

Level No.	Q^a (MeV)	$E_x{}^b$ (MeV)	$(d\sigma/d\Omega)_{max}{}^c$ mb/sr(lab)	θ_{max} deg (lab)	l_n	$\left(\frac{2J_f+1}{2J_i+1}\right)S$
0	6.541	0	0.17	38	3	0.58
1	6.490	0.051	0.44	37	3	1.33
2	6.401	0.140	$\leq$0.002			
3	6.314	0.227	0.17	30	3	0.62
4	6.262	0.279	0.33	18	(1)	0.10
5	6.097	0.444	0.11	30	3	0.31
6	5.964	0.577	$\leq$0.007			
7	5.918	0.623	$\leq$0.003			
8	5.769	0.772	0.20	37	3	0.61
9	5.708	0.833	0.10	38	3	0.32
10	5.566	0.975	0.17	38	3	0.50
11	5.451	1.090	0.16	17	1	0.03
12	5.410	1.131	0.018	0	(0)	0.001 (2*s*)
13	5.400	1.141	0.01	38	(3)	0.03
14	5.270	1.271	0.005			
15	5.218	1.323	0.025	17	(1)	0.04
16	5.147	1.394	0.035	18	1	0.06
17	5.106	1.435	0.006	20	(1)	0.001
18	5.015	1.526	0.01			
19	4.893	1.648	0.07	0	0	0.005 (2*s*)
20	4.864	1.677	0.2	18	1	0.03
21	4.849	1.692	0.04	0	0	0.002
22	4.788	1.753	0.01	40	(3)	0.03
23	4.776	1.765	0.03	18	(1)	0.005
24	4.738	1.803	0.34	18	1	0.05
25	4.717	1.824	$\leq$0.005			
26	4.690	1.851	$\leq$0.01			
27	4.651	1.890	0.09	19	1	0.014
28	4.616	1.925	0.11	18	1	0.017
29	4.482	2.059	0.28	0	(0)	0.016 (2*s*)
30	4.470	2.071	0.82	19	1	0.10
31	4.423	2.118	1.4	17	1	0.17
32	4.367	2.174	$\leq$0.005			
33	4.333	2.208	0.015			
34	4.316	2.225	0.36	18	1	0.05
35	4.245	2.296	$\leq$0.01			
36	4.234	2.307	0.47	17	1	0.06
37	4.207	2.334	5.7	17	1	0.80
38	4.175	2.366	0.046	16	1	0.007
39	4.126	2.415	0.48	19	1	0.06
40	4.086	2.455	1.35	18	1	0.18
41	4.008	2.533	0.88	19	1	0.11
42	3.975	2.566	1.3	18	1	0.16
43	3.951	2.590	0.07	0	(0)	0.001 (3*s*)
44	3.893	2.648	0.08	0	(0)	0.001 (3*s*)
45	3.871	2.670	0.02			
46	3.825	2.716	1.95	18	1	0.24
47	3.808	2.733	0.35	18	1	0.04
48	3.761	2.780	0.80	0	0	0.014 (3*s*)
49	3.728	2.813	0.29	20	1	0.035
50	3.704	2.837	0.18	0	0	0.004 (3*s*)
51	3.679	2.862	2.80	18	1	0.31
52	3.644	2.897	0.35	18	1	0.04
53	3.602	2.939	0.035	0	(0)	0.001 (3*s*)
54	3.559	2.982	1.5	19	1	0.175
55	3.536	3.005^d	$\leq$0.2			
56	3.520	3.021^d				
57	3.509	3.032^d				
58	3.480	3.061	$\leq$0.01			
59	3.454	3.087	0.11	17	1	0.013
60	3.399	3.142	0.31	0	0	0.005 (3*s*)
61	3.358	3.183	0.72	17	1	0.08
62	3.300	3.241	0.95	17	1	0.11
63	3.254	3.287	0.07	19	1	0.008
64	3.220	3.321	0.42	18	1	0.046
65	3.150	3.391	0.90	19	1	0.10
66	3.121	3.420	0.70	17	1	0.075
67	3.092	3.449	0.78	17	1	0.083
68	3.061	3.480	0.41	17	1	0.044
69	3.032	3.509	0.40	18	1	0.042
70	3.002	3.539	0.95	19	1	0.10
71	2.955	3.586	0.07	19	1	0.008
72	2.923	3.618	1.10	19	1	0.115
73	2.880	3.661	0.26	16	1	0.027
74	2.846	3.695	0.20	18	(1)	0.02
75	2.826	3.715	0.15	18	(1)	0.015
76	2.770	3.771	0.95	20	1	0.096
77	2.749	3.792	0.35	19	1	0.036
78	2.719	3.822	0.31	19	1	0.031
79	2.702	3.839	0.15^e		(1)	0.015
80	2.663	3.878	0.6^e		(1)	0.058
81	2.600	3.941	0.39^e		1	0.038
82	2.581	3.960	0.15	20	(1)	0.014
83	2.561	3.980	0.30	20	(1)	0.028

[a] The estimated uncertainty is 8 keV for level Nos. 0 through 10; 10 keV for level Nos. 11 through 44; and 12 keV for the other levels.
[b] The estimated uncertainty is 4 keV for level Nos. 1 through 10; 6 keV for level Nos. 11 through 44; and 8 keV for the other levels.
[c] The estimated error in the absolute measured cross section is 12%.
[d] Because of the closeness of the peaks, they were not resolved to measure their individual angular distributions.
[e] Large uncertainty from C^{13} ground-state contamination.

was made on the basis of the position of the first maximum.

Table II gives the Q values and excitation energies in Sc^{46} between 4.0 and 6.0 MeV. The groups in this region were analyzed only in the five gaps between 7.5 and 37.5 deg and were scanned from an exposure made with only one-tenth of the main exposure. The short exposure gave better resolution than that achieved with the longer exposure, because of the reduction of background arising from the carbon, nitrogen, and oxygen groups.

Table III gives the angular-distribution results for the groups showing the largest cross sections in this excitation region. Because of slight variations in resolution in the various gaps of the spectrograph, it was not always possible to resolve the very closely spaced peaks at all the observed angles. In those cases, the l_n assignment is that for the more prominent member of the group.

III. RESULTS

A. Stripping Analysis

The experimental angular distributions were fitted using a distorted-wave Born-approximation code (DWBA) originated by Bassel *et al.*[11] The deuteron-potential parameters were obtained by fitting the 7.5-MeV deuteron elastic-scattering data on Sc^{45} obtained in this Laboratory.[12] The search code ABACUS[13] employ-

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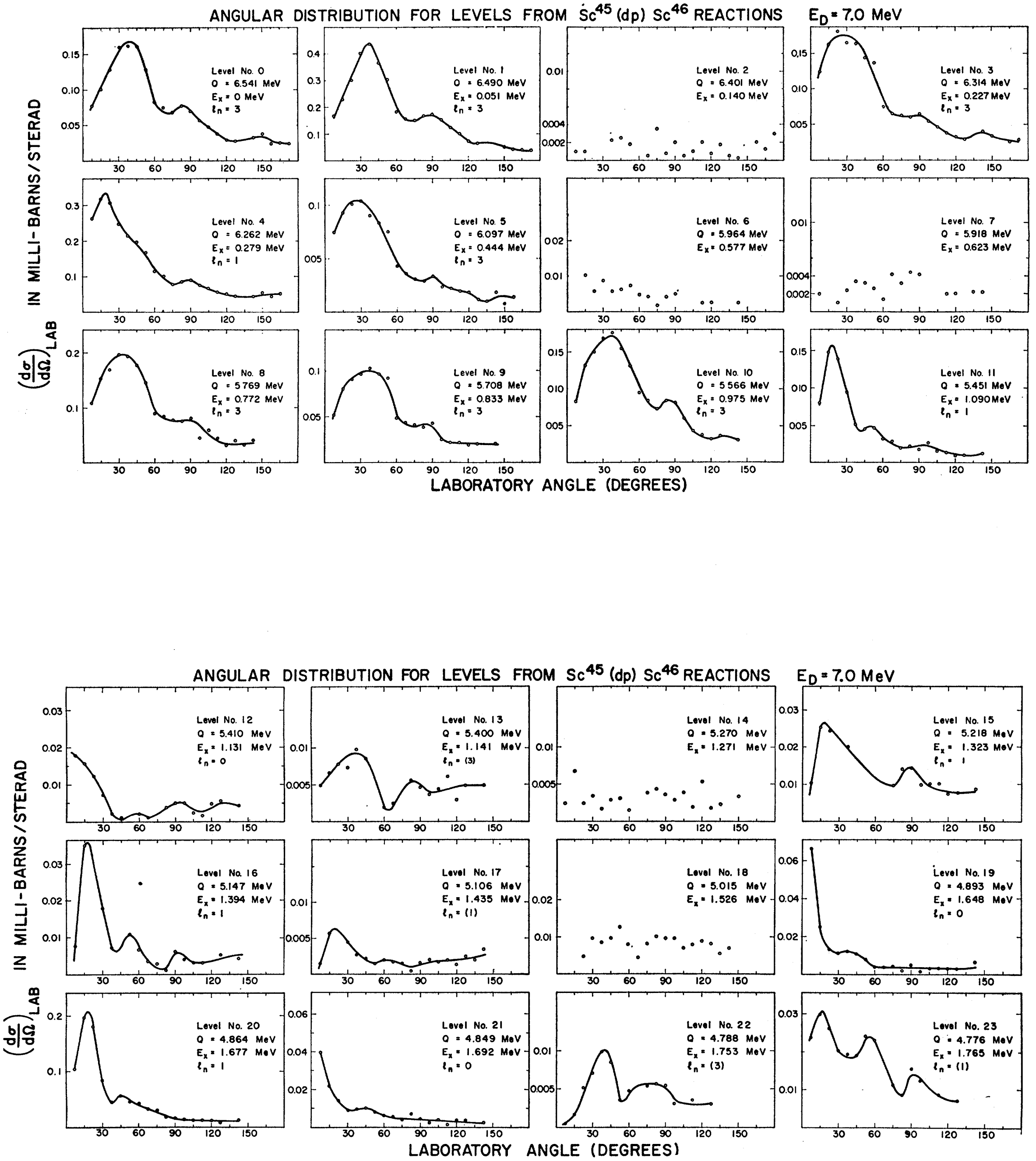

FIG. 3. Measured absolute angular distributions for levels from $Sc^{45}(d,p)Sc^{46}$ reactions up to 1.8-MeV excitation energy in Sc^{46}. The solid line is a smooth curve through the experimental points.

ing a least-squares criterion was used in this fitting, and the *B*4 set of parameters was used as a starting point. This *B*4 set corresponds to an average of fits for elastically scattered deuterons on the titanium isotopes.[14] The proton-potential parameters were obtained from an analysis of proton elastic-scattering data performed by Perey.[15] With the use of the potentials listed in Table IV, angular distributions $\sigma(\theta)$ were predicted for the (d,p) reactions. The calculations were zero-range calculations, and a lower cutoff equal to zero was used on the radial integrals. The predicted $\sigma(\theta)$ for a given state was summed over several angles and compared with the sum of the experimental values at the same

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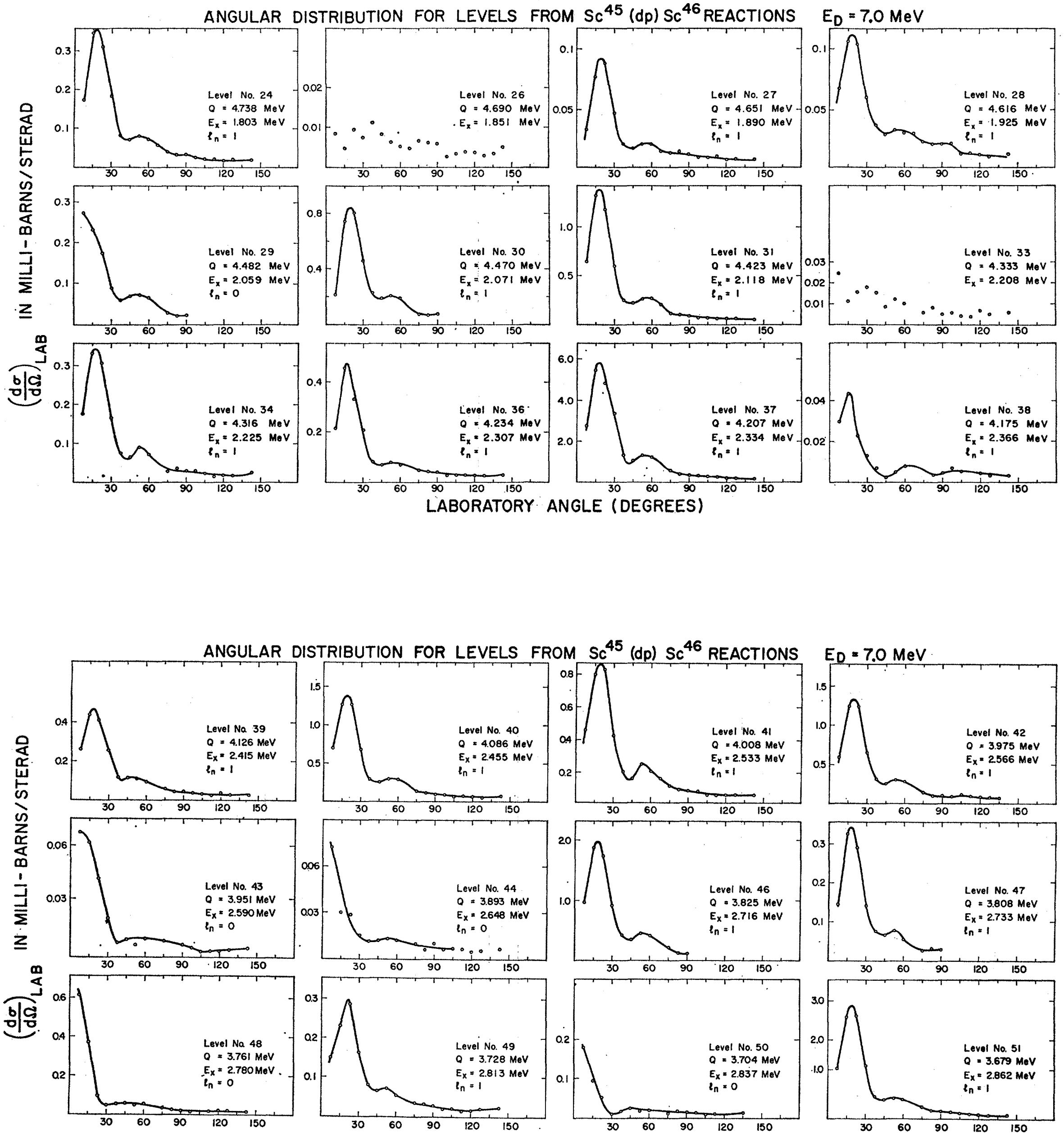

FIG. 4. Measured absolute angular distributions from $Sc^{45}(d,p)Sc^{46}$ reactions from 1.8- up to 2.86-MeV excitation energy in Sc^{46}. The solid line represents a smooth curve through the experimental points.

angles in order to obtain the transition strength

$$\left(\frac{2J_f+1}{2J_i+1}\right)S,$$

according to the relation

$$\sum\frac{d\sigma}{d\Omega}=1.5\frac{2J_f+1}{2J_i+1}S\sum\sigma(\theta).$$

Here J_i and J_f are the initial and final nuclear spins, respectively. The numerical factor 1.5 is related to the use of the Hulthen wave function to describe the deuteron, and S represents the spectroscopic factor. The transition strengths are indicated in column 7 of both Tables I and III.

The experimental angular distributions corresponding to the levels in Sc^{46} with the largest cross sections of $l_n=3$, $l_n=1$, and $l_n=0$ transitions are shown in Fig. 6. The smooth curve is the DW prediction calculated using the code JULIE.

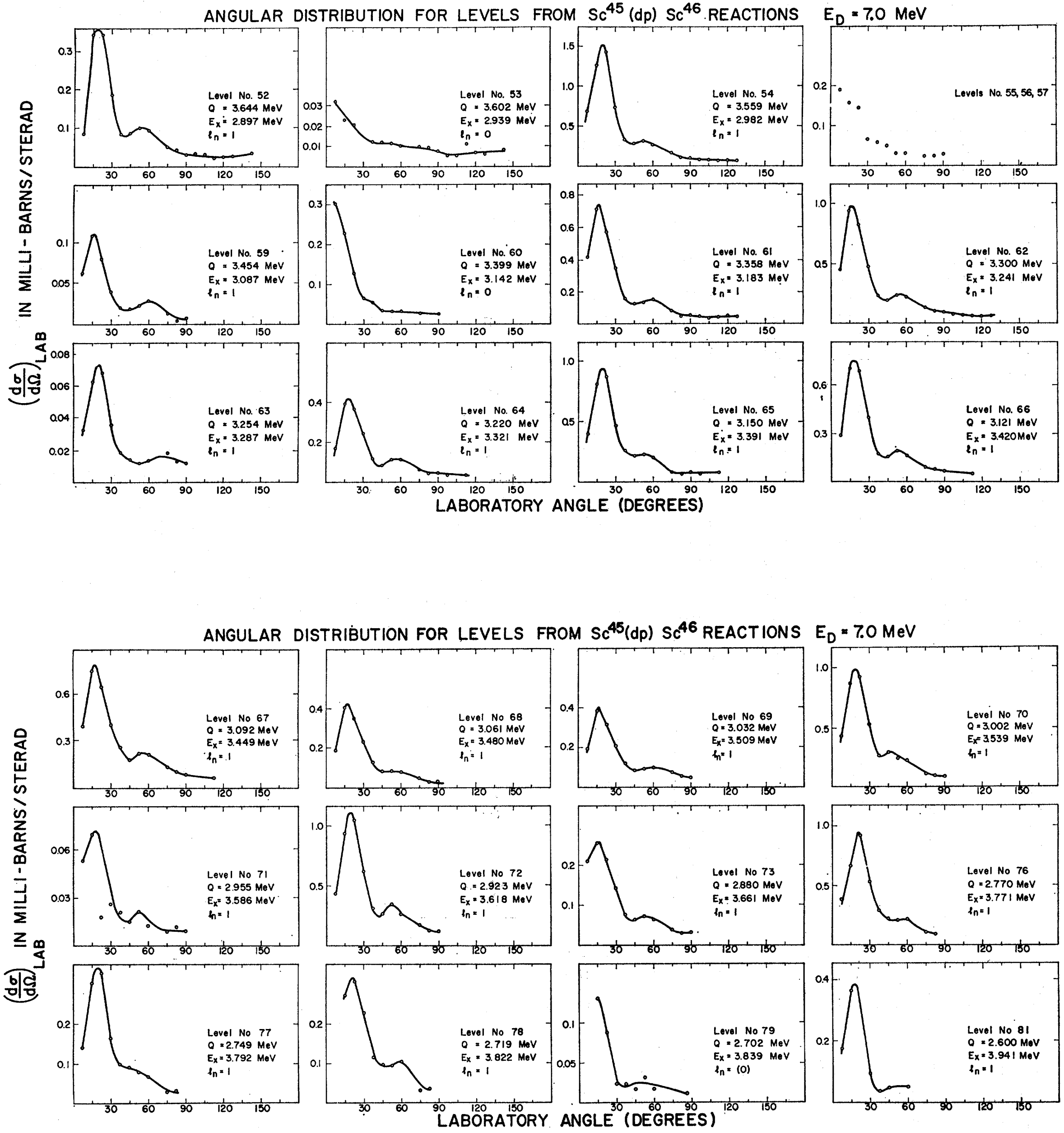

FIG. 5. Measured absolute angular distributions from $Sc^{45}(d,p)Sc^{46}$ reactions from 2.9- up to 4.0-MeV excitation energy in Sc^{46}. The solid line represents a smooth curve through the experimental points.

The energy-level diagrams of Sc^{45} (Ref. 16) and of Sc^{46} are presented in Fig. 7, together with the results of the present stripping analysis of the levels in Sc^{46}. The transition strengths are indicated in different columns according to their l_n value.

Level No. 2 at 0.140 MeV corresponds to the isomeric state with a half-life of 20 sec.[17,18] From measurements of the ratio of internal-conversion electrons to gamma rays,[4] which was found to be of the order of 1, it was assumed that this state belongs to a 2^4 pole isomeric transition. Thus, a tentative $J=7$ was assigned. Recent measurements of low-energy gamma rays following neutron capture[5,6] in Sc^{46} do not show a transition between the 140-keV state and the 51-keV first excited state; however, the (d,p) cross section corresponding to this 51-keV transition is greater than any other $l_n=3$ transition. Actually, it is 2.5 times larger than the cross section leading to the ground state, which has a spin

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[18] B. Hammermesh and V. Hummel, Phys. Rev. 88, 916 (1952).

TABLE II. Q values and excitation energies for the levels between 4.0 and 6.0 MeV in Sc^{46} formed through the $Sc^{45}(d,p)Sc^{46}$ reaction.

Level No.	Q (MeV)[a]	E_x (MeV)[b]	Level No.	Q (MeV)[a]	E_x (MeV)[b]
84	2.531	4.010	127	1.533	5.008
85	2.511	4.030	128	1.519	5.022
86	2.471	4.070	129	1.498	5.043
87	2.449	4.092	130	1.479	5.062
88	2.421	4.120	131	1.459	5.082
89	2.405	4.136	132	1.426	5.115
90	2.356	4.185	133	1.402	5.139
91	2.340	4.201	134	1.389	5.152
92	2.308	4.233	135	1.374	5.167
93	2.291	4.250	136	1.347	5.194
94	2.271	4.270	137	1.333	5.208
95	2.249	4.292	138	1.304	5.237
96	2.223	4.318	139	1.291	5.250
97	2.214	4.327	140	1.269	5.272
98	2.194	4.347	141	1.240	5.301
99	2.179	4.362	142	1.214	5.327
100	2.165	4.376	143	1.196	5.345
101	2.146	4.395	144	1.176	5.365
102	2.127	4.414	145	1.165	5.376
103	2.105	4.436	146	1.154	5.387
104	2.089	4.452	147	1.136	5.405
105	2.065	4.476	148	1.100	5.441
106	2.036	4.505	149	1.076	5.465
107	2.004	4.537	150	1.024	5.517
108	1.982	4.559	151	1.012	5.529
109	1.962	4.579	152	0.976	5.565
110	1.947	4.594	153	0.948	5.593
111	1.929	4.612	154	0.922	5.619
112	1.895	4.646	155	0.897	5.644
113	1.879	4.662	156	0.879	5.662
114	1.853	4.688	157	0.845	5.696
115	1.831	4.710	158	0.812	5.729
116	1.811	4.730	159	0.788	5.753
117	1.787	4.754	160	0.770	5.771
118	1.761	4.780	161	0.745	5.796
119	1.746	4.795	162	0.728	5.813
120	1.722	4.819	163	0.706	5.835
121	1.697	4.844	164	0.663	5.878
122	1.669	4.872	165	0.633	5.908
123	1.647	4.894	166	0.611	5.930
124	1.616	4.925	167	0.590	5.951
125	1.587	4.954	168	0.565	5.976
126	1.571	4.970			

[a] The estimated uncertainty is 13 keV for level Nos. 84 through 127 and 16 keV for the other levels.

[b] The estimated uncertainty is 10 keV for level Nos. 84 through 127 and 12 keV for the other levels.

$J^{\pi}=4^{+}$ (Ref. 19). Therefore, a J value for the 51-keV state in Sc^{46} equal to or greater than 4 can be predicted. In a theoretical analysis of the level structure in Sc^{46}, McCullen *et al.*[20] suggest $J=6$. Since no gamma ray is seen to connect this 51-keV state with the isomeric state that decays to the $J^{\pi}=4^{+}$ ground state, it is possible that the spin of the isomeric state is not $J=7$, as suggested from the gamma-ray measurements, but rather $J=0$ or 1.

The energy-level scheme in Sc^{46} up to 1.0 MeV, proposed by Neill *et al.*[5] and based on the observed intensities of neutron-capture gamma rays, is in agreement with the levels reported in this work, except for one level which they assign at 0.289 MeV. This level is not seen in the present experiments, but it is only 10 keV above our level No. 4 ($E_x=0.279$ MeV), which is a rather strong $l_n=1$ transition. The proton angular distribution for level No. 4 reported here does show evidence of a possible admixture of $l_n=1$ and $l_n=3$. On the other hand, the energy scheme in Sc^{46} up to 0.675 MeV, suggested by Bolotin,[6] differs from that of Neill *et al.*[5] and from the one here reported in that Bolotin proposes a level at 0.289 MeV but not the level at 0.279 MeV which was suggested by Neill *et al.* and has been observed in the present (d,p) work. Another discrepancy in the (n,γ) experiments occurs in the region just above 600 keV in Sc^{46}. Bolotin[6] places a level at 0.675 MeV, and Neill *et al.*[5] places one at 0.627 MeV. In our (d,p) experiments, a very weakly excited transition to a state at 0.623 MeV (level No. 7) is observed, but there is no indication of a level at 0.675 MeV.

Up to 2.0 MeV, six new states are reported in the present work that were not observed by Bjerregaard *et al.*[9] However, in their $Ti^{48}(d,\alpha)Sc^{46}$ work, they report a level at 0.511 MeV that is not seen in the present (d,p) experiments.

In the following section, the analysis of the observed angular distributions will be discussed.

B. The $l_n=3$ Groups

In Sc^{46}, eight levels up to approximately 1-MeV excitation energy are observed with $l_n=3$. They can be

TABLE III. Levels in Sc^{46} between 4.0 and 6.0 MeV formed through the $Sc^{45}(d,p)Sc^{46}$ reaction with largest cross section. $E_d=7.0$ MeV.

Level No.	Q (MeV)	E_x (MeV)	$(d\sigma/d\Omega)_{\max}$[a] mb/sr(lab)	$\theta_{\max}$ deg (lab)	l_n	$\left(\frac{2J_f+1}{2J_i+1}\right)S$
94	2.271	4.270	0.73[b]	18	(1)	0.066
95	2.249	4.292				
99	2.179	4.362	0.36	20	1	0.032
100	2.165	4.376	1.28[b]	18	(1)	0.115
101	2.146	4.395				
104	2.089	4.452	1.05	20	1	0.092
105	2.065	4.476	0.93	20	1	0.081
106	2.036	4.505	0.43	18	1	0.037
116	1.811	4.730	1.21[b]	18	(1)	0.10
117	1.787	4.754				
122	1.669	4.872	1.46[b]	20	(1)	0.119
123	1.647	4.894				
127	1.533	5.008	0.78[b]	17	(1)	0.062
128	1.519	5.022				
132	1.426	5.115	1.07	20	1	0.081
137	1.333	5.208	0.83	20	1	0.064
144	1.176	5.365	1.28[b]	17	(1)	0.093
145	1.165	5.376				
146	1.154	5.387				
147	1.136	5.405				
156	0.879	5.662	0.64	18	1	0.046
157	0.845	5.696	0.65[b]	18	(1)	0.047
158	0.812	5.729				

[a] The estimated error in the absolute measured cross section is 12%.

[b] Because of the closeness of the peaks, they were not resolved. The value of the quoted cross section corresponds to the total yield.

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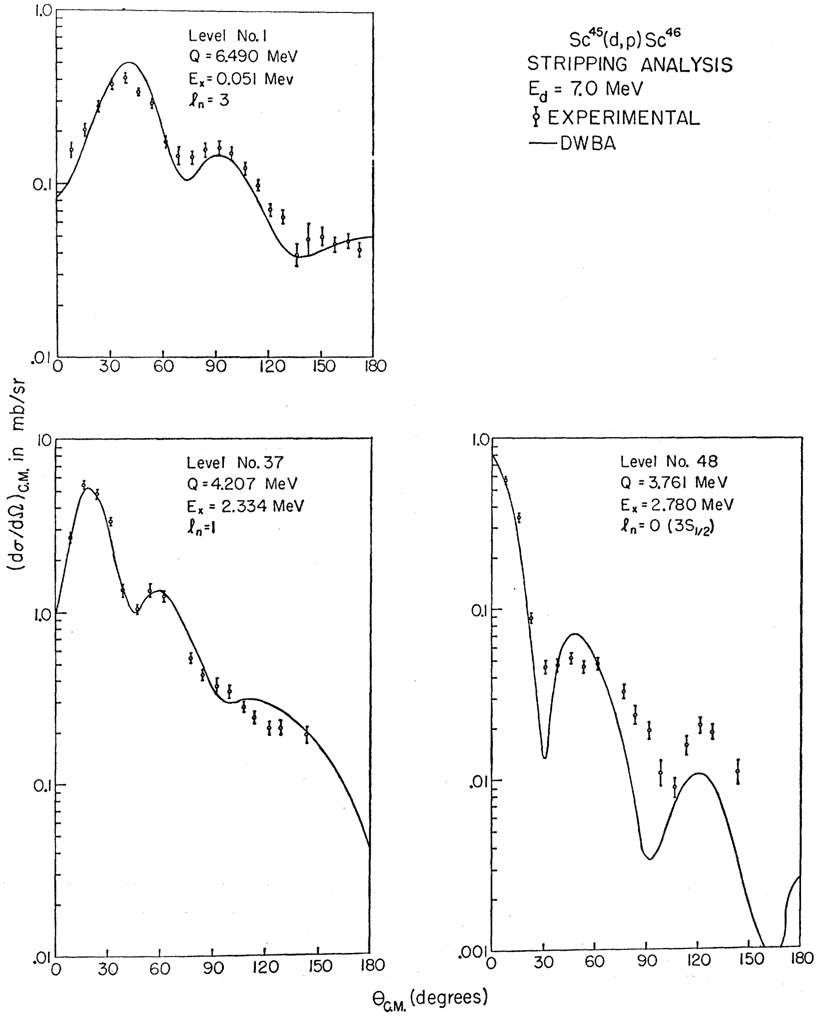

FIG. 6. Angular distributions of the strongest groups from $Sc^{45}(d,p)Sc^{46}$ with $l_n=3$, $l_n=1$, and $l_n=0$, respectively. The curves are derived from the DWBA calculations.

interpreted as being formed by the coupling of one $1f_{7/2}$ proton to a Ca^{45} core with spin $J=\frac{7}{2}$. That the levels are split up to 1 MeV indicates a strong neutron-proton interaction.

If all the transition strengths for the $l_n=3$ state observed in Sc^{46}, as given in Table I, are added up, the result is

$$\sum\left(\frac{2J_f+1}{2J_i+1}\right)S=4.33.$$

The simple shell-model prediction indicates a sum equal to 4, the number of neutron hole states in the Sc^{45} target. This means that all the levels arising from the $(f_{7/2})^5$ neutron configuration are probably seen in the present experiment.

McCullen *et al.*[20] have made theoretical calculations on the spectroscopy in the nuclear $1f_{7/2}$ shell. They identify the strongest $l_n=3$ state with the spin-6 level, and they give the positions and the spectroscopic factors with the other $l_n=3$ states. Their predictions denote a fair agreement with the experimental data here reported. (See Table V.) However, other configurations are needed to explain some other low-lying levels weakly excited in the present experiment. It is very likely that some of the low-lying nonstripping levels could be explained as $d_{3/2}$ or $s_{1/2}$ hole states excited from the coupling of a neutron with the Sc^{45} target nucleus whose ground-state wave function may have components of the form

$$[\pi(f_{7/2})^1\ \nu(f_{7/2})^6(d_{3/2})^{-2}]_{7/2},$$

and

$$[\pi(f_{7/2})^1\ \nu(f_{7/2})^6(s_{1/2})^{-2}]_{7/2}.$$

Here π indicates protons; ν indicates neutrons; and the

TABLE IV. Optical-model potential parameters used in the $Sc^{45}(d,p)Sc^{46}$ analysis.

Particle	V (MeV	W' (MeV)	r_0 (F)	a (F)	r_0' (F)	a' (F)	r_{0c} (F)
d	103.6	24.6	1.00	0.838	1.35	0.65	1.30
p	52.4	10.8	1.25	0.65	1.25	0.47	1.25

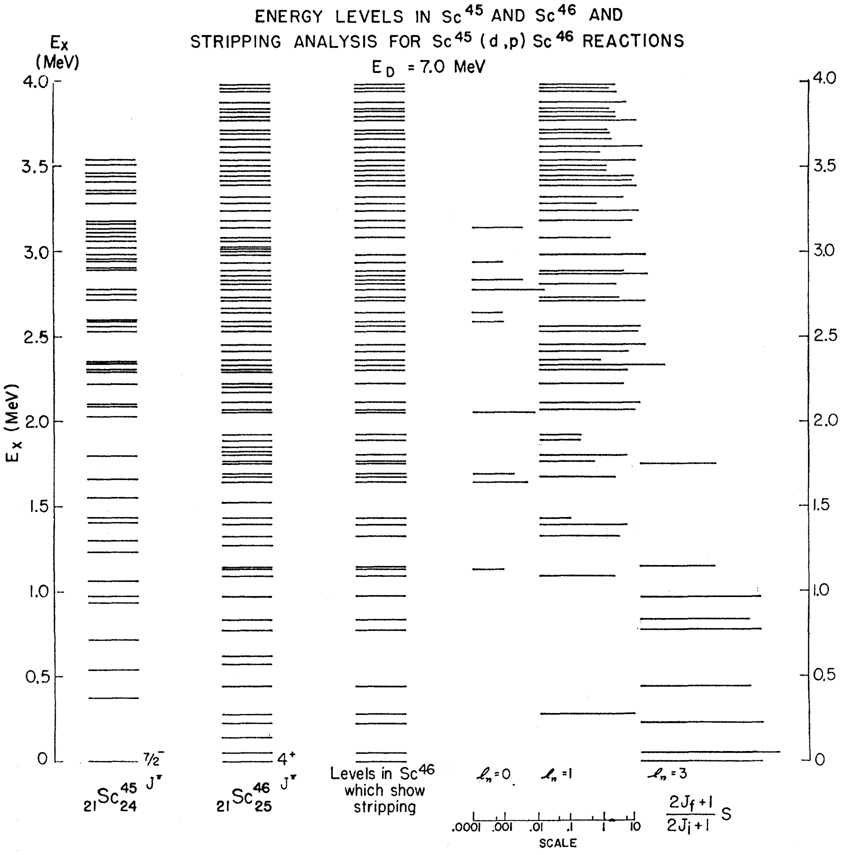

FIG. 7. Energy-level diagram of Sc^{45} and Sc^{46} and stripping analysis for the $Sc^{45}(d,p)Sc^{46}$ reactions. The transition strengths $[(2J_f+1)/(2J_i+1)]S$ from Tables I and III are indicated in columns according to the l_n value.

square brackets symbolize vector coupling to a spin of $\frac{7}{2}$. Bansal and French[21] predict $d_{3/2}$ hole states approximately at 1.0 MeV in Sc^{46} which could be the level Nos. 6 and 7 at 577- and 623-keV excitation energy here reported.

Yntema and Satchler[1] report levels at 0.135, 0.59, and 1.27 MeV from their (d,He^3) pickup experiments on Ti^{47} performed at 21.5 MeV with low resolution. The level at 0.135 MeV is interpreted as a transition to a $d_{3/2}$ hole state, which would correspond to the isomeric state (level No. 2). Likewise, the other two observed states are assigned $l_n=2$ and $l_n=0$, corresponding very likely to level Nos. 6 and/or 7 and to state No. 14, respectively, in this work.

TABLE V. States in Sc^{46} excited by the $Sc^{45}(d,p)Sc^{46}$ reaction and characterized by $l_n=3$ distributions.

	Experimental data			Theoretical predictions (McCullen *et al.*[a])		
Level	E_x (MeV)	$\left(\frac{2J_f+1}{2J_i+1}\right)S$	J_f	(MeV)	$\left(\frac{2J_f+1}{2J_i+1}\right)S$	J_f
0	0.000	0.58	4	0.00	1.24	6
1	0.051	1.33	(6)	0.11	0.37	4
3	0.227	0.62		0.13	0.42	3
5	0.444	0.31		0.22	0.77	5
8	0.772	0.61		0.32	0.12	2
9	0.833	0.32		0.87	0.37	5
10	0.975	0.50		0.88	0.38	4
13	1.141	0.03		1.21	0.24	7
22	1.753	0.03		1.58		1
				1.61		2
				2.03	0.06	6
				2.07	0.04	3

[a] Reference 20.

C. The $l_n=1$ Groups

The $l_n=1$ levels observed in Sc^{46} are due to states of the $2p_{3/2}$ and $2p_{1/2}$ shell-model configuration. By adding all the transition strengths for the $l_n=1$ states in Sc^{46}, as given in Tables I and III, the result is

$$\sum\left(\frac{2J_f+1}{2J_i+1}\right)S=5.12.$$

The theoretical prediction indicates a sum equal to 6. Taking into consideration the uncertainties in the DWBA calculations[22] and the experimental errors, it is considered that the agreement obtained here is good. This indicates that approximately all the levels of the $2p$ shell-model configuration have been excited in the present work.

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TABLE VI. Sum-rule limits. The experimental data shown in the second column are $\sum[(2J_f+1)/(2J_i+1)]S$ for the observed levels up to 6.0-MeV excitation energy in Sc^{46}.

Transition	$2s_{1/2}$	$1f_{7/2}$	$(2p_{3/2}+2p_{1/2})$	$3s_{1/2}$
Theory[a]	0	4.0	6.0	2.0
Experiment	0.024[b]	4.33	5.12[d]	0.026[e]
	0.063[c]			0.044[f]

[a] Assuming pure shell-model neutron-proton configuration (see, for example, Ref. 26).

[b] Includes level Nos. 12, 19, 21, and 29.

[c] Includes all the levels with $l_n=0$.

[d] Includes all the levels up to 4.0-MeV excitation but only those with largest cross section between 4.0- and 6.0-MeV excitation energy in Sc^{46}.

[e] Includes levels with $l_n=0$ above 2.5-MeV excitation energy.

[f] Includes all the levels with $l_n=0$.

No back-angle "dip" effects in the angular distributions, as reported on even-even targets by Lee and Schiffer,[23] were observed in the present experiments. This could have permitted differentiation between $p_{3/2}$ and $p_{1/2}$ states.

D. The $l_n=0$ Groups

A few weak $l_n=0$ levels are seen at a rather low excitation energy. They are likely due to $2s$ core excitation. Since the $3s_{1/2}$-$1f_{7/2}$ splitting is approximately 5.0 MeV,[24,25] levels with $l_n=0$ corresponding to the $3s_{1/2}$ configuration should appear at a high excitation energy. If it is assumed that the states below 2.0-MeV excitation energy in Sc^{46} are due to the $2s_{1/2}$ configuration, the sum of the transition strength values from Table I is 0.024; if it is assumed that the states with $l_n=0$ above 2.5-MeV excitation energy in Sc^{46} are due to the $3s_{1/2}$ configuration, the sum of the transition strengths is 0.026. This is 1.3% of the single-particle prediction[26] and would indicate that either there are other strong $l_n=0$ states at an excitation energy higher than 6.0 MeV in Sc^{46} or there are several other $l_n=0$ levels with small cross section at an excitation energy higher than 4.0 MeV in Sc^{46} for which the angular distributions were not determined in the present experiment.

In Table VI, the experimental results are compared with the theoretical sum-rule limits for the observed $l_n=0$, 1, and 3 transitions.

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