Low-Lying Sc^{44} Levels from the $Sc^{45}(p,d)Sc^{44}$ Reaction*

EDWIN KASHY
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
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The level structure of Sc^{44} has been investigated by measuring the energy spectrum of deuterons from the $Sc^{45}(p,d)Sc^{44}$ reaction at 17.5 MeV. The results show deuteron groups corresponding to 11 levels below 1.7 MeV at the following energies: 0, 0.266, 0.344, 0.646, 0.748, 0.952, 1.025, 1.165, 1.14, 1.51, and 1.66 MeV. The angular distributions of the deuterons have been obtained and show that the 6 lowest lying levels observed correspond to the pickup of an $f_{7/2}$ neutron from Sc^{45}. A comparison is made of the present results with some recent theoretical predictions.

I. INTRODUCTION

INTEREST in Sc^{44} has been aroused by some recent theoretical calculations of the Sc^{44} level structure.[1] Little is known about nuclear levels of Sc^{44} and the reactions yielding information on its level structure are limited since only Sc^{45} is a stable isotope. Furthermore, since it is an odd-odd nucleus, the high-level density expected requires good energy resolution to make an investigation of the $Sc^{45}(p,d)Sc^{44}$ reaction meaningful. With the advent of solid state surface barrier detectors with low noise and high resolution, and since the Princeton cyclotron beam spread has been reduced to $\sim$25 keV by magnetic analysis, the present experiment was made possible.

II. EXPERIMENTAL PROCEDURE

The 17.5-MeV proton beam from the Princeton FM cyclotron was magnetically analyzed using a double-focusing spectrometer with slits set so that a beam spread of 25 keV resulted. The beam then entered a 20-in. scattering chamber especially designed for the use of solid state detectors.[2] The two targets used consisted of natural scandium (100% Sc^{45}), one evaporated upon 0.00025 in.-thick Mylar supporting foil with a thickness of 0.56 mg/cm^2, and the other a self-supporting scandium foil of 1.06 mg/cm^2 thickness. The reaction particles were observed by means of a three-detector telescope consisting of a thin, $\sim$50-μ-thick silicon surface barrier transmission detector followed by a 500-μ-thick transmission detector. These two detectors, which were thick enough to stop the most energetic deuterons of interest, were backed by a third detector of large area which was used to give an anticoincidence pulse if a particle traveled through the first two detectors without being stopped. The third detector was essential for obtaining spectra with low background, especially for small angles where the elastic proton cross section is very large. A schematic of the experimental arrangement is shown in Fig. 1. The pulse of the first detector is a measure of the specific ionization of a reaction particle, and that in the second a measure of

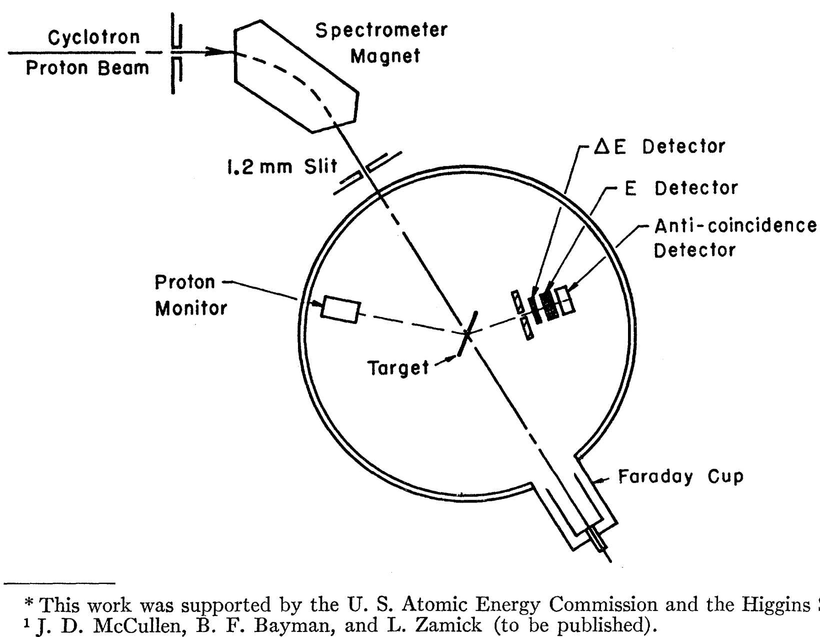

FIG. 1. Schematic of the scattering chamber showing arrangement of the ΔE, the E, and the anticoincidence detectors.

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[1] J. D. McCullen, B. F. Bayman, and L. Zamick (to be published).
[2] A. Lieber (unpublished).

the residual energy of the particle, assuming the particle is stopped in the second detector. The true energy is obtained by a coherent summing of the charge from each of the detectors. That charge is then measured by means of a charge sensitive preamplifier. The coherent summing circuit was suggested by R. L. Chase and is shown in Fig. 2. In order to get the mass of a particle, the product $(dE/dx)\times(E)$ was effected by means of a pulse multiplier.[3] That product which is approximately proportional to the mass was displayed on a 2-dimensional analyzer versus the energy pulse. The simplified flow diagram of Fig. 2 represents one of the latest circuits used, with the anticoincidence part of the circuit not shown. Since the range of deuteron energies of interest was rather small, i.e., ~1.6 MeV, and since no tritons of the same energy are formed in this reaction, some of the data were obtained by requiring that the energy loss in the dE/dx detector be such that deuterons were the only particles in the energy region of interest which satisfied the requirement. The energy was then analyzed if no anticoincidence events were present in the third detector.

In addition to the counter telescope used in measuring the (p,d) cross sections, an additional detector whose position remained fixed with respect to the beam was used during most of the experiment to monitor the protons elastically scattered from the scandium. This detector was a 700-μ silicon-surface barrier detector. An absorber on the front of the detector was used to stop the protons elastically scattered from either carbon or oxygen, but allowed the more energetic protons scattered for scandium to reach the detector.

The inherent resolution of the detectors, amplifier, and multichannel analyzer system was measured by means of a pulser. In the present experiment, this resolution was 40 keV (full width at half-maximum). The best over-all deuteron peak resolution obtained was 57 keV. This represents a sizable improvement in over-all resolution over previous (p,d) investigations of a similar nature

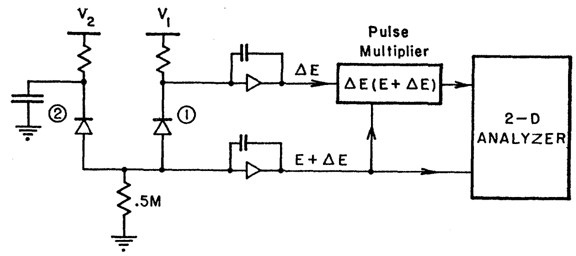

FIG. 2. Simplified flow diagram of the electronics used showing coherent summing circuit.

The energy scale for the deuterons was established in terms of the $F^{19}(p,d)F^{18}$ deuteron spectrum. Since the (p,d) cross section of fluorine is large and its ground level Q value and energy of excited levels well known, this represented an ideal way of obtaining accurate Q values and level spacings for Sc^{44} in a way rather insensitive to the exact value of the incident energy.

RESULTS

An energy spectrum of deuterons taken at a laboratory angle of 40 deg is shown in Fig. 3. There were 8 levels identified below 1.2 MeV and angular distributions were obtained for each. The deuteron angular distributions for these levels are shown in Fig. 4. Three additional deuteron groups corresponding to excitation

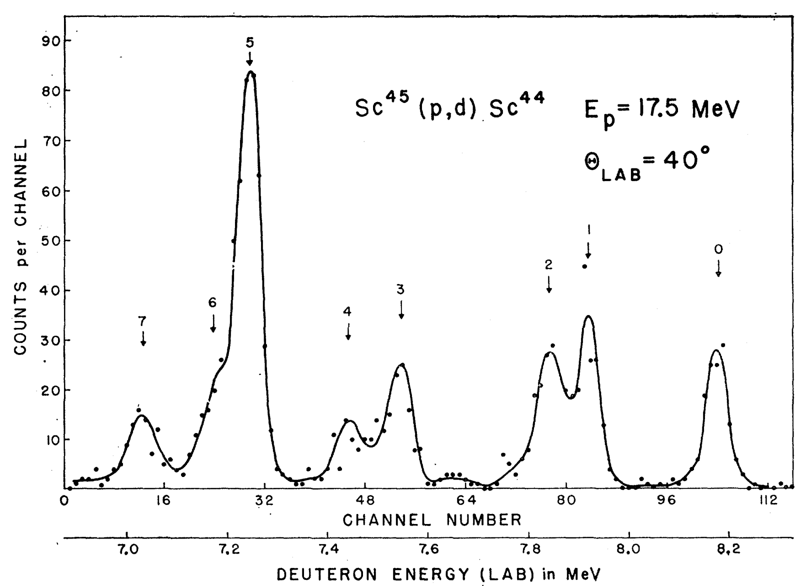

FIG. 3. Energy spectrum of deuterons at laboratory angle of 40°.

[3] G. Giannelli and L. Stanchi, Nucl. Instr. Methods 8, 79 (1960).

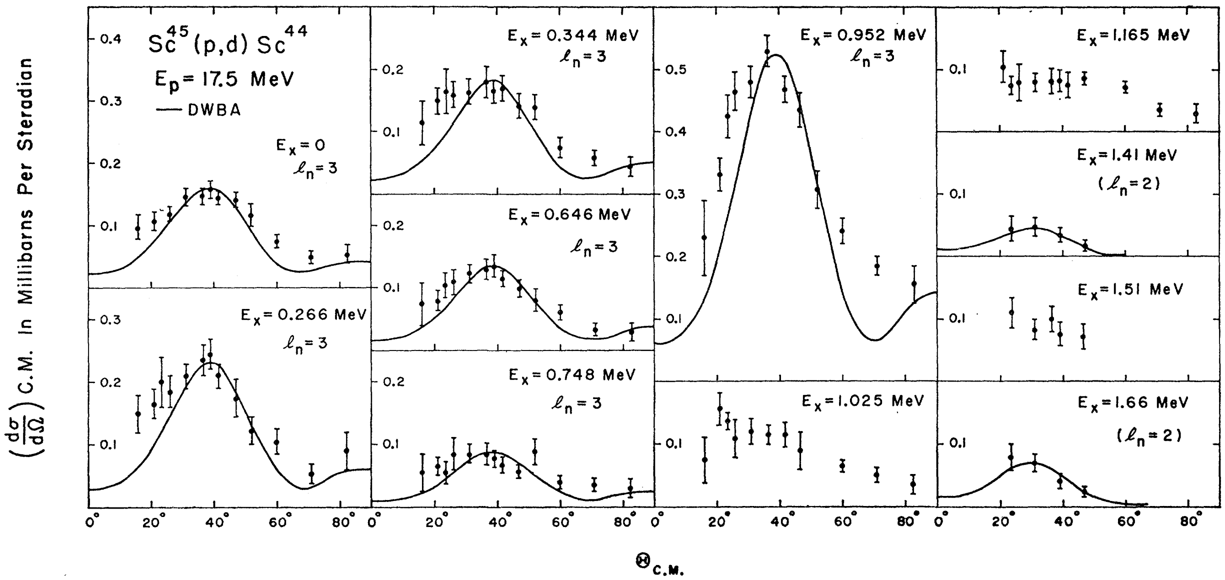

FIG. 4. Angular distributions of deuterons for the 11 deuteron groups observed below 1.7-MeV excitation energy. The solid lines represent DWBA calculations.

energies of 1.41, 1.51, and 1.66 MeV were observed. The (p,d) cross sections for these were measured for only a few angles and are shown in Fig. 4. No other level was observed below 2.5-MeV excitation energy with a (p,d) cross section at 35° greater than 40 μb/sr. The uncertainty in the absolute value of the differential cross section was estimated at $\pm 10\%$. This does not include the statistical uncertainties and uncertainties in resolving the peaks. These are indicated by the error flags of Fig. 4.

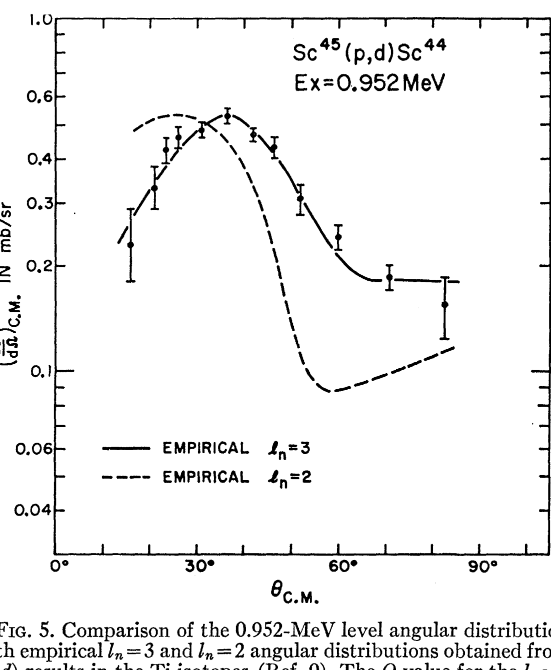

FIG. 5. Comparison of the 0.952-MeV level angular distribution with empirical $l_n=3$ and $l_n=2$ angular distributions obtained from (p,d) results in the Ti isotopes (Ref. 9). The Q value for the $l_n=3$ curve is the same as for the scandium 0.952-MeV level while for the $l_n=2$ it is somewhat more negative ($Q=-11.2$ MeV).

The energies and maximum cross sections of the levels are listed in Table I, together with the energies of previously reported levels.[4] Good agreement as to excitation energy is observed between present and previous work for the 0.266- and 0.646-MeV levels. A ground-state Q value of -9.125 ± 0.022 MeV was measured for this reaction assuming -8.218 MeV for $F^{19}(p,d)F^{18}$ ground-level transition Q value, and -9.158 MeV for the Q value of the transition to the 940-keV level of F^{18} as standards.

In order to extract the experimental spectroscopic factors (S), distorted wave Born approximation (DWBA) calculations were done using the Oak Ridge distorted wave code[5] and the resulting angular distributions were used to extract the (p,d) spectroscopic factor for each level. No attempt was made to "fit" the data, but rather optical parameters found in the literature were used.[6–8] The results of the DW calculations are shown in Fig. 4, where the theoretical angular distributions have been normalized to give the same peak cross section as is measured experimentally. It is

[4] F. Ajzenberg-Selove, N. B. Gove, T. Lauritsen, C. L. McGinnis, R. Nakasima, J. Scheer, and K. Way, *Energy Levels of Nuclei: A=5 to A=257* (Springer-Verlag, Berlin, 1961).
[5] R. H. Bassel, R. N. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL 3240 (unpublished).
[6] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[7] C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).
[8] The optical parameters were: For the neutrons, $r_0=1.25$ F $a=0.65$ F. For the protons, $V=48$ MeV, $W=0$, $r_0=1.25$ F, $r_c=1.25$ F, $a=0.65$ F, $r_0'=1.25$ F, $a'=0.47$ F, $W'=44$ MeV. For the deuterons, $V=77.6$ MeV, $W=0$, $r_0=1.3$ F, $r_c=1.3$ F, $a=0.73$ F, $r_0'=1.35$ F, $a'=0.65$ F, $W'=90$ MeV.

TABLE I. Experimental results for the $Sc^{45}(p,d)Sc^{44}$ reaction.

Peak number	E_x(MeV) Present work	E_x(MeV)[a] Previous results	$\frac{d\sigma}{d\Omega}_{max}$ mb/sr	l_n	$S_{exp}=\frac{\sigma_{exp}}{\sigma_{DW}}$
0	0	0	0.16	3	0.30
...	...	0.069	...	...	...
...	...	0.147	...	...	...
1	0.266±0.009	0.27	0.23	3	0.47
2	0.344±0.010	...	0.18	3	0.38
...	...	0.42	...	...	...
3	0.646±0.012	0.65	0.14	3	0.32
4	0.748±0.015	...	0.09	3	0.22
5	0.952±0.015	...	0.52	3	1.36
6	1.025±0.020	...	0.12(30°)	...	...
7	1.165±0.017	...	0.08(30°)	...	...
...	1.41 ±0.02	...	0.05	(2)	...
...	1.51 ±0.02	...	0.08(30°)	...	...
...	1.66 ±0.02	...	0.07(30°)	(2)	...

[a] See Ref. 4.

seen that the theoretical curves reproduce the experimental shapes reasonably well except that at forward angles the theory appears to be consistently lower than the data in the first six angular distributions. In view of the discrepancy between DWBA calculations and the experimental results, and in order to insure that the $l_n=3$ assignments were correct, the angular distribution of the deuterons for the 0.952-MeV level was compared to an empirical $l_n=3$ angular distribution for the same Q value taken from a recent investigation of the (p,d) reaction on Ti isotopes with 17.5-MeV protons.[9] This comparison is shown in Fig. 5, where it is seen that the agreement for $l_n=3$ is excellent. Also shown in Fig. 5 is an empirical angular distribution for $l_n=2$ taken from the same investigation for a slightly more negative Q value, i.e., $Q=-11.2$ MeV.

It can be seen from Figs. 4 and 5 that the angular distributions for the ground level and for the 0.266, 0.344-, 0.646-, and 0.952-MeV levels are formed by the pickup of an $l=3$ neutron from Sc^{45}. The error flags on the data in the angular distribution of the 0.748-MeV level make the decision somewhat more difficult, but there is little doubt that it also corresponds to $l_n=3$. The differential cross section for the 1.025-MeV level was difficult to obtain, as that level lies close to the 0.952-MeV level which is strongly excited. The rise in the cross section at 21 and 24 deg appears to rule out $l_n=3$ for this transition. The 1.165-MeV level may be due to $l_n=3$, but this information will have to await further study. The rapid rise in cross section from 47 to 31 deg indicates that the 1.41- and 1.62-MeV levels may correspond to $l_n=2$ (see Fig. 4). These would then correspond to some of the Sc^{44} levels expected when a neutron is picked up from the $1d_{3/2}$ shell. The experimental spectroscopic factors derived from the comparison of theory with experiment are listed in Table I. The sum of the experimental spectroscopic factors for the six $l_n=3$ transitions observed here is 3.1. That value is remarkably close to the value of 4.0 for $\sum S_i$ expected, assuming pure $(f_{7/2})^4$ neutron configuration in Sc^{45}. The summation is taken over all $l_n=3$ transitions, and indicates that these transitions contain most of the $f_{7/2}$ pickup strength. The value of 3.1 measured here may, of course, vary somewhat depending upon the optical parameter used, as there appears to be some ambiguity in the values of these parameters.

[9] E. Kashy and T. W. Conlon (to be published).

DISCUSSION

It is tempting to assign for the levels below 1.2 MeV corresponding to $l_n=3$ an origin of simple jj coupling between a $1f_{7/2}$ proton and $[(1f_{7/2})^3]_{j=7/2}$, $v=1$ neutrons with total $J^\pi=0^+, 1^+, 2^+, 3^+, 4^+, 5^+, 6^+$, and 7^+. However, the experimental spectroscopic factors do not show any correlation with $(2J+1)/16$ as the spectroscopic factors which would then be expected if the neutron seniority in Sc^{45} were 0, assuming separate proton and neutron seniority. On the other hand, the agreement between the present results and theoretical calculations by McCullen, Bayman, and Zamick is quite encouraging. In their calculations, they use information on levels of Sc^{42} in order to obtain the value

TABLE II. Theoretical results of McCullen, Bayman, and Zamick[a] for the $Sc^{45}(p,d)Sc^{44}$ reaction.

E_x(MeV)	J^π	S_{theor}	S_{exp}/S_{theor}
0	2+	0.42	0.7
0.09	6+	0.49	1.0
0.28	1+	0.25	1.5
0.70	3+	0.28	1.1
0.86	4+	0.32	0.7
1.17	7+	1.43	1.0
1.30	5+	0.25	...
2.8	0+	0.17	...
3.08	1+	0.20	...

[a] See Ref. 1.

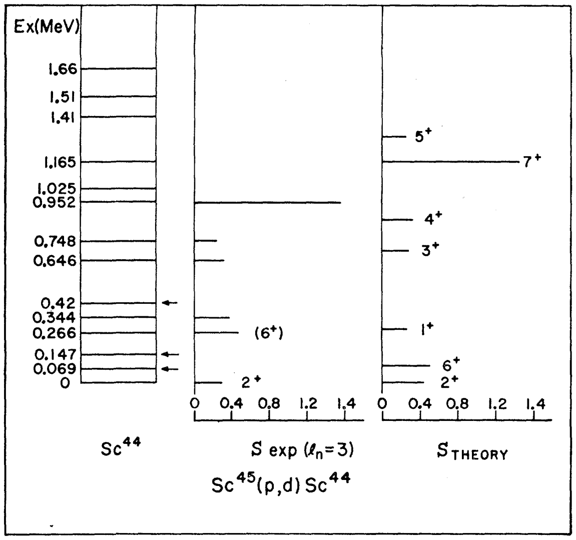

FIG. 6. Energy-level diagram for Sc^{44} and graphical comparison of the experimental results with the theoretical results of McCullen, Bayman, and Zamick for the $Sc^{45}(p,d)Sc^{44}$ reactions. The arrows indicate those levels not observed in the present investigation.

of the nucleon-nucleon interaction. This enables them, assuming pure $f_{7/2}$ configuration for the protons and neutrons, to calculate the expected energy level structure for Sc^{44} and, in addition, the spectroscopic factors for the transitions to these levels by the $Sc^{45}(p,d)Sc^{44}$ reaction. Their results are somewhat uncertain since the Sc^{42} energy-level structure is not completely known. A list of their calculated spectroscopic factors, energies, angular momenta, and parities for the levels is given in Table II for those levels predicted to show non-negligible (p,d) yields. Also listed in Table II are the ratios of the theoretical and experimental spectroscopic factors, assuming that the levels correspond to each other consecutively. A graphical comparison of theory and experiment is also shown in Fig. 6, together with an energy-level diagram of Sc^{44}. It is not clear at the present what spectroscopic information can be extracted from that comparison, although it is interesting to note that the large spectroscopic factor for the 7^+ level in the theoretical calculation remain over a wide range of assumption for the Sc^{42} spectrum. This would indicate a probable assignment of $J^\pi = 7^+$ for the 0.952-MeV level. This assignment could be checked to a certain extent by $(p,d\gamma)$ to ascertain whether the 0.952-MeV level decays exclusively to the 0.266-MeV level.

It is also of some interest to note that two known levels of Sc^{44} at 69 and 147 keV which are observed from γ rays following the β decay of Ti^{44} have not been excited to any degree in the (p,d) process. It is clear that they must belong to a configuration which is present in Sc^{45} only to a very small extent or that the transition was such that a $\Delta v = 3$ would be involved and would then be only very weakly excited in the present reaction.

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