(He^3,d) Reaction on the $N=28$ Nuclei*†

D. D. ARMSTRONG AND A. G. BLAIR
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received 22 July 1965)

A beam of 22-MeV He^3 ions from the Los Alamos variable-energy cyclotron was used to investigate the (He^3,d) reaction on Ca^{48}, V^{51}, Cr^{52}, and Fe^{54}. A semiconductor E-ΔE mass-identification detector system was employed. The use of a summing preamplifier for performing the coherent addition of the E and ΔE pulses allowed the energy resolution to be reduced to the inherent energy spread of the cyclotron beam, which is 100 to 120 keV. Levels or groups of levels were resolvable up to an excitation of 5 to 6 MeV for all the nuclei that were studied, and angular distributions were obtained for the deuterons corresponding to these levels. The T-SALLY distorted-wave calculation was used to extract spectroscopic information concerning the levels. The formalism developed by Macfarlane and French for the j-j coupling version of the nuclear shell model was used to assign the levels to the $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1g_{9/2}$ single-particle states. Estimates of the positions of the centroids for the $T=T_z$ component of these single-particle states were made. The seniority mixing of the two 4^+ states in Cr^{52} belonging to the $(f_{7/2})^4$ configuration was determined and compares favorably with the predictions made by Komoda.

I. INTRODUCTION

STUDIES of direct reactions have proved to be fruitful in obtaining information about nuclear energy levels and nuclear structure. The (d,p) stripping reaction and (d,t) pickup reaction have been utilized to amass a large amount of information concerning the single-particle (SP) neutron states of nuclei (see, for example, the summaries in Ref. 1). Much less is known about the SP proton states. Until very recently studies of proton levels by use of the appropriate stripping and pickup reactions were usually confined to the light-nuclei region, owing to either poor energy resolution or low available bombarding energy. In the past two or three years these limitations have, to a large extent, been removed, and the studies of proton stripping and pickup reactions have been extended to include the intermediate-weight nuclei region. In particular, the advent of high-resolution semiconductor detectors has permitted a significant improvement in energy resolution.

This paper reports the results of a study of the (He^3,d) reaction on Ca^{48}, V^{51}, Cr^{52}, and Fe^{54}, using a beam of 22-MeV He^3 ions from the Los Alamos variable-energy cyclotron. These nuclei are characterized by a closed (28) neutron shell and to good approximation can be considered spherical. Thus, the proton levels excited in the present study should be described well in terms of the j-j coupling version of the nuclear shell model; that is, the ground states of the residual nuclei should be $(1f_{7/2})^n$ configurations, and the excited states should be formed by populating, in order of increasing excitation energy, the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ SP states. Residual interactions fragment the SP strength and thus one expects to observe more than one level corresponding to each of the latter three SP states.

A partial angular distribution for each resolved deuteron group was obtained and was compared to the predictions of the distorted-wave (DW) calculation T-SALLY[2] to establish the l-transfer value for the captured proton and to obtain the desired spectroscopic information. The sum rules developed by Macfarlane and French[1,3] were then used to identify the components of the various SP states. In addition, the study of the $(1f_{7/2})^4$ states by the $V^{51}(He^3,d)Cr^{52}$ reaction yielded information concerning the seniority mixing of the 2^+ and 4^+ states of this configuration.

II. EXPERIMENTAL PROCEDURE

The beam geometry and basic construction of the scattering chamber have been reported earlier.[4] The detector assembly was of the type suitable for use in our $E=\Delta E$ particle identification system and consisted of a 500-μ gold surface barrier ΔE detector,[5] followed by a 3-mm gold surface barrier lithium-drifted E detector.[6] The detector assembly was thermoelectrically cooled[7] to approximately -15°C. A vertical slit aperture placed before the detector assembly resulted in an angular resolution of approximately 1° and a solid angle of approximately 7×10^{-4} sr for all runs. Preliminary runs evidenced an appreciable rate of deposition of carbon onto the targets, the origin of which was apparently untrapped vapors from the oil vacuum pumps and vapors from other sources of hydrocarbons such as O-rings and

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Based in part on a thesis presented by D. D. Armstrong to the University of New Mexico in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
[1] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. 32, 567 (1960).
[2] We are indebted to R. M. Drisko and R. H. Bassel for furnishing us with this program.
[3] J. B. French and M. H. Macfarlane, Nucl. Phys. 26, 168 (1961).
[4] H. E. Wegner and W. S. Hall, Phys. Rev. 119, 1654 (1960).
[5] Model RMEJ150-500, Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee.
[6] Model W-60-3SB, Technical Measurement Corporation, San Mateo, California; Catalog No. 100-LSBG-3000-1D, Solid State Radiations, Los Angeles, California.
[7] Type 814-J, Westinghouse, Semiconductor Division, Youngwood, Pennsylvania.

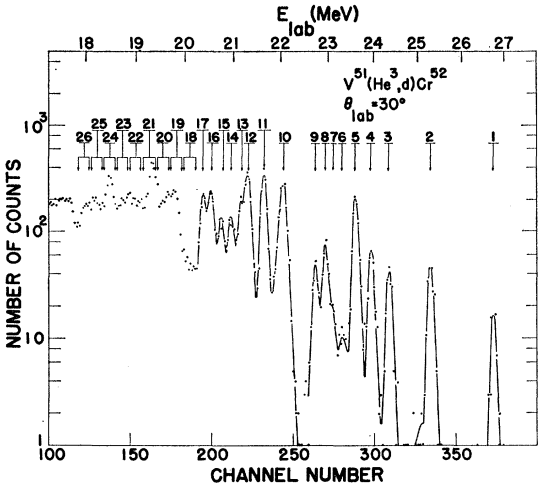

FIG. 1. Pulse-height spectrum of the deuterons from the $V^{51}(He^3,d)Cr^{52}$ reaction. The solid line represents the results of a least squares computer routine which fit a skewed Gaussian distribution with an exponential tail to each resolved peak in the pulse-height spectrum. The number indicated in the figure has been assigned to each deuteron group for ease of identification in the discussion in the text.

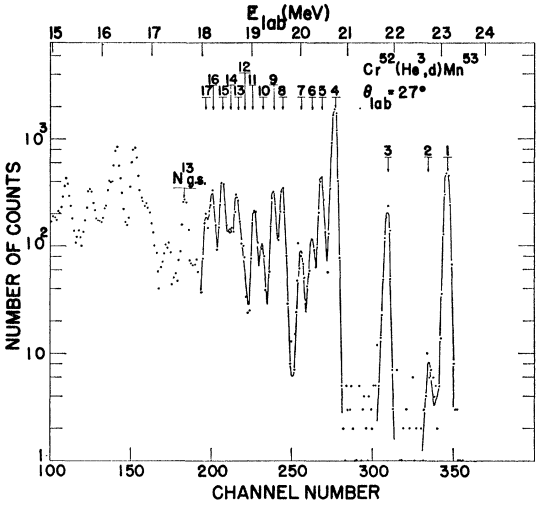

FIG. 2. Pulse-height spectrum of the deuterons from the $Cr^{52}(He^3,d)Mn^{53}$ reaction. See caption for Fig. 1.

their lubricants. A liquid-nitrogen-cooled baffle was installed in the scattering chamber; the rate of carbon deposition thereafter was negligible.

The electronic E-ΔE particle-identification system that was used has been discussed thoroughly in the literature.[8] However, prior to the present study a summing circuit which coherently adds the E and ΔE pulses was included in the basic system. Coherent addition has the important advantage of improving the energy-resolving capability of the system by eliminating the Landau energy spread introduced into the detected particles during their passage through the ΔE detector, and by eliminating the effect of the nonuniformity of the ΔE detector. Without the summing circuit the energy resolution was 300 to 400 keV (full width at half-maximum, fwhm); with it, the energy resolution was 100 to 120 keV (fwhm), the inherent energy spread of the cyclotron beam.

The particle-identification system was adjusted to generate gating pulses for only those $E+\Delta E$ pulses corresponding to deuterons. A gated 400-channel pulse-height analyzer was then used to display the pulse-height spectrum of the $E+\Delta E$ pulses. Pulse-height spectra were obtained for a suitable range of scattering angles. Each pulse-height spectrum was read out as information on punched paper tape and printed paper tape and was simultaneously plotted. The information on the punched tape was later transferred to punched cards suitable for use on the Los Alamos digital computers.

All the target foils were prepared from isotopically enriched materials[9] by evaporation. The Ca^{48} was evaporated onto a Mg^{24} backing and the Fe^{54} onto a gold backing, while the Cr^{52} and V^{51} targets were unbacked. The various foils ranged in areal density from 170 $\mu g/cm^2$ to 540 $\mu g/cm^2$.

The He^3 beam passing through the target was collected in a Faraday cup, and the total charge for each experimental run was integrated by means of a vibrating-reed electrometer current integrator.[10] The beam energy was determined and monitored by means of a slowing-down technique similar to that described by Northrop and Stokes.[11] In the present experiment,

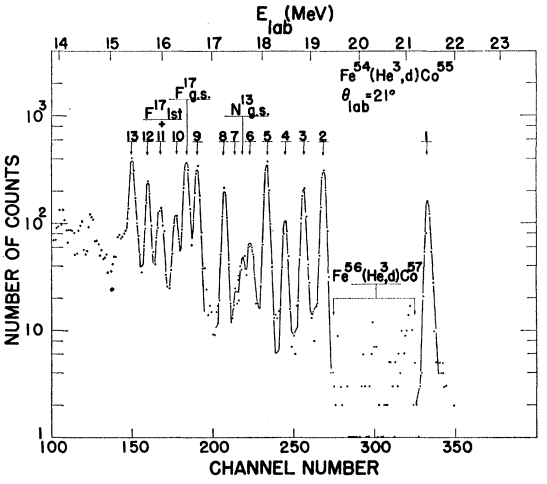

FIG. 3. Pulse-height spectrum of the deuterons from the $Fe^{54}(He^3,d)Co^{55}$ reaction. See caption for Fig. 1.

[8] R. H. Stokes, J. A. Northrop, and K. Boyer, Rev. Sci. Instr. **29**, 61 (1958); R. H. Stokes, *ibid.* **31**, 768 (1960).

[9] Oak Ridge National Laboratory, Isotope Division, Oak Ridge, Tennessee.

[10] R. J. Helmer and A. H. Hemmendinger, Rev. Sci. Instr. **28**, 649 (1957).

[11] J. A. Northrop and R. H. Stokes, Rev. Sci. Instr. **29**, 287 (1958).

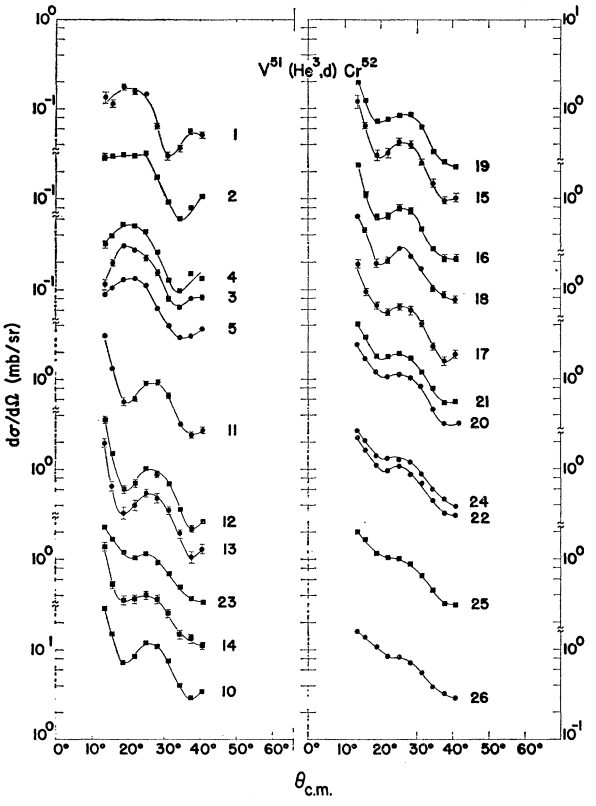

FIG. 4. Angular distributions of all but the weakest deuteron groups from the $V^{51}(He^3,d)Cr^{52}$ reaction, up to 8.7 MeV of excitation. The number assigned to each angular distribution corresponds to the group number of Fig. 1. The lines drawn through the data points are intended only as visual guides.

the error limit in the determination of the mean energy is estimated to be ± 200 keV. The variation of the beam energy at the center of a target was less than ± 50 keV over an entire angular distribution.

III. DATA REDUCTION

Typical pulse-height spectra of the deuterons from the (He^3,d) reaction on V^{51}, Cr^{52}, and Fe^{54} are shown in Figs. 1–3. The solid curve drawn through the data points is the result of a least-squares computer routine which fits a skewed Gaussian distribution with an exponential tail to each peak in the pulse-height spectrum and computes the area under each peak.[12] Each pulse-height spectrum was so analyzed and the differential cross section was computed by standard methods. Each deuteron group has been assigned the number indicated in the figure for ease of identification in the discussion that follows.

The deuteron spectrum from the 7% Fe^{56} in the Fe^{54} target overlapped the deuteron spectrum from the Fe^{54} and was a serious source of background. Therefore, pulse-height spectra for the $Fe^{56}(He^3,d)Co^{57}$ reaction were obtained by using a natural iron target. A channel-by-channel subtraction of the Fe^{56} data was satisfactory and was done prior to the area analysis of the peaks in the $Fe^{54}(He^3,d)Co^{55}$ pulse-height spectrum.

Equally serious complications of the study of the $Fe^{54}(He^3,d)$ reaction were the $C^{12}(He^3,d)N^{13}$ and $O^{16}(He^3,d)F^{17}$ reactions on the carbon and oxygen contaminants in the target. The deuteron groups corresponding to the ground state of N^{13} and the ground state and first excited state of F^{17} were the troublesome ones. Since the kinematic shift in the deuteron energy as a function of scattering angle is larger for light elements than for heavier elements, the positions of the contaminant groups relative to the groups from the $Fe^{54}(He^3,d)$ reaction were different for each scattering angle. At nearly every scattering angle one or more of the contaminant groups were not resolved from a group corresponding to an excited state of Co^{55}. For use in such instances, angular distributions for the deuteron groups from the (He^3,d) reaction on carbon and oxygen were obtained by using a Mylar film as a target. These angular distributions were then normalized to the Fe^{54} target data by comparison of the intensity of the contaminant groups, at those scattering angles for which they were resolved, with the intensity determined for them by using the Mylar film. Thus, satisfactory sub-

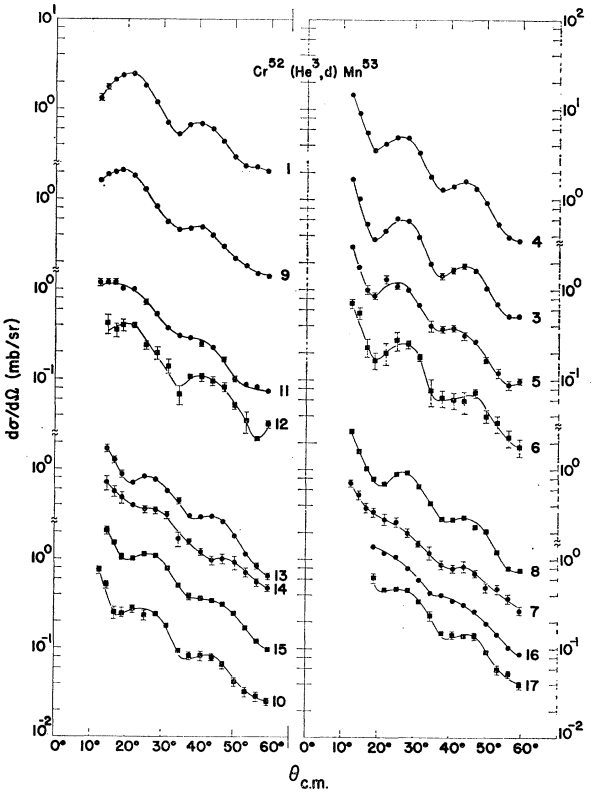

FIG. 5. Angular distributions of all but the weakest deuteron groups from the $Cr^{52}(He^3,d)Mn^{53}$ reaction, up to 5.1 MeV of excitation. See caption for Fig. 4.

[12] P. T. McWilliams, W. S. Hall, and H. E. Wegner, Rev. Sci. Instr. 33, 70 (1962); W. S. Hall (private communication).

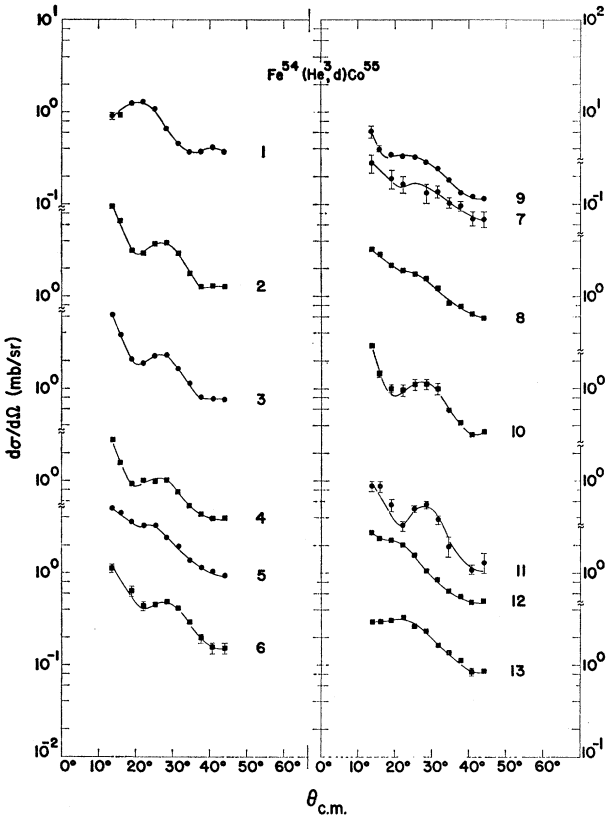

FIG. 6. Angular distributions of all but the weakest deuteron groups from the $Fe^{54}(He^3,d)Co^{55}$ reaction, up to 6.1 MeV of excitation. See caption for Fig. 4.

tractions of the contaminant groups were possible when they were not resolved.

Energy calibration of the deuteron spectra was accomplished by comparison with the well-known spectra from the (He^3,d) reaction on the isotopes $Ni^{58,60,62,64}$ in a natural nickel target, and on C^{12} which was present in all the targets. Excitation energies based on the ground-state Q values given in the Nuclear Data Tables[13] were calculated for the Cr^{52}, Mn^{53}, and Co^{55} excited states. The ground-state Q value reported by Erskine *et al.*[14] was used to calculate the excitation energies for the Sc^{49} states. For all possible comparisons, the excitation energies obtained in the present study agreed to within ± 25 keV with the excitation energies reported by other investigators.

The angular distributions obtained for the (He^3,d) reaction on V^{51}, Cr^{52}, and Fe^{54} are shown in Figs. 4–6. Each angular distribution is associated with the cross-section scale adjacent to its forward angle points. The error bars indicate, primarily, standard deviations; in some instances, however, the error bars include uncertainties introduced by contaminant subtractions. Points without error bars are in error by less than the size of the symbol used to plot them. The numbers correspond to the numbers assigned to the deuteron groups in the associated pulse-height spectra.

IV. SPECTROSCOPIC ANALYSIS

Since the ground states of the residual nuclei are expected to be formed by adding $1f_{7/2}$ protons to the target nuclei and the excited states by populating the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ SP states, the angular distributions are expected to be characteristic of an orbital angular momentum of either $l=1$ or $l=3$. Comparisons of the predictions of the DW calculation T-SALLY to typical angular distributions are shown in Fig. 7 and indicate that the distribution which has a maximum near 20° is characteristic for $l=3$ for the captured proton, while the distribution with a maximum near 25° is characteristic of $l=1$. The predictions of the DW calculation have been arbitrarily normalized to the data at the maximum near 20° for the $l=3$ distributions and at the maximum near 25° for the $l=1$ distributions. The optical-model parameters for the DW calculation were obtained from fits to elastic-scattering data. Those for the deuterons were from set B of the parameters published by Perey and Perey[15]; the He^3 parameters[16] are listed in Table I.

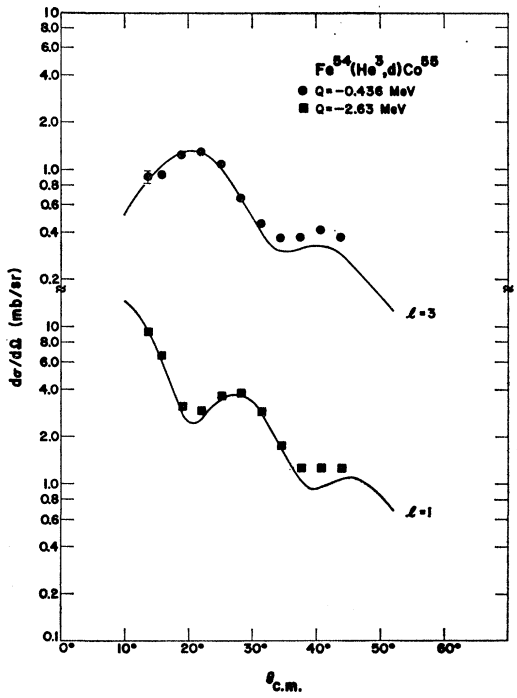

FIG. 7. Comparison of the predictions of the DW calculation to the angular distributions for group 1 ($Q=-0.436$ MeV) and group 2 ($Q=-2.63$ MeV) of Fig. 6.

[13] *Nuclear Data Tables*, Part I (National Academy of Sciences–National Research Council, Washington 25, D. C., 1961).

[14] J. R. Erskine, J. P. Schiffer, and A. Marinov, Bull. Am. Phys. Soc. **11**, 80 (1964).

[15] C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).

[16] R. H. Bassel, D. D. Armstrong, and A. G. Blair (to be published).

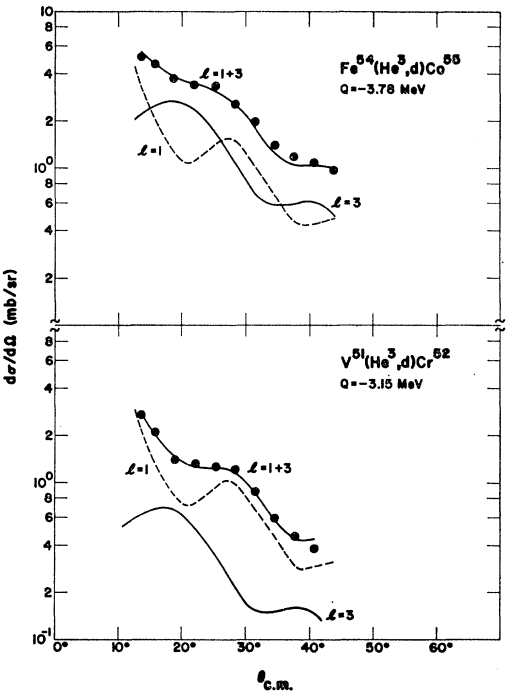

FIG. 8. Decomposition of the angular distributions for groups from the $Fe^{54}(He^3,d)Co^{55}$ reaction and the $V^{51}(He^3,d)Cr^{52}$ reaction into their $l=1$ and $l=3$ components.

The DW calculation employed a radial cutoff of 4.2 F. In the present study the use of the separation energy for the captured proton was found to be more appropriate than the prescription of using constant well depth to calculate the bound-state wave function.[17,18]

A few of the angular distributions in Fig. 2 seem to be characteristic of neither an $l=1$ nor $l=3$ angular momentum transfer. However, these were quite easily shown to be sums of $l=1$ and $l=3$ or $l=1$ and $l=4$ angular distributions. The fraction of each component in a composite angular distribution was determined by employing two computer routines.[19] The first routine was used to compute polynomial fits to typical experimentally determined $l=1$ and $l=3$ angular distributions, and to $l=4$ angular distributions predicted by the DW calculation. The second routine used these polynomials to compute a least squares fit to the composite angular distribution. The results of two such analyses are shown in Fig. 8. In all cases, the fraction of each component was determined to within $\pm 15\%$.

TABLE I. Optical-model parameters obtained for He^3 ions elastically scattered from the listed nuclei. Both the real and imaginary potential wells were of the Woods-Saxon type. These parameters were used in the DW calculations.

Isotope	V_0 (MeV)	r_{0R} (fermis)	a_R (fermis)	W (MeV)	r_{0I} (fermis)	a_I (fermis)
Ca^{40}	100.5	1.076	0.822	7.57	1.945	0.704
Ca^{48}	100.2	1.061	0.830	9.15	1.856	0.705
V^{51}	99.6	1.069	0.795	10.8	1.775	0.711
Cr^{52}	98.8	1.069	0.814	13.5	1.705	0.726
Fe^{54}	96.8	1.069	0.873	16.5	1.705	0.726
Fe^{56}	95.6	1.069	0.821	13.6	1.705	0.736

[17] R. Sherr, E. Rost, and B. Bayman, Bull. Am. Phys. Soc. **9**, 458 (1964); R. Sherr, E. Rost, and M. E. Rickey, Phys. Rev. Letters **12**, 420 (1964).
[18] A. G. Blair and D. D. Armstrong, Phys. Letters **16**, 57 (1965).

Although the l values for the capture protons are unambiguously determined by comparisons of the predictions of the DW calculation to the experimental data, the partial angular distributions obtained for the present study cannot be used to determine their total angular momentum j. Thus, a proton captured with an orbital angular momentum of l may be associated with either the SP state having $j=l+\frac{1}{2}$ or the one having $j=l-\frac{1}{2}$. The fact that the SP state with the largest j lies lowest in excitation can be very useful in making the proper associations; but when there is a multiplicity of levels associated with each SP state, additional criteria are needed. Studies of neutron SP states indicate that there is usually a grouping of the levels associated with each SP state and the half-width of the distribution of the levels is approximately one-third of the excitation energy for the centroid of the levels.[20] Such groups are not always apparent from a qualitative examination of the data, especially for p states which have a small spin-orbit splitting. Additional criteria are available in the form of sum rules, as developed by Macfarlane and French.[1,3] Application of the combined criteria provides a means of assigning probable j values to the levels, but some of these assignments, particularly in cases of weakly excited levels, are not certain.

To apply the formalism developed by Macfarlane and French, one notes that the measured differential cross section $(d\sigma/d\Omega)$ is related to the DW calculation predicted σ by

$$d\sigma/d\Omega = N[(2J_f+1)/(2J_0+1)]C^2S\sigma, \qquad (1)$$

where N is a normalization factor that includes the overlap of the wave function of the proton with the internal wave function of the deuteron in the He^3 nucleus, J_0 and J_f are the spins of the initial and final states, respectively, C is the isobaric spin Clebsch-Gordan coupling coefficient, and S is the spectroscopic (nuclear overlap) factor. The isobaric spin Clebsch-Gordan coefficient is included in Eq. (1) since a proton added to a neutron-rich nucleus in an orbit either empty of neutrons or partially filled with neutrons forms one of two final states which differ in their isobaric spin. The

[19] W. S. Hall (private communication).
[20] B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).

C^2 factors simply determine the way in which the total cross section divides between the states of different T.

The strength of a transition is ordinarily defined to be $[(2J_f+1)/(2J_0+1)]C^2S$. The total strength G associated with a given SP state is then the sum of the strengths for all the levels that are identified as fragments of that SP state. French and Macfarlane[3] have shown that for a proton stripping reaction

$$G=(N-Z+1)^{-1}\langle n\rangle_j, \quad \text{for} \quad T_f=T_0+\tfrac{1}{2}, \qquad (2)$$

and

$$G=\langle p\rangle_j-(N-Z+1)^{-1}\langle n\rangle_j, \quad \text{for} \quad T_f=T_0-\tfrac{1}{2}, \qquad (3)$$

where N and Z are the number of neutrons and protons, respectively, in the target nucleus, $\langle n\rangle_j$ and $\langle p\rangle_j$ are the average number of neutron holes and proton holes, respectively, in the j SP state in the target nucleus, and T_0 and T_f are the initial-state and final-state isobaric spin quantum numbers, respectively.

Equations (2) and (3) are particularly useful for odd-even target nuclei for which there is a multiplicity of J_f values for the fragments of any j SP state and for which the J_f value is in general not known. However, for an even-even target nucleus we have $J_0=0$ and $J_f=j$; in this case a more convenient way of writing (2) and (3), in which the isobaric spin splitting of the SP strength is indicated more clearly, is the following:

$$\sum C^2S=\frac{1}{(2j+1)(N-Z+1)}\langle n\rangle_j, \quad \text{for} \quad T_f=T_0+\tfrac{1}{2}, \qquad (4)$$

and

$$\sum C^2S=\frac{1}{(2j+1)}\left[\langle p\rangle_j-\frac{1}{N-Z+1}\langle n\rangle_j\right], \quad \text{for} \quad T_f=T_0-\tfrac{1}{2}. \qquad (5)$$

The sum rules (2), (3), (4), and (5) formed the basis for interpreting the data. The experimental values for the sums were determined from Eq. (1) by using the predictions of the DW calculation and making tentative assignments of the levels to the various SP states. Reassignments were made when necessary if it was reasonable to do so. In obtaining the experimental strengths, account has been taken of recent work which indicates that the cross section should depend upon the value of $\mathbf{l}\cdot\mathbf{s}$ of the captured proton; a dependence of $+22\%$ and -22% for $j=\frac{7}{2}$ and $\frac{5}{2}$, respectively, and $+10\%$ and -10% for $j=\frac{3}{2}$ and $\frac{1}{2}$, respectively, was used.[21]

Since for all the even-even target nuclei used in the present study there was no $l=3$ state strongly excited by the (He^3,d) reaction below 3 MeV of excitation, the ground state was assumed to contain all the $1f_{7/2}$ SP strength. The normalization factor N in Eq. (1) was primarily determined by the assumption that the ground state was a pure $1f_{7/2}$ configuration and secondarily by the total $1f_{7/2}$ and $1f_{5/2}$ SP strengths. A more consistent analysis of the data resulted from the use of a different normalization factor for each isotope; the value for N for all the present cases was within the limits of 3.7 ± 0.6. This value is consistent with the value obtained from a study at this Laboratory of the (He^3,d) reaction on the nickel isotopes[22] and is consistent with the value obtained by Bassel[23] from an analysis of the overlap of the internal wave function of the deuteron and the wave function of the proton in the He^3 nucleus. There is the possibility that some of the variation of N can be attributed to admixtures of other than $(1f_{7/2})^n$ configurations in the ground-state wave functions.

[21] G. R. Satchler (private communication).

TABLE II. Results from present study of the $Ca^{48}(He^3,d)Sc^{49}$ reaction.

Single-particle state	Group number	Excitation energy (MeV)	C^2S (experimental)	ΣC^2S (experimental)	ΣC^2S (predicted)
$1f_{7/2}$	1	g.s.	0.91	0.91	1.00
$1f_{5/2}$	3	3.86	0.15	1.11	0.89
	4	4.11	0.21		
	5	4.34	0.09		
	7	4.76	0.15		
	8	5.09	0.37		
	9	5.39	0.14		
$2p_{3/2}$	2	3.10	0.60	0.85	0.89
	6	4.51	0.25		
$2p_{1/2}$[a]	7	4.76	0.02	0.78	0.89
	8	5.09	0.07		
	10	5.69	0.27		
	11	5.83	0.08		
	b	5.9	0.04		
	b	6.3	0.05		
	b	6.6	0.11		
	b	6.9	0.14		

[a] Some of the groups assigned to this state may actually be $2p_{3/2}$ transitions.
[b] This group represents a summation over approximately 300 keV of unresolved states. The major component of its angular distribution appears to be $l=1$.

V. DISCUSSION OF SPECIFIC REACTIONS

A. $Ca^{48}(He^3,d)Sc^{49}$

The results of the study of this reaction were reported previously.[24] However, we have reanalyzed the data in terms of the predictions of the T-SALLY DW calculation, and the results of this analysis are included here for the

[22] A. G. Blair (to be published).
[23] R. H. Bassel (private communication).
[24] D. D. Armstrong and A. G. Blair, Phys. Letters **10**, 204 (1964).

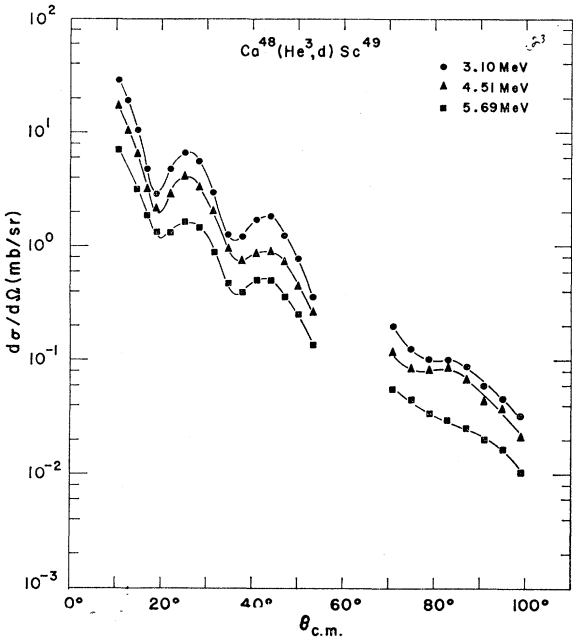

FIG. 9. Angular distributions for 3.10- and 4.51-MeV levels ($2p_{3/2}$) and the 5.69-MeV level ($2p_{1/2}$) excited by the (He^3,d) reaction on Ca^{48}. In the angular region from approximately 70° to 100° the distributions exhibit the difference in structure for $2p_{3/2}$ and $2p_{1/2}$ levels that was observed in the study of the (He^3,d) reaction on the nickel isotopes.

sake of completeness. (See Table II.) The present analysis yields no changes in the SP assignments, and yields values of C^2S differing by only a few percent from the earlier results. In the present analysis, however, there was no need to assume different normalization factors for each l value, as had previously been done. Furthermore, some of the angular distributions have been extended into the region from approximately 70° to 100°, a region in which the $2p_{3/2}$ and $2p_{1/2}$ angular distributions apparently show a j dependence effect. The supplemented angular distributions for the most strongly excited $l=1$ transitions, namely, to the 3.10-, 4.51-, and 5.69-MeV levels, are shown in Fig. 9. From the figure it is evident that the distributions for the 3.10- and 4.51-MeV levels exhibit similar structure in this angular range but that the distribution for the 5.69-MeV level is different. The structure of the angular distributions is similar to that observed in the angular distributions obtained from a study of the (He^3,d) reaction on those nickel isotopes[22] which excited levels that were known to be $2p_{3/2}$ and $2p_{1/2}$. The angular distributions are consistent with the assignment of the 3.10- and 4.51-MeV levels to the $2p_{3/2}$ SP state and, with less assurance, the 5.69-MeV level to the $2p_{1/2}$ SP state.

B. $V^{51}(He^3,d)Cr^{52}$

The nucleus Cr^{52} has four protons outside closed shells of 20 protons and 28 neutrons. The low excited states are expected to be simply described in terms of the various $(f_{7/2})^4$ configurations. From such configurations one would expect to observe the following states: a 0^+ ground state with seniority $v=0$ (no unpaired protons), 2^+, 4^+, and 6^+ excited states with $v=2$ (2 unpaired protons), and 2^+, 4^+, 5^+, and 8^+ excited states with $v=4$ (4 unpaired protons). These levels have been studied extensively both theoretically[25,26] and experimentally.[27–29] $Cr^{52}(n,n'\gamma)$ reaction studies[27] and studies[28] of the γ decay following the beta decay of Mn^{52} have been used to assign spins and parities of 2^+, 4^+, 4^+, and 6^+ to the levels at 1.434, 2.370, 2.766, and 3.112 MeV, respectively.

The values of C^2S for the $1f_{7/2}$ transitions are listed in Table III. The correspondence of the excitation energies for groups 2, 3, 4, and 5 to those reported for the 2^+, 4^+, 4^+, and 6^+ levels, respectively, was used to assign the spins and parities of these groups. The experimental values of $C^2S=1.31$ for the summed strength for the 4^+ levels and $C^2S=1.31$ for the 6^+ level are in good agreement with the predicted value of 1.33. The value of C^2S of 1.08 for the 2^+ level is, however, 20% smaller than predicted, indicating that like the 4^+ component the 2^+ component could be divided between two or more levels. The only other candidates for another 2^+ level are the weakly excited levels corresponding to groups 6, 7, and 9. Unfortunately, interference of deuterons from the (He^3,d) reaction on a contaminant in the target made it impossible to obtain unambiguous angular distributions for these groups.

The $1f_{5/2}$ SP strength is distributed over a large number of levels and is located in a region of excitation in which single levels or groups of 2 or 3 levels could not be resolved. In addition, some of the levels in this region are components of the $2p_{3/2}$ or $2p_{1/2}$ SP states. Groups 19 through 26 represent sums over approximately 300 keV of these unresolved levels. The angular distributions for

TABLE III. Results for the $1f_{7/2}$ SP state from the present study of the $V^{51}(He^3,d)Cr^{52}$ reaction.

Single-particle state	Group number	Excitation energy (MeV)	J^π	C^2S (experimental)	ΣC^2S (experimental)	ΣC^2S (predicted)
$1f_{7/2}$	1	g.s.	0^+	4.00	4.00	4.00
	2	1.434	2^+	1.08	1.08	1.33
	3	2.370	4^+	0.51	1.31	1.33
	4	2.766	4^+	0.81		
	5	3.112	6^+	1.31	1.31	1.33

[25] I. Talmi, Phys. Rev. **126**, 1096 (1962).
[26] T. Komoda, Nucl. Phys. **51**, 234 (1964).
[27] D. M. Van Patter, N. Nath, S. M. Shafroth, S. S. Malik, and M. A. Rothman, Phys. Rev. **128**, 1246 (1962).
[28] R. R. Wilson, A. A. Bartlett, J. J. Kraushaar, J. D. McCullen, and R. A. Ristinen, Phys. Rev. **125**, 1655 (1962).
[29] T. Katoh, M. Nozawa, Y. Yoshizawa, and Y. Koh, J. Phys. Soc. Japan **15**, 2140 (1960).

TABLE IV. Results for the $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ SP states from the present study of the $V^{51}(He^3,d)Cr^{52}$ reaction. The assignment of each group having an $l=1$ distribution to the $2p_{3/2}$ or $2p_{1/2}$SP state is made according to the criteria discussed in the text, and cannot be considered definite.

Single-particle state	Group number	Excitation energy (MeV)	$\frac{2J_f+1}{2J_0+1}C^2S$ (experimental)	$\sum\frac{2J_f+1}{2J_0+1}C^2S$ (experimental)	$\sum\frac{2J_f+1}{2J_0+1}C^2S$ (predicted)
$1f_{5/2}$[a]	19	6.8	0.09	3.85	5.00
	20	7.1	0.44		
	21	7.4	0.86		
	22	7.6	0.41		
	23	7.9	0.49		
	24	8.2	0.56		
	25	8.4	0.52		
	26	8.7	0.48		
$2p_{3/2}$	8	3.78	0.11	2.92	3.33
	10	4.67	0.48		
	11	5.09	0.38		
	12	5.42	0.35		
	13	5.57	0.18		
	14	5.77	0.13		
	15	5.96	0.15		
	16	6.18	0.26		
	17	6.34	0.21		
	18	6.60	0.09		
	19[a]	6.8	0.28		
	20[a]	7.1	0.30		
$2p_{1/2}$[a]	21	7.4	0.57	1.99	1.67
	22	7.6	0.31		
	23	7.9	0.30		
	24	8.2	0.37		
	25	8.4	0.25		
	26	8.7	0.17		

[a] These groups represent summations over approximately 300 keV of unresolved levels.

these deuteron groups were composites of $l=1$ and $l=3$ angular distributions. The method discussed previously was used to decompose each angular distribution into its components. The strengths for the $1f_{5/2}$ components are listed in Table IV. The excitation energies listed for these groups of unresolved levels are the mean energies. The comparison of the experimental and theoretical strengths shows that not all of the $1f_{5/2}$ strength was observed. The procedure of summing groups of levels could not be extended to higher excitation because of the interference of deuterons from the (He^3,d) reaction on the C^{12} contaminant in the target.

To illustrate the difficulty encountered in attempts to assign the $l=1$ groups to SP states, a very crude assignment of these groups to the $2p_{3/2}$ and $2p_{1/2}$ SP states is given in Table IV. The agreement of the experimental and theoretical strengths is very good. However, the centroids for the $2p_{3/2}$ and $2p_{1/2}$ SP strengths are approximately 5.5 and 7.5 MeV, respectively, and the rule that the half-width of the distribution of the levels is one-third the excitation energy for the centroid indicates that in the region of 5 to 7.3 MeV of excitation the components of the $2p_{3/2}$ and $2p_{1/2}$ SP states are intermingled. The methods of the present study cannot be used to separate them. To make meaningful assignments of the $l=1$ levels to these SP states, an experiment that is capable of determining the j of the captured proton will be necessary.

A further interpretation of the strengths of the $1f_{7/2}$ transitions is possible in terms of the seniorities of the 2^+ and 4^+ states. As was indicated earlier in this section, states of the $(f_{7/2})^4$ configuration with $\nu=2$ and $\nu=4$ are allowed for both the 2^+ and 4^+ states of Cr^{52}. Talmi[25] predicts that the $\nu=4$, 4^+ state lies lower in excitation than the $\nu=2$, 4^+ state, but concludes that the experimental information[27,28] indicates that the seniorities of these two states may be mixed. The uncertainties in his method of estimating the magnitude of the mixing and the fact that no $4^+\rightarrow 4^+$ γ transition was observed in the work of Wilson *et al.*[28] prevented him from drawing any definite conclusions concerning the magnitude of the seniority mixing. Considering all possible configurations of 4 protons in $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ SP states, Komoda[26] has calculated the expected mixing on the basis that the only important interactions were two-body interactions of either the Serber type or Rosenfeld type. The lower 4^+ state is predicted to be primarily $\nu=2$ for a Rosenfeld interaction and primarily $\nu=4$ for a Serber interaction.The $V^{51}(He^3,d)Cr^{52}$ reaction can be used to determine the mixing since the ground state of V^{51} is a unique $\nu=1$ state and the seniority selection rule for this reaction is $\Delta\nu=1$. Thus, one can excite only those $(1f_{7/2})^4$ states of Cr^{52} with either $\nu=0$ or $\nu=2$. Since both 4^+ states are observed in this study, it is clear that the strength for each of these states is a measure of its $\nu=2$ component. The experimental ratio of C^2S for the $\nu=2$ component of the lower 4^+ state to that for the higher state is 0.62, which agrees well with Komoda's value of 0.63 for a range parameter of 1.1 for the Serber interaction. However, Komoda predicts that, as a result of the configuration interaction, approximately 20% of the $\nu=2$ strength should be found in still other 4^+ states. A comparison of the experimental and theoretical values of $\sum C^2S$ (see Table III) does not indicate such a reduction in the strength of the two 4^+ states. The experimental sum could be in error as much as $\pm 10\%$ which could account for some disagreement. Also, to the extent that the configuration responsible for the mixing is $[(1f_{7/2})^3{}_{J=7/2}(1f_{5/2})]_{J=4}$, the strength would be in error by an amount corresponding to the amplitude of this component in the wave functions of the 4^+ states, since the transfer of a $1f_{7/2}$ proton cannot be distinguished from the transfer of a $1f_{5/2}$ proton by present study methods. Komoda has not published the amplitudes for each component of the wave functions of the 4^+ states, so no definite conclusions can be reached concerning the magnitude of this error. Neither of these considerations would affect the ratio obtained for the $\nu=2$ components seriously; therefore, the agreement with Komoda's predictions can be considered as good.

TABLE V. Results from the present study of the $Cr^{52}(He^3,d)Mn^{53}$ reaction.

Single-particle state	Group number	Excitation energy (MeV)	C^2S (experimental)	ΣC^2S (experimental)	ΣC^2S (predicted)
$1f_{7/2}$	1	g.s.	0.47	0.47	0.50
$1f_{5/2}$	7	3.10	0.04	0.86	0.80
	9	3.67	0.39		
	11	4.06	0.17		
	12	4.29	0.07		
	14	4.57	0.04		
	16	4.96	0.15		
$2p_{3/2}$	3	1.29	0.07	0.76	0.80
	4	2.40	0.45		
	5	2.66	0.09		
	6	2.88	0.02		
	7	3.10	0.02		
	8	3.47	0.07		
	10	3.90	0.02		
$2p_{1/2}$	11	4.06	0.03	0.57	0.80
	13	4.43	0.14		
	14	4.57	0.05		
	15	4.74	0.20		
	16	4.96	0.07		
	17	5.08	0.08		

Seniority mixing of the 2^+ states is also possible. Wilson *et al.*[28] have reported a level at 2.965 MeV which they tentatively identify as the $\nu=4$, 2^+ state. This level is not observed for the $V^{51}(He^3,d)$ reaction, in agreement with Komoda's prediction that less than 0.1% of the strength of the $\nu=2$, 2^+ state is mixed with the $\nu=4$, 2^+ state; this prediction is based on the assumption of a Serber-type interaction with a range parameter of 1.1. Komoda also predicts that approximately 23% of the $\nu=2$, $J^\pi=2^+$ strength is contained in other 2^+ states which are not predominantly $(f_{7/2})^4$ configurations, in good agreement with the difference in the experimental and theoretical values for C^2S of 20% in Table III. Van Patter *et al.*[27] have argued that the 2.965-MeV level is a collective state and that the $\nu=4$, 2^+ level lies higher in excitation. The results of the present study cannot answer this question.

A level at 3.80 MeV has been tentatively identified as a 5^+ or 6^+ level.[27,28] If the 3.78-MeV level of the present study corresponds to this 3.80-MeV level, the $l=1$ angular distribution for the deuterons from this level would prohibit the 6^+ assignment and would be compatible with the 5^+ assignment.

C. $Cr^{52}(He^3,d)Mn^{53}$

Very little is known about the levels of Mn^{53} from previous work. The ground-state spin and parity have been established as $\frac{7}{2}^-$, the spin and parity of the 0.383-MeV level are in doubt, and no spin assignments have been made for the 1.298- and 2.275-MeV levels.[30] Of these levels, that at 2.275 MeV was not observed in the present study. The 0.383-MeV level was very weakly excited and no new information about its properties was obtained from the present study; however, the probable spins and parities of the 1.298-MeV level and of several additional levels were determined.

The assignments of the observed levels to SP states, their excitation energies, and their values of C^2S are listed in Table V. The agreement of the theoretical and experimental values for the $1f_{5/2}$ and $2p_{3/2}$ SP states is good. The comparison of the values for the $2p_{1/2}$ SP state indicates that not all of the components of this state were observed.

D. $Fe^{54}(He^3,d)Co^{55}$

At the time the present study was initiated, no information concerning the excited levels of Co^{55} had been reported in the literature. However, during the progress of this study, three levels at 1.8, 2.2, and 2.45 MeV (all ± 0.2 MeV) were reported by Kumabe *et al.*[31] from a study of the $Ni^{58}(p,\alpha)Co^{55}$ reaction. Also, preliminary results of the study of the $Fe^{54}(d,n)Co^{55}$ reaction were reported, indicating levels at 2.15, 2.55, 2.92, 3.55, and 4.15 MeV (all ± 0.05 MeV).[32] On the

TABLE VI. Results for the $T_f=\frac{1}{2}$ states from the present study of the $Fe^{54}(He^3,d)Co^{55}$ reaction.

Single-particle state	Group number	Excitation energy (MeV)	C^2S (experimental)	ΣC^2S (experimental)	ΣC^2S (predicted)
$1f_{7/2}$	1	g.s.	0.22	0.22	0.25
$1f_{5/2}$	5	3.34	0.54	0.74	0.67
	8	4.18	0.20		
$2p_{3/2}$	2	2.19	0.35	0.67	0.67
	3	2.59	0.21		
	5	3.34	0.11		
$2p_{1/2}$	4	2.98	0.22	0.56	0.67
	6	3.67	0.11		
	7	3.92	0.03		
	8	4.18	0.08		
	11	5.53	0.12		
$1g_{9/2}$	9	4.71	0.11	0.27	0.67
	13	6.01	0.16		

[30] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1961), NRC 60-4-27.

[31] S. Kumabe, H. Ogata, T. Kamatuzaki, N. Inone, S. Tonita, Y. Yamada, and S. Matsumoto, Nucl. Phys. **46**, 437 (1963).

[32] D. S. Gemmell, L. L. Lee, Jr., J. P. Schiffer, and A. B. Smith, *Nuclear Spectroscopy with Direct Reactions I. Contributed Papers* (Argonne National Laboratory, Argonne, Illinois), ANL-6848.

TABLE VII. Results for the $T_f=\frac{3}{2}$ states from the present study of the $Fe^{54}(He^3,d)Co^{55}$ reaction.

Single-particle state	Group number	Excitation energy (MeV)	C^2S (experimental)	C^2S (expected)
$1f_{5/2}$	12	5.72	0.27	0.20[a]
	13	6.01	0.02	0.02[a]
$2p_{3/2}$	9	4.71	0.22	0.27[a]
$2p_{1/2}$	10	5.14	0.26	0.20[a]

[a] This value is based on the results of the study of the $Fe^{54}(d,p)Fe^{55}$ reaction by Fulmer *et al.* (Ref. 33).

basis of the results of the study of the $Fe^{54}(d,n)$ reaction, the captured proton was definitely assigned a value of $l=1$ for both the 2.15- and 2.55-MeV levels and tentative l values of 1, 3, and 1 for the 2.92-, 3.55-, and 4.15-MeV levels, respectively.[32] The level at 1.8 MeV was not excited by either the (d,n) reaction or by the (He^3,d) reaction of the present study. The results of the present study confirm the l assignments for the 2.15-, 2.55-, and 2.92-MeV states and indicate that the 4.15-MeV state is an unresolved group of levels. Several other levels were observed and were assigned probable spins and parities. The summary of the results of the present study of Co^{55} is given in Tables VI and VII. Since both $T_f=\frac{1}{2}$ and $T_f=\frac{3}{2}$ components of the $2p_{3/2}$ and $1f_{5/2}$ SP states were observed, the SP states are indexed as to the total isobaric spin associated with each component.

Except for the 3.55-MeV level, the excitation energies obtained for the levels observed in the study of the $Fe^{54}(d,n)$ reaction are in agreement to within experimental error with those obtained in the present study. We would like to indicate a possible correspondence between the 3.55-MeV level and the 3.67-MeV level (group 6), but this seems unlikely especially since the 3.55-MeV level was tentatively identified as an $l=3$ level and we found the 3.67-MeV level to be an $l=1$ level. The agreement of the predicted and experimental strengths is, in general, good for all the SP states. Further, the distribution of the levels in the $T_f=\frac{1}{2}$ components of the SP states is in agreement with the rule for estimating the width of the distribution. Not all of the $1g_{9/2}$ SP strength was observed because the levels were not resolvable at excitations greater than that for group 13. The $T_f=\frac{3}{2}$ levels which we have reported earlier[18] are the isobaric analogs of the low-lying Fe^{55} levels. The predicted values of C^2S for the $T_f=\frac{3}{2}$ components are given for each level and are based on the results of studies of the $Fe^{54}(d,p)Fe^{55}$ reaction.[33]

[33] R. H. Fulmer, A. L. McCarthy, B. L. Cohen, and R. Middleton, Phys. Rev. **133**, B955 (1964).

VI. SUMMARY

The centroid for the levels associated with the $T_f=T_z$ component of each SP state is listed in Table VIII and is based on the strengths and SP state assignments in Tables II-VII. A comparison of the centroids for the SP states in Sc^{49} with the centroids for the neutron SP states in Ca^{41} is useful in understanding the similarities and differences of the neutron SP structure and proton SP structure of nuclei in this portion of the periodic table. Therefore, the results of the study of the $Ca^{40}(d,p)Ca^{41}$ reaction by Belote *et al.*[34] are also included in Table VIII. The comparison of the results for Sc^{49} with those for Ca^{41} is difficult because only the $T_f=\frac{7}{2}$ component of each proton SP state was observed for Sc^{49} and because the centroid determined by including the $T_f=\frac{9}{2}$ component of the SP state (that is, the centroid for the unperturbed SP state) is the pertinent one for the purpose of the comparison. The $T_f=\frac{9}{2}$ states in Sc^{49} are, of course, the isobaric analogs of the Ca^{49} states. The position of the Ca^{49} ground state analog in Sc^{49} can be estimated by using the (p,n) reaction Q values for the ground state analogs reported by Anderson, Wong, and McClure,[35] and the results of the study of the $Ca^{48}(d,p)Ca^{49}$ reaction[34] can then be used to determine the approximate positions of the other $T_f=\frac{9}{2}$ levels in Sc^{49}. From such an analysis the centroids of the $T_f=\frac{9}{2}$ components of the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ SP states are at excitations of approximately 11, 13, and 15 MeV, respectively. The excitations for the centroids of the unperturbed $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ SP states in Sc^{49} are then calculated to be 4.4, 5.7, and 6.9 MeV, respectively.

Based on the position of the unperturbed centroids, the spin-orbit splitting of the $1f_{7/2}$ and $1f_{5/2}$ proton SP states in Sc^{49} is 5.7 MeV which compares closely to the

TABLE VIII. Location of the centroid for each proton single-particle (SP) state that was determined in the present study. The location of the centroids for the similar neutron SP states in Ca^{41} are included for the comparisons that are discussed in the text.

Single-particle state ($T_f=T_z$)	Excitation energy for the centroids of the SP states (MeV) Sc^{49}	Cr^{52}	Mn^{53}	Co^{55}	Ca^{41}
$1f_{7/2}$	0	1.15	0	0	0[a]
$2p_{3/2}$	3.55	5.6	2.49	2.43	2.08[a]
$2p_{1/2}$	5.9	7.8	4.7	3.96	4.12[a]
$1f_{5/2}$	4.70	7.9	4.01	3.58	5.50[a]

[a] This is the excitation energy for the centroid of this neutron SP state in Ca^{41}. This value was reported by Belote *et al.* (Ref. 34) from their study of the $Ca^{40}(d,p)Ca^{41}$ reaction.

[34] T. A. Belote, E. Kashy, A. Sperduto, H. A. Enge, and W. W. Buechner, *Nuclear Spectroscopy with Direct Reactions I. Contributed Papers* (Argonne National Laboratory, Argonne, Illinois), ANL-6848.

[35] J. D. Anderson, C. Wong, and J. W. McClure, Phys. Rev. **126**, 2170 (1962).

value of 5.50 MeV for the similar neutron SP states in Ca^{41}. Similarly, the 2.5-MeV spin-orbit splitting of the $2p_{3/2}$ and $2p_{1/2}$ proton SP states, and the 2.04-MeV splitting of the neutron SP states are nearly the same. In this respect, there appears to be little difference between the proton and neutron SP structure for these nuclei. However, one also notes that the sequence of the $2p_{1/2}$ and $1f_{5/2}$ states is interchanged for the proton SP states. Such an interchange can be understood on the basis of the self-binding effect which has been discussed in the literature for neutron SP states.[36] On this basis, the $1f_{7/2}$ and $1f_{5/2}$ proton SP states in Sc^{49} would be expected to be lowered in excitation with respect to the $2p_{3/2}$ and $2p_{1/2}$ proton SP states, since the $1f_{7/2}$ neutron SP state is filled for Sc^{49}. Comparison of the relative positions of the centroids of the $1f$ and $2p$ proton SP states in Sc^{49} with the similar neutron SP states in Ca^{41} indicates a lowering of the $1f$ states of approximately 2.4 MeV. Another pertinent comparison would be between the $1f$ and $2p$ proton states in Sc^{49} and the same states in Sc^{41}. However, the information that exists in the literature for the Sc^{41} levels is not sufficiently detailed to be very useful.

Cohen has found that the self-binding effect is evidenced but is much smaller for neutron-neutron interactions.[36] The results of the present study can be used to investigate the self-binding effect for proton-proton interactions through a comparison of the centroids of the unperturbed $1f$ and $2p$ states in Sc^{49} with those in Co^{55} to observe the effect of partially filling the $1f_{7/2}$ proton SP state. Based on the same assumptions that were used in calculating the centroids for the unperturbed SP states in Sc^{49}, the unperturbed $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ proton SP states in Co^{55} are at excitations of 4.0, 4.6, and 5.8 MeV, respectively. This results in the $1f$ centroid being 2.6 MeV below the $2p$ centroid in Co^{55}, compared to 2.8 MeV in Sc^{49}. Thus, the self-binding effect for proton-proton interactions is at most very small.

[36] B. L. Cohen, Phys. Rev. **130**, 227 (1963).

ACKNOWLEDGMENTS

The authors would like to thank Dr. R. H. Bassel who analyzed our He^3 elastic-scattering data and who furnished us with the optical-model parameters for He^3 ions that were used in the distorted-wave calculation. We are indebted to Dr. G. R. Satchler for valuable discussion and correspondence. We also wish to thank Judith C. Gursky and Larry Allen of this Laboratory who devoted much time and effort to the fabrication of the target foils. The assistance of W. S. Hall in modifying the various computer programs is gratefully acknowledged.