PHYSICAL REVIEW VOLUME 134, NUMBER 4B 25 MAY 1964

(p,d) Reactions on Nuclei from V to Ni†

J. C. Legg* and E. Rost
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 8 January 1964)

Pickup (p,d) reactions on V^{51}, Cr^{52}, Mn^{55}, Fe^{54}, Fe^{56}, Fe^{57}, Fe^{58}, Co^{59}, Ni^{58}, and Ni^{60} have been studied using 17.0- and 18.5-MeV protons. The experimental results were analyzed using the predictions of a direct-reaction model using distorted waves. The distorted-wave theory predicted quite accurately the dependence of cross section on bombarding energy, while the plane wave theory failed in that respect. The ground states of V^{51}, Cr^{52}, and Fe^{54} were found to have almost pure $(1f_{7/2})^8$ neutron configurations, thus furnishing more evidence that the $1f_{7/2}$ neutron shell is a major shell. The results for the heavier nuclei indicate a strong mixing of $1f_{5/2}$ and $2p$ neutrons in the ground state. The spin assignments obtained for a few levels are in disagreement with γ-ray angular correlation measurements.

INTRODUCTION

Experience with (p,d) and (d,t) reactions on light nuclei has shown that these reactions are useful for determining configuration of the target nucleus and in certain cases the neutron configuration of states in the final nucleus. Consequently, there has been considerable interest in studying these reactions on heavier targets.[1–3] In the region with $A\sim55$, neutrons are filling both the $2p_{3/2}$ and $1f_{5/2}$ shells and experimental measurements of the neutron configurations are therefore of great interest.

However, the analysis of pickup reactions in this mass region is more complicated than for light nuclei. Distortions are quite important in this mass region so that a simple Butler analysis of the experimental results is too inaccurate. A distorted wave (DW) analysis is an improvement for such reactions but some care is necessary to insure consistency in the extracted results. At the present time the absolute cross sections predicted by the DW theory are uncertain by a factor of about two. The relative cross sections, however, are believed to be much better.

This paper presents the results of (p,d) experiments on V^{51}, Cr^{52}, Fe^{54}, Mn^{55}, Fe^{56}, Fe^{57}, Fe^{58}, Co^{59}, Ni^{58}, and Ni^{60}. The angular distributions of the deuterons observed show shapes characteristic of $l=1$ or $l=3$ stripping (pickup) curves. No attempt was made to obtain an optimum DW fit to any of the experiments because of experimental uncertainties. Instead, reasonable optical potentials were chosen *a priori* and used in the DW predictions. Thus, the DW curves used in this work are predictions and are not fits. However, comparison of the DW predictions with the results of these experiments and with the results of the (p,d) experiments performed at a proton bombarding energy[2] of 22 MeV indicates that these predictions reproduce the energy variation of these reactions quite well in contrast to the Butler theory. This suggests that ratios of spectroscopic factors obtained from these calculations are much more reliable than those obtained using the Butler theory to analyze the data.

EXPERIMENTAL METHODS

The experiment was performed in a 60-in. scattering chamber using 17.0- and 18.5-MeV protons from the

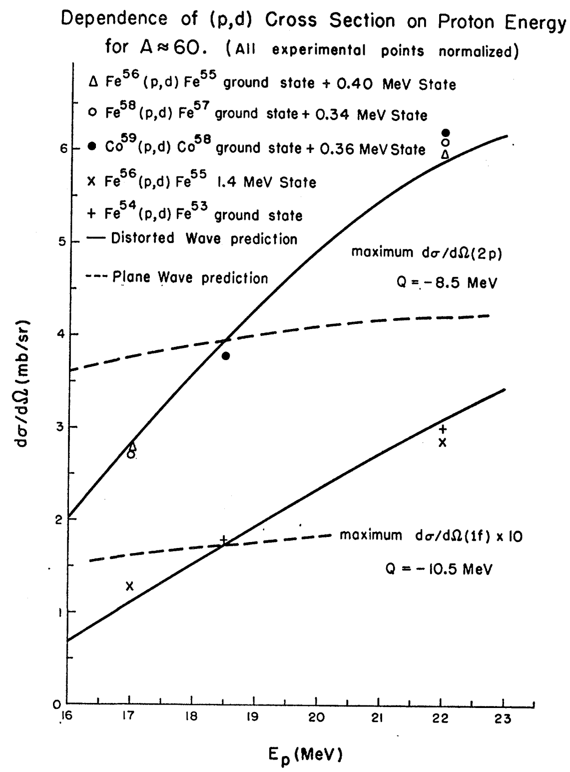

FIG. 1. DW predictions for $1f$ and $2p$ neutron pickup at proton energies between 16 and 23 MeV. Each pair of experimental cross sections shown was arbitrarily normalized to the DW predictions at 22 MeV. The dashed curves are plane wave predictions arbitrarily normalized at 18.5 MeV.

† This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.
* Present address: Department of Physics, Rice University, Houston, Texas.
[1] B. Zeidman, J. L. Yntema, and B. J. Raz, Phys. Rev. **120**, 1723 (1960).
[2] C. D. Goodman, J. B. Ball, and C. B. Fulmer, Phys. Rev. **127**, 574 (1962).
[3] M. H. Macfarlane, B. J. Raz, J. L. Yntema, and B. Zeidman, Phys. Rev. **127**, 204 (1962).
[4] G. Schrank, Rev. Sci. Instr. **26**, 677 (1955).
[5] J. C. Legg, Phys. Rev. **129**, 272 (1963).

Princeton variable-energy cyclotron. The proton beam energy was calibrated and stabilized by making use of an end-point ionization detector described by Schrank.[4]

The detection system was similar to that described previously.[5] Thin metallic foils of Cr, Mn, V, and Co rolled from high-purity metals of natural isotopic abundance were used as targets. All other targets were thin metallic foils which had been enriched in the desired isotope by the Stable Isotope Division of ORNL or by the Electromagnetic Separation Group of Harwell. The energy resolution of the detection system was on the order of 45 keV and almost all of the peak width seen in the energy spectra is caused by the cyclotron beam energy spread. This energy spread varied from day to day between 100 and 180 keV.

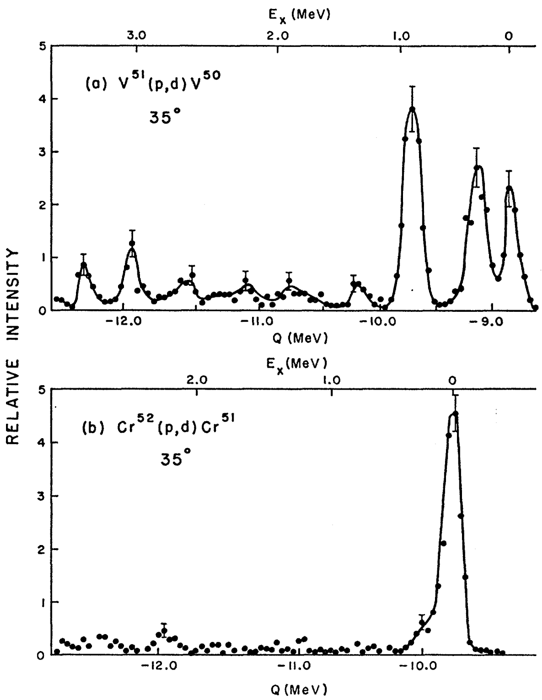

FIG. 2. Deuteron spectra obtained at 35° from (a) $V^{51}(p,d)V^{50}$ and (b) $Cr^{52}(p,d)Cr^{51}$.

The detection system was energy calibrated by comparing the $F^{19}(p,d)F^{18}$, $B^{11}(p,d)B^{10}$, and $O^{18}(p,d)O^{17}$ reactions with standard Q-value tables. In general, the measured ground-state Q values for nuclei with $A\sim 55$ agreed reasonably well with the accepted Q values. The only exception to this agreement is in the $Ni^{58}(p,d)Ni^{57}$ reaction. Here the Q value from mass tables was -9.700 MeV,[6] whereas the measured Q value was -9.98 ± 0.05 MeV.

The identification of states or groups of states was in most cases quite straightforward, except for V^{51},

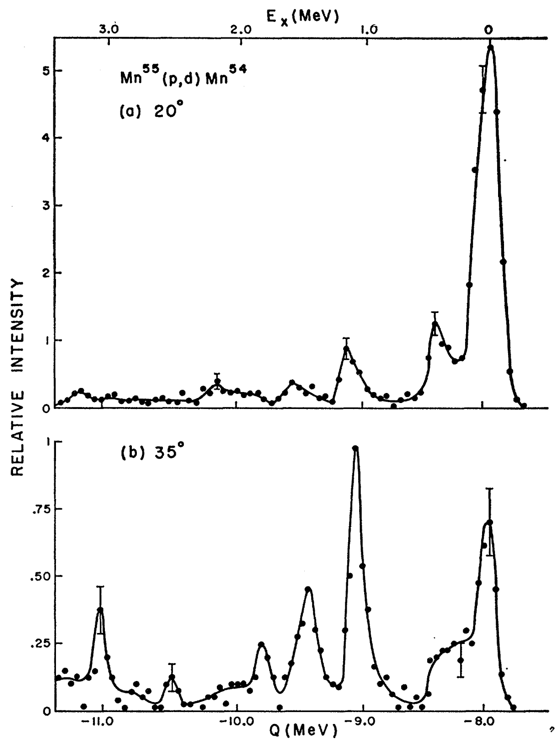

FIG. 3. Deuteron spectra obtained from $Mn^{55}(p,d)Mn^{54}$ at angles of 20° and 35°.

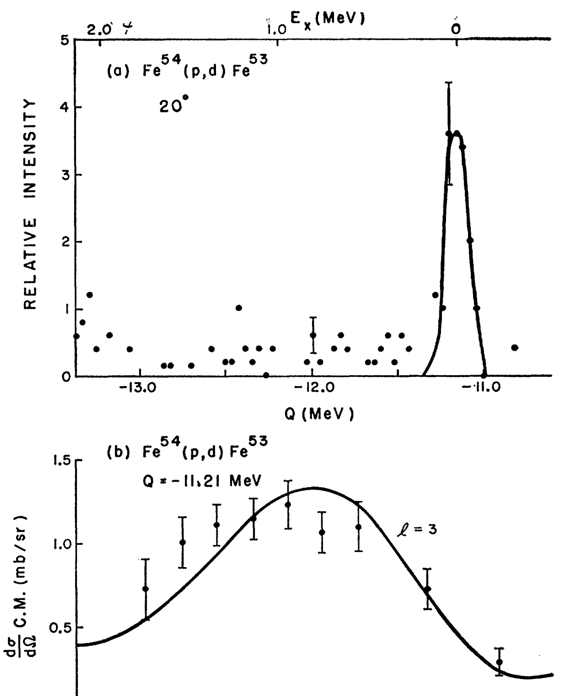

FIG. 4. (a) Deuteron spectrum obtained at 20° from $Fe^{54}(p,d)Fe^{53}$. (b) Angular distribution for the $Fe^{54}(p,d)Fe^{53}$ ground-state reaction. The solid curve is a normalized DW prediction for $l=3$ pickup.

[6] Nucl. Data Tables, U. S. At. Energy Comm., 1960, **1961**, p. 183.

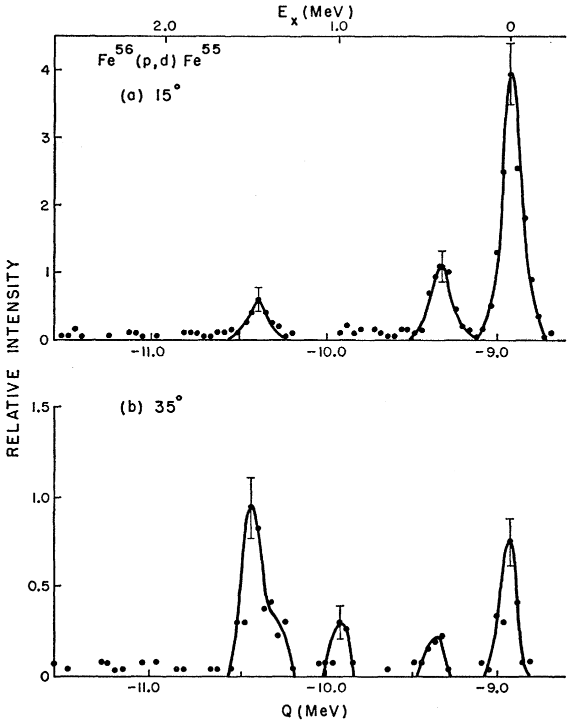

FIG. 5. Deuteron spectra obtained from $Fe^{56}(p,d)Fe^{55}$ at angles of 15° and 35°.

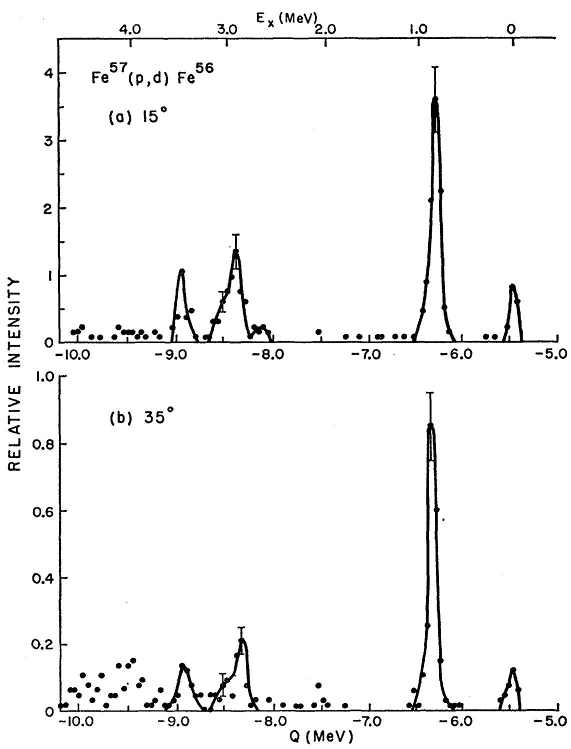

FIG. 6. Deuteron spectra obtained from $Fe^{57}(p,d)Fe^{56}$ at angles of 15° and 35°. The group at $Q=-8.9$ MeV is the $Fe^{56}(p,d)Fe^{55}$ ground state.

Mn^{55}, and Co^{59} where the residual nucleus is odd-odd. Here the spectra indicate that the reactions lead to many states with small cross sections, so that the labeled groups are only the more prominent groups which were observed. Especially for these reactions, further experiments with much better resolution and statistics would be desirable.

DISTORTED WAVE CALCULATIONS

The distorted wave theory of direct nuclear reactions was used to interpret the data. The theory is well described elsewhere[7] so that we will list only the relevant formulas and discuss the choice of parameters.

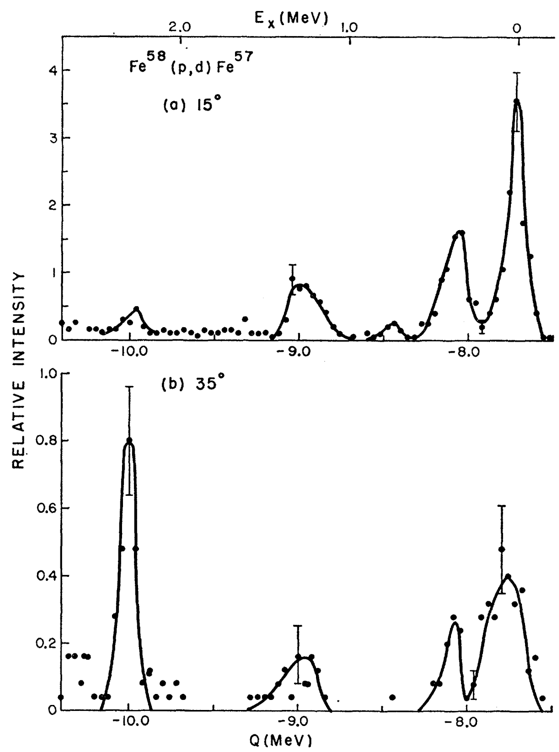

FIG. 7. Deuteron spectra obtained from $Fe^{58}(p,d)Fe^{57}$ at angles of 15° and 35°.

The cross section for the reaction $A(p,d)B$ which proceeds by the pickup of a neutron of angular momentum l is

$$\frac{d\sigma}{d\Omega}=\frac{k_d}{k_p}\frac{M_dM_p}{(2\pi\hbar^2)^2}\frac{3}{4}A_{pn}^2S_l(A,B)\sum_m\frac{|B^{lm}(\theta)|^2}{2l+1}, \qquad (1)$$

$$B^{lm}(\theta)=\int\Phi^{(-)*}(\mathbf{k}_d,\mathbf{r})u_{nl}(r)Y_l^{m}(\hat{r})\Phi^{(+)}(\mathbf{k}_p,\mathbf{r})d\mathbf{r}. \qquad (2)$$

Here M_d and M_p denote the reduced masses of the d-B

[7] R. H. Bassel, R. M. Drisko, and G. R. Satchler, ORNL-3240 (unpublished).

and p-A systems, $\hbar\mathbf{k}_d$ and $\hbar\mathbf{k}_p$ their relative momenta, and $\Phi^{(+)}$ and $\Phi^{(-)}$ the distorted wave functions of relative motion satisfying

$$[-(\hbar^2/2M)\nabla^2+U(r)-E]\Phi=0. \qquad (3)$$

$U(r)$ is a central "optical potential" which describes the absorption and refraction of the incident and emergent waves. The target nucleus A is composed of the final nucleus B coupled to a single neutron with orbital angular momentum l. $S_l(A,B)$ denotes the probability of this composition and is called the spectroscopic factor of the reaction. It is normalized to be N for N equivalent neutrons outside an inert core.

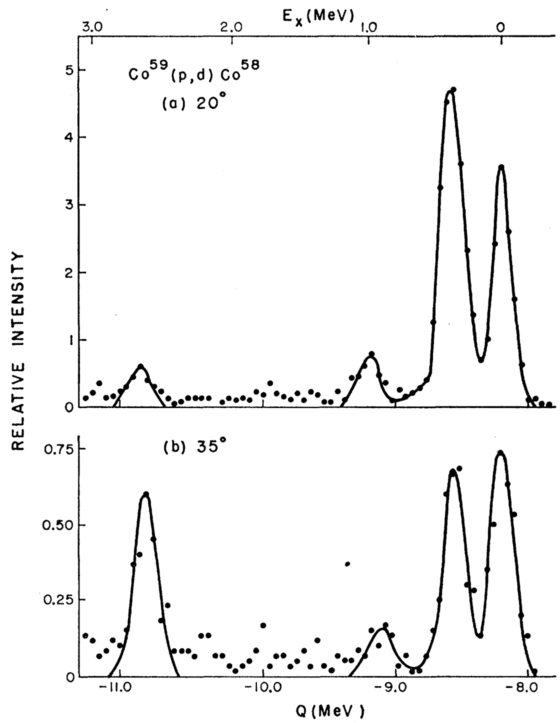

FIG. 8. Deuteron spectra obtained from $Co^{59}(p,d)Co^{58}$ at angles of 20° and 35°.

Finally, A_{pn}^2 is a factor which appears upon performing the zero-range approximation[7] and is given by 1.0×10^4 MeV^2 (fermi)[3]. A single exponential is assumed for the internal deuteron wave function in obtaining this value.

The computer program SALLY[7] is designed to evaluate Eq. (1) if it is given information to compute the neutron wave function and the proton and deuteron distorted waves. The neutron wave function of orbital angular momentum l and $(n-1)$ radial nodes is computed by solving the Schrödinger equation assuming a real Saxon well of form

$$V(r)=\frac{-V}{1+\exp\dfrac{r-1.25A^{1/3}}{0.65}}. \qquad (4)$$

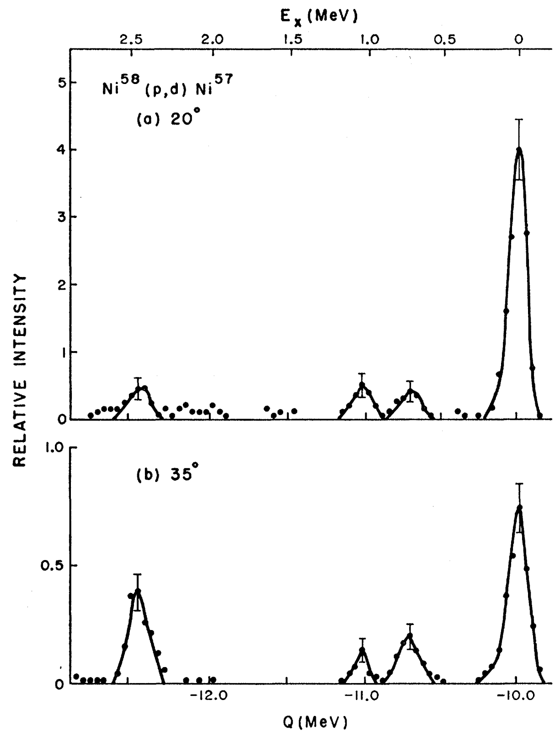

FIG. 9. Deuteron spectra obtained from $Ni^{58}(p,d)Ni^{57}$ at angles of 20° and 35°.

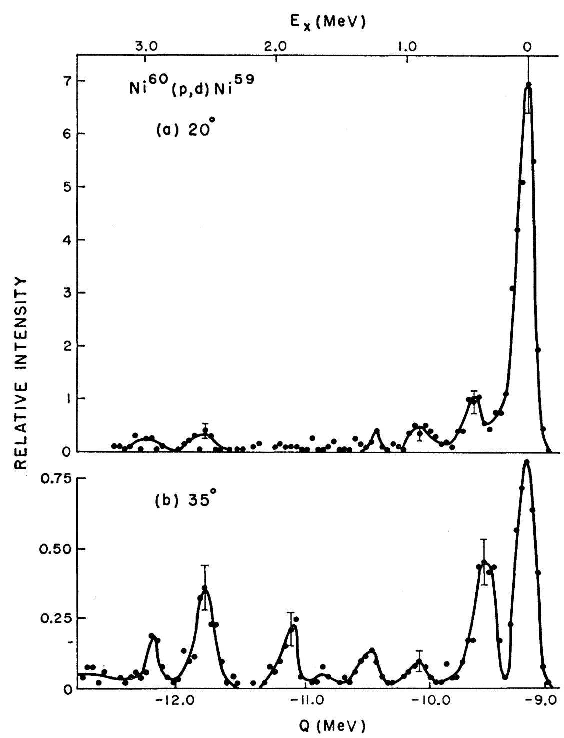

FIG. 10. Deuteron spectra obtained from $Ni^{60}(p,d)Ni^{59}$ at angles of 20° and 35°.

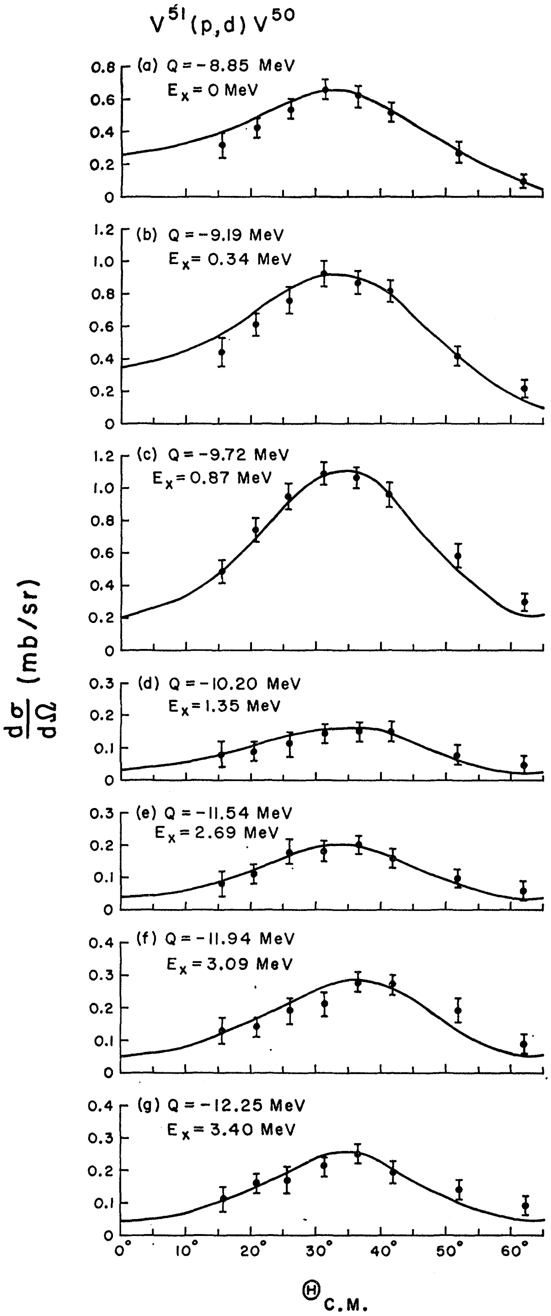

FIG. 11. Angular distributions of deuteron groups observed from the $V^{51}(p,d)V^{50}$ reaction. The solid curves are normalized DW predictions for $l=3$ pickup. Extracted spectroscopic factors are given in Table I.

All potentials are in MeV; all lengths in fermis. The depth V is adjusted so that the neutron has the binding energy $B=2.226-Q$ MeV.

The optical well for the proton is given by

$$U_p(r)=\frac{-48}{1+\exp\dfrac{r-1.25A^{1/3}}{0.65}}+i0.47\frac{d}{dr}\frac{44}{1+\exp\dfrac{r-1.25A^{1/3}}{0.47}} \tag{5}$$

plus the Coulomb potential from a sphere of radius $1.25A^{1/3}$. The choice of parameters here follows the work of Perey[8] and gives excellent fits to proton elastic scattering data. The choice of deuteron optical parameters is much less clear. We use

$$U_d(r)=-\frac{59+i19}{1+\exp\dfrac{r-1.45A^{1/3}}{0.63}} \tag{6}$$

plus the Coulomb potential from a sphere of radius $1.45A^{1/3}$. These parameters were obtained by interpolation from optical potentials used to fit deuteron elastic scattering from nuclei in this mass region.[9] Fortunately, sizable variations of the parameters yield the same *relative* features in comparing neighboring nuclei or energies. However, the uncertainty in the deuteron optical parameters as well as the use of the zero-range approximation require a generous tolerance in comparing absolute cross sections with experiment.

Figure 1 shows the DW predictions for $1f$ and $2p$ neutron pickup at proton energies between 16 and 23 MeV. Experimental cross sections at 17, 18.5, and 22 MeV are compared to these predictions (the 22-MeV data were taken from Goodman *et al.*[2]) and are arbitrarily normalized to the DW predictions at 22 MeV. This procedure removes the spectroscopic factor dependence from the data. Also shown for comparison is the plane wave predictions arbitrarily normalized at

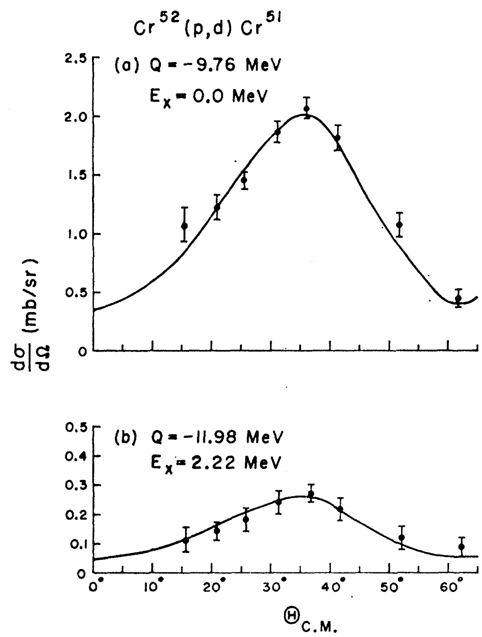

FIG. 12. Angular distributions of deuteron groups observed from the $Cr^{52}(p,d)Cr^{51}$ reaction. The solid curves are normalized DW predictions for $l=3$ pickup.

[8] F. G. Perey, Phys. Rev. **131**, 745 (1963).

[9] M. A. Melkanoff, T. Sawada, and N. Cindro, Phys. Letters **2**, 98 (1962).

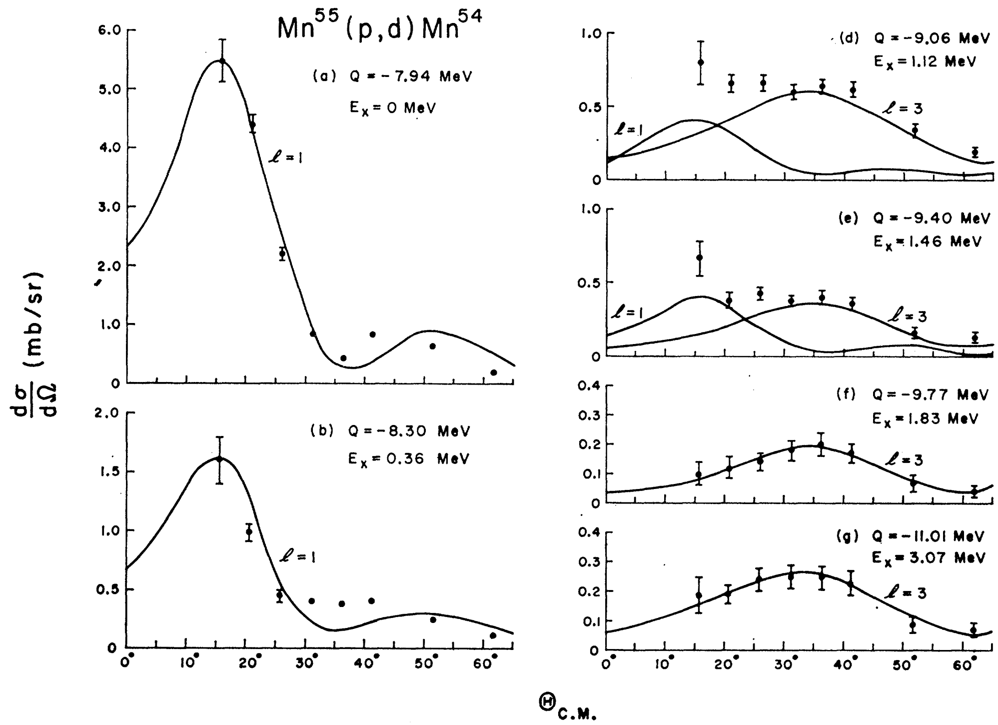

FIG. 13. Angular distributions of deuteron groups observed from the $Mn^{55}(p,d)Mn^{54}$ reaction. The solid curves are normalized DW predictions for $l=1$ and $l=3$ pickup.

18.5 MeV. Obviously, the DW predictions are highly successful in reproducing the dependence of (*p*,*d*) cross sections on energy. However, the plane wave predictions are totally inadequate. This comparison gives us confidence in the relative spectroscopic factors obtained by a DW analysis.

RESULTS

Deuteron spectra were obtained at 5° intervals between 15° and 40°, and also at 50°, 60°, and 70°. Angular distributions were extracted for the discrete states and also for groups of unresolved states observed in these spectra. Differential cross sections were calculated using the integrated beam current, the number of counts in a group of deuterons, the solid angle of the counter telescope, and the weight and isotopic composition of the target. The solid angle was measured geometrically and also by observing the elastic scattering of protons from a weighed carbon foil at several angles. These gave values of the solid angle which agreed within 5%. It was felt that the major sources of uncertainty in the values of the cross sections were the nonuniformity of the metal foils and the statistics. For a measured cross section of 5 mb/sr the probable error in cross section was estimated to be 15%; for a cross section of 1 mb/sr the estimated error was 20%; for a cross section of 0.5 mb/sr the estimated error was 25%;

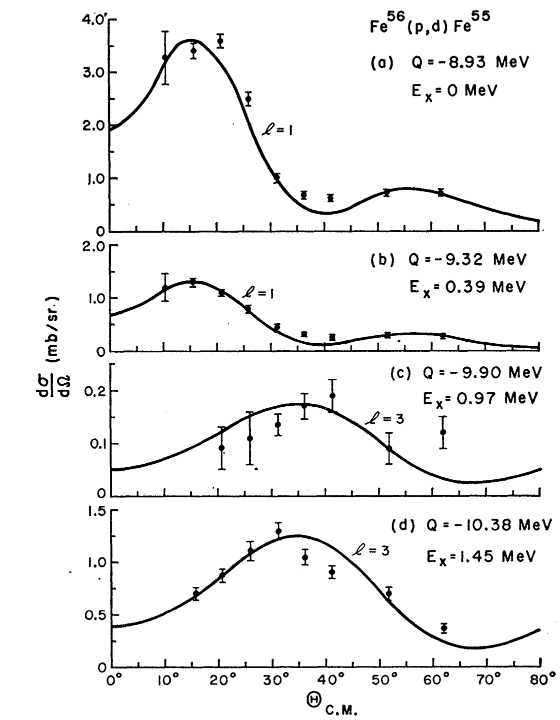

FIG. 14. Angular distributions of deuteron groups observed from the $Fe^{56}(p,d)Fe^{55}$ reaction. The solid curves are normalized DW predictions for $l=1$ and $l=3$ pickup.

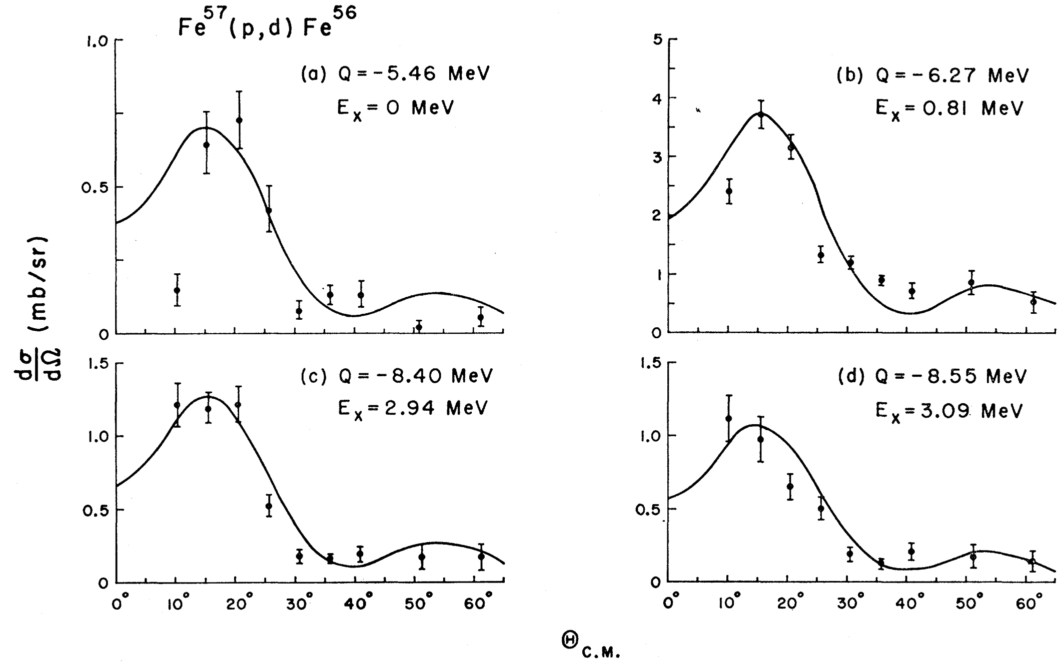

FIG. 15. Angular distributions of deuteron groups observed from the $Fe^{57}(p,d)Fe^{56}$ reaction. The solid curves are normalized DW predictions for $l=1$ pickup.

and for a cross section of 0.1 mb/sr the estimated error was 40%.

Figures 2 through 10 show typical spectra observed during the course of these experiments. For reactions where both $l=1$ and $l=3$ angular distributions were observed, spectra at two angles are shown. Figure 4 also shows the measured angular distribution from the $Fe^{54}(p,d)Fe^{53}$ ground-state reaction together with the DW prediction assuming $l=3$. Angular distributions for the other reactions observed in these experiments are shown in Figs. 11 through 19. For simplicity, the theoretical curves were often obtained by interpolation (in Q and A) so individual fits should not be taken too literally.

The results of these experiments are tabulated in Table I. In this table are listed the deuteron groups observed, known states with which these groups may be identified where possible, assigned l values, peak cross sections, and spectroscopic factors extracted with the DW theory.

$V^{51}(p,d)V^{50}$

The spectrum shown in Fig. 2(a) is typical of the difficulties encountered in this work in observing pickup reactions with an odd-odd residual nucleus. Many deuteron groups are obviously present in the spectrum and the 150-keV resolution of these experiments is not adequate for separating these groups.

Angular distributions for groups with excitations in V^{50} of 0, 0.34, 0.87, 1.35, 2.69, 3.09, and 3.40 MeV are shown in Fig. 11. All of these angular distributions indicate pickup of a neutron with $l=3$. There is some evidence of groups at approximately 1.9- and 2.3-MeV excitation although angular distributions were not measured.

$Cr^{52}(p,d)Cr^{51}$

Figure 2(b) shows the spectrum of deuterons resulting from a natural Cr target (84% Cr^{52}). Angular distributions for deuteron groups corresponding to 0- and 2.22-MeV excitation in Cr^{51} are shown in Fig. 12. Both of these angular distributions indicate that the neutron is picked up with $l=3$. There is some evidence suggesting the presence of a weak group of deuterons corresponding to an excitation of 0.24 MeV which is unresolved from the much more intense ground-state peak. It is also possible that this group may arise from a (p,d) reaction on one of the other Cr isotopes present.

$Fe^{54}(p,d)Fe^{53}$

Figures 4(a) and 4(b) show the spectrum and the angular distribution for the ground-state deuterons from a Fe^{54} target. The solid curve in Fig. 4(b) is the DW prediction for $l=3$ pickup normalized at 25°. Only the ground-state group of deuterons were identifiable and reproducible in spectra obtained from this reaction. However, the data do not rule out the possibility of a Fe^{53} state at approximately 2.5-MeV excitation analogous to the $Cr^{52}(p,d)Cr^{51}$ reaction. Because of the very negative Q value, such a reaction would have a very small cross section according to DW predictions. A deuteron group resulting from this reaction would not then be identifiable in these experiments.

The fact that no strong $l=1$ angular distributions were observed from (p,d) reactions on V^{51}, Cr^{52}, and Fe^{54} indicates that the ground states of these nuclei have almost pure $(1f_{7/2})^8$ neutron configurations. This absence is particularly noteworthy since a $l=1$ transition is favored by more than an order of magnitude over an $l=3$ transition according to DW predictions. This result strengthens the hypothesis that the $1f_{7/2}$ shell is a major shell.

$Mn^{55}(p,d)Mn^{54}$

Deuteron spectra resulting from this reaction may be seen in Figs. 3(a) and 3(b). Again, the resolution problem in a reaction leading to an odd-odd nucleus is evident in these spectra. Angular distributions for deuteron groups at excitations of 0, 0.36, 1.12, 1.46, 1.83, and 3.07 MeV are shown in Fig. 13. The groups at 0 and 0.36 MeV have $l=1$ angular distributions; the groups at 1.12 and 1.46 MeV have angular distributions showing a mixture of $l=1$ and $l=3$; and the groups at 1.83 and 3.07 MeV have $l=3$ angular distributions. There is also some indication of weak groups at 0.81-, 2.2-, and 2.5-MeV excitation.

The $1f$ neutron occupation number in the Mn^{55} ground state is the sum of spectroscopic factors for all $l=3$ reactions. This definition of "neutron occupation number" corresponds to that of Macfarlane *et al.*[3] A similar sum of spectroscopic factors for $l=1$ will determine the $2p$ neutron occupation number. Using the ratios of sums of spectroscopic factors, one may then obtain ratios of neutron occupation numbers for the Mn^{55} ground state.

If one assumes that all deuteron groups due to $1f_{5/2}$ or $2p$ neutron pickup are observed, one obtains a ratio of approximately 3:1 for $1f_{5/2}$ to $2p$ neutron occupation numbers in the Mn^{55} ground state. However, it is certainly possible that some of these groups, particularly the 3.1-MeV group, are due to pickup of a $1f_{7/2}$ core neutron. If the 3.1-MeV group were assumed to be due to $f_{7/2}$ pickup the ratio would be reduced to approxi-

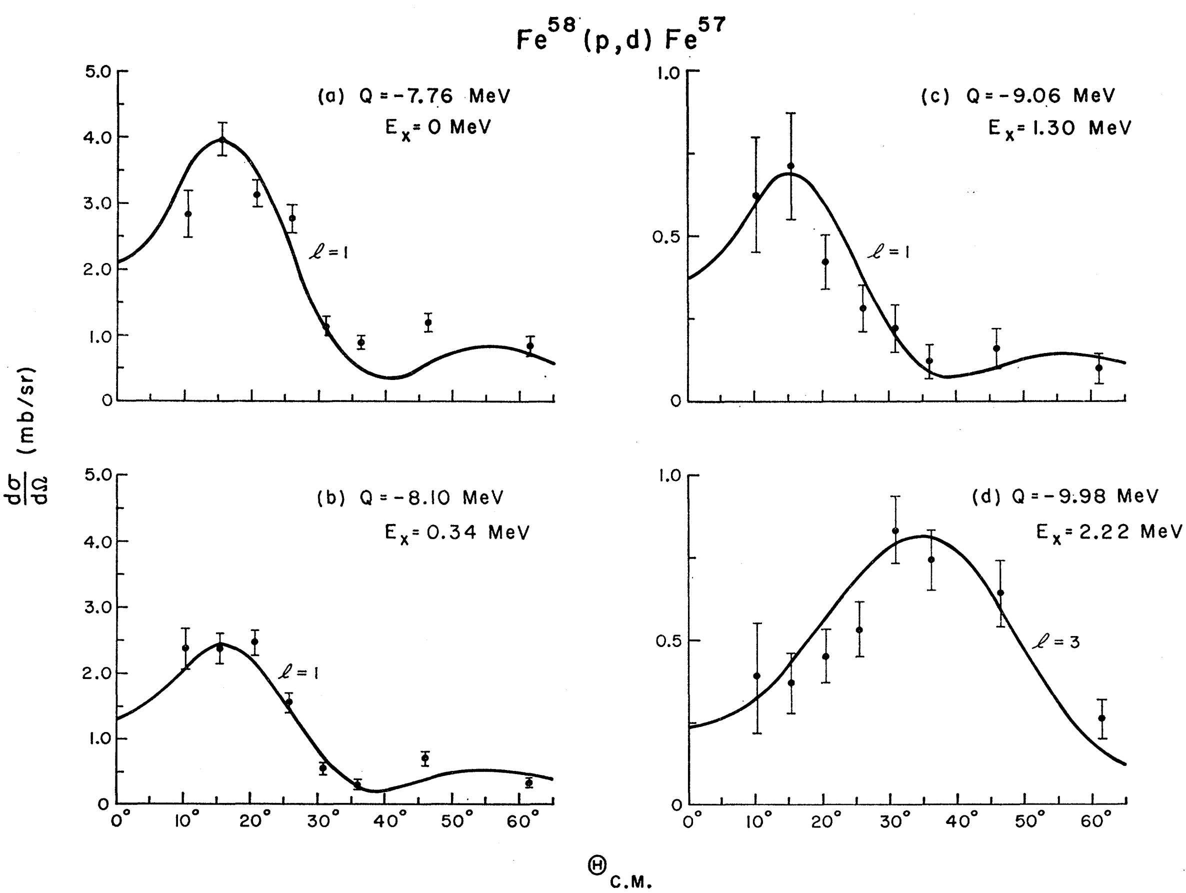

FIG. 16. Angular distributions of deuteron groups observed from the $Fe^{58}(p,d)Fe^{57}$ reaction. The solid curves are normalized DW predictions for $l=1$ and $l=3$ pickup. The angular distribution for the deuteron group at 1.30 MeV was obtained by subtraction of the contribution of the $Fe^{56}(p,d)Fe^{55}$ ground-state deuterons from the unresolved group at $Q=-8.9$ MeV using the $Fe^{56}(p,d)Fe^{55}$ measured cross section and the target's quoted isotopic abundance.

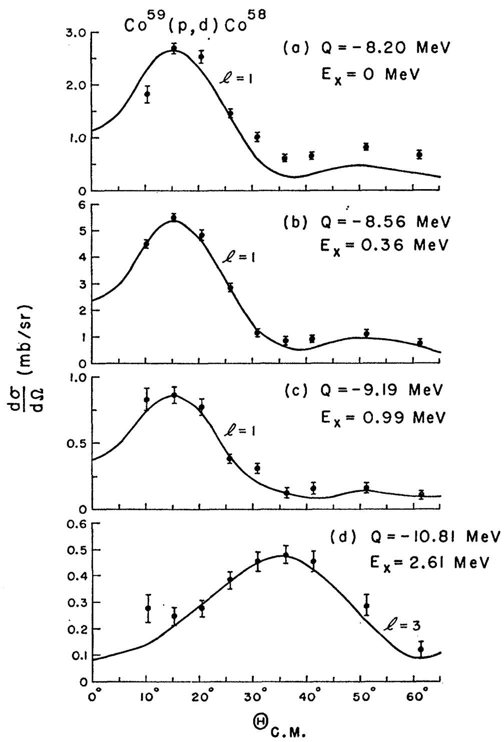

FIG. 17. Angular distributions of deuteron groups observed from the $Co^{59}(p,d)Co^{58}$ reaction. The solid curves are normalized DW predictions for $l=1$ and $l=3$ pickup.

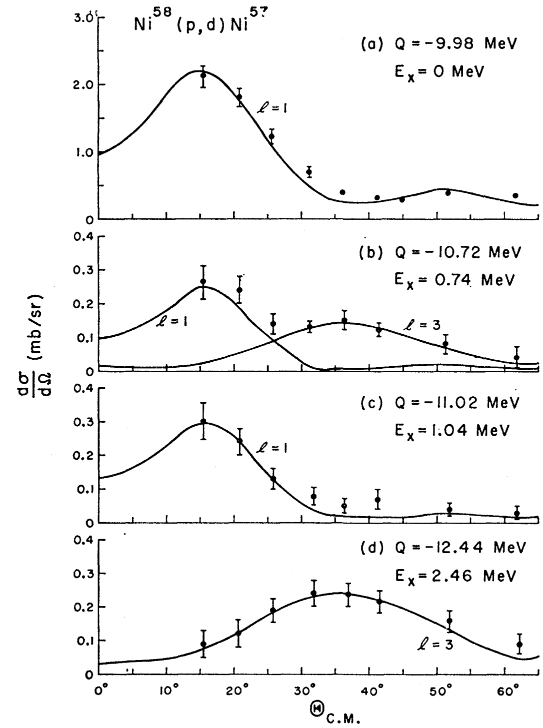

FIG. 18. Angular distributions of deuteron groups observed from the $Ni^{58}(p,d)Ni^{57}$ reaction. The solid curves are normalized DW predictions for $l=1$ and $l=3$ pickup.

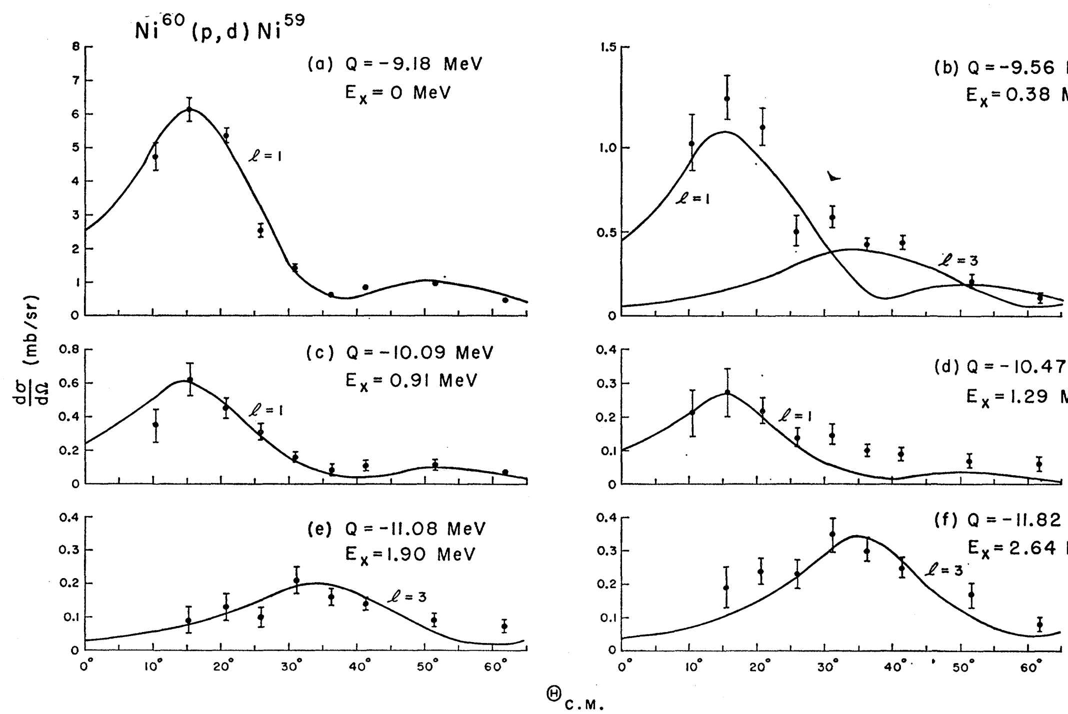

FIG. 19. Angular distributions of deuteron groups observed from the $Ni^{60}(p,d)Ni^{59}$ reaction. The solid curves are normalized DW predictions for $l=1$ and $l=3$ pickup.

TABLE I. Summary of experimental results.

Reaction	Proton energy (MeV)	Measured Q value (MeV)	Residual nuclear levels: Excitation (MeV)	Spin parity	l	Peak cross section mb/sr	Spectroscopic factor
$V^{51}(p,d)V^{50}$	18.5	−8.85	0	6+	3	0.66	1.3
		−9.19	0.34		3	0.92	1.8
		−9.72	0.87		3	1.09	3.0
		−10.20	1.35		3	0.15	0.6
		−11.54	2.69		3	0.20	1.3
		−11.94	3.09		3	0.28	2.3
		−12.25	3.40		3	0.25	2.2
$Cr^{52}(p,d)Cr^{51}$	18.5	−9.76	0	$\frac{7}{2}-$	3	2.06	6.0
		−11.98	2.22		3	0.27	1.9
$Fe^{54}(p,d)Fe^{53}$	18.5	−11.20	0	$\frac{7}{2}-$	3	1.26	6.0
$Mn^{55}(p,d)Mn^{54}$	18.5	−7.94	0	3+	1	6.43	0.83
		−8.30	0.36		1	1.61	0.27
		−9.06	1.12		1	0.40	0.12
					3	0.60	1.2
		−9.40	1.46		1	0.40	0.13
					3	0.35	0.67
		−9.77	1.83		3	0.20	0.53
		−11.01	3.07		3	0.25	1.2
$Fe^{56}(p,d)Fe^{55}$	17.0	−8.93	0	$\frac{3}{2}-$	1	3.59	1.0
		−9.32	0.39		1	1.26	0.42
		−9.88	0.95	$\frac{5}{2}-$	3	0.19	0.87
		−10.35	1.42	$\frac{7}{2}-$	3	1.15	6.1
$Fe^{57}(p,d)Fe^{56}$	17.0	−5.46	0	0+	1	0.75	0.06
		−6.27	0.81	2+	1	3.70	0.37
		−8.40	2.94		1	1.19	0.27
		−8.55	3.09		1	0.96	0.24
$Fe^{58}(p,d)Fe^{57}$	17.0	−7.76	0	$\frac{1}{2}-$			
			(0.014)	$\frac{3}{2}-$	1	3.95	0.70
			(0.136)	$\frac{5}{2}-$	3	0.40	0.80
		−8.10	0.34		1	2.36	0.48
		−9.06	1.30		1	0.71	0.21
		−9.98	2.22		3	0.83	4.4
$Co^{59}(p,d)Co^{58}$	18.5	−8.20	0	2+			
			0.025	5+	1	2.69	0.42
		−8.56	0.36		1	5.48	0.92
		−9.19	0.99		1	0.86	0.19
		−10.81	2.61		3	0.48	2.2
$Ni^{58}(p,d)Ni^{57}$	18.5	−9.98	0	$\frac{3}{2}-$	1	2.12	0.90
		−10.72	0.74		1	0.25	0.08
					3	0.15	0.60
		−11.02	1.04		1	0.30	0.10
		−12.44	2.46		3	0.24	2.0
$Ni^{60}(p,d)Ni^{59}$	18.5	−9.18	0	$\frac{3}{2}-$	1	6.15	1.3
		−9.56	0.34		3	0.40	0.93
			0.47		1	1.15	0.30
		−10.09	0.91		1	0.62	0.23
		−10.47	1.29		1	0.27	0.12
		−11.08	1.90		3	0.19	0.93
		−11.82	2.64		3	0.35	2.5

mately 2:1. These ratios may be compared to the calculations of Schwarcz,[10] which predict a ratio of approximately 1:1 for $1f_{5/2}$ to $2p_{3/2}$ neutrons in the Mn^{55} ground state.

$Fe^{56}(p,d)Fe^{55}$

Figure 5 shows deuteron spectra from this reaction and Fig. 14 the angular distributions for the deuteron groups at excitations of 0, 0.39, 0.95, and 1.42 MeV. Previous high-resolution work on the states of Fe^{55} using the $Fe^{54}(d,p)Fe^{55}$ reaction[11] indicates that all but the 1.42-MeV group correspond to single states in Fe^{55}, since the only states below 1.5 MeV observed in the (d,p) spectra were at excitations of 0, 0.413, 0.933, 1.322, and 1.413 MeV. The ground-state and 0.39-MeV

[10] E. H. Schwarcz, Phys. Rev. **129**, 727 (1963).

[11] J. Rapaport and A. Sperduto, Massachusetts Institute of Technology Laboratory for Nuclear Science Progress Report, May, 1961 (unpublished), p. 131.

state deuterons have typical $l=1$ angular distributions while the 0.95- and 1.42-MeV deuteron groups appear to have $l=3$ angular distributions. It is believed that the 1.42-MeV group is due mainly to the 1.413-MeV state in Fe^{55} with approximately 15% of the deuterons in the group due to the 1.322-MeV state in Fe^{55}.

Cohen[12] has suggested that if one observes the same ratio of cross sections to two states in pickup and stripping experiments the states probably have the same spin, while if one observes different ratios in the two experiments the states must have different spins.

The Fe^{55} results of this experiment are somewhat puzzling. Recent γ-ray work[13] suggests an assignment of $\frac{1}{2}-$ for the spin and parity of the 0.413-MeV state in Fe^{55}. However, the 0.4-MeV state to ground state cross-section ratio was found to be $\frac{1}{3}$ in the $Fe^{54}(d,p)Fe^{55}$ reaction and found to be $\frac{1}{3}$ in the present work. The spin of the 0.413-MeV state should then be the same as that of the ground state, i.e., $\frac{3}{2}$, following Cohen's argument. If the spin of the Fe^{55} 0.413-MeV state is indeed $\frac{1}{2}-$, the ratio of $p_{1/2}$ to $p_{3/2}$ neutron occupation numbers in the Fe^{56} ground state is $\frac{1}{2}$. This ratio is surprisingly large, especially since the ratio $p_{1/2}$ to $p_{3/2}$ neutrons in the Fe^{57} ground state is probably much smaller (see below). For this reason, it is felt that the spin of the Fe^{55} 0.413-MeV state may well be $\frac{3}{2}$. Certainly a more definitive spin assignment for this state would be welcome.[13a]

The major part of the strong $l=3$ group at 1.42-MeV excitation is probably due to core excitation, since its spectroscopic factor agrees with the $Fe^{54}(p,d)Fe^{53}$ ground state group and this state does not give a good stripping pattern in the $Fe^{54}(d,p)Fe^{55}$ reaction. The 0.95-MeV group is assigned to $f_{5/2}$ neutron pickup. The unresolved group at 1.3 MeV may be due to $f_{5/2}$ neutron pickup, although the fact that it was unresolved from the much larger 1.4-MeV state deuteron peak makes this assignment uncertain.

An estimate of the neutron occupation numbers in the Fe^{56} ground state may be made by assuming that the 0.95-MeV state and 1.3-MeV (unresolved) state were formed by $f_{5/2}$ neutron pickup. Assuming that 15% of the 1.4-MeV group is the contribution of the 1.3-MeV state, the ratio of spectroscopic factor sums, $\sum S(1f_{5/2})/\sum S(2p)$, is approximately 5/4. This gives a $1f_{5/2}$ neutron occupation number of 1.1 and a $2p$ neutron occupation number of 0.9 for the Fe^{56} ground state.

$Fe^{57}(p,d)Fe^{56}$

Deuteron spectra for this reaction are given in Fig. 6. (The deuteron group at $Q=-8.9$ MeV results from the $Fe^{56}(p,d)Fe^{55}$ ground-state reaction.) Figure 15 shows angular distributions for deuteron groups at excitations of 0, 0.81, 2.94, and 3.09 MeV. All of these groups have predominantly $l=1$ angular distributions although a rather large $l=3$ intensity could be present and unidentifiable in these groups. There is also evidence for a weak $l=1$ deuteron group at 2.65 MeV.

It is of interest that the ratio of $l=1$ strengths for the 0.8 MeV transition to the ground-state transition is measured to be approximately 5 in the present experiment, whereas this ratio is given a value of 2 in the $Fe^{57}(d,t)Fe^{56}$ experiment of Zeidman *et al.*[1] Our value of 5 is in good agreement with the results of the $Fe^{57}(p,d)Fe^{56}$ experiment performed by Goodman *et al.*[2]

The $Fe^{57}(p,d)Fe^{56}$ results may be used to estimate the ratio of the $2p_{3/2}$ neutron occupation number to the $2p_{1/2}$ neutron occupation number in the Fe^{57} ground state. The ground state of Fe^{57} is $\frac{1}{2}-$ and the ground state of Fe^{56} is $0+$. Conservation of angular momentum requires that the ground state reaction proceed only by $p_{1/2}$ pickup and that reactions to $2+$ states proceed only by $p_{3/2}$ pickup. States of Fe^{56} which have been assigned spins and parities of $2+$ on the basis of the β decay of Mn^{56} and the angular correlation of the subsequent γ-rays lie at 0.845, 2.660, and 2.958 MeV. It is felt that the energy measurements are good enough to support the assumption that three observed deuteron groups, two strong and one weak, are due to these Fe^{56} states. The deuteron group at 3.09-MeV excitation cannot be definitely assigned as $p_{1/2}$ or $p_{3/2}$ neutron pickup. However, it is hard to conceive of any reason why the Fe^{56} state at 3.09 MeV should have a much larger spectroscopic factor for $p_{1/2}$ neutron pickup than the Fe^{56} ground state so a $p_{3/2}$ assignment seems more plausible. Depending on whether one assumes $p_{1/2}$ or $p_{3/2}$ neutron pickup, or some mixture of these, to the 3.09-MeV state, the ratios of $p_{3/2}$ to $p_{1/2}$ occupation numbers in the Fe^{57} ground state will range between values of 2.5 and 14. We believe that the lower limit is probably incorrect. A direct measurement of the spin and parity of the 3.09-MeV level would be of some interest.

$Fe^{58}(p,d)Fe^{57}$

Figure 7 shows deuteron energy spectra for this reaction. Angular distributions for deuteron groups at 0-, 0.34-, 1.30-, and 2.22-MeV excitation are shown in Fig. 16. The first three groups have predominantly $l=1$ angular distributions while the last group has an $l=3$ angular distribution. The Fe^{58} target used had an isotopic abundance of 76.7% Fe^{58} and 20.7% Fe^{56}. The deuteron group at 1.30 MeV is unresolved from the $Fe^{56}(p,d)Fe^{55}$ ground state deuterons; consequently the number of deuterons in the 1.30-MeV group was obtained by subtraction of the predicted number of Fe^{56} ground-state deuterons using the $Fe^{56}(p,d)Fe^{55}$ measured cross sections and the target's isotopic abundance.

[12] B. L. Cohen, Phys. Rev. **125**, 1358 (1962).
[13] J. R. Maxwell, K. T. Hecht, and W. C. Parkinson, Bull. Am. Phys. Soc. **8**, 367 (1963).
[13a] *Note added in proof.* The recent work of L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. Letters **12**, 108 (1964), indicates that the spin of the 0.413-MeV state is $\frac{1}{2}-$. As indicated above, this result determines that the $2p_{1/2}$ and $2p_{3/2}$ neutron occupation numbers for the Fe^{56} ground state are equal.

Presumably the major contribution to the ground state group of deuterons comes from the $\frac{3}{2}-$ state at 14 keV in Fe^{57} since the ground state of Fe^{57} would require $2p_{1/2}$ neutron pickup. It may be seen from Figs. 6(b) and 13 that the known $\frac{5}{2}-$ state at 136 keV which would have $l=3$ angular distribution makes a noticeable contribution to this group. It is estimated that the 0.136-MeV state has a peak cross section of 0.4 mb/sr.

In these results, we see only one strong well-separated deuteron group with $l=3$. This group at 2.22-MeV excitation does not correspond to any strong level seen in the $Fe^{56}(d,p)Fe^{57}$ reaction, so it is probably due to pickup of an $f_{7/2}$ core neutron just as in the $Fe^{56}(p,d)Fe^{55}$ reaction. The ratio of cross sections of the 0.367-MeV state to the 0.014-MeV state has approximately the same value for the (d,p) and (p,d) reactions,[15] which indicates a $\frac{3}{2}$ spin assignment for the 0.367-MeV state. On the other hand, the ratio of the cross sections of the 1.27-MeV state to the 0.014-MeV state is much larger in the (d,p) reaction.[15] This is an indication that the 1.27 MeV level is probably $\frac{1}{2}-$ and that the reaction to this state proceeds via pickup of a $p_{1/2}$ neutron. This assignment does not agree with that of Bartholomew and Gunye,[16] who have tentatively assigned the 1.27-MeV state a spin of $\frac{3}{2}$. The spin-$\frac{1}{2}$ assignment for the 1.27-MeV state leads to a ratio of $p_{3/2}$ to $p_{1/2}$ neutron occupation numbers in the Fe^{58} ground state of approximately 5:1. The estimated 0.4-mb/sr cross section for the unresolved 0.136-MeV state then leads to a ratio of $f_{5/2}$ to $p_{3/2}$ to $p_{1/2}$ neutron occupation numbers for the Fe^{58} ground state of 3.7:5.5:1.

$Co^{59}(p,d)Co^{58}$

Deuteron spectra from this reaction may be seen in Fig. 8. The angular distributions for deuteron groups corresponding to excitations of 0, 0.36, 0.99, and 2.61 MeV in Co^{58} are shown in Fig. 17. The first three groups have $l=1$ angular distributions while the 2.61-MeV group has an $l=3$ angular distribution. There is also some evidence of a group at 1.75 MeV. As in the case of (p,d) reactions on V^{51} and Mn^{55} the spectra indicate the presence of many small deuteron groups which are unresolved and which form a low-intensity deuteron background between the more intense deuteron groups.

The lack of information on the structure of Co^{58} obtained by other means makes it very difficult to draw any conclusions from these experiments. There are certainly small deuteron groups between 1- and 2.5-MeV excitation whose angular distributions and cross sections could not be accurately measured. It is felt that the $l=3$ peak at 2.61 MeV is probably too small to be a core-excitation state. This would imply that this state is reached by $f_{5/2}$ neutron pickup and that the ratio of $f_{5/2}$ to p neutron occupation numbers in the Co^{59} ground state is approximately 1.2:1. Such a ratio is certainly consistent with results from other nuclei in this region.

$Ni^{58}(p,d)Ni^{57}$

As noted previously, the measured ground-state Q value for this reaction did not agree with the published Q value obtained from nuclear mass data. The measured Q value was -9.98 ± 0.05 MeV which does not agree with the published Q value of -9.700 MeV.[6]

Deuteron spectra from this reaction may be seen in Fig. 9. Angular distributions for deuteron groups at excitations of 0, 0.74, 1.04, and 2.46 MeV in Ni^{57} are shown in Fig. 18. The ground state group has an $l=1$ angular distribution; the 0.74-MeV group angular distribution indicates a mixture of $l=1$ and $l=3$. The 1.04-MeV group has an $l=1$ distribution and the 2.46-MeV group has an $l=3$ distribution.

There is essentially no other information available about the level structure of Ni^{57} and therefore it is impossible to determine occupation numbers for $2p_{3/2}$ and $2p_{1/2}$ neutrons separately. No strong $l=3$ group of deuterons was observed in this reaction which could be assigned to a core-excitation state, in contrast to the $Fe^{56}(p,d)Fe^{55}$ and the $Fe^{58}(p,d)Fe^{57}$ reactions. Possibly the group observed at 2.46-MeV excitation corresponds to a core-excitation state but if this is the case it is hard to explain the relative weakness of this group as compared to those observed in the Fe reactions. If it is assumed that both $l=3$ groups observed are due to $f_{5/2}$ neutron pickup, one obtains a ratio of $f_{5/2}$ to $2p$ neutron occupation numbers for the Ni^{58} ground state of approximately 2.5, if it is assumed that the state at 2.46 MeV is a core-excitation state one obtains a ratio of approximately 0.55. The former number is in closer agreement with the results of experiments on other nuclei in this region and with theoretical estimates for the Ni^{58} ground-state wave function.[3,17]

$Ni^{60}(p,d)Ni^{59}$

Figure 10 shows deuteron spectra for this reaction. Angular distributions for deuteron groups at excitations of 0, 0.38, 0.91, 1.29, 1.90, and 2.64 MeV in Ni^{59} are shown in Fig. 19. The ground state, 0.91-MeV, and 1.29-MeV groups have $l=1$ angular distributions; the 0.38-MeV group contains the known levels at 0.34 and 0.47 MeV, and has a mixed $l=1$ and $l=3$ distribution; and the 1.90- and 2.64-MeV groups have $l=3$ distributions. There is also some evidence of weak groups at 1.68- and 2.95-MeV excitations.

[14] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C.).
[15] F. Alba, A. Sperduto, W. W. Buechner, and H. A. Enge, Bull. Am. Phys. Soc. **7**, 315 (1962).
[16] G. A. Bartholomew and M. R. Gunye, Bull. Am. Phys. Soc. **8**, 367 (1963).
[17] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 9 (1960).

The results of the $Ni^{60}(p,d)Ni^{59}$ experiment, when compared with those of the $Ni^{58}(d,p)Ni^{59}$ experiment,[18] produce some interesting information about the low-lying states reached by $2p$ neutron transfer. Again, we use Cohen's argument[12] that $\frac{3}{2}-$ state reaction strengths should have the same ratio to the ground state strength in the (d,p) and (p,d) reactions while reactions to $\frac{1}{2}-$ states should be much stronger relative to the ground state in the (d,p) reaction than in the (p,d) reaction. This yields the following spin assignments: 0.47 MeV, $\frac{1}{2}-$; 0.89 MeV, $\frac{3}{2}-$; and 1.32 MeV, $\frac{1}{2}-$. The assignment for the 0.47-MeV state is in agreement with all sources; the assignment for the 0.89-MeV state is in agreement with that of Cote *et al.*[19] and Bartholomew and Gunye,[16] but disagrees with that of Cohen *et al.*[18]; and the assignment for the 1.32-MeV state agrees with that of Cohen *et al.*, but disagrees with that of Bartholomew and Gunye.

The observed $l=3$ deuteron groups are somewhat puzzling. The unresolved $l=3$ group observed at 0.38 MeV is obviously $f_{5/2}$ neutron pickup to the Ni^{59} state at 0.34 MeV. However, the (d,p) experiment of Cohen *et al.* revealed only an $l=4$ group near 1.9 MeV and a weak $l=3$ group at 2.64 MeV in addition to the 0.34-MeV group. The groups observed at 1.9 and 2.6 MeV in the (d,p) and (p,d) experiments to Ni^{59} probably are not due to the same neutron transfer since their strengths relative to the 0.34-MeV group are not the same in both reactions, even if it were conceded that the 1.9-MeV group seen by Cohen *et al.*, actually was due to $f_{5/2}$ stripping. Though these arguments are by no means conclusive, it is felt that there is a very strong possibility that the 1.9- and 2.6-MeV deuteron groups are due to pickup of $f_{7/2}$ core neutrons.

If all of our spin assignments are correct one obtains for the Ni^{60} ground state a ratio of $f_{5/2}$ to $p_{3/2}$ to $p_{1/2}$ neutron occupation numbers which is approximately 2.8:5.2:1. The $f_{5/2}$ occupation number is certainly underestimated here because of the failure to observe and obtain reliable cross sections for other $\frac{5}{2}$ states in Ni^{59}.

[18] B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).

[19] R. E. Cote, H. E. Jackson, Jr., L. L. Lee, Jr., and J. P. Schiffer, Bull. Am. Phys. Soc. **7**, 551 (1962).

DISCUSSION OF RESULTS

The results obtained in this work are readily explained in shell-model terms. The success of this model negates some of the major reasons given by Goodman *et al.*[2] for using a Nilsson model to describe some nuclei in this region and a spherical shell model to describe others. For example, the $Co^{59}(p,d)Co^{58}$ spectrum is not a simpler spectrum than the $Fe^{58}(p,d)Fe^{57}$ spectrum, although better energy resolution will be necessary to determine exactly how complicated the $Co^{59}(p,d)Co^{58}$ spectrum is. In addition the $1f_{5/2}$ single-particle level does appear in Fe^{55} at approximately 1 MeV, contrary to the conclusions of Goodman *et al.*[2]

Discrepancies are found between two methods of distinguishing between $\frac{3}{2}-$ and $\frac{1}{2}-$ levels. Levels in Fe^{55}, Fe^{57}, and Ni^{59} are assigned a spin $\frac{1}{2}-$ or $\frac{3}{2}-$ by γ-ray angular correlation experiments but are assigned a spin of $\frac{3}{2}-$ or $\frac{1}{2}-$ by comparison between (d,p) and (p,d) experiments to the same nucleus. Another independent assignment of spins would be welcome in resolving these conflicts.

Finally, the results of this work indicate a strong mixing of $1f_{5/2}$ and $2p$ neutrons in the ground states of nuclei containing 29–32 neutrons. The values of the ratio of $1f_{5/2}$ to $2p$ neutron occupation numbers obtained here necessarily rest on some questionable assumptions. However, the value of this ratio in all cases where such a ratio was determined is greater than 0.5 and less than 2. Certainly this result indicates strong mixing and also indicates that the fluctuation from nucleus to nucleus is much less than had been previously reported.[3]

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the continued interest and suggestions of Professor R. Sherr and Professor E. Kashy and the aid of James Ritter in data reduction.