SUMMARY

A unique feature of the results obtained here is that this is the first instance where a second isotope of the same element has been found to possess an anomalous negative scattering amplitude. This would suggest a further search for nuclear scattering resonance effects on the observed neutron scattering for nickel isotopes. Also the value of $b_{Ni^{64}}$ is the lowest scattering amplitude measured so far.

Since the measured coherent scattering amplitude of elemental nickel, $b_{Ni}=1.03\times10^{-12}$ cm, is used as a standard for comparison it was of interest to calculate this amplitude from the measured values of the scattering amplitudes of five stable isotopes of nickel. As given in Table III the calculated value differs by approximately $\frac{1}{2}\%$ from the measured value.

ACKNOWLEDGMENTS

The authors are grateful to Ralph Bane for oxidizing and reducing the isotope samples and to D. D. Zauberis for technical assistance in preparation of this paper.

PHYSICAL REVIEW VOLUME 156, NUMBER 4 20 APRIL 1967

Nuclear Spectroscopy in Cr^{52}, Cr^{53}, and Cr^{54} by the (p,d), (p,t), and (p,p') Reactions*

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(Received 10 October 1966)

The $Cr^{54}(p,d)$ and $Cr^{54}(p,t)$, $Cr^{53}(p,d)$ and (p,t), $Cr^{53}(p,p')$, and $Cr^{52}(p,t)$ reactions were studied with 17.5-MeV protons from the Princeton FM cyclotron. Thin, essentially self supported, isotopic chromium foils were used in these experiments, the deuterons and tritons being identified by a dE/dx-E solid-state-detector telescope. The total experimental resolution of this system for the various deuteron and triton groups was between 55 and 70 keV. Angular distributions for many (p,d), (p,t), and (p,p') transitions were obtained from 15° to 150°. Spectroscopic factors were determined for $l_n=0$, 1, 2, and 3 (p,d) transitions, using distorted-wave Born-approximation calculations which included both finite-range and nonlocal effects. In the $Cr^{53}(p,d)$ reaction, both the 0^+ ground state and the 1.434-MeV 2^+ level in Cr^{52} were excited by $l_n=1$ transitions, showing admixture in the Cr^{53} ground state of the configuration $\{(Cr^{52}\ 1.434\ MeV)^{2^+}2p_{3/2}\}^{3/2}$. Levels in Cr^{52} and Cr^{53} were strongly excited in the (p,d) reaction with $l_n=3$ angular distributions, and these transitions are ascribed to $1f_{7/2}$ pickup. In the $Cr^{54}(p,d)Cr^{53}$ reaction, definite J dependence was observed in both $l_n=1$ ($J=\frac{1}{2}$ or $\frac{3}{2}$) and $l_n=3$ ($J=\frac{5}{2}$ or $\frac{7}{2}$) transitions. A single $l_n=0$ transition was found in the $Cr^{54}(p,d)$ reaction which seems to exhaust most of the $T_<$ spectroscopic strength. The $Cr^{54,53,52}(p,t)$ experiments along with the $Cr^{53}(p,d)$ work indicate that a large component of the 2.648-MeV 0^+ level in Cr^{52} is a two-particle–two-hole neutron configuration. In the $Cr^{53}(p,p')$ reaction, the 0.563-MeV $\frac{1}{2}^-$, 1.001-MeV $\frac{5}{2}^-$, 1.284-MeV $\frac{7}{2}^-$, and 1.967-MeV levels were strongly excited, and their angular distributions are similar to that of the $Cr^{52}(p,p')Cr^{52}$ 1.434-MeV 2^+ transition. The results of the $Cr^{54}(p,d)$, $Cr^{53}(p,d)$, and $Cr^{53}(p,p')$ experiments are used in conjunction with the weak-coupling model and the theoretical model calculations of Maxwell and Parkinson and of Ramavataram to discuss the structure of the low-lying levels of Cr^{53}.

1. INTRODUCTION

THE purpose of this paper is to present experimental results, obtained using the (p,d), (p,t), and (p,p') reactions, which bear on the structure of the nuclear states in Cr^{54}, Cr^{53}, and Cr^{52}. This work may be viewed as a continuation of the study at Princeton of $1f_{7/2}$ nuclei, using the (p,d), (p,t), and (p,p') reactions.[1–4]

In the analysis of the $Cr^{54}(p,d)$ and $Cr^{53}(p,d)$ transitions the distorted-wave Born-approximation (DWBA) theory,[5] in the form of the Oak Ridge computer program JULIE, is used to obtain values for l_n, the orbital angular momentum of the picked-up neutron, and for the spectroscopic factor S_{l_n,j_n}, which represents the overlap of the target nucleus with the final nuclear state plus the picked-up neutron (l_n,j_n), multiplied by the total number of such neutrons in the target. A rather complete search of the available sets of proton and deuteron optical-model parameters was made in order to find that set or group of sets which gave the best agreement with our experimental (p,d) results, both with respect to the angular distribution and to the reasonableness of the extracted (p,d) spectroscopic factors. We used a DWBA program which incorporated

* This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund, and made use of computer facilities supported in part by National Science Foundation Grant No. NSF-GP 579.

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both finite-range and nonlocal effects in the reaction mechanism. In the case of the $Cr^{54}(p,d)Cr^{53}$ reaction we were able to investigate J dependence in the (p,d) angular distributions which had been previously reported both in the (p,d) reaction[6-8] and in its inverse, the (d,p) reaction.[9,10] In the study of the $Cr^{54}(p,t)$, $Cr^{53}(p,t)$, and $Cr^{52}(p,t)$ reactions the characteristic $L=0$ angular distributions allowed us to identify states in the final nucleus with the same spin as that of the target. We were also able to obtain examples of $L=2(p,t)$ angular distributions in the case of the $Cr^{54}(p,t)Cr^{52}$ and $Cr^{53}(p,t)Cr^{51}$ reactions. The excitation of the low-lying levels of Cr^{53} in the (p,p') reaction has also been determined in order to augment our study of their structure in the $Cr^{54}(p,d)$ reaction.

2. EXPERIMENTAL SETUP AND PROCEDURE

The $Cr(p,d)$, (p,t), and (p,p') reactions were studied with 17.5-MeV protons from the Princeton FM cyclotron. The external proton beam was energy analyzed by a double-focusing spectrometer magnet before entering a 20-in. scattering chamber[11] where the reaction studies took place. The entrance and exit slit widths of the spectrometer magnet were usually set so that the energy resolution of the beam in the scattering chamber was 30 keV, although the study of some back angle angular distributions ($\theta_{lab}>90°$) was done with a 60-keV proton beam. For data at forward angles ($\theta_{lab}<30°$–$40°$) we used an internal rf electrode called the C [12] to inincrease the microscopic duty cycle of the proton beam from 3% to 10–20%. Typical beam intensities for a resolution of 30 keV were 25 nA without the C, and 5 nA with the C operating to give a 12% duty cycle. The duty cycle of the proton beam could be measured quantitatively by a duty-cycle meter designed by Pollock.[13]

Isotopically enriched chromium targets were made from metal powder supplied by the Oak Ridge National Laboratory. The enrichments were 99.87% for Cr^{52}, 98.9 and 96.4% for Cr^{53}, and 97.98% for Cr^{54}. A Denton DEG-801 electron gun was used to evaporate the chromium sample from a carbon boat onto $\frac{1}{4}$-mil copper foil, with the evaporation taking place inside an evaporator designed by Nolen.[14] The chromium coated side of the copper foil was painted with a thin layer of polystyrene, and the copper backing was then dissolved by a 1:2.5 solution of nitric acid. With some luck we were able to obtain six $\frac{1}{2}$-in.$\times\frac{1}{2}$-in. chromium foils from each evaporation. The carbon and oxygen contaminations on a 525-μg/cm^2 Cr^{54} foil were found to be 23 and 40 μg/cm^2, respectively. This was calculated from the proton monitor spectrum and the absolute cross sections at 90° from proton elastic scattering on C^{12} and O^{16}.[15,16]

The deuteron and triton groups were identified by a dE/dx-E telescope of solid-state detectors. The dE/dx detector was 50 μ thick, and the most energetic deuterons of interest stopped in the E detector. A block diagram of the electronics is shown in Fig. 1. The data were stored in a 4096-channel pulse height analyzer operated in the 256$\times$16 mode. The total energy E' lost in the dE/dx and E detectors was stored in 256 channels, and the product $E'\times dE/dx\cong KMZ^2$ was stored in 16 channels. Pulses above a certain energy from an anticoincidence detector located behind the dE/dx-E detector telescope shut off the analyzer for a period 10 μsec. This minimized the effect of elastic proton pulses on the quality of the data. The dead time of the analyzer due to the anticoincidence pulses was monitored by a scaler, and this dead time was always found to be negligible in the calculation of absolute cross sections. The two-dimensional spectra were converted by hand into one-dimensional deuteron and triton spectra, and the total experimental resolution was between 55 and 70 keV. Elastic protons were monitored by a 2000-μ thick detector, which was usually located at a laboratory angle of 90°.

Relative cross sections for the (p,d) and (p,t) transitions were obtained from the chromium elastic proton peak in the spectrum of the monitor detector. Absolute cross sections for the $Cr^{53}(p,d)Cr^{52}$g.s., $Cr^{54}(p,d)$-Cr^{53}g.s., and $Cr^{52}(p,d)Cr^{51}$g.s. transitions at a laboratory angle of 40° were calculated from the deuteron spectrum of a thick (2.55 mg/cm^2), rolled foil of natural chromium. Figure 2 presents this deuteron spectrum. The peaks for the $Cr^{53}(p,d)Cr^{52}$g.s. and $Cr^{54}(p,d)Cr^{53}$g.s. transitions are well separated from those of any other $Cr(p,d)$ transition, while the data obtained with isotopic foils are used to correct the $Cr^{52}(p,d)Cr^{51}$ peak for deuterons due to $Cr^{54}(p,d)Cr^{53}$ and $Cr^{53}(p,d)Cr^{52}$ transitions. These three absolute-cross-section measurements are then used to convert the sets of relative cross sections into sets of absolute cross sections.

3. OPTICAL-MODEL PARAMETERS FOR THE DWBA THEORY

Table I presents the DWBA proton and deuteron optical-model parameters used in this work to fit the experimental (p,d) angular distributions and to extract spectroscopic information. The parameters of Table I

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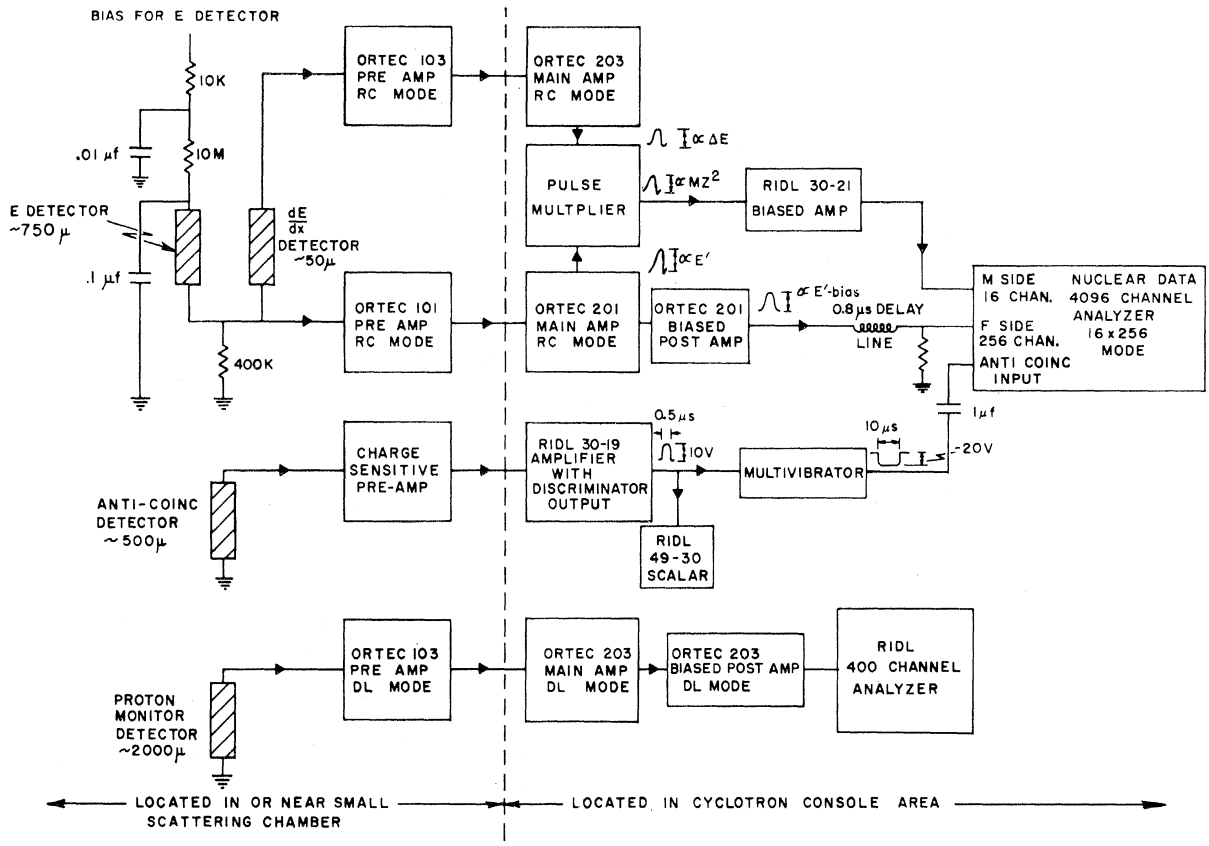

FIG. 1. Block diagram of the electronics used in the (p,d) and (p,t) experiments.

were selected from a survey of the available, published sets of proton and deuteron optical-model parameters, in which we determined those sets or group of sets which best fitted the experimental data.

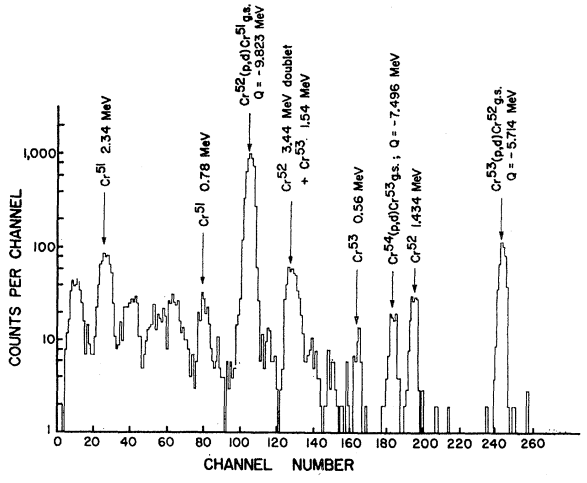

FIG. 2. Deuteron spectrum from the Cr(p,d) reaction on a thick (2.55 mg/cm^2), rolled foil of natural chromium. $E_p=17.5$ MeV, and $\theta_{lab}=40°$. These data were used to determine absolute cross sections for the (p,d) and (p,t) transitions.

Four different sets of proton optical-model parameters were used in order to investigate the sensitivity of the (p,d) DWBA cross section to variation in these parameters. These sets were found in the work of Perey,[17] Andrews *et al.*,[18] Rosen *et al.*,[19] and Lee *et al.*[20] All four parameter sets were determined from an optical-model analysis of proton elastic scattering in the region $A\cong 50\pm 10$, and for proton energies ranging from 10 to 20 MeV. In general we found that the calculated DWBA (p,d) angular distributions were quite insentitive to the particular proton parameter set used. The set of proton optical-model parameters used in the final analysis of all our experimental (p,d) angular distributions was taken from the work of Perey[17] and is tabulated in Table I. This consists of the well-known set of Perey "geometrical" parameters—r_0, a, r_0', a'—and the values of V_0 and W' which best fitted the 17-MeV proton elastic scattering angular distribution on Fe measured by Dayton and Schrank[21] at Princeton. The

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optical-model potential for protons includes a spin-orbit strength V_{so} equal to 8.5 MeV.

Seven different sets of deuteron optical-model parameters were included in the investigation of the sensitivity of the DWBA angular distributions to variations in these parameters. They were the sets *dB* and *dC* of Smith[22] from the optical-model analysis of 7-MeV deuteron scattering on Cr^{52}; the Dickens-Perey[23] sets *B* and *C* along with a best-fit set of parameters, all three of which were obtained from an optical-model analysis of Ni(*d*,*d*) scattering in the energy range of 5 to 25 MeV; the "av. *Z*" set of Lee *et al.*[20] from the optical-model analysis of Ca^{40} deuteron elastic scattering in the energy range of 7 to 12 MeV; and the set 5(SW)B8 of Andrews *et al.*[24] from the optical-model analysis of $Cr^{52}(d,d)$ scattering at 8 MeV. The DWBA angular distributions were found to be quite sensitive to the set of deuteron optical-model parameters chosen in a given calculation. When the various DWBA angular distributions were compared with the experimental (*p*,*d*) angular distributions, the best fits to the data were obtained with the two Smith sets and the set *B* of Dickens and Perey. The DWBA fits to the experimental data were not quite so good using the Lee *et al.* set of parameters and were much worse when the other three sets of parameters were used. All three of the deuteron parameter sets which gave the best fits to the experimental (*p*,*d*) data had a real potential well depth V_0 equal to 90 ± 10 MeV, while two of the parameter sets which gave much worse fits to the data had V_0 equal to 55 ± 5 MeV. This behavior might be understood from the argument that the deuteron is two weakly coupled nucleons. Therefore, the potential it sees should be, to first order, twice that of one nucleon; that is, V_0 (deuteron)$\approx 2\times V_0$(proton) $\approx 2\times 48\approx 96$ MeV.

From the three sets of deuteron optical-model parameters which gave the best fits to the experimental data, the set of *dB* of Smith was chosen to be used in the analysis of almost all our (*p*,*d*) data. The Smith set *dB* had one distinct advantage over the other two sets. In the experimental (*p*,*d*), $l_n=3$ angular distribution corresponding to the pickup of an $1f_{7/2}$ neutron the cross section has a broad forward maximum, peaking at 35°, with a shoulder from 60° to 85°. This behavior is seen in the DWBA angular distribution when the Smith set *dB* is used. However, with the other two sets—Smith *dC*, and Dickens-Perey *B*—the DWBA angular distributions have a distinct minimum at 65° and a second maximum at 90°, two characteristics which are not seen in the experimental (*p*,*d*) angular distributions. Aside from this fact there is little to choose between the three sets as to the quality of the fit they give with the experimental data. The Dickens-Perey set *B* does have the advantage that V_0 and W', the respective real and imaginary well depths, are calculated as a function of energy. Dickens and Perey found that for deuteron energies less than 7.5 MeV the real well depth V_0 increases rather sharply as the deuteron energy decreases. Now in some of our (*p*,*d*) transitions the energy of the outgoing deuteron was 5–6 MeV, so that for these transitions we used the energy-dependent Dickens and Perey set *B* rather than the Smith set *dB*. The deuteron optical-model parameters for the Smith set *dB* and the Dickens-Perey set *B* ($E_d=7.5$ MeV) are listed in Table I. In a few calculations a spin-orbit strength V_{so} of 5 MeV was included in the deuteron optical potential. It was found to have no important effect on the DWBA angular distributions, even at back angles.

In Table I the neutron well parameters r_{0n}, a_n, and λ are the same as those used by Lee *et al.*[20] in their study of the $Ca^{40}(d,p)$ reaction. In their work Lee *et al.*[20] found that the peak DWBA cross section was quite sensitive to the values of r_{0n} and λ, and we found similar dependences in our Cr(*p*,*d*) work.

Our final DWBA calculations used a computer pro-

TABLE I. Optical-model parameters used in DWBA program.

$$V(r)=U_c(r)-V_0\left[\frac{1}{1+e^x}\right]+iW'\frac{d}{dx'}\left[\frac{1}{e^{x'}+1}\right]+\left(\frac{\hbar}{m_\pi c}\right)^2 V_{so}\boldsymbol{\sigma}\cdot\mathbf{l}r^{-1}\frac{d}{dr}\left[\frac{1}{1+e^x}\right]$$

where:

$$U_c(r)=\frac{Ze^2}{2r_{0c}A^{1/3}}\left[3-\left(\frac{r}{r_{0c}A^{1/3}}\right)^2\right] \qquad r<r_{0c}A^{1/3}$$

$$U_c(r)=\frac{Ze^2}{r} \qquad r>r_{0c}A^{1/3}$$

$$x=\frac{r-r_0A^{1/3}}{a} \qquad x'=\frac{r-r_0'A^{1/3}}{a'}$$

1. Proton parameters[a]

$r_{0c}=r_0=r_0'=1.25$ F $\quad a=0.65$ F $\quad a'=0.47$ F

$V_0=47.9$ MeV $\quad W'^{b}=46.0$ MeV $\quad V_{so}=8.5$ MeV

2. Deuteron parameters

Smith set *dB*[c]	Dickens-Perey set *B*[d]
$r_0=r_{0c}=1.2$ F, $r_0'=1.36$ F	$r_0=1.15$ F, $r_{0c}=1.3$ F, $r_0'=1.34$ F
$a=0.4243$ F, $a'=0.9901$ F	$a=0.81$ F, $a'=0.68$ F
$V_0=92.83$ MeV	$V_0=95.0$ MeV, $W'^{b}=78.0$ MeV
$W'^{b}=32.57$ MeV	
no spin-orbit term	no spin-orbit term

3. Neutron well parameters

$r_{0n}=1.2$ F $\quad a_n=0.65$ F $\quad \lambda=25.0$

[a] Taken from analysis of 17-MeV proton elastic scattering on Fe, Table VI, p. 751 of Ref. 17.
[b] $W'=4W_D$. W_D is the parameter often quoted in the literature. W' is the value we put in the DWBA computer program JULIE.
[c] Reference 22.
[d] Reference 23; $E_d=7.5$ MeV.

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gram which approximated both finite-range (FR) and nonlocal (NL) effects in the (p,d) reaction mechanism. This approximation was effected by calculating a new neutron wave function $u_{lj}^{\mathrm{FR-NL}}(\mathbf{r})$, in general complex, by an auxiliary program called GORFF.[25] $u_{lj}^{\mathrm{FR-NL}}(\mathbf{r})$ replaces the usual bound neutron wave fuuction $u_{lj}(\mathbf{r})$ in the DWBA program, and the DWBA angular distribution is then calculated by the JULIE program in the same manner as when FR and NL effects are not included. For $l_n=1(p,d)$ transitions the peak DWBA cross section increases by $15\pm5\%$ when the FR-NL DWBA program is used; for $l_n=3(p,d)$ transitions there is almost no change in the peak DWBA cross section.

In many cases the DWBA angular distribution was also calculated using a radial cutoff R_c. In this work we usually used $R_c=4.7$, which is about the nuclear surface ($R=1.25A^{1/3}$), and $R_c=5.5$ F, or slightly less than 1 F outside the nuclear surface. For some cases the use of a radial cutoff improved the DWBA fit to the experimental data. This will be discussed in detail in the sections where the experimental results are presented (Secs. 4 and 5). The use of the FR-NL DWBA program decreased the effect of the radial cutoff on the peak cross section. For example, in the $l_n=1$, $2p_{3/2}$, $\mathrm{Cr}^{54}(p,d)\mathrm{Cr}^{53}$ $\frac{3}{2}^-$ g.s. transition the use of a radial cutoff, $R_c=4.7$ F, decreases the DWBA peak cross section by 16% when the zero-range program is used. With the FR-NL program the decrease is 5%. The use of a radial cutoff, $R_c=4.7$ F, in the $l_n=3$, $1f_{7/2}$, $\mathrm{Cr}^{52}(p,d)\mathrm{Cr}^{51}$ $\frac{7}{2}^-$ g.s. transition decreases the DWBA peak cross section by 34% with the zero-range program. With the FR-NL program the decrease is 20%.

4. $\mathrm{Cr}^{53}(p,d)\mathrm{Cr}^{52}$ DATA AND DISCUSSION

We are able to use the $\mathrm{Cr}^{53}(p,d)$ reaction as a probe of the structure of both the target nucleus and the levels in the residual nucleus. In the simplest picture the ground-state wave function of $\mathrm{Cr}^{53}(J=\frac{3}{2}^-)$ could be considered as the ground state of $\mathrm{Cr}^{52}(J=0^+)$ plus a $2p_{3/2}$ neutron. However, this ground-state wave function could contain admixtures of the general form: excited state of Cr^{52} plus a $2p_{3/2}$, $2p_{1/2}$, or $1f_{5/2}$ neutron, coupling to total spin $J=\frac{3}{2}$. For example, there might be a considerable admixture of the form $\{[\mathrm{Cr}^{52}(1.434\ \mathrm{MeV})]^{2+}2p_{3/2}\ \mathrm{neutron}\}^{3/2}$. If this were the case, then there would be an $l_n=1$ ($j_n=\frac{3}{2}$), (p,d) transition to the 1.434-MeV 2^+ level in Cr^{52}, and the spectroscopic strength of this transition would give a quantitative measure of this admixture in the Cr^{53} ground-state wave function.

One model for the low-lying levels in Cr^{52} has considered such levels as due to the various possible configurations of four $f_{7/2}$ protons in ${}_{24}\mathrm{Cr}_{28}{}^{52}$, the neutron shell being closed at $N=28$. There are eight possible configurations for four identical $f_{7/2}$ particles: one $J=0^+$ level; two $J=2^+$ levels, $(v=2)$ and $(v=4)$; two $J=4$ levels, also $(v=2)$ and $(v=4)$; and one level each with $J=5^+$, 6^+, and 8^+. Shell-model calculations for the energy spectrum of $f_{7/2}$ configurations were first carried out by Edmunds and Flowers,[26] while Talmi[27] and de-Shalit[28] have presented specific calculations for the level structure of Cr^{52}. This model has been quite successful in reproducing the experimentally determined energies and spins for the low-lying levels in Cr^{52}. Such pure $f_{7/2}{}^4$ levels in Cr^{52} can be reached in the (p,d) reaction only if they are present in the ground state of Cr^{53} coupled to a neutron above the $1f_{7/2}$ shell. In particular, one cannot reach pure $f_{7/2}{}^4$ levels with $J\geq5$, since a $2p_{3/2}$, $2p_{1/2}$, or $1f_{5/2}$ neutron cannot couple with $J\geq5$ to give a resultant spin of $\frac{3}{2}$. However, in the $\mathrm{Cr}^{53}(p,d)$ reaction one can reach strongly, by the pickup of an $1f_{7/2}$ neutron, levels in Cr^{52} which have a large component in their wave functions of an $1f_{7/2}$ neutron hole coupling to a $2p_{3/2}$ neutron—we are here assuming that the neutron outside the closed $1f_{7/2}$ shell in the ground state of Cr^{53} is for the most part a $2p_{3/2}$ neutron. Such a $(1f_{7/2}{}^{-1}2p_{3/2})$ neutron configuration can couple to spins 2^+, 3^+, 4^+, and 5^+. It would be interesting to see where such $(f_{7/2}{}^{-1}p_{3/2})^{J=2^+\ \mathrm{to}\ 5^+}$ levels lie in energy with respect to the pure $(f_{7/2}{}^4)$ proton levels of Talmi[27] and of de-Shalit.[28] In particular it would be interesting to see whether such a $(f_{7/2}{}^{-1}p_{3/2})$ neutron configuration mixes to any considerable extent with the pure $f_{7/2}$ proton configurations of the same spin and parity in the wave functions of the levels of Cr^{52}.

Sherr *et al.*[6] in their $\mathrm{Cr}(p,d)$ work at 28 MeV, using a natural chromium target, saw prominent peaks corresponding to $\mathrm{Cr}^{53}(p,d)$ transitions to the Cr^{52} ground state, the 1.434 MeV 2^+ level, and a level or group of levels at $\sim$3.44 MeV. The ground-state and 1.434-MeV (p,d) transitions had $l_n=1$ angular distributions, while the transition to the 3.44-MeV level had an $l_n=3$ angular distribution. The deuteron peak which they attribute to a level in Cr^{52} at $\sim$3.27 MeV ($Q\cong-8.98$ MeV) is due to the $\mathrm{Cr}^{54}(p,d)\mathrm{Cr}^{53}$ 1.53-MeV transition ($Q=-9.03$ MeV), which is a strong $l_n=3$ transition (see Sec. 5). As was pointed out by Sherr *et al.*,[6] their preliminary results were most interesting, and showed the need to do the $\mathrm{Cr}(p,d)$ studies with isotopic targets and higher resolution.

Figure 3 shows the deuteron spectrum from the $\mathrm{Cr}^{53}(p,d)\mathrm{Cr}^{52}$ reaction at $\theta_{\mathrm{lab}}=30°$, using a self-supported Cr^{53} foil. The relatively low negative Q value (-5.714 MeV) of the $\mathrm{Cr}^{53}(p,d)$ reaction allows one to study levels in Cr^{52} up to an excitation energy of $\sim$7.5 MeV with 17.5 MeV protons. However, most of our

[25] GORFF is a modification of the Oak Ridge program FLANNEL FLURP by J. K. Dickens and R. H. Bassel. W. Gerace made the necessary modifications.

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[28] A. de-Shalit, *Selected Topics in Nuclear Theory* (International Atomic Energy Agency, Vienna, 1963), p. 220.

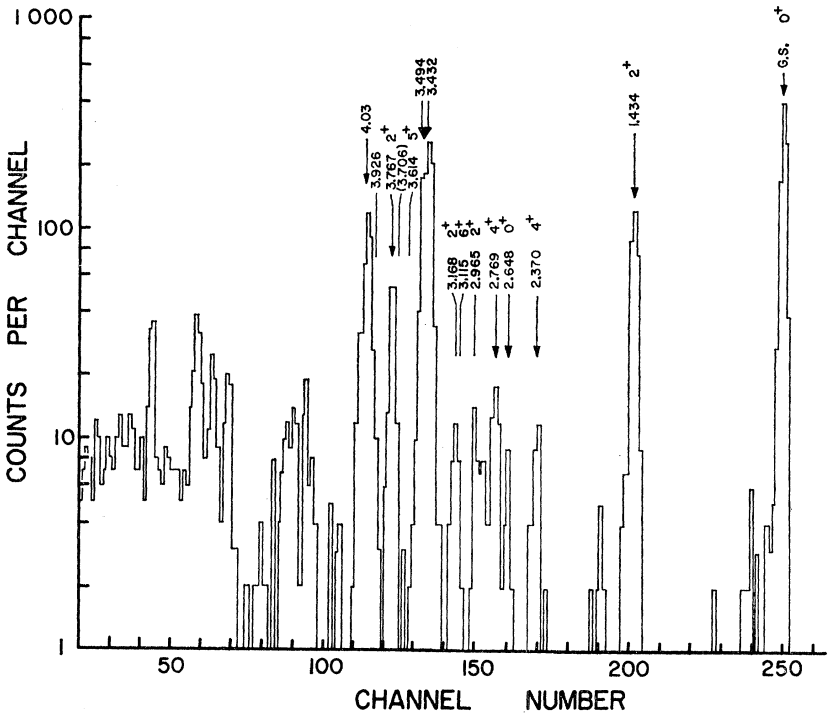

FIG. 3. Deuteron spectrum from the $Cr^{53}(p,d)Cr^{52}$ reaction on a thin ($\sim$0.5 mg/cm^2), isotopic (96.4%)Cr^{53} foil. $E_p=17.5$ MeV, and $\theta_{lab}=30°$. The Cr^{52} energy-level diagram is taken from the work of Refs. 30 and 36. All energy levels marked with an arrow will have their (p,d) angular distributions presented in this work.

$Cr^{53}(p,d)$ data was taken with an isotopic Cr^{53} foil on a thin aluminum backing. The strong deuteron groups from the $Al^{27}(p,d)$ reaction ($Q=-10.82$ MeV) thus masked the $Cr^{53}(p,d)$ transitions to levels in Cr^{52} above an excitation energy of $\sim$5 MeV.

The low-lying level structure of Cr^{52} has been studied in an extensive number of experimental investigations. Valuable information on the spins and parities of levels in Cr^{52} has been obtained by Wilson *et al.*[29] and Freedman *et al.*,[30] who studied the γ cascades following the β^+ and EC decay of the Mn^{52} 6^+ ground state to high spin levels (5^+ and 6^+) in Cr^{52}. Katoh *et al.*[31] have studied the γ cascades following the β^+ decay of the 2^+, 21-min, isomeric level in Mn^{52} ($E_x=0.383$ keV), while Malmskog[32] has studied the γ cascades following weak β^- branches from the decay of the 2^+ ground state of V^{52}. Valuable reaction studies include the $Cr^{52}(n,n'\gamma)$ work of van Patter *et al.*,[33] the $Cr^{52}(e,e')$ scattering studies of Belliard *et al.*[34] at 200 MeV, and the $Cr^{52}(p,p')$ experiments of three investigators: Veje *et al.*[35] at 11 to 12.9 MeV, Matsuda[36] at 14.7 MeV, and Funsten, Roberson, and Rost[4] at 17.5 MeV. At Princeton in addition to the work of Funsten, Roberson, and Rost, Sherr *et al.*[37] have studied the cross sections and angular distributions of the $Mn^{55}(p,\alpha)$ reaction to levels in Cr^{52}. Spin assignments to various excited states of Cr^{52} have been made by Kaye and Willmott[38] from triple angular correlations of the γ-ray cascades from levels excited in $Cr^{52}(p,p')$ scattering. A summary of the results of these experiments is shown by the energy diagram in Fig. 3. The energies of levels are taken from the work of Freedman *et al.*[30] whenever possible (their γ-ray energies are determined to better than 1 keV), and otherwise from the (p,p') work of Matsuda.[36] $Cr^{53}(p,d)$ angular distributions will be presented to all levels marked with an arrow in Fig. 3. At least up to an excitation energy of 4 MeV in Cr^{52} we found no evidence for any level excited in the $Cr^{53}(p,d)$ reaction which had not been previously reported in the literature.

Figure 4 shows the $l_n=1$ angular distributions to the ground state, 1.434-MeV 2^+ state and the 2.648-MeV 0^+ state in Cr^{52}. The (p,d) transitions to the Cr^{52} 0^+ ground state and 1.434-MeV 2^+ state are strong, while the 2.648-MeV 0^+ level is excited quite weakly in the (p,d) reaction. Comparing the experimental cross sections at 15° with the DWBA predictions, one obtains $l_n=1$, $2p_{3/2}$ spectroscopic factors of 0.51, 0.18, and 0.018 for

[29] R. R. Wilson, A. A. Bartlett, J. J. Kraushaar, J. D. McCullen, and R. A. Ristenen, Phys. Rev. **125**, 1655 (1962).
[30] M. S. Freedman, F. Wagner, Jr., F. T. Porter, and H. H. Bolotin, Phys. Rev. **146**, 791 (1966).
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[32] S. Malmskog, Nucl. Phys. **49**, 239 (1963).
[33] D. M. van Patter, N. Nath, S. M. Shafroth, S. S. Malik, and M. A. Rothman, Phys. Rev. **128**, 1246 (1962).
[34] J. Bellicard, P. Baneau, and D. Blum, Nucl. Phys. **60**, 319 (1964).
[35] E. Veje, C. Droste, O. Hansen, and S. Holm, Nucl. Phys. **57**, 451 (1964).
[36] K. Matsuda, Nucl. Phys. **33**, 536 (1962).
[37] R. Sherr, in *International Symposium on Direct Reactions and Nuclear Reaction Mechanisms, Padua, 1962* (Gordon and Breach, Science Publishers, Inc., New York, 1963), p. 1025; also R. Sherr, F. Brady, H. O. Funsten, and N. R. Roberson (private communication).
[38] G. Kaye and J. C. Willmott, Nucl. Phys. **71**, 561 (1965).

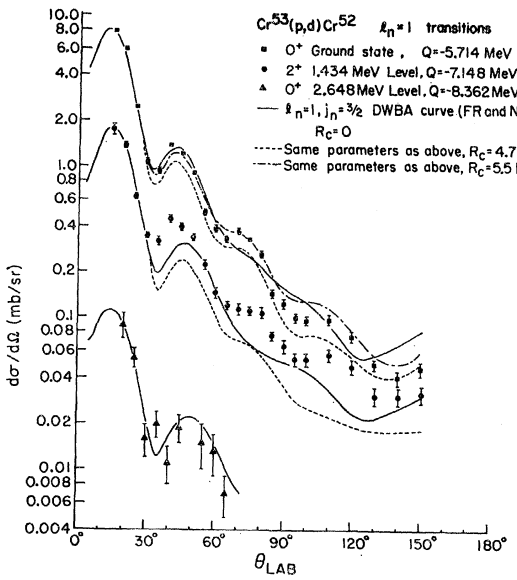

FIG. 4. Experimental, $l_n=1$, $Cr^{53}(p,d)Cr^{52}$ angular distributions to the 0^+ ground state, 1.434-MeV 2^+ level, and 2.648-MeV 0^+ level. The data are fitted with $l_n=1$, $2p_{3/2}$ DWBA (FR and NL) curves.

the (p,d) transitions to the ground state, 1.434-MeV 2^+ level, and the 2.648-MeV 0^+ level, respectively. The fine DWBA (FR and NL) $l_n=1$, $2p_{3/2}$ fit to the angular distribution of the $Cr^{53}(p,d)Cr^{52}$ g.s. transition should be emphasized. When a radial cutoff of 4.7 F ($4.7=1.25A^{1/3}$) or 5.5 F is used, the DWBA curve is able to reproduce the main characteristics of the experimental angular distribution, including the shoulders from $\sim 60°$ to 75° and from $\sim 95°$ to 115°. The use of these radial cutoffs ($R_c=4.7$ or 5.5 F) does not change the value of the DWBA cross section at 15° from the $R_c=0$ value.

While the angular distributions to the 0^+ ground state and 0^+ 2.648-MeV level must correspond to pure $l_n=1$, $2p_{3/2}$ neutron pickup transitions from the selection rules of the reaction mechanism, the angular distribution to the 1.434-MeV 2^+ level may have four separate incoherent components corresponding to $2p_{3/2}(l_n=1)$, $2p_{1/2}(l_n=1)$, $1f_{5/2}(l_n=3)$, and $1f_{7/2}$ $(l_n=3)$ neutron pickup. The spectroscopic strength of the first three of these components would depend on the admixtures in the Cr^{53} ground state of the configurations: $\{[Cr^{52}(1.434\ \text{MeV})]^{2+}\ 2p_{3/2}\}^{3/2}$; $\{[Cr^{52}(1.434\ \text{MeV})]^{2+}\ 2p_{1/2}\}^{3/2}$; and $\{[Cr^{52}(1.434\ \text{MeV})]^{2+}\ 1f_{5/2}\}^{3/2}$, respectively, while the strength of the $l_n=3$, $1f_{7/2}$ component would depend on the amount of admixture in the Cr^{52} 1.434-MeV 2^+ level of the neutron configuration $(f_{7/2}^{-1}p_{3/2})^{2+}$. We can get some idea of the total $l_n=3$ spectroscopic strength to the 1.434-MeV level ($Q=-7.148$ MeV) by comparing its experimental (p,d) angular distribution with the $Cr^{53}(p,d)l_n=1$ angular distribution to the ground state of Cr^{52} ($Q=-5.714$ MeV), and the $Cr^{54}(p,d)$ $l_n=1$ angular distribution to the $\frac{3}{2}^-$ ground state of Cr^{53} ($Q=-7.496$ MeV). Both of these transitions must represent pure $2p_{3/2}$ neutron pickup. Now in the neighborhood of $\theta_{\text{lab}}=35°$ the $l_n=1$ angular distribution is going through a relative minimum while the $l_n=3$ angular distribution is at its maximum value. We find that in this region the cross section to the Cr^{52} 1.434-MeV level is 150 ± 50 μb/sr higher than one would expect from the shape of either of the pure $l_n=1$ angular distributions normalized at 15°. A cross section of 150 ± 50 μb/sr at 35° represents an $l_n=3$ spectroscopic strength of 0.20 ± 0.07 for $1f_{7/2}$ neutron pickup and 0.28 ± 0.10 for $1f_{5/2}$ neutron pickup. Thus we can determine an upper limit of ~ 0.2 for the total $(p,d)l_n=3$ spectroscopic strength to the 1.434-MeV 2^+ level in Cr^{52}, although we cannot determine what linear conbination of $1f_{5/2}$ and $1f_{7/2}$ neutron pickup strength this figure represents. The question of how much of the $l_n=1$ spectroscopic strength represents $2p_{1/2}$ neutron pickup rather than $2p_{3/2}$ pickup is very difficult to answer from our experimental data. When we plot the ratio of $d\sigma/d\Omega[Cr^{53}(p,d)Cr^{52}$ 1.434 MeV $2^+]$—correcting for $l_n=3$ admixture—to $d\sigma/d\Omega$ $[Cr^{54}(p,d)Cr^{53}$ g.s. $\frac{3}{2}^-]$ in the region from 90° to 130°, we find that the ratio is a constant $\pm 25\%$. However, from 90° to 130° the ratio of $d\sigma/d\Omega[Cr^{54}(p,d)Cr^{53}$ 0.56 MeV $\frac{1}{2}^-]$—$2p_{1/2}$ neutron pickup—to $d\sigma/d\Omega[Cr^{54}(p,d)$-$Cr^{53}$ g.s. $\frac{3}{2}^-]$—$2p_{3/2}$ neutron pickup—varies by a factor of 4 with a deep minimum at 120°–125°, indicative of the Lee-Schiffer dip[9] in the $j_n=\frac{1}{2}$ transition. Therefore, we might say that there is no evidence for

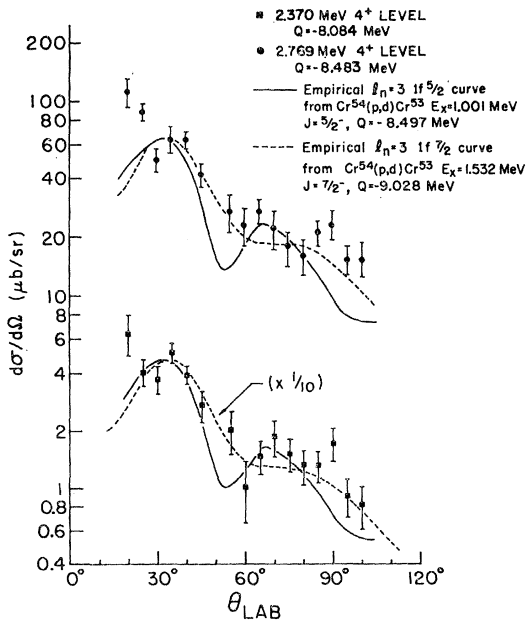

FIG. 5. Experimental $Cr^{53}(p,d)Cr^{52}$ angular distributions to the 2.370-MeV 4^+ level and the 2.769-MeV 4^+ level. The data are fitted with empirical $l_n=3$ curves from the $Cr^{54}(p,d)Cr^{53}$ 1.001-MeV $\frac{5}{2}^-$ and $Cr^{54}(p,d)Cr^{53}$ 1.532-MeV $\frac{7}{2}^-$ transitions. For both transitions the experimental cross section at 20° is $\sim$twice that predicted by a pure $l_n=3$ transition.

a $j_n=\frac{1}{2}$ pickup strength greater than $\frac{1}{4}$ that for $j_n=\frac{3}{2}$ pickup in the total $l_n=1$ spectroscopic strength for the $Cr^{53}(p,d)Cr^{53}$ 1.434-MeV 2^+ transition, but this upper limit of $\frac{1}{4}$ is only a very rough estimate.

The weakness of the (p,d), $l_n=1$ transition to the 2.648-MeV 0^+ level ($S=0.018$) is indicative of the fact that only a small part of its wave function is the configuration $\{(\pi f_{7/2}{}^4)^0(\nu f_{7/2}{}^8)^0\}^0$—the only $J=0$ configuration possible in Cr^{52} based entirely on $f_{7/2}$ particles. Therefore, the wave function of the 2.648-MeV 0^+ level must have admixtures of higher-shell configurations. We shall have more to say about the wave function of this level when we discuss the results of our study of the $Cr^{54}(p,t)Cr^{52}$ reaction in Sec. 7. There we shall show that the major part of the wave function for this level is a two-particle–two-hole configuration.

Figure 5 shows the (p,d) angular distributions to the two low-lying 4^+ levels in Cr^{52} at 2.370 and 2.769 MeV. By the (p,d) selection rules the transition from the $\frac{3}{2}^-$ ground state of Cr^{53} to a 4^+ level in Cr^{52} can proceed only by an orbital angular momentum transfer of $l_n=3$, both $1f_{5/2}$ and $1f_{7/2}$ neutron pickup being allowed. The $1f_{5/2}$ transition strength would depend on an admixture in the Cr^{53} ground state of the form $\{Cr^{52}(4^+)1f_{5/2}\}^{3/2}$, while the $1f_{7/2}$ transition strength would depend on an admixture in the 4^+ Cr^{52} wave function of the form $\{(\pi f_{7/2}{}^4)^0(\nu f_{7/2}{}^{-1}p_{3/2})^4\}^4$. Neither low-lying 4^+ level is excited very strongly, indicating that both of the possible admixtures favoring $l_n=3$ transitions are small. From the (p,d) cross sections at 35°: $d\sigma/d\Omega$ (2.370 MeV 4^+) $=45$ μb/sr and $d\sigma/d\Omega$(2.769 MeV 4^+) $=60\,\mu$b/sr, we obtain $l_n=3$, $1f_{7/2}$ spectroscopic strengths to these levels of 0.07 and 0.10, respectively ($l_n=3$, $1f_{5/2}$ spectroscopic strengths would be ~45% higher). Because of the poor statistical accuracy of the experimental data we cannot determine by $l_n=3$ J dependence the separate $1f_{7/2}$ and $1f_{5/2}$ components in the total angular distribution to these levels. The solid curve in Fig. 5 is an empirical $l_n=3$, $1f_{5/2}$ angular distribution from the $Cr^{54}(p,d)Cr^{53}$ 1.001-MeV $\frac{5}{2}^-$ transition, while the dotted curve is an empirical $l_n=3$, $1f_{5/2}$ angular distribution from the $Cr^{54}(p,d)Cr^{53}$ 1.532-MeV $\frac{7}{2}^-$ transition. Possibly the $l_n=3$, $1f_{7/2}$ curve fits the data better than the $l_n=3$, $1f_{5/2}$ curve. It should be noted that both experimental cross sections at 20° are at least a factor of 2 greater than that predicted by an $l_n=3$ angular distribution. The origin of this forward peaking is not known, $l_n=1$ strength being forbidden by the selection rules of first-order direct-reaction theory. This forward peaking may represent the effect of second-order processes on the (p,d) angular distribution. We have shown in this section that the ground state of Cr^{53} contains a considerable admixture of the configuration $\{[Cr^{52}1.434\ MeV]^{2^+}\ 2p_{3/2}\}^{3/2}$. Now in a second-order process the incoming proton could excite the Cr^{52} 2^+ configuration in the Cr^{53} g.s. to a Cr^{52} 4^+ configuration by an $L=2$ transition, and then pick up the $2p_{3/2}$ neutron: $p+\{Cr^{52}(2^+)2p_{3/2}\}^{3/2}\rightarrow p+\{Cr^{52}(4^+)2p_{3/2}\}^{5/2,7/2}\rightarrow d+Cr^{52}(4^+)$. Also, the proton could pick up a $2p_{3/2}$ neutron, leaving the Cr^{52} nucleus in its 2^+ configuration, and the 2^+ state could then be excited to a 4^+ state by the outgoing deuteron: $p+\{Cr^{52}(2^+)2p_{3/2}\}^{3/2}\rightarrow d+Cr^{52}(2^+)\rightarrow d+Cr^{52}(4^+)$. In either case the residual Cr^{52} nucleus is left in a 4^+ state, and the (p,d) angular distribution could show forward peaking due to the pickup of a $2p_{3/2}$ neutron. It should be mentioned that the $Mn^{55}(p,\alpha)Cr^{52}$ work of Sherr *et al.*[37] and the $V^{51}(He^3,d)Cr^{52}$ work of Armstrong and Blair[39] have shown that proton seniority is not a good quantum number in the 2.370- and 2.769-MeV 4^+ levels; that is, the $v_p=2$ and $v_p=4$ $(f_{7/2}{}^4)^{J=4}$ proton configurations are well mixed in these two low-lying 4^+ levels of Cr^{52}.

The 2.965-MeV 2^+ level and the 3.112-MeV 6^+–3.161-MeV 2^+ doublet (unresolved in our data) are excited quite weakly in the $Cr^{53}(p,d)Cr^{52}$ reaction, although their angular distributions do show some forward peaking. Typical cross sections in the angular range 60° to 90° are ~10 μb/sr for the 2.965-MeV level and ~20 μb/sr for the 3.112–3.161 MeV doublet. From the experimental cross sections at 20° and 35° we can place upper limits on the $l_n=1$ and $l_n=3(1f_{7/2})$ spectroscopic strengths to these levels: $S_{l_n=1}$(2.965 MeV 2^+)<0.008, $S_{l_n=1}$(3.161 MeV 2^+)<0.015, $S_{l_n=3}$(2.965 MeV 2^+)<0.08, $S_{l_n=3}$(3.161 MeV 2^+)<0.1. We have applied these limits only to the 2^+ member of the 2^+-6^+ doublet, as a 6^+ level in Cr^{52} cannot be excited by either $l_n=1$ or $l_n=3$ neutron pickup in a first-order transition from the $\frac{3}{2}^-$ ground state of Cr^{53}.

In the excitation energy range of 3.0 to 4.5 MeV in Cr^{52} four levels are excited strongly in the (p,d) reaction, and each transition shows a very good $l_n=3$ angular distribution. These levels are the 3.432–3.494-MeV doublet, the 3.767 MeV 2^+ level and a level at 4.03 MeV. The angular distributions to the levels are presented in Fig. 6. We were not able to experimentally resolve the peaks due to the 3.432- and 3.494-MeV levels, so that the sum of the cross sections to these two states is shown in Fig. 6. Both levels in the doublet are excited strongly, since the experimental doublet peak is consistently wider than that of a well-separated single level. The peak shape of the 4.03-MeV level ($Q=-9.74$ MeV) in the deuteron spectrum has a tail due to a contribution from the $Cr^{52}(p,d)Cr^{51}$ g.s. transition ($Q=-9.82$ MeV). This contribution to the 4.03-MeV peak was subtracted out, using the previously determined $Cr^{52}(p,d)Cr^{51}$ g.s. cross sections and the isotopic abundance of Cr^{52}(3.69%) in the Cr^{53} targets.

The individual $l_n=3(1f_{7/2})$ spectroscopic strengths to these levels are 2.3 for the 3.432–3.494-MeV doublet, 0.36 for the 3.767-MeV 2^+ state and 1.14 for the 4.03-MeV state, giving a total $l_n=3$ spectroscopic

[39] D. D. Armstrong and A. G. Blair, Phys. Rev. **140**, B1226 (1965).

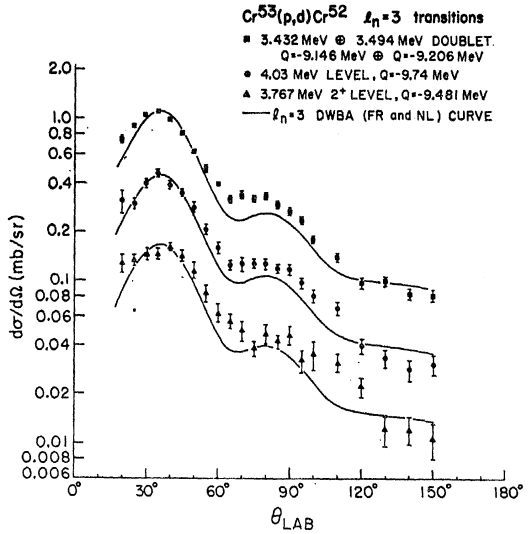

FIG. 6. Experimental, $l_n=3$, $Cr^{53}(p,d)Cr^{52}$ angular distributions to the 3.432–3.494 doublet, the 3.767-MeV 2^+ level, and a level at 4.03 MeV. The data are fitted with $l_n=3$, $1f_{7/2}$ DWBA (FR and NL) curves.

strength of 3.8 to the quartet. We have assumed here that the $l_n=3$ transitions to these levels consist entirely of $1f_{7/2}$ neutron pickup. Small admixtures of $1f_{5/2}$ neutron pickup strength may be present in the transitions to $J=2^+$, 3^+, and 4^+ levels, but the size of the $l_n=3$ spectroscopic factors precludes them being very important—the total $l_n=3$, $1f_{5/2}$ spectroscopic strength should be much less than 1. Therefore, we are on rather firm ground in maintaining that the large $l_n=3$ spectroscopic strengths are indicative of the fact that these levels in Cr^{52} have large components in their wave functions of an $1f_{7/2}$ neutron hole coupling to a $2p_{3/2}$ neutron, $(f_{7/2}^{-1}p_{3/2})$—a configuration which can be reached from the ground state of Cr^{53} by picking up any one of the eight closed-shell $1f_{7/2}$ neutrons. This same neutron configuration, $(1f_{7/2}^{-1}2p_{3/2})$, has also been excited in the $Ti^{49}(d,p)Ti^{50}$ work of Barnes *et al.*[40] Here the target has a single $1f_{7/2}$ neutron hole, and the $(1f_{7/2}^{-1}2p_{3/2})$ configuration in Ti^{50} can be reached by stripping a $2p_{3/2}$ neutron in the (d,p) reaction. The configuration $(f_{7/2}^{-1}p_{3/2})$ can couple to states of spin 2^+, 3^+, 4^+, and 5^+, and one might like to consider our quartet of experimentally excited levels as having the four different indicated spins. However, only the spin of the 3.767-MeV 2^+ level has been determined experimentally.[4,34] If the spin of one of the 3.434–3.494 MeV doublet states were 5^+, then this level might be populated in the β^+—EC decay of the 6^+ Mn^{52} ground state, but the recent work of Freedman *et al.*[30] gives no evidence that either the 3.434- or 3.494-MeV level is populated in this decay. The total $l_n=3$, $1f_{7/2}(p,d)$ spectroscopic strength to T lower states ($T=2$) in Cr^{52} should be 7.33 from the French and Macfarlane formula.[41] The difference between the total strength of 7.33 and the summed experimental strength of 3.8 to the four levels is probably taken up by two factors: one, our DWBA calculations may be predicting too large $l_n=3$ peak cross sections; and two, other 2^+, 3^+, 4^+, and 5^+ levels in Cr^{52} have some $l_n=3$, $1f_{7/2}$ strength in the $Cr^{53}(p,d)Cr^{52}$ reaction. For example, the 4^+ levels at 2.370 and 2.769 MeV could have $l_n=3$ spectroscopic strengths of 0.07 and 0.10, respectively. However, it should be noted that no levels, other than the above-mentioned quartet, in the excitation energy range between 3 and 5 MeV have individual $l_n=3$ spectroscopic strengths ≥ 0.20. Therefore, if the $(f_{7/2}^{-1}p_{3/2})^{J=2^+,3^+,4^+,5^+}$ configuration mixes in other levels, the admixture is quite small in any one level. In particular the 3.614-MeV 5^+ level, whose spin has been measured by Kaplan and Shirley,[42] has an $l_n=3$ spectroscopic factor ≤ 0.04. Table II presents the measured $l_n=1$ and $l_n=3$ spectroscopic factors in the $Cr^{53}(p,d)Cr^{52}$ reaction to levels in Cr^{52} with excitation energies less than 4.1 MeV.

TABLE II. Experimentally determined $l_n=1$ and $l_n=3$ spectroscopic factors in the $Cr^{53}(p,d)$ Cr^{52} reaction to levels in Cr^{52} below 4.1 MeV.

Level energy (MeV) and spin	$S_{l_n=1}$ ($2p_{3/2}$ pickup assumed; if $2p_{1/2}$ multiply by 1.1)	$S_{l_n=3}$ ($1f_{7/2}$ pickup assumed; if $1f_{5/2}$ multiply by 1.45)
Ground state 0^+	0.51	
1.434 2^+	0.18	Upper limit $\sim 0.20 \pm 0.07$
2.370 4^+		0.07
2.648 0^+	0.018	
2.769 4^+		0.10
2.965 2^+	<0.008	<0.08
3.115 6^+		
3.161 2^+	<0.015	<0.1
3.432–3.494 Doublet (3^+, 4^+, 5^+)		2.3
3.614 5^+		<0.04
3.767 2^+	<0.01	0.36
3.926 $J=?$	(Very weakly excited)	(Very weakly excited)
4.03 (3^+, 4^+, 5^+)		1.14

In conclusion Fig. 7 shows the comparison of an $(f_{7/2}^4)$ calculation[28] for the level scheme of $_{24}Cr_{28}^{52}$ and the experimental situation up to 4 MeV. Our data is quite consistent with $(f_{7/2}^4)$ proton configurations being reasonably good wave functions for the 1.434-MeV 2^+ level, the 2.370- and 2.769-MeV 4^+ levels, and the 3.614-MeV 5^+ level. The small experimental $l_n=3$ spectroscopic strengths to these $J=2^+$ to 5^+ levels imply that the $(f_{7/2}^{-1}p_{3/2})^{J=2^+ \text{ to } 5^+}$ configuration is only a small component of their wave functions. The very small $l_n=3$ spectroscopic factor ($S<0.04$) to the 3.614-MeV 5^+ level is particularly interesting, as there is almost certainly another 5^+ level within 200 to 400 keV with a large $(f_{7/2}^{-1}p_{3/2})^{5^+}$ component. However,

[40] P. D. Barnes, C. K. Bockelman, O. Hansen, and A. Sperduto, Phys. Rev. **140**, B42 (1965).
[41] J. B. French and M. H. Macfarlane, Nucl. Phys. **26**, 168 (1961).
[42] M. Kaplan and D. A. Shirley, Nucl. Phys. **37**, 522 (1962).

the configurations of these two levels do not seem to mix. With regard to the second 2^+ level, the $(f_{7/2}{}^4)$ picture does not seem to work so well. From a comparison of excitation energies one would like to consider the $v=4$, 2^+ state in the $(f_{7/2}{}^4)$ calculations ($E_x=3.61$) as the experimental 2^+ level at 3.767 MeV, but our experiment has shown that this level has a large $(f_{7/2}{}^{-1}p_{3/2})^{2^+}$ component in its wave function. Certainly the most important shortcoming of the $(f_{7/2}{}^4)$ theory, as a complete picture for Cr^{52} below $E_x=4$ MeV, is that it just does not predict enough states up to 4 MeV to explain the level structure of Cr^{52} in this region. Therefore, other nuclear configurations must be important. One result of this work has been to show that the neutron configuration $(f_{7/2}{}^{-1}p_{3/2})^{J=2^+ \text{ to } 5^+}$ is a large component of some levels in Cr^{52}, at least in the excitation region from 3.4 to 4.2 MeV.

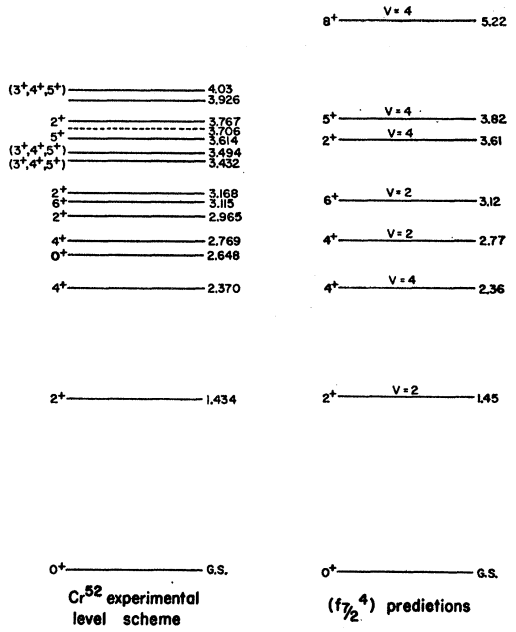

FIG. 7. Comparison of the experimental level structure in Cr^{52} up to 4 MeV in excitation energy with the calculations of de-Shalit (Ref. 28) assuming pure $(f_{7/2}{}^4)$ proton configurations.

5. $Cr^{54}(p,d)Cr^{53}$ DATA AND DISCUSSION

Figure 8 shows a deuteron spectrum from the $Cr^{54}(p,d)Cr^{53}$ reaction at $\theta_{lab}=40°$. The energy-level diagram of Cr^{53} up to 3.6 MeV in excitation is taken from the work of Bjerregaard *et al.*[43] They studied the level structure of Cr^{53} by the $Cr^{52}(d,p)$ reaction (E_x up to 3.6 MeV) and by the $Mn^{55}(d,\alpha)$ reaction (E_x up to 2.5 MeV) using low-energy deuterons (3–4.3 MeV). Their energies are quoted to ±8 keV or better. We have assumed that all levels below 3.6 MeV in excitation which are excited in the (p,d) reaction correspond to levels seen by Bjerregaard *et al.* In general the experimental excitation energies, found using either the Cr^{53} g.s. and O^{15} g.s. or the Cr^{53} g.s. and Cr^{53} 1.532-MeV peak positions to obtain a $\Delta E_x/\Delta$ channel calibration curve, agree with the Bjerregaard values to within ±20 keV.

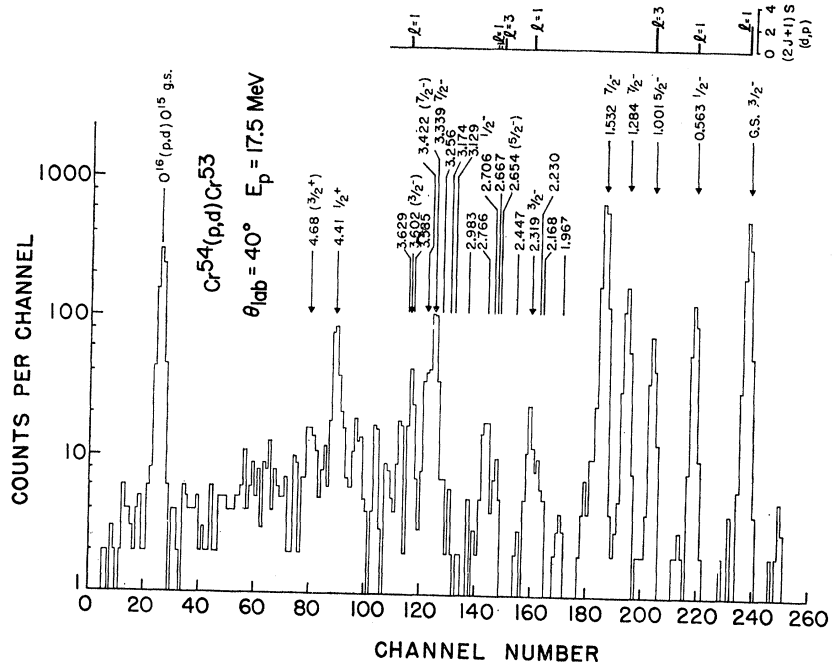

FIG. 8. Deuteron spectrum from the $Cr^{54}(p,d)Cr^{53}$ reaction on a thin (~0.5 mg/cm²), isotopic (97.98%) Cr^{54} foil. $E_p=17.5$ MeV, and $\theta_{lab}=40°$. The Cr^{53} energy-level diagram up to an excitation energy of 3.63 MeV is taken from the work of Ref. 43. All energy levels marked with an arrow will have their (p,d) angular distributions presented in this work. The $(2J+1)S$ spectroscopic strengths in the $Cr^{52}(d,p)Cr^{53}$ reaction are taken from the work of Ref. 47.

[43] J. H. Bjerregaard, P. F. Dahl, O. Hansen, and G. Sidenius, Nucl. Phys. **51**, 641 (1964).

Above 3.6 MeV in Cr^{53} only one state is excited strongly in the (p,d) reaction, that being a level at 4.41 ± 0.02 MeV which has an angular distribution characteristic of $l_n=0$. Those levels whose angular distributions are presented in this work are marked with an arrow in Fig. 8. The $Cr^{52}(d,p)$ reaction has been studied in many experiments including those of Bedewi and Tadros,[44] Bochin *et al.*,[45] Andrews *et al.*,[46] Sperduto and Wiedner,[47] and Bock *et al.*[48] A graph on the right-hand side of Fig. 8 shows the values of $(2J+1)S$ obtained in the (d,p) work of Sperduto and Wiedner[47] for strongly excited levels in Cr^{53} up to an excitation energy of 3.6 MeV.

All of the first five levels in Cr^{53} are excited rather strongly in the $Cr^{54}(p,d)Cr^{53}$ reaction. The ground-state spin of Cr^{53} is known to be $\frac{3}{2}^-$ from the experiment of Bowers[49] on the paramagnetic resonance spectrum of Cr^{53}. A spin assignment of $\frac{1}{2}^-$ for the 0.563 level has been strongly suggested by at least three different experimental techniques. One, the $(d,p)l_n=1$ angular distribution to this level as measured by Andrews *et al.*[46] shows the dip at back angles which has been found to be characteristic of $J=\frac{1}{2}$.[9,50] Two, in a thermal-neutron-capture γ-ray experiment using Cr^{52} as a target, Bartholomew and Gunye[51] found that the angular correlation between the 7.36-MeV γ ray populating the 0.563-MeV level from the $\frac{1}{2}^+$ capture state and the 0.563-MeV γ ray was isotropic. This suggests a spin of $J=\frac{1}{2}$ for the 0.563-MeV level from the γ cascade $(\frac{1}{2}^+\rightarrow\frac{1}{2}^-\rightarrow\frac{3}{2}^-)$, although certain $E2$ to $M1$ ratios will give isotropic angular correlations in the γ cascade sequence $(\frac{1}{2}^+\rightarrow\frac{3}{2}^-\rightarrow\frac{3}{2}^-)$. Three, the form, as a function of neutron energy, of the $Cr^{53}(n,n'\gamma)$ cross section to the 0.563-MeV level, which was measured by Van Patter *et al.*,[33] suggests a spin of $\frac{1}{2}$. The Cr^{53} level at 1.001 MeV has been assigned a spin of $\frac{5}{2}^-$ on the basis of $l_n=3$ spectroscopic strength $[(2J+1)S=2.4]$ in the $Cr^{52}(d,p)$ reaction.[47] If the spin of the 1.001-MeV level were $\frac{7}{2}^-$, this spectroscopic strength would mean that the $1f_{7/2}$ neutron shell was at least $\sim30\%$ empty, which is a result in contradiction to the assumption of the $1f_{7/2}$ shell closure at $N=28$. The best evidence for the spin assignments of $J=\frac{7}{2}^-$ to the levels at 1.284 and 1.532 MeV comes from the present work. In the $Cr^{54}(p,d)Cr^{53}$ reaction both of these levels are excited with $l_n=3$ angular distributions of similar shape, which show a J dependence when compared to the $l_n=3(p,d)$ angular distribution to the $\frac{5}{2}^-$ 1.001-MeV state. Both the 1.284- and 1.532-MeV levels are excited weakly in the $Cr^{52}(d,p)Cr^{53}$ reaction by comparison with the $\frac{5}{2}^-$ level at 1.001 MeV: $[\sigma(1.284)/\sigma(1.001)]\cong0.18$ and $[\sigma(1.532)/\sigma(1.001)]\cong0.12$.[46] This can be explained in the simple shell-model picture by the closed $1f_{7/2}$ neutron shell in Cr^{52}. In the $Cr^{52}(p,p\gamma)Cr^{53}$ work of Rollefson *et al.*[52] it is found that a level at 3.70-MeV decays almost entirely through the 1.284-MeV level. With good certainty the spin and parity assignments for the 3.70-MeV level are $\frac{9}{2}^+$, as it shows an $l_n=4$ stripping pattern in the $Cr^{52}(d,p)$ reaction,[46,47] and thus represents a $1g_{9/2}$ single-particle state. This $\frac{9}{2}^+$ level could decay to a $\frac{7}{2}^-$ level through an $E1$ transition, and its measured branching ratio is additional evidence that the spin of the 1.284 level is $\frac{7}{2}^-$.

The only experimental evidence which bears on the spin assignment for the 1.967-MeV level is the observation of Rollefson *et al.*[52] that it decays primarily to the ground state. Since the parity of this state is almost certainly negative (the positive-parity hole and single-particle levels lie higher in energy), this would limit the spin to $\leq\frac{7}{2}$; since, for example, a $\frac{9}{2}^-$ state would be expected to decay either to the $\frac{5}{2}^-$ 1.001-MeV level by an $E2$ transition or to the $\frac{7}{2}^-$ levels by an $M1+E2$ transition, rather than to the ground state by an $M3$ transition. The 1.967 level is excited weakly in both the (d,p)[46] and (p,d) reactions, but it has appreciable strength in the $Cr^{53}(p,p')$ reaction as will be discussed in the next section (Sec. 6).

The spins of certain other Cr^{53} levels at higher excitation energies [mainly those excited strongly in the (d,p) reaction] have been determined by the same experimental techniques described in the discussion of the low-lying levels. The 2.319-MeV level has been assigned a spin of $\frac{3}{2}$ by the $l_n=1$ J dependence of its (d,p) cross section[46]; the $(n,\gamma\gamma)$ angular correlation work (definite anisotropy)[51]; and the behavior of its $(n,n'\gamma)$ excitation function.[33] A spin of $\frac{5}{2}^-$ would be indicated for the 2.654-MeV level from its $l_n=3$ strength in the (d,p) reaction: $(2J+1)S=0.81$.[47] At least one of the $(d,p)l_n=1$ doublet of levels at 2.667 and 2.706 MeV (Sperduto and Wiedner[47] give energies 2.681 and 2.723 MeV) has a spin $\frac{1}{2}$ from the $(n,\gamma\gamma)$ angular correlation work.[51] Finally a level at 3.62 ± 0.02 MeV is assigned a spin $\frac{3}{2}$ on the basis of its $l_n=1$ J dependence in the (d,p) reaction[46] and from the $(n,\gamma\gamma)$ experiment,[51] where a slight anisotropy in the angular correlation of the two γ's is found. None of these levels are excited strongly in the $Cr^{54}(p,d)$ reaction. On the basis of the $Cr^{54}(p,d)Cr^{53}$ reaction we are able to give rather certain spin assignments of $\frac{7}{2}^-$ to the 3.339-MeV level and $\frac{1}{2}^+$ to the 4.41-MeV level, as will be discussed in this section.

[44] F. A. Bedewi and S. Tadros, Nucl. Phys. **19**, 604 (1960).
[45] V. P. Bochin, K. I. Zherebtsova, V. A. Zolotarev, V. A. Komarov, L. V. Krasnov, V. F. Litvin, Yu A. Nemilov, B. G. Novatsky, and Sh. Piskorzh, Nucl. Phys. **51**, 161 (1964).
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[48] R. Bock, H. H. Duhm, S. Martin, R. Rudel, and R. Stock, Nucl. Phys. **72**, 273 (1965).
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[50] J. P. Schiffer, in *Argonne Conference on Nuclear Spectroscopy with Direct Reactions*, edited by F. E. Throw (Argonne National Laboratory, Argonne, Illinois, 1964), Report No. ANL-6878, Vol. II, p. 279.
[51] G. A. Bartholomew and M. R. Gunye, Can. J. Phys. **43**, 1128 (1965).
[52] A. A. Rollefson, R. C. Bearse, J. C. Legg, G. C. Phillips, and G. Roy, Nucl. Phys. **63**, 561 (1965).

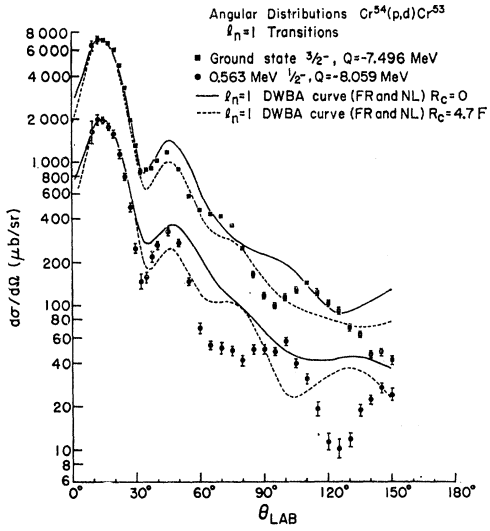

FIG. 9. Experimental $l_n=1$, $Cr^{54}(p,d)Cr^{53}$ angular distributions to the $\frac{3}{2}^-$ ground state and the $\frac{1}{2}^-$ 0.563-MeV level. The ground-state transition is fit with an $l_n=1$, $2p_{3/2}$ DWBA (FR and NL) curve, while the transition to the 0.563-MeV level is fitted with an $l_n=1$, $2p_{1/2}$ DWBA (FR and NL) curve.

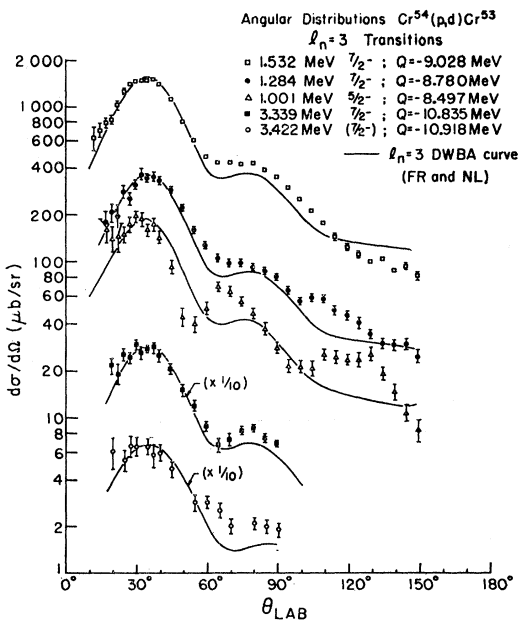

FIG. 10. Experimental, $l_n=3$, $Cr^{54}(p,d)Cr^{53}$ angular distributions to the $\frac{5}{2}^-$ 1.001-MeV level, the $\frac{7}{2}^-$ 1.284-MeV level, the $\frac{7}{2}^-$ 1.532-MeV level, the $\frac{7}{2}^-$ 3.339-MeV level, and the $(\frac{7}{2}^-)$3.422-MeV level. The transition to the 1.001-MeV level is fit with an $l_n=3$, $1f_{5/2}$ DWBA (FR and NL) curve, while the transitions to the levels at 1.284 MeV, 1.532 MeV, 3.339 MeV, and 3.422 MeV are fitted with $l_n=3$, $1f_{7/2}$ DWBA (FR and NL) curves.

Figure 9 presents the $l_n=1$ (p,d) angular distributions to the $\frac{3}{2}^-$ ground state of Cr^{53} and the $\frac{1}{2}^-$ first excited state at 0.563 MeV. The dependence of these angular distributions on the total angular momentum J of the transferred neutron is very definite. This J dependence of $l_n=1$ transitions in the (p,d) reaction at $E_p=17.5$ MeV is seen in two main characteristics of the angular distributions. One, in the $J=\frac{1}{2}$, $l_n=1$ case the angular distribution has a broad shoulder of constant cross section between $\sim 65°$ and 95°, while in the $J=\frac{3}{2}$, $l_n=1$ case it decreases by a factor of ~ 4 in this region with only narrow shoulders. Two, the $J=\frac{1}{2}$, $l_n=1$ angular distribution has a deep minimum at a back angle between $\sim 120°$ to 130°,[9] which is not seen in the $J=\frac{3}{2}$, $l_n=1$ angular distribution. These same two characteristic differences between $l_n=1(p,d)$ transitions to $J=\frac{1}{2}$ and $J=\frac{3}{2}$ final states are seen by Glashausser[7] in the $Fe^{56}(p,d)$ reaction at 18 MeV and the $Ni^{58}(p,d)$ reaction at 20 MeV—at these proton energies the outgoing deuterons have about the same energy (9–10 MeV) as in our $Cr^{54}(p,d)$ work with 17.5-MeV protons. The calculated $l_n=1$ spectroscopic factors to the $\frac{3}{2}^-$ ground state and the 0.563-MeV $\frac{1}{2}^-$ level are 0.83 and 0.31, respectively, this showing an admixture in the Cr^{54} g.s. of the configuration $(2p_{1/2}{}^2)^0$.

Figure 10 presents the $l_n=3$ (p,d) angular distributions to five levels in Cr^{53}: the $\frac{5}{2}^-$ level at 1.001 MeV, the $\frac{7}{2}^-$ levels at 1.284, 1.532, and 3.339 MeV, and a probable $\frac{7}{2}^-$ level at 3.422 MeV. As in the $l_n=1$ case, one can see in the angular distribution a definite dependence on the angular momentum J of the picked-up neutron. The angular distribution corresponding to $1f_{5/2}$ neutron pickup falls off faster with angle after its maximum than that corresponding to $1f_{7/2}$ neutron pickup; and the $l_n=3$, $1f_{5/2}$ transition shows a definite second maximum at 65°, which is not found in the $l_n=3$, $1f_{7/2}$ transitions. This same $l_n=3$ J dependence has also been found by Glashausser in $E_p=18$ MeV $Fe^{56}(p,d)$ transitions and $E_p=20$ MeV $Ni^{58}(p,d)$ transitions to $J=\frac{5}{2}$ and $\frac{7}{2}$ final states. Sherr *et al.*[6] found a marked J dependence in $1f_{5/2}$ and $1f_{7/2}(p,d)$ transitions at $E_p=28$ MeV. The first maximum of an $1f_{5/2}$ neutron pickup transition was at more forward angle, and the cross section fell off faster with increasing angle than that of an $1f_{7/2}$ neutron pickup transition.

The (p,d) $l_n=3$ spectroscopic factor to the $\frac{5}{2}^-$ 1.001-MeV level was determined to be 0.51 from the DWBA (FR and NL) calculations. The $l_n=3$ spectroscopic factors to the $\frac{7}{2}^-$ levels at 1.284, 1.532, 3.339, and 3.422 MeV were determined to be 0.70, 3.2, 1.2, and 0.30, respectively. The large $l_n=3$ (p,d) spectroscopic factor $(S=1.2)$ to the 3.339-MeV level, and the fact that this level has not been reported with $l_n=3$ spectroscopic strength in the $Cr^{52}(d,p)$ work of Sperduto and Wiedner[47] make the spin assignment of $\frac{7}{2}$ to this level quite strong. The same arguments would also assign a spin of $\frac{7}{2}$ to the 3.422-MeV level $[S_{l_n=3}(p,d)=0.30]$. The total experimental $l_n=3$, $1f_{7/2}$ spectroscopic strength to these four levels in Cr^{53} is then 5.4. This should be compared to the predicted $T_<(T=\frac{5}{2})$, $l_n=3$, $1f_{7/2}$ spectroscopic strength of 7.43 from the formulas of French and Macfarlane.[41] Taking into account uncertainties in the absolute spectroscopic strengths extracted from the

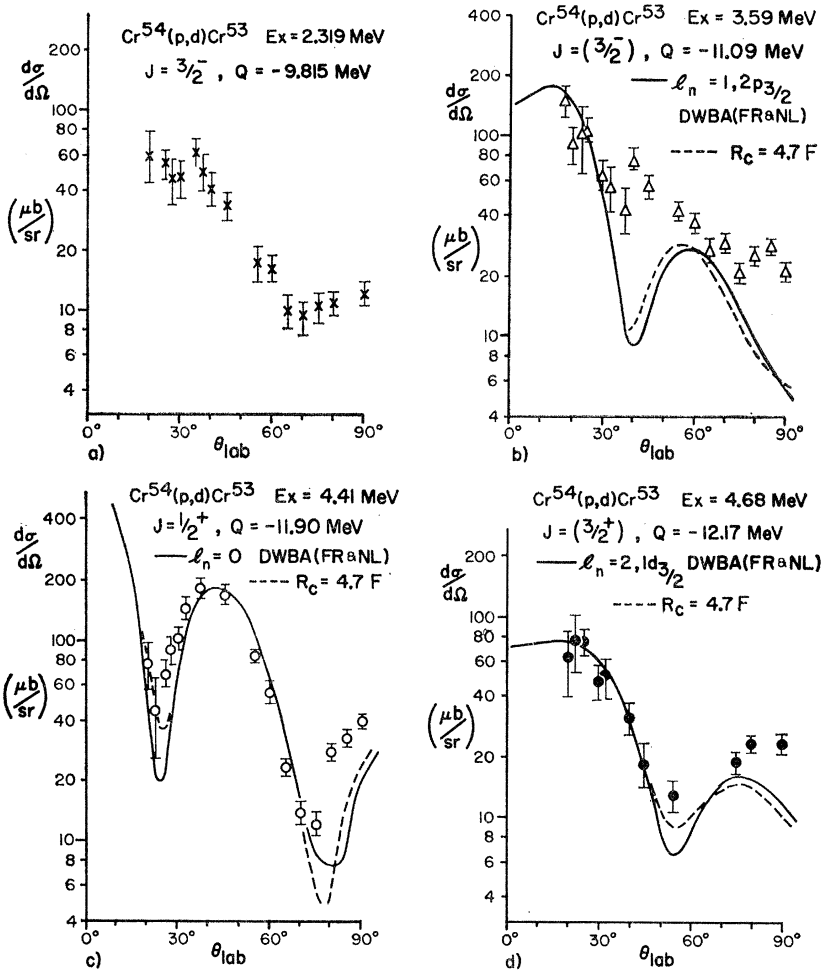

FIG. 11. (a) Experimental $Cr^{54}(p,d)Cr^{53}$ angular distribution to a $\frac{3}{2}^-$ level at 2.319 MeV. This transition cannot be fitted with an $l_n=1$, $2p_{3/2}$ DWBA (FR and NL) curve. (b) Experimental $Cr^{54}(p,d)Cr^{53}$ angular distribution to a $(\frac{3}{2}^-)$ level at 3.59±0.02 MeV. The data is fit with an $l_n=1$, $2p_{3/2}$ DWBA (FR and NL) curve, using the Dickens and Perey deuteron parameters (see Table I) with a real deuteron well depth of 100 MeV. (c) Experimental $Cr^{54}(p,d)Cr^{53}$ angular distribution to a $\frac{1}{2}^+$ level at 4.41±0.02 MeV. The data are fitted with an $l_n=0$, $2s_{1/2}$ DWBA (FR and NL) curve, using the Dickens-Perey deuteron parameters (see Table I) with a real deuteron well depth of 105 MeV. (d) Experimental $Cr^{54}(p,d)Cr^{53}$ angular distribution to a $(\frac{3}{2}^+)$ level at 4.68±0.02 MeV. The data are fitted with an $l_n=2$, $1d_{3/2}$ DWBA (FR and NL) curve, using the Dickens-Perey deuteron parameters (see Table I) with a real deuteron well depth of 110 MeV.

data by the DWBA theory, it would thus appear that we have located most of $T_<$, $l_n=3$, $1f_{7/2}$ spectroscopic strength in the levels of Cr^{53}.

The $l_n=0(p,d)$ angular distribution to the 4.41±0.02-MeV $\frac{1}{2}^+$ level in Cr^{53} is presented in Fig. 11(c). We are able to fit the angular distribution very well from 25 to 70° using the DWBA curves. Figure 11(c) shows the DWBA fit to the data using the Dickens-Perey set B parameters with an extrapolated well depth, $V=105$ MeV, to better characterize the low-energy deuterons. The use of a radial cutoff, $R_c=4.7$ F,—the dotted line in Fig. 11(c)—does not improve the fit to the experimental data substantially. With no radial cutoff the $l_n=0$ spectroscopic strength to the 4.41-MeV level is 1.40, a figure derived from the ratio of the experimental cross section at the second maximum, ~40°, to the DWBA prediction. This spectroscopic factor is quite sensitive to the real deuteron well depth and the use of a radial cutoff: for $V_D=100$ MeV, $S=1.80$, and for $V_D=110$ MeV, $S=1.05$; while for $V_D=105$ MeV and $R_c=4.7$ F, $S=1.00$. Although we cannot quote the absolute $l_n=0$ spectroscopic strength to this level to better than 30% or so, it does seem clear that the wave function of this level is well described in terms of an $2s_{1/2}$ neutron hole in the ground state of Cr^{54}. The total $T_<l_n=0$ spectroscopic strength is 1.71.[41] Sperduto and Wiedner[47] do not report seeing this level in their study of the $Cr^{52}(d,p)$ reaction. The first $l_n=0(d,p)$ transition they find is to a level at 4.696 MeV.

One of the more interesting aspects of the $Cr^{54}(p,d)$ data is the weak excitation of the $\frac{3}{2}^-$ 2.319-MeV level. This level is excited quite strongly in the $Cr^{52}(d,p)$ reaction. Sperduto and Wiedner[47] find that the $l_n=1$ (d,p) spectroscopic strength to this level (their energy is 2.327 MeV) is 40% that of the $Cr^{52}(d,p)$ ground-state transition. If this state had 40% of the ground state $l_n=1$ spectroscopic strength in the $Cr^{54}(p,d)$ reaction, we would expect to see an $l_n=1$ angular distribution with a peak cross section of 1.2 mb/sr, taking into account the Q dependence of the (p,d) reaction. The angular distribution to the 2.319-MeV $\frac{3}{2}^-$ level is shown in Fig. 11(a). This angular distribution does not resemble an $l_n=1$ transition; in fact it can be fitted reasonably well with a DWBA $l_n=3$ curve. It is possible that there is an unresolved $\frac{5}{2}^-$ or $\frac{7}{2}^-$ level which is being excited in the $Cr^{54}(p,d)$ reaction rather than the 2.319-

MeV level; but this explanation of the shape of the angular distribution still does not answer the question of why the $l_n=1$ spectroscopic strength is so weak. A possible explanation lies in the fact that the Cr^{54} ground state probably has a much more complicated structure than the Cr^{52} ground state. A study of the $Cr^{52}(p,d)$ reaction at Princeton[53] has shown that the ground state of Cr^{52} is rather well described by a closed $1f_{7/2}$ neutron shell at $N=28$ and four $1f_{7/2}$ protons coupled to zero. Thus in the $Cr^{52}(d,p)$ reaction the $l_n=1$, $2p_{3/2}$ spectroscopic strength is a direct measure of the admixture of the configuration $\{(\pi f_{7/2}{}^4)^0\nu 2p_{3/2}\}^{3/2}$ in a given $\frac{3}{2}^-$ level in Cr^{53}. However, the ground state of Cr^{54}, in addition to neutron configurations such as $(2p_{3/2}{}^2)^0$, $(1f_{5/2}{}^2)^0$, and $(2p_{1/2}{}^2)^0$, probably has a configuration of the form $\{(\pi f_{7/2}{}^4 v=2)^2(\nu 2p_{3/2}{}^2)^2\}^0$; that is

$$\mathrm{Cr}^{54}(\mathrm{g.s.})^{0+}=\alpha\{(\pi f_{7/2}{}^4)^0(\nu 2p_{3/2}{}^2)^0\}^0 +\beta\{(\pi f_{7/2}{}^4 v=2)^2(\nu 2p_{3/2}{}^2)^2\}^0+\cdots.$$

Now a $\frac{3}{2}^-$ level in Cr^{53} is a linear combination of configurations such as $\{(\pi f_{7/2}{}^4)^0\nu 2p_{3/2}\}^{3/2}$, $\{(\pi f_{7/2}{}^4 v=2)^2\text{-}\nu 2p_{3/2}\}^{3/2}$, etc.; this is, $\mathrm{Cr}^{53}{}^{3/2^-}$ (any given level) $=\alpha'\{(\pi f_{7/2}{}^4)^0\nu 2p_{3/2}\}^{3/2}+\beta'\{(\pi f_{7/2}{}^4 v=2)^2\nu 2p_{3/2}\}^{3/2}+\cdots$, and it can be easily shown that the $l_n=1$, $2p_{3/2}(p,d)$ spectroscopic factor to a $\frac{3}{2}$ state in Cr^{53} with coefficients α' and β' is given by: $S(p,d)=2|\alpha\alpha'+\beta\beta'|^2$. Thus, while the $l_n=1$, $2p_{3/2}$ spectroscopic strength in the $Cr^{52}(d,p)$ reaction is dependent only on the value of the coefficient α', $S(d,p)=(\alpha')^2$, the (p,d) $l_n=1$ spectroscopic strength to a $\frac{3}{2}^-$ level in Cr^{53} depends not only on the absolute values of α, α', β, and β', but also on their relative sign. In particular it can be true that $S(p,d)$ to a certain $\frac{3}{2}$ level is approximately zero because of cancellation in the coherent sum of the coefficients, while $S(d,p)$ to the same level is quite large. If $L=2$ spectroscopic factors could be extracted by a (p,t) reaction theory, the coefficient β could be determined by the strength of the $Cr^{54}(p,t)Cr^{52}$ 1.434-MeV 2^+ transition.

Using the energy levels of Bjerregaard *et al.*[43] for calibration, we find that a level at 3.592±0.015 MeV is excited with some strength at forward angles in the $Cr^{54}(p,d)$ reaction. The (p,d) angular distribution to this level is fit fairly well with an $l_n=1$ DWBA curve, except for the 40° and 45° points, as is shown in Fig. 11(b). The $l_n=1(p,d)$ spectroscopic strength to this level is 0.12±0.03. Bock *et al.*[48] report exciting levels at 3.587 and 3.610 MeV with respective $l_n=1$, (d,p), $(2J+1)S$ strengths of 0.06 and 0.86, while Sperduto and Wiedner[47] report a (d,p), $l_n=1$ transition to a level at 3.629 MeV with a $(2J+1)S$ strength of 0.96. There is a systematic difference of ~5.5 keV per MeV of excitation between the excitation energies reported by Bjerregaard *et al.*[43] and by Sperduto and Wiedner,[47] so that the 3.629-MeV level of Sperduto and Wiedner would be about 3.609 MeV on the Bjerregaard *et al.* energy scale, and almost definitely corresponds to the 3.610-MeV level of Bock *et al.*[48] Also, as was mentioned earlier, a level at 3.62±0.02 MeV has been rather definitely assigned a spin of $\frac{3}{2}$.[46,51] Thus it would be most consistent to assume that we are exciting in the (p,d) reaction at least one of the doublet of $l_n=1$ levels at 3.6 MeV seen in the (d,p) work of Bock *et al.*,[48] with the spin of this level being $\frac{3}{2}$.

Figure 11(d) presents the (p,d) angular distribution for a level in Cr^{53} at $E_x=4.68\pm0.02$ MeV. At forward angles (20° to 50°) this transition is fitted quite well by an $l_n=2$, $1d_{3/2}$ DWBA (FR and NL) curve. With the Dickens-Perey set B deuteron parameters and an extrapolated deuteron well depth of 110 MeV, the $1d_{3/2}$, (p,d) spectroscopic strength is 0.85 for $R_c=0$, and 0.73 for $R_c=4.7$ F. For $V_{\mathrm{deut}}=105$ MeV and $R_c=0$, the (p,d) spectroscopic strength is 1.05, while for $V_{\mathrm{deut}}=115$ MeV and $R_c=0$, $S(p,d)=0.74$. Thus the approximate $l_n=2$, $1d_{3/2}(p,d)$ spectroscopic strength for this transition is 0.85±0.2. This figure should be compared with the total $T_<$, $1d_{3/2}$ hole strength of 3.43 for the $Cr^{54}(p,d)$ reaction.[41] We have assumed here that the spin of the 4.68-MeV level is $\frac{3}{2}^+$ since this is the lowest-lying state in Cr^{53} reached by an $l_n=2$ transition in the (p,d) reaction and the $1d_{3/2}$ hole states should be lower in energy than the $1d_{5/2}$ hole states.

Table III presents a summary of the experimentally determined spectroscopic strengths for Cr^{53} levels excited in the $Cr^{54}(p,d)$ reaction. For the transitions to the ground state and the first four excited states of Cr^{53} quite good agreement is found between our $Cr^{54}(p,d)$

TABLE III. $Cr^{54}(p,d)Cr^{53}$ spectroscopic factors.

Excitation energy in MeV	J	l_n	$S(p,d)$
g.s.	$\frac{3}{2}^-$	1	0.83
0.563	$\frac{1}{2}^-$	1	0.31
1.001	$\frac{5}{2}^-$	3	0.51
1.284	$\frac{7}{2}^-$	3	0.70
1.532	$\frac{7}{2}^-$	3	3.2
1.967	J?	(weakly excited)	$S(p,d)<0.08$ if $J=\frac{5}{2}^-$; $S(p,d)<0.06$ if $J=\frac{7}{2}^-$
2.319	$\frac{3}{2}^-$	no $l_n=1(p,d)$ stripping distribution from $d\sigma/d\Omega(20°)$; $S_{l_n=1}<0.02$	
2.654	$\frac{5}{2}^-$	(weakly excited) from $d\sigma/d\Omega_{\max}(40°)$; $S_{l_n=3}<0.08$	
2.706	$\frac{1}{2}^-$	(weakly excited) from $d\sigma/d\Omega_{\max}(20°)$; $S_{l_n=1}<0.012$	
3.339	$\frac{7}{2}^-$	3	1.2
3.422	$(\frac{7}{2}^-)$	3	0.30
3.59	$\frac{3}{2}^-$	1	0.12±0.03
4.41	$\frac{1}{2}^+$	0	1.40[a]
4.68	$(\frac{3}{2}^+)$	2	0.85[b]

[a] $V_D=105$ MeV, $R_c=0$.
[b] $V_D=110$ MeV, $R_c=0$.

[53] C. A. Whitten, Jr., doctoral thesis, Princeton University, 1966 (unpublished).

results and the $Cr^{54}(He^3,\alpha)$ and $Cr^{54}(d,t)$ results of Bock *et al.*[54]

6. $Cr^{53}(p,p')$ DATA AND DISCUSSION

Figure 12 presents an inelastic proton spectrum for the $Cr^{53}(p,p')$ reaction at $\theta_{lab}=50°$. The 1.001-MeV $\frac{5}{2}^-$ level, the 1.284-MeV $\frac{7}{2}^-$ level and the 1.967-MeV $J=?$ level are all excited quite strongly, while the cross section to the 1.532-MeV $\frac{7}{2}^-$ level is down by at least an order of magnitude when compared with those to the "strong" levels. The 0.563-MeV $\frac{1}{2}^-$ level is also strongly excited in the (p,p') reaction, but at $\theta_{lab}=50°$ its peak is obscured by elastic proton peaks from carbon and oxygen contaminants in the Cr^{53} target. These contaminant peaks move across the Cr^{53} inelastic proton spectrum as a function of angle so that the 0.563-MeV peak is obscured from 40° to 55°; the 1.001-MeV peak cannot be analyzed at 55°, or from 65° to 70°; the 1.284-MeV peak is blocked at 70°, and from 80° to 85°; and the 1.967-MeV peak cannot be analyzed at 85°, and from 100° to 110°. The angles where the data were taken were specifically chosen so that the maximum amount of information could be extracted about the angular distribution of each of these four levels. Figure 12 shows that many levels in Cr^{53} above 2 MeV in excitation are excited with some strength in the (p,p') reaction, but, between 2 and 3.4 MeV, no single level is excited with a cross section comparable to the four above-mentioned low-lying levels.

Figure 13 presents the (p,p') angular distributions of the 0.563-, 1.001-, 1.284-, and 1.967-MeV levels. The dashed lines are drawn smoothly through the experimental points. In the forward direction all the angular distributions are quite similar and show a definite maximum at 35°. The triangular points in Fig. 13 represent the sum of the cross sections to all four levels. When a particular inelastic peak was obscured by either the carbon or oxygen elastic peak, the cross section to this level was estimated from the similarity of its angular distribution with those of the other three levels. At any one angle only a single cross section was estimated by this procedure, so that the error introduced in the summed cross section should be small. The black line in Fig. 13 represents the $Cr^{52}(p,p')$ angular distribution to the 1.434-MeV 2^+ level, which was measured in a separate experiment. The peak cross section of 5.1 mb/sr at $\theta_{lab}=35°$ for the $Cr^{52}(p,p')Cr^{52}$ 1.434-MeV 2^+ reaction was taken from the $Cr^{52}(p,p')$ experiment of Funsten *et al.*[4] at Princeton. There is a striking similarity in shape and absolute value between the (p,p') angular distribution to the Cr^{52} 1.434-MeV 2^+ level, and the summed (p,p') angular distributions to the 0.563-, 1.001-, 1.284-, and 1.967-MeV Cr^{53} levels, particularly in the angular range 25° to 55°. The strong inelastic excitation of the 0.563-, 1.001-, 1.284-, and 1.967-MeV levels has also been reported by Meriwether *et al.*[55] in the $Cr^{53}(\alpha,\alpha')$ reaction and by Bock *et al.*[54] in the $Cr^{53}(d,d')$ reaction.

The $Cr^{53}(p,p')$ excitation of four low-lying levels with $l=2$ angular distributions similar to the $Cr^{52}(p,p')$ 1.434-MeV 2^+ angular distribution suggests that the weak-coupling model may be a useful tool in describing

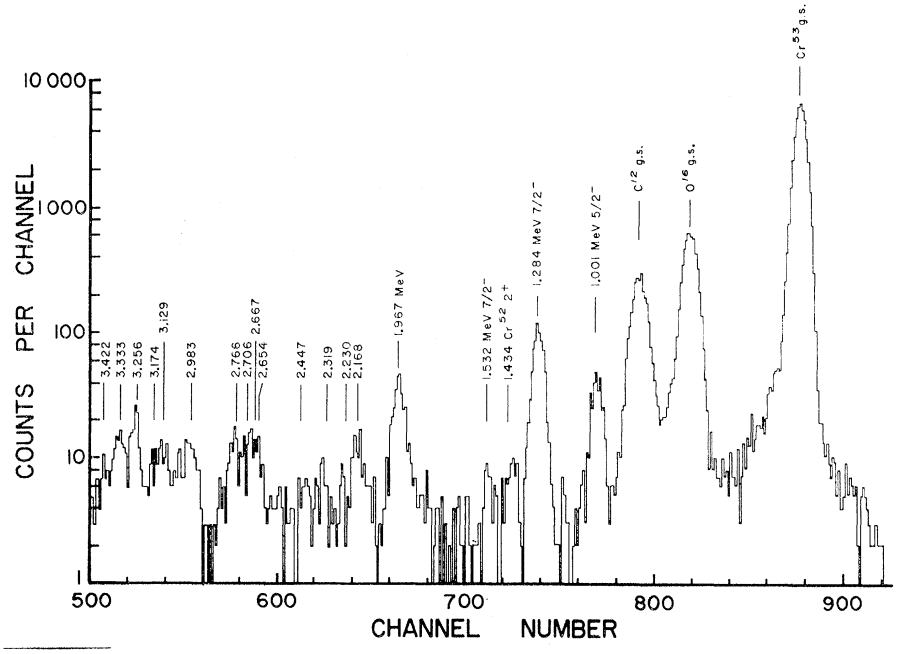

FIG. 12. Proton spectrum from the $Cr^{53}(p,p')Cr^{53}$ reaction on a thin (~0.5 mg/cm²), isotopic (96.4%)Cr^{53} foil. $E_p=17.5$ MeV, and $\theta_{lab}=50°$. The 1.001-MeV $\frac{5}{2}^-$ level, the 1.284-MeV $\frac{7}{2}^-$ level, and the 1.967-MeV level are all strongly excited in proton inelastic scattering along with the 0.563-MeV $\frac{1}{2}^-$ level, whose peak is obscured at $\theta_{lab}=50°$ by the oxygen elastic proton peak.

[54] R. Bock, H. H. Duhm, R. Jahr, R. Santo, and R. Stock, Phys. Letters **19**, 417 (1965).
[55] J. R. Meriwether, I. Gabrielli, D. L. Hendrie, J. Mahoney, and B. G. Harvey, Phys. Rev. **146**, 804 (1966).

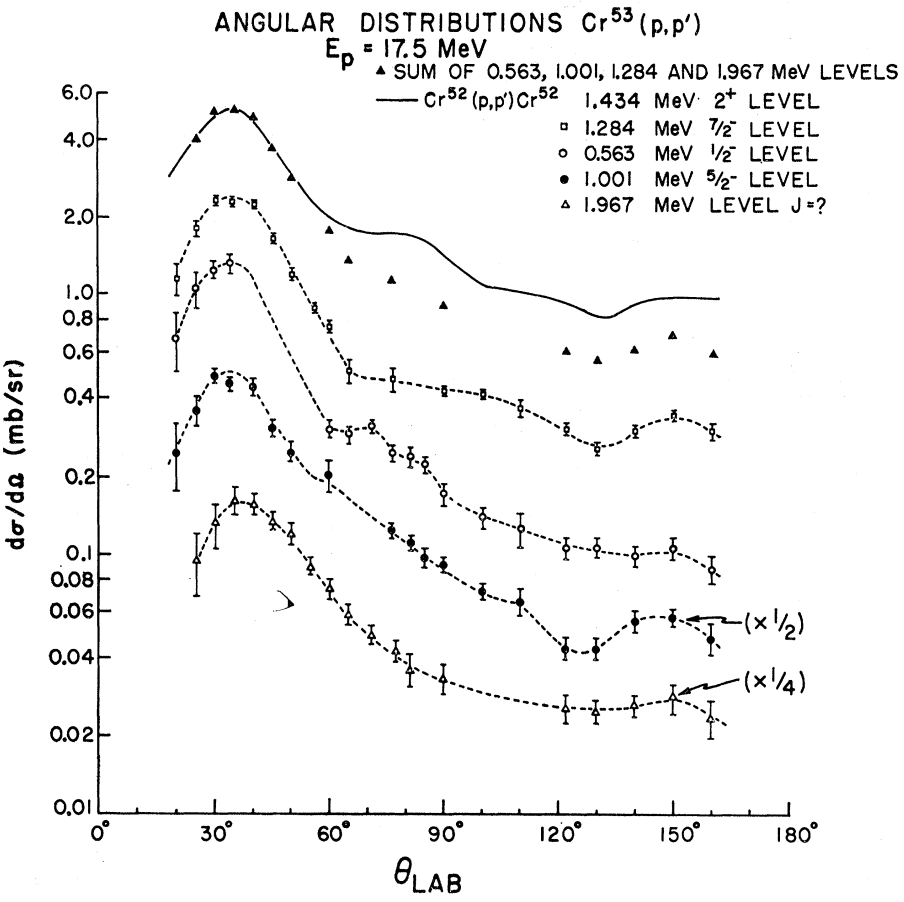

FIG. 13. Experimental $Cr^{53}(p,p')Cr^{53}$ angular distributions to the 0.563-MeV $\frac{1}{2}^-$ level, the 1.001-MeV $\frac{5}{2}^-$ level, the 1.284-MeV $\frac{7}{2}^-$ level, and the 1.967-MeV level. The triangular points represent the sum of the cross sections to these four levels, while the solid line represents the $Cr^{52}(p,p')Cr^{52}$ 1.434-MeV 2^+ angular distribution, which was measured in a separate experiment. The dashed lines are just drawn smoothly through the experimental points and have no theoretical significance.

the properties of these Cr^{53} levels. In this model,[56,57] which is used for odd-even nuclei, the odd nucleon is considered to be coupled weakly to the collective modes of the neighboring even-even nucleus. In the case of Cr^{53} the low-lying levels would be described by the coupling of a $2p_{3/2}$ neutron to the 2^+ 1.434-MeV level in Cr^{52}, thus forming a quartet of levels with spins $J=\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$, and $\frac{7}{2}^-$. Table IV presents a comparison of the experimental results with the predictions of the weak-coupling model. The theory predicts rather well the excitation of the 1.284-MeV $\frac{7}{2}^-$ level, and the cross section to all four levels; but it underestimates by a factor of 2.6 the (p,p') excitation of the 0.563 MeV, $J=\frac{1}{2}^-$ level. If the spin of the 1.967-MeV level were $\frac{5}{2}^-$, the total cross section to $\frac{5}{2}^-$ levels would be about that predicted by the theory, but there is no direct experimental evidence to support (or contradict) this spin assignment. Figure 12 shows that the known $\frac{3}{2}^-$ level at 2.319 MeV is quite weakly excited in the (p,p') reaction. In the case of the $_{25}Cu_{34}^{63}(p,p')$ reaction, which has been analyzed with some success in terms of the weak-coupling model—a $2p_{3/2}$ proton outside the Ni^{62} core—, the $\frac{3}{2}^-$ member of the $J=\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$, and $\frac{7}{2}^-$ quartet seems to be quite weakly excited.[58] The $Cr^{53}(\alpha,\alpha')$ work of Meriwether *et al.*[55] and the $Cr^{53}(d,d')$ work of Bock *et al.*[54] are in good agreement with our $Cr^{53}(p,p')$ data. In both of these studies the experimental

TABLE IV. Comparison of experimental results in $Cr^{53}(p,p')$ with the predictions of the weak-coupling model.

Level energy (MeV) and spin in Cr^{53}	$\frac{d\sigma}{d\Omega_{exp}}(35°)$ (mb/sr)	$\frac{d\sigma}{d\Omega_{weak\text{-}coupling}}$
0.563 $\frac{1}{2}^-$	1.32	0.5
1.001 $\frac{5}{2}^-$	0.95	1.5
1.284 $\frac{7}{2}^-$	2.42	2.0
1.967 $J=?$[a]	~0.63	

$$\sum \frac{d\sigma}{d\Omega_{exp}}(35°) = 5.3 \text{ mb/sr};$$

$$\frac{d\sigma}{d\Omega_{Cr^{52}(p,p')Cr^{52}1.434\ MeV2^+}}(35°) = 5.1 \text{ mb/sr}.$$

[a] Center of gravity for the four Cr^{53} levels equals 1.264 MeV if the spin of the 1.967-MeV level is assumed to be $\frac{3}{2}$.

[56] A. de-Shalit, Phys. Rev. **122**, 1530 (1961).

[57] J. S. Blair, in *Symposium on Nuclear Structure with Direct Reactions* (Argonne National Laboratory, Argonne, Illinois, 1964), Report No. ANL-6878, Vol. II, p. 143.

[58] F. Perey, R. J. Silva, and G. R. Satchler, Phys. Letters 4, 25 (1963).

excitation of the 1.284-MeV $\frac{7}{2}^-$ level is about that predicted by the weak-coupling model, while the experimental excitation of the 0.563-MeV $\frac{1}{2}^-$ level is enhanced by a factor of 2–3 and the experimental excitation of the 1.001-MeV $\frac{5}{2}^-$ level is down by a factor of ~0.5 from that predicted. The excitation of the 1.97-MeV level is also about the same as that seen in this work.

The results of our $Cr^{54}(p,d)$ experiment and the $Cr^{52}(d,p)$ experiments cited previously are inconsistent with a weak-coupling model description of the wave functions for the low-lying levels of Cr^{53} (up to 2 MeV). The Cr^{52} (d,p) results of Sperduto and Wiedner[47] and Bock *et al.*[48] indicate that about 50% of the 0.563-MeV $\frac{1}{2}^-$ level consists of a $2p_{1/2}$ single-particle configuration, and that about 40% of the 1.001-MeV $\frac{5}{2}^-$ level consists of an $1f_{5/2}$ single-particle configuration. Our $Cr^{54}(p,d)$ results also indicate $2p_{1/2}$ and $1f_{5/2}$ single-particle components in the wave functions of the 0.563 and 1.001-MeV levels, respectively, while about 10% of the $\frac{7}{2}^-$ 1.284-MeV level consists of the Cr^{54} ground state plus an $1f_{7/2}$ neutron hole. In the $Cr^{54}(p,d)$ reaction we also see a second $\frac{7}{2}^-$ level at 1.532 MeV, excited weakly in the (p,p') reaction, whose wave function has a 40% admixture of the Cr^{54} ground state plus an $1f_{7/2}$ neutron hole. Thus the $\{[Cr^{52}(1.434)]^{2^+}2p_{3/2}\}^J$, $J=\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-, \frac{7}{2}^-$, configuration does not describe the total structure of the wave functions for the low-lying levels of Cr^{53}. Other configurations, such as single-particle $2p_{1/2}$ and $1f_{5/2}$ configurations and single $1f_{7/2}$ neutron hole configurations, must also be important components of their nuclear wave functions. We should also note here that our $Cr^{53}(p,d)Cr^{52}$ experiment has shown that the Cr^{53} ground state, $J=\frac{3}{2}^-$, cannot be considered as only the Cr^{52} ground state, $\{(\pi f_{7/2}{}^4)^0$-$(\nu f_{7/2}{}^8)^0\}^0$, plus a $2p_{3/2}$ neutron. There is about a 20% admixture in the Cr^{53} ground state of the configuration $\{[Cr^{52}(1.434)]^{2^+}2p_{3/2}\}^{3/2}$; that is, the $J=\frac{3}{2}$ weak-coupling configuration is mixed into the Cr^{53} ground-state wave function.

Two explicit calculations for levels in Cr^{53}, taking into account both excitations of the Cr^{52} core and the single particle $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ configurations, have been presented by Maxwell and Parkinson[59] in a shell-model calculation, and by Ramavataram[60] in a unified-model calculation. Table V presents some comparisons between the predictions of these two models and the experimental data in the $Cr^{53}(p,d)$ and $Cr^{52}(d,p)$ reactions.[47] The agreement in the specific cases shown in Table V is quite good, with both models approximately reproducing the experimental results. In particular, it should be noted that the small theoretical $l_n=3$, $1f_{5/2}$ spectroscopic factors to the Cr^{52} 1.434-MeV 2^+, 2.369-MeV 4^+, and 2.766-MeV 4^+ levels ($S_{l=3,\ j=5/2}=0.02$ to

TABLE V. Comparison of Maxwell and Parkinson[a] and of Ramavataram[b] models for Cr^{53} with our $Cr^{53}(p,d)$ experiment and the $Cr^{52}(d,p)$ experiment of Sperduto and Wiedner.[c]

$Cr^{53}(p,d)Cr^{52}$	Experimental result	Normalized experimental results[d]	Predictions of Maxwell and Parkinson[a]	Predictions of Ramavataram[b]
$S_{l_n=1}(p,d)$ $Cr^{53}(p,d)Cr^{52}$g.s.	0.51	0.72	0.70	0.67
$S_{l_n=1}(p,d)$ $Cr^{53}(p,d)Cr^{52}$1.434-MeV 2^+	$0.18(2p_{3/2}+2p_{1/2})$	0.25	$0.16(2p_{3/2})+0.065(2p_{1/2})=0.225$	$0.17(2p_{3/2}+0.07(2p_{1/2})=0.24$
$S(p,d)$ $l_n=3$	$\cong 0.20(1f_{7/2}+1f_{5/2})$		$0.02(1f_{5/2})$	$0.027(1f_{5/2})$
$\sum S_{l_n=3}(p,d)$ to 2.370- and 2.769-MeV 4^+ levels	$\cong 0.19(1f_{7/2}+1f_{5/2})$		$0.05(1f_{5/2})$	
$Cr^{52}(d,p)Cr^{53}$ [c]	Normalized experimental results[e]		Predictions of Maxwell and Parkinson[a]	Predictions of Ramavataram[b]
$S(d,p)$ $Cr^{52}(d,p)Cr^{53}$g.s.	0.58		0.70	0.67
$S(d,p)$ $Cr^{52}(d,p)Cr^{53}$0.563-MeV $\frac{1}{2}^-$	0.36		(predict level at 0.66 MeV) 0.37	(predict level at 0.39 MeV) 0.33
$S(d,p)$ $Cr^{52}(d,p)Cr^{53}$1.001-MeV $\frac{5}{2}^-$	0.41		(predict level at 1.08 MeV) 0.29	(predict level at 0.95 MeV) 0.34

[a] Reference 59. [b] Reference 60. [c] Reference 47.
[d] Sum of $l_n=1$, (p,d) spectroscopic factors to Cr^{52} ground state, 1.434-MeV 2^+, and 2.648-MeV 0^+ levels are normalized to one.
[e] We have normalized the $l_n=1$, (d,p) spectroscopic factors of Ref. 46 so that the total spectroscopic strength to $\frac{3}{2}^-$ levels in Cr^{53} (g.s., 2.327, and 3.629 MeV) equals one.

[59] J. R. Maxwell and W. C. Parkinson, Phys. Rev. **135**, B82 (1964).
[60] K. Ramavataram, Phys. Rev. **132**, 2255 (1963).

0.05) would indicate that most of the $l_n=3$ spectroscopic strength to these levels is through $1f_{7/2}$ neutron pickup. This would indicate in turn that these levels have some $(1f_{7/2}^{-1}p_{3/2})$ admixture in their wave functions.

The question then arises as to whether the strong excitation of the Cr^{53} low-lying levels in the (p,p') reaction can be explained theoretically, taking into account the large single particle admixtures in their wave functions indicated by the (p,d) and (d,p)[47,48] experiments, and the Maxwell and Parkinson, and Ramavataram models. Thankappan and True[61] have proposed a model in the case of Cu^{63} which reproduces quite well both the large single-particle proton admixtures in the Cu^{63} low-lying levels found by Blair[62] in the $Ni^{62}(He^3,d)Cu^{63}$ reaction, and the $B(E2)$'s to these levels found in inelastic scattering.[63] A Thankappan and True type calculation for Cr^{53} would be interesting, both as an attempt to reconcile the pickup and stripping data with the inelastic scattering data, and as a study of the systematics of the theory parameters as one moves from the $A=62$ region to the $A=52$ region.

7. $Cr^{54}(p,t)Cr^{52}$, $Cr^{53}(p,t)Cr^{51}$, AND $Cr^{52}(p,t)Cr^{50}$ DATA AND DISCUSSION

Figure 14 presents typical triton spectra from the $Cr^{54}(p,t)$, $Cr^{53}(p,t)$, and $Cr^{52}(p,t)$ reactions. The four Cr^{52} levels excited strongly enough in the $Cr^{54}(p,t)$ reaction to allow analysis of their angular distributions are the 0^+ ground state, the 2^+ 1.434-MeV level, the 0^+ 2.648-MeV level, and the 2^+ 3.168-MeV level. The 4^+ levels in Cr^{52} at 2.370 MeV and 2.769 MeV are excited quite weakly in the (p,t) reactions, and at angles greater than 60° where we do see their peaks in the triton spectra-due to the larger number of counts representing a given cross section—the cross sections to these levels are ~1–3 μb/sr. We are not able to resolve the 3.115-MeV 6^+–3.168-MeV 2^+ doublet, but the cross section to a 6^+ level in the (p,t) reaction should be very small. The 2.965-MeV 2^+ level is not seen in the (p,t) reaction. Above an excitation energy of 3.2 MeV in Cr^{52} a few levels are excited with some strength in the (p,t) reaction, but their angular distributions were not analyzed due to poor statistics. In particular a level at 3.41±0.03 MeV is excited with a cross section of ~25 μb/sr at $\theta_{lab}=35°$. In the $Cr^{53}(p,t)Cr^{51}$ reaction only the Cr^{51} $\frac{7}{2}^-$ ground state and the $\frac{3}{2}^-$ level at 0.776 MeV are excited strongly. As the 30-keV/channel, 256-channel, data spectrum permitted us to investigate only an energy range of ~7.5 MeV, the 5.8-MeV difference in Q values between the $Cr^{53}(p,d)$ reaction

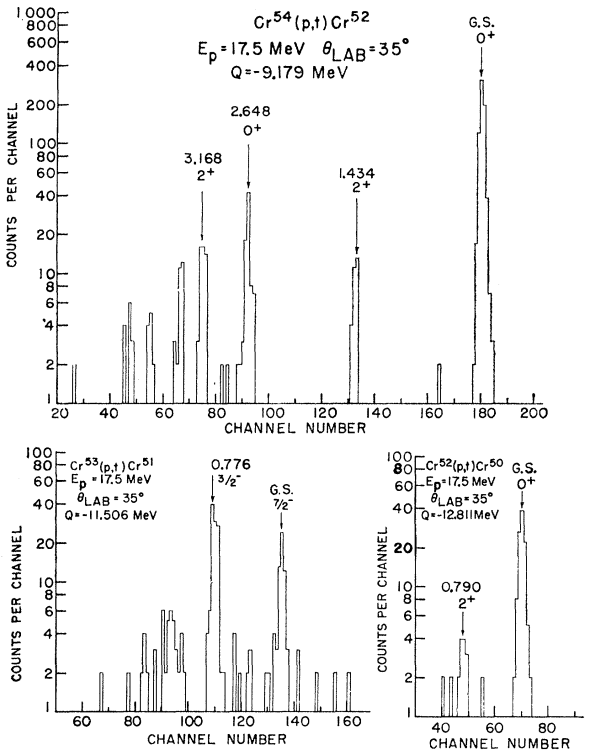

FIG. 14. Triton spectra from the $Cr^{54}(p,t)Cr^{52}$, $Cr^{53}(p,t)Cr^{51}$, and $Cr^{52}(p,t)Cr^{50}$ reactions. $E_p=17.5$ MeV, and $\theta_{lab}=35°$. All energy levels marked with an arrow will have their (p,t) angular distributions presented in this work.

($Q=-5.714$ MeV) and the $Cr^{53}(p,t)$ reaction ($Q=-11.506$ MeV) limited us to the study of levels in Cr^{51} with excitation energies less than ~1.5 MeV in most of our data. However, data were taken at $\theta_{lab}=35°$ where we investigated $Cr^{53}(p,t)$ transitions up to an excitation energy of ~2.5 MeV in Cr^{51}. The lab angle of 35° was chosen because an $L=0$ transition has its second maximum from ~30° to 40°. From the $\theta_{lab}=35°$ data we found no evidence for a (p,t) transition to the Cr^{51} 1.927-MeV $\frac{3}{2}^-$ level, a state could be excited by an $L=0(p,t)$ transition. The large negative Q value of the $Cr^{52}(p,t)$ reaction ($Q=-12.811$ MeV) limited us to the study of the transitions to the 0^+ ground state and 2^+0.790-MeV level in Cr^{50}.

Figure 15 presents the $Cr^{54}(p,t)Cr^{52}$ ground-state angular distribution from 10° to 150°. This a beautiful $L=0$ transition ($0^+\rightarrow 0^+$) with a strong forward maximum and dampened oscillations as the angle increases. Although the background at 10° was quite large (~110 μb/sr per channel), the ground-state peak stood out quite well due to the large forward angle cross section. Figure 16 presents $L=0(p,t)$ angular distributions from 20° to 150°, corresponding to the $Cr^{54}(p,t)Cr^{52}$ 2.648 MeV 0^+ transition, the $Cr^{53}(p,t)Cr^{51}$ 0.776-MeV $\frac{3}{2}^-$ transition, and the $Cr^{52}(p,t)Cr^{50}$ ground-state 0^+ transition. All these angular distributions are quite similar in shape and in the absolute value of their cross sec-

[61] V. K. Thankappan and W. W. True, Phys. Rev. **137**, B793 (1965).

[62] A. G. Blair, in *Symposium on Nuclear Structure with Direct Reactions* (Argonne National Laboratory, Argonne, Illinois, 1964), Report No. ANL-6878, Vol. II, p. 115.

[63] R. L. Robinson, F. K. McGowan, and P. H. Stelson, Phys. Rev. **134**, B567 (1964).

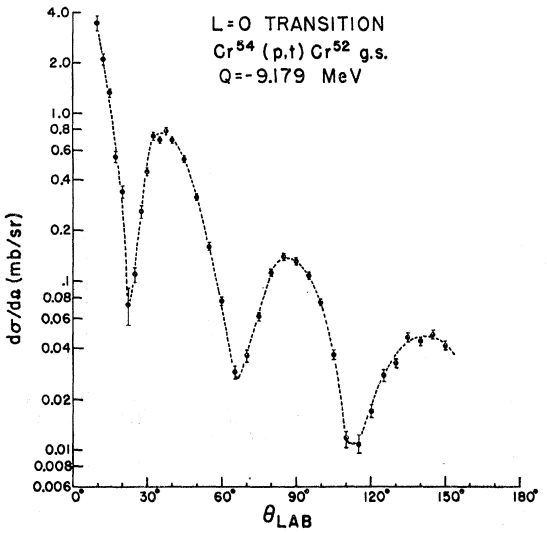

FIG. 15. Experimental, $L=0$, $Cr^{54}(p,t)Cr^{52}$ angular distribution to the 0^+ ground state. The dashed line is just drawn smoothly through the experimental points and has no theoretical significance.

tions, while the Q values for the three transitions differ by less than 1 MeV. There could be an incoherent $L=2$ component in the angular distribution of the $Cr^{53}(p,t)Cr^{51}$ 0.776-MeV $\frac{3}{2}^-$ transition, either from the (p,t) transition to the 0.776-MeV $\frac{3}{2}^-$ level itself, or from

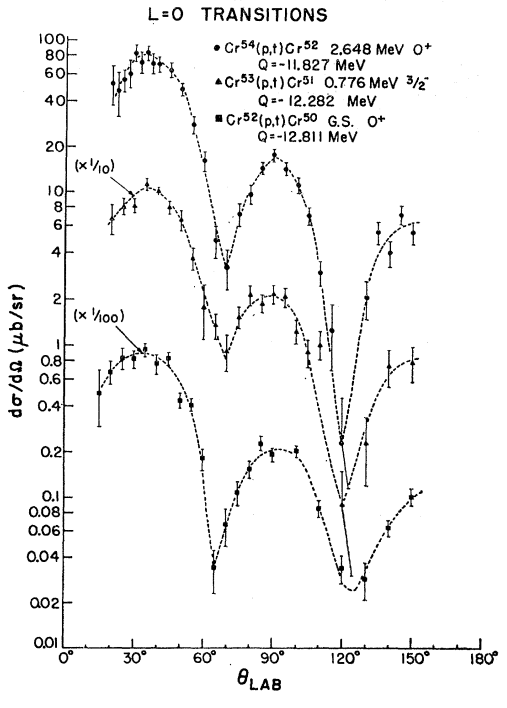

FIG. 16. Experimental, $L=0$, (p,t) angular distributions corresponding to the $Cr^{54}(p,t)Cr^{52}$ 2.648 MeV 0^+ transition, the $Cr^{53}(p,t)Cr^{51}$ 0.766-MeV $\frac{3}{2}^-$ transition, and the $Cr^{52}(p,t)Cr^{50}$ ground-state 0^+ transition. The dashed lines are just drawn smoothly through the experimental points and have no theoretical significance.

the (p,t) transition to the unresolved 0.803-MeV $(\frac{1}{2}^-)$ level in Cr^{51}. However, this $L=2$ component is quite small, as the minima in the $Cr^{53}(p,t)Cr^{51}$ 0.776-MeV $\frac{3}{2}^-$ angular distribution are as deep as those in the two pure $L=0$ transitions. We were not able to see the forward peaking in the $L=0$ transitions of Fig. 16 which was seen in the $L=0$ transition of Fig. 15. However, these $L=0$ transitions could not be studied at very forward angles, say 10°, as their cross sections were down by about an order of magnitude from that of the $Cr^{54}(p,t)Cr^{52}$ g.s. transition; and therefore their peaks were hidden under a large background at very forward angles. It does seem, however, that the $L=0$ transitions of Fig. 16 do have a much less pronounced forward minimum than the $L=0$ transition of Fig. 15, where the cross section at the first minimum (22.5°) is $\sim 1/10$ the cross section at the second maximum (35°). At Princeton McIntyre[64] has measured the $L=0$ angular distribution for the $Zn^{64}(p,t)Zn^{62}$ g.s. transition, and he finds that it is quite similar in the forward direction to the angular distributions of Fig. 16. The Q value for the $Zn^{64}(p,t)Zn^{62}$ g.s. transition is -12.49 MeV, within ± 0.6 MeV of the Q values for the $L=0$ transitions of Fig. 16. Thus the observed behavior of the (p,t), $L=0$ angular distributions at forward angles. may be due to a Q dependence in the reaction mechanism.

Figure 17 presents four $L=2(p,t)$ angular distributions: $Cr^{54}(p,t)Cr^{52}$1.434 MeV 2^+, $Cr^{54}(p,t)Cr^{52}$3.168 MeV 2^+, $Cr^{53}(p,t)Cr^{51}$ g.s. $\frac{7}{2}^-$, and $Cr^{52}(p,t)Cr^{50}$0.790 MeV 2^+. The $L=2$ angular distributions have a much less pronounced structure than that of the $L=0$ angular distributions, but they all show definite forward peaking with perhaps a maximum at about 25°. In Figs. 15, 16, and 17 the dotted lines are only meant to be smooth curves through the data; they have no theoretical significance.

Perhaps the most interesting result of the $Cr(p,t)$ experiments is the strong $L=0$ transition to the 2.648-MeV 0^+ level in Cr^{52}. As was discussed in the $Cr^{53}(p,d)$ section, this level cannot be explained in the $(f_{7/2}{}^n)$ picture, since the four $1f_{7/2}$ protons in $_{24}Cr_{28}{}^{52}$ can couple to only one 0^+ level—the ground state. Also, the very small $l_n=1$ spectroscopic factor ($S=0.018$) to this level in the $Cr^{53}(p,d)$ reaction indicates that there is only a very small admixture of the configuration $\{(\pi f_{7/2}{}^4)^0(\nu f_{7/2}{}^8)^0\}^0$ in the wave function of the 2.648-MeV level. Now the $Cr^{52}(p,t)Cr^{50}$ 0^+ g.s. and $Cr^{53}(p,t)$-Cr^{51} $\frac{3}{2}^-$ 0.766-MeV, $L=0$ transitions can be understood as the pickup of two $1f_{7/2}$ neutrons coupled to zero, leading mainly to the respective final configurations $\{(\pi f_{7/2}{}^4)^0(\nu f_{7/2}{}^{-2})^0\}^0$ and $\{(\pi f_{7/2}{}^4)^0[(\nu f_{7/2}{}^{-2})^0$-$\nu 2p_{3/2}]^{3/2}\}^{3/2}$. The spectroscopic strengths of these (p,t) transitions should be about equal, as the MBZ calcu-

[64] L. C. McIntyre, Princeton University (private communication).

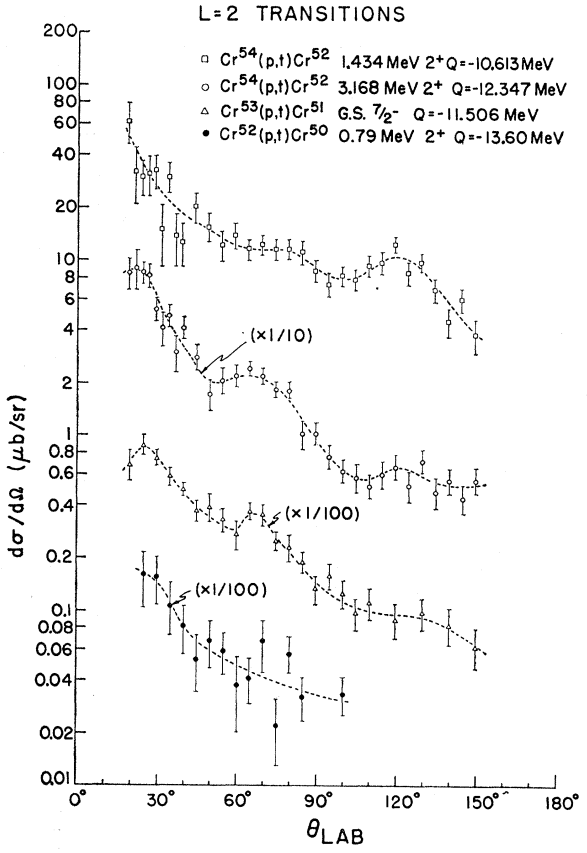

FIG. 17. Experimental $L=2$, (p,t) angular distributions corresponding to the $Cr^{54}(p,t)Cr^{52}$ 1.434-MeV 2^+ and 3.168-MeV 2^+ transitions, the $Cr^{53}(p,t)Cr^{51}$ ground-state $\frac{7}{2}^-$ transition, and the $Cr^{52}(p,t)Cr^{50}$ 0.79-MeV 2^+ transition. The dashed lines are just drawn smoothly through the experimental points and have no theoretical significance.

lations[65] predict that 67% of the Cr^{50} ground-state wave function is the configuration $\{(\pi f_{7/2}{}^4)^0(\nu f_{7/2}{}^{-2})^0\}^0$, while $Cr^{50}(d,p)Cr^{51}$ reaction studies[45,66] show that the 0.776-MeV level has a large $2p_{3/2}$ single-particle component. The Q values of these two transitions are within 500 keV of each other, so that their absolute cross sections are about equal: $d\sigma/d\Omega(35°)=110\pm10$ μb/sr for $Cr^{53}(p,t)Cr^{51}$ $\frac{3}{2}^-$ 0.776 MeV, $Q=-12.282$ MeV while $d\sigma/d\Omega(35°)=90\pm10$ μb/sr for $Cr^{52}(p,t)Cr^{50}$ g.s., $Q=-12.811$ MeV. The fact that the $Cr^{54}(p,t)Cr^{52}$ 0^+ 2.648-MeV $L=0$ transition has the same shape, and approximately the same Q value ($Q=-11.827$ MeV) and absolute cross section $[d\sigma/d\Omega(35°)=80\pm10$ μb/sr] as the other two $L=0(p,t)$ transitions strongly supports the contention that this (p,t) transition proceeds by the pickup of two $1f_{7/2}$ neutrons coupled to zero from the ground state of Cr^{54}. As the Cr^{54} ground state contains two neutrons above the $1f_{7/2}$ shell, this means that the 2.648-MeV 0^+ level in Cr^{52} contains a large two-particle–two-hole neutron component, the two holes being $1f_{7/2}$ neutrons, and the two particles being $2p_{3/2}$ neutrons with perhaps some admixture of $2p_{1/2}$ and $1f_{5/2}$ neutrons.

The fact that the $Cr^{54}(p,t)L=2$ transition to the 3.161-MeV 2^+ level in Cr^{52} is stronger than that to the 1.434-MeV 2^+ level, although its Q value is more negative by $\sim$1.7 MeV, is also interesting. If the wave function of the 1.434-MeV 2^+ level is taken to be $\{(\pi f_{7/2}{}^4v=2)^2(\nu f_{7/2}{}^8)^0\}^2$, then the (p,t) strength to this level will be dependent on admixtures in the ground state of Cr^{54} of the form $\{(\pi f_{7/2}{}^4v=2)^2[(\nu f_{7/2}{}^8)^0(\nu 2p_{3/2}{}^2)^2]\}^0$, and such admixtures may be quite small. However, if the 3.161-MeV 2^+ level contains a component of the form $\{(\pi f_{7/2}{}^4)^0[(\nu f_{7/2}{}^{-2})^2(\nu 2p_{3/2}{}^2)^0]^2\}^2$, then the $Cr^{54}(p,t)$ reaction can proceed directly to such a component by picking-up two $1f_{7/2}$ neutrons coupled to spin 2. The total spectroscopic strength for reaching such a component is given by[67]

$$S_{L=2}=\frac{n(n-2)(2L+1)}{(2j-1)(2j+1)}=5,$$

and this might be an explanation of the large cross section to the 3.161-MeV 2^+ level.

8. CONCLUSIONS

As a continuation of the Princeton work on the (p,d), (p,t), and (p,p') reactions in the $f_{7/2}$ region,[1–4] we have used these reactions to study nuclear structure in the chromium isotopes. In most cases our resolution of 60–70 keV at forward angles enabled us to study the angular distributions of transitions to unambiguous single levels in the residual nucleus. The statistical accuracy of our data is as good as or better than most of the previously reported work on the (p,d) and (p,t) reactions at our proton energy, and this fact allowed us to study weak transitions with cross sections of the order of 10–50 μb/sr. Our angular distributions from 15° to 150° enabled us to make a more complete comparison between the experimentally observed (p,d) angular distributions and the DWBA predictions for the (p,d) reaction mechanism. In the case of the Cr^{54}-$(p,d)Cr^{53}$ reaction we were able to see J dependence in the (p,d) angular distributions similar to that reported in the (d,p) reaction.[9] The use of isotopic targets in the Cr reaction studies allowed us to study (p,d) and (p,t) transitions which would have been completely masked if a natural chromium target were used.

In general quite good agreement was found between the DWBA predictions for the (p,d) angular distributions and the experimental data, in regard both to the shape of the (p,d) angular distribution and to the reasonableness of the (p,d) spectroscopic factors extracted from the experimental data by the DWBA theory. For the

[65] J. D. McCullen, B. F. Bayman, and L. Zamick, Princeton Technical Report No. NYO-9891, 1964 (unpublished).
[66] J. C. Legg, Rice University (private communication).
[67] G. Bassani, N. Hintz, and C. K. Kavaloski, Phys. Rev. 136, B1006 (1964).

strong (p,d) transitions in Secs. 4 and 5 a comparison of the experimentally extracted spectroscopic factors with the theoretical predictions would seem to indicate that the DWBA theory gives absolute spectroscopic factors which are accurate to within 20–30%. The use of a radial cutoff of 4.7 or 5.5 F in the DWBA theory improved the fit to the experimental $l_n=1$ (p,d) angular distributions. No way was found to reproduce the observed experimental J dependence in the (p,d) reaction with the DWBA theory. At our incident proton energy of 17.5 MeV the (p,d) angular distributions predicted by a DWBA program which approximated both finite-range and nonlocal effects in the reaction mechanism were not significantly different from the (p,d) angular distributions predicted by a zero-range DWBA theory.

The value of the (p,d) and (p,t) reactions in elucidating valuable information about the nuclear structure of the states involved in a given transition has been demonstrated and discussed in some detail in Secs. 4, 5, and 7. As has been emphasized previously, the (p,d) reaction can provide information regarding both the configuration of the target-nucleus–higher-shell admixture, etc.—and the configuration of the residual-nucleus–$1f_{7/2}$ neutron-hole strength, etc.; and the (p,t) reaction is a very powerful probe of states in the residual nucleus with the same spin as the target nucleus, due to the characteristic $L=0$ angular distributions of these transitions. However, these reactions alone certainly cannot begin to present the total structure of the nuclear states involved. The discussion of the data presented here makes it clear that the results of many different kinds of reaction studies are necessary before the structure of the nuclear levels is elucidated in any clear cut way. For example, the combination of the $Cr^{54}(p,d)$, $Cr^{52}(d,p)$, and $Cr^{53}(p,p')$ reaction studies certainly says more about the structure of the low-lying levels of Cr^{53} than any one of these reactions alone.

The comparison of the $Cr^{54}(p,d)Cr^{53}$ and $Cr^{52}(d,p)Cr^{53}$ data[47,48] with the $Cr^{53}(p,p')$ data would suggest a Thankappan and True type calculation[61] for Cr^{53}. One would like to explain not only the (p,d) and (d,p) single-particle strengths for the low-lying levels of Cr^{53}, but also the excitation of these levels in inelastic scattering.

ACKNOWLEDGMENTS

The author wishes to thank Dr. R. Sherr for his guidance, criticism, and encouragement throughout the progress of this work. Discussions with Dr. E. Rost, Dr. G. T. Garvey, Dr. C. Glashausser, Dr. J. Nolen, and Dr. R. Pollock are gratefully acknowledged. A. Emann and J. Hasili of the maintenance staff for the Princeton cyclotron were most helpful during the entire running time on the cyclotron. The work of the support staff of the Princeton physics department, in particular C. Harrison, J. Kempler, and R. Matthews, is gratefully acknowledged. W. Gerace, L. Feldman, and C. Riggi performed many of the DWBA computations necessary in this work. The author wishes to thank Dr. W. Parkinson and Dr. K. Ramavataram for providing him with unpublished data.