PHYSICAL REVIEW VOLUME 111, NUMBER 3 AUGUST 1, 1958

Proton Angular Distributions from $Cr^{52,53}(d,p)$ Reactions*

A. J. ELWYN† AND F. B. SHULL
Wayman Crow Laboratory, Washington University, St. Louis, Missouri
(Received April 11, 1958)

Targets enriched in Cr^{52} and Cr^{53} were bombarded with 10-Mev deuterons. Angular distributions were measured and Q values determined for four proton groups from $Cr^{52}(d,p)Cr^{53}$ and for six groups from $Cr^{53}(d,p)Cr^{54}$. For the former reaction the Q values were 5.74, 5.17, 4.77, and 3.43 Mev. For the latter the Q values were 7.55, 6.69, 6.24, 4.88, 4.36, and 3.76 Mev. All angular distributions were of type $l_n=1$ except for $Q=4.77$ Mev in $Cr^{52}(d,p)$, for which $l_n=3$. The latter group is interpreted as possibly a single-particle $f_{5/2}$ state, and these data may therefore reveal the relative position of single-particle $f_{5/2}$ and $p_{3/2}$ levels.

BUTLER[1] and others have shown that the yield of protons from medium-energy (d,p) reactions should be strongly anisotropic. The proton angular distribution depends upon the incident deuteron energy and most particularly upon the spins and parities of the target nucleus and the residual nucleus. The most favored direction of proton emission is closely related to the orbital momentum $l_n\hbar$ of the neutron which is captured at the same time, and thus l_n can be determined by locating the peak of the proton angular distribution. In Butler's formulation of the theory, Coulomb forces were ignored, the proton was assumed not to interact with the residual nucleus, and scattering of the incident deuteron beam was neglected, all in the interests of simplification. As a consequence, the theory predicts zero yield in certain directions, whereas experimental yields merely display minima. Also, the relative magnitudes of subsidiary maxima often turn out greater than predicted. Again, the angular spread of the principal hump in the proton angular distribution is often different in theory and experiment. Nevertheless there generally has been fair agreement on the direction of maximum yield, which is sufficient to determine l_n with confidence.

Stripping reaction data have been used extensively to confirm spin and parity predictions of nuclear shell theory, especially for ground states. For low mass nuclides, up to about $A=40$, the data are generally in excellent agreement with theory, at least for ground states. Beyond $A=40$ the amount of available data falls off rapidly, probably because the Coulomb barrier is becoming more formidable and because yields tend to become smaller with increasing Z. Coulomb corrections to the simple Butler theory become more important and even a correction due to nuclear effects is reported by Tobocman and Kalos[2] to be "enhanced as the Coulomb effect becomes more important." Thus interpretation of data becomes less reliable at higher values of Z and A.

This paper summarizes the results of a study of (d,p) reactions with isotopically enriched targets of chromium, using low-resolution apparatus.

All reactions were initiated by deuterons of 10-Mev energy from the Washington University cyclotron. Since the Coulomb barrier encountered was about six Mev, Coulomb effects, while not negligible, should not confuse the results. Continued indications of consistency with shell theory are found in these data.

I. APPARATUS AND PROCEDURE

The scattering chamber was circular and approximately 18 inches in diameter. Exit holes were bored at angles of 10°, 20°, 30°, etc. on one side and 15°, 25°, 35°, etc. on the other side of the beam axis. The detector was a coincidence telescope of two pillbox-shaped proportional counters, supported on a rotatable arm for positioning. Larger pulses were required from the second counter than from the first; to register a coincidence, a proton had to reach the end of its range in or just beyond the second counter. The total amount of absorbing material traversed by protons in reaching the second counter was variable from minimum to maximum in 100 equal steps (each step 1.72 mg/cm^2 of aluminum) by remote control of two overlapping absorber wheels, each of which carried 10 graduated absorber stacks. The minimum total absorber thickness could be varied as desired by insertion of additional sheets of absorber in the proton path.

A similar telescope, minus the absorber wheels, served as a monitor, and was permanently fixed in the ceiling of the chamber, viewing the target from a 35° angle. The monitor recorded a count for every entering proton having energy higher than some preset lower limit. The limit was made high enough to exclude protons from the C^{12} and O^{16} which were always present. All data were eventually expressed in counts per monitor count, to eliminate errors caused by target damage during a run.

Pulses from the counters were fed through preamplifiers to linear amplifiers, integral pulse-height discriminators, and thence to a 0.2-microsecond resolving time coincidence analyzer. Pulses from the monitor were treated in similar fashion.

* This research was supported by the U. S. Air Force through the Air Force Office of Scientific Research.
† Now at Brookhaven National Laboratory, Upton, New York.
[1] S. T. Butler, Proc. Roy. Soc. (London) A208, 559 (1952).
[2] W. Tobocman and M. H. Kalos, Phys. Rev. 97, 132 (1955).

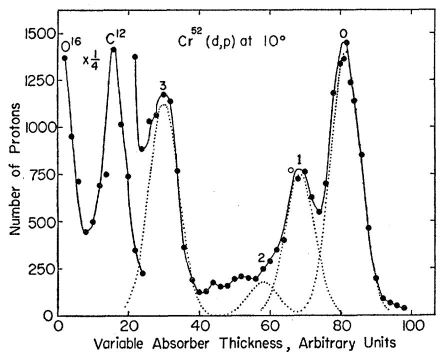

FIG. 1. Proton spectrum from $Cr^{52}(d,p)Cr^{53}$ at 10°. The proton group labeled "2" is from an $l_n=3$ reaction, and is clearly present at angles of 30° to 40°.

The target materials[3] were always in the form of insoluble oxides, which were ground fine and mixed with water. The slower settling fine particles were allowed to accumulate on a support foil of 0.25-mil polyethylene foil cemented to a metal frame. A target changer permitted as many as three different targets to be presented alternately to the beam without opening the vacuum chamber. This facilitated comparison of spectra from targets having different isotopic constitutions. One target was enriched in Cr^{52} to 99.1%, and the other was enriched to 90.1% Cr^{53} and 9.3% Cr^{52}. For the Cr^{52} target, no contaminant correction was made in the proton spectrum. For Cr^{53} a subtractive correction was made to remove contributions made by Cr^{52}.

The spread at half-maximum of a well-resolved peak ranged from about 280 kev for 12.5-Mev protons to about 450 kev for 18-Mev protons. Proton ranges were determined at the half-maximum point on the high-energy side of a proton peak. This corresponds roughly to a situation where half the particles of the group penetrate to the second counter and half do not, the spread being due to straggling. The measured range is

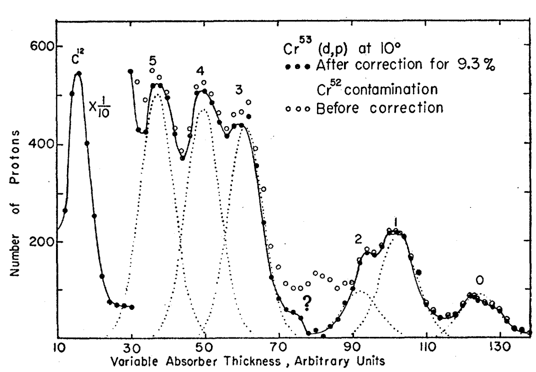

FIG. 2. Proton spectrum from $Cr^{53}(d,p)Cr^{54}$ at 10°. The solid points are corrected for the presence of 9% Cr^{52} in the target. The subtractive correction was obtained from Fig. 1.

[3] Isotopically enriched materials were provided by the Stable Isotopes Division of the U. S. Atomic Energy Commission.

the total aluminum equivalent of the absorber which has to be penetrated in order to just reach the sensitive volume of the second counter.

The resolving power of the detector was low, and several instances of two or more overlapping peaks were encountered. To analyze these we made use of the nearly Gaussian shape observed for several well-resolved peaks we have found in this and in earlier work. We attempted to analyze overlapping spectra into Gaussian peaks of the proper widths. This procedure was made easier by the availability of auxiliary information about level structure in the residual nucleus, from radioactivity studies and other nuclear reactions (see Fig. 5).

The ordinate for the spectra shown in Figs. 1 and 2 is the number of coincidence counts per 1280 monitor counts. The abscissa gives the thickness of the absorber carried by the overlapping absorber wheels, in units of 1.72 mg/cm^2 of aluminum. The energy of a proton group is determined from the measured range in aluminum and known range-energy relations for protons

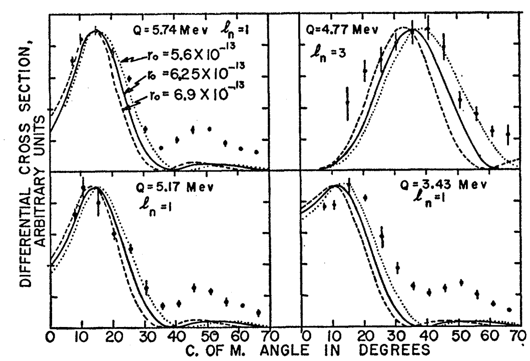

FIG. 3. Proton angular distributions from $Cr^{52}(d,p)Cr^{53}$. The curves are theoretical fits, using different radius parameters in the Butler theory. Maximum intensities for the four groups are compared in Table I.

in aluminum.[4] The incident deuteron energy was determined for each target by measuring the energy of protons from the $C^{12}(d,p)C^{13}$ ground state reaction, using a Q value of 2.73 Mev.

Theoretical angular distributions were computed from the theory of Butler.[1] Three values of the adjustable radius parameter were used, one being the Gamow radius of $r=(1.70+1.22A^{\frac{1}{3}})\times10^{-13}$ cm, and the others being, respectively, 10% greater and 10% less than that radius. The theoretical curves are arbitrarily normalized at the maximum of the experimental distribution on which they are superposed (Figs. 3 and 4).

II. RESULTS AND DISCUSSION

Figure 1 shows the range spectrum at 10° of protons from the nearly 100% pure Cr^{52} target, whose thickness

[4] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663, second revision (UCRL-121), 1949 (unpublished).

was about 1.6 mg/cm². Figure 2 presents the corrected and uncorrected proton spectra at 10° from the 90% pure Cr^{53} target, 1.45 mg/cm² thick, in which Cr^{52} was the principal contaminant; the necessary subtractive correction was obtained from Fig. 1. The group labeled "2" in Fig. 1 displays an $l_n=3$ angular distribution and is clearly resolved at angles of 30° to 40°. At 10° its intensity is so low that it disappears in the tail of group "1", and its intensity can only be estimated by analysis of the spectrum into overlapping Gaussian curves.

The angular distributions for the $Cr^{52}(d,p)$ reaction are plotted in Fig. 3, while those for six proton groups from $Cr^{53}(d,p)$ appear in Fig. 4. A summary of Q values, l_n values, spins, and parities assigned to residual states, and relative intensities measured at the peak of each angular distribution is given in Table I.

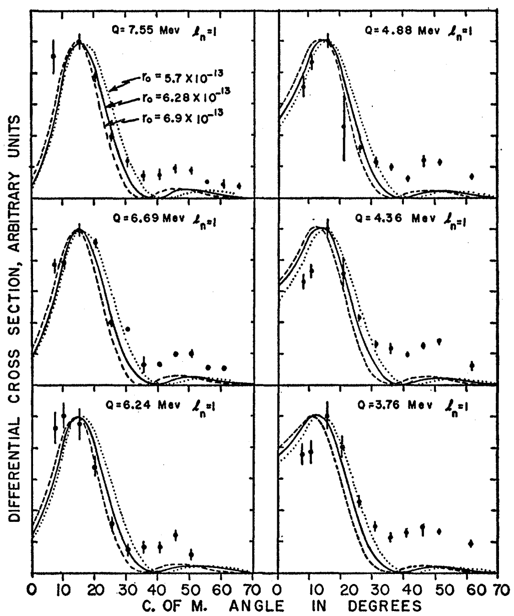

FIG. 4. Proton angular distributions from $Cr^{53}(d,p)Cr^{54}$. The curves are theoretical fits, using different radius parameters in the Butler theory. Maximum intensities for the six groups are compared in Table I.

The Q values of Table I have been checked against and compared with the following: (a) energies of gamma rays following the capture of slow neutrons in a chromium specimen having normal isotopic abundances, measured by Kinsey and Bartholomew[5] and (b) studies of the radioactive decays of Mn^{54} by Deutsch and Elliott[6] and of V^{54} by Schardt and Dropesky.[7] The degree of internal consistency of the data from these sources is shown graphically in Fig. 5, where the energy levels of the residual nuclides Cr^{53} and Cr^{54} are displayed in columns according to the source of information. For convenience in plotting, the energy scale in Fig. 5 is for the gamma-ray energies leading to the various levels shown in the (n,γ) column; it has been assumed that each gamma ray represents a transition directly from the capture state to the ground state. The (d,p) data have been presented with respect to this scale by adding the deuteron binding energy (2.23 Mev) to each Q value, giving, in effect, the binding energy, E_n, of the last neutron in the residual nucleus.

It seems evident from Fig. 5 and Table II that the degree of consistency is as satisfactory as could be expected in view of the limited resolving power of the (d,p) experiments. The proton groups observed are so broad that they undoubtedly represent close-lying unresolved levels in some cases. Moreover a (d,p) reaction requiring $l_n=3$ will usually be drowned in competition with the normally much more probable

TABLE I. Summary of data from $Cr(d,p)$ reactions. The last column compares counting rates observed at the peaks of the angular distributions, to an arbitrary scale which is consistent throughout.

	Exc. energy of resid. nucleus	Q (Mev)	l_n	Final spin and parity	Relative maximum intensity[a]
$Cr^{52}(d,p)Cr^{53}$	0	5.74±0.07	1	$\frac{3}{2}(-)$	1325
	0.57	5.17±0.08	1	$\frac{1}{2}, \frac{3}{2}(-)$	750
	0.97	4.77±0.10	3	$\frac{5}{2}, \frac{7}{2}(-)$	185
	2.31	3.43±0.07	1	$\frac{1}{2}, \frac{3}{2}(-)$	1125
$Cr^{53}(d,p)Cr^{54}$	0	7.55±0.07	1	0 (+)	90
	0.86	6.69±0.07	1	0,1,2,3(+)	210
	1.31	6.24±0.10	1	0,1,2,3(+)	90
	2.67	4.88±0.08	1	0,1,2,3(+)	435
	3.19	4.36±0.10	1	0,1,2,3(+)	470
	3.79	3.76±0.10	1	0,1,2,3(+)	500

[a] Intensities of angular distribution maxima.

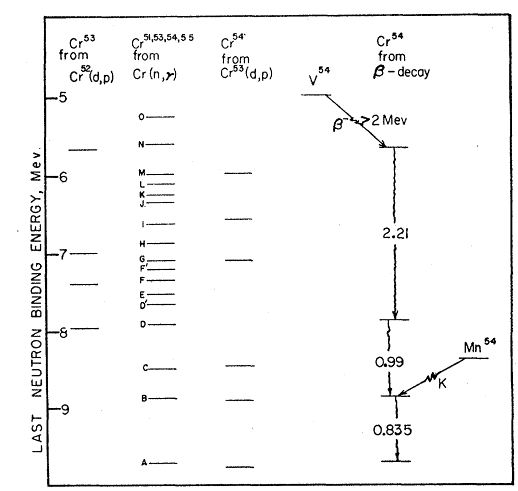

FIG. 5. Comparison diagram of energy levels in Cr^{53} and Cr^{54}, as determined in the present work, and as determined by neutron-capture gamma-ray studies[5] and by radioactivity measurements.[6,7] Some of the (n,γ) levels may be from Cr^{51} and Cr^{55}, since chromium of normal isotopic abundance was used.

[5] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. 89, 375 (1953).
[6] M. Deutsch and L. G. Elliott, Phys. Rev. 65, 211 (1944).
[7] A. W. Schardt and B. J. Dropesky, Bull. Am. Phys. Soc. Ser. II, 1, 162 (1956).

TABLE II. Comparison of energy levels as determined (a) for Cr^{53} and Cr^{54} from Cr(*d*,*p*) reactions and (b) as found by energy measurements of neutron capture gamma rays (Kinsey and Bartholomew, reference 5).

Residual nuclide	(*d*,*p*) Q(Mev)	E_n(Mev)	γ ray[a]	(*n*,γ) E_γ(Mev)	Relative intensity
Cr^{54}	7.55	9.78	*A*	9.716	7
Cr^{54}	6.69	8.92	*B*	8.881	19
Cr^{54}	6.24	8.47	*C*	8.499	7
Cr^{53}	5.74	7.97	*D*	7.929	8
			D'	7.67	0.2
			E	7.54	0.2
Cr^{53}	5.17	7.40	*F*	7.364	3
			F'	7.21	0.2
Cr^{54}	4.88	7.11	*G*	7.097	2.6
Cr^{53}	4.77	7.00			
			H	6.872	0.6
Cr^{54}	4.36	6.59	*I*	6.644	3.0
			J	6.358	0.3
			K	6.26	0.9
			L	6.12	0.7
Cr^{54}	3.76	5.99	*M*	6.00	1
Cr^{53}	3.43	5.66	*N*	5.61	2
Cr^{54}	3.16	5.39			
			O	5.26	1

[a] Letter designation of γ rays as given in reference 5.

$l_n=1$ reactions which predominate in this mass region. As mentioned before, however, one such $l_n=3$ proton group was observable in the $Cr^{52}(d,p)$ reaction because of a fortuitous gap in the family of $l_n=1$ groups which accompany it, and special mention is made below of the associated level in Cr^{53}.

After neutron number $N=28$ in shell theory, the next levels to be filled include $p_{\frac{3}{2}}$, $f_{\frac{5}{2}}$, $p_{\frac{1}{2}}$, and $g_{9/2}$. With 24 protons and 29 neutrons, the ground state of Cr^{53} should be a $p_{\frac{3}{2}}$ state, which is consistent with its measured spin of $\frac{3}{2}$ and with an $l_n=1$ angular distribution in the $Cr^{52}(d,p)$ reaction. French and Raz[8] had previously analyzed the results of (d,p) reactions on calcium isotopes, and using this analysis as a guide, Raz[9] suggested the following interpretation of the four levels in Cr^{53} observed from the $Cr^{52}(d,p)$ reaction. If it is assumed that the Cr^{53} ground state is pure single-particle $p_{\frac{3}{2}}$, the level at 0.97 Mev ($l_n=3$) then has the right relative cross section to be the single-particle $f_{\frac{5}{2}}$ state. If true, this would be the first experimental determination of the position of the single-particle $f_{\frac{5}{2}}$ state with respect to the $p_{\frac{3}{2}}$, and its presence would support a contention by French and Raz that single-particle $f_{\frac{5}{2}}$ and $f_{7/2}$ Butler cross sections have the same order of magnitude. In addition, the 0.57-Mev ($l_n=1$) level has approximately the right relative cross section to be the single-particle $p_{\frac{1}{2}}$ state. The fourth level, at 2.31 Mev ($l_n=1$), might then be regarded as a $p_{\frac{3}{2}}$ state.

In $Cr^{53}(d,p)$ we find $l_n=1$ for all observable proton groups, and, since the Cr^{53} ground state is $\frac{3}{2}-$, the resulting levels in Cr^{54} can all be labeled $0+$, $1+$, $2+$, or $3+$. No $4+$ levels were observed, but this is not surprising since this would require $l_n=3$, for which the yield is expected to be small by comparison with $l_n=1$. In particular, it is conceivable that such a weak group, perhaps corresponding to the Cr^{54} level at 1.825-Mev excitation observed in the V^{54} decay, could escape detection because of competition with a stronger group from the $Cr^{52}(d,p)$ ground state reaction, due to the 9% contamination of Cr^{52} in the Cr^{53} target. No indication of such a group appeared however, at angles of 30° to 40°, where an $l_n=3$ angular distribution would be expected to peak.

[8] J. B. French and B. J. Raz, Phys. Rev. **104**, 1411 (1956).
[9] B. J. Raz, Bull. Am. Phys. Soc. Ser. II, **1**, 336 (1956); also private communication.