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INVESTIGATION OF STRIPPING REACTIONS ON CHROMIUM ISOTOPES

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The angular distributions of protons from the (d, p) reactions on the chromium isotopes Cr^{50}, Cr^{52}, Cr^{53}, and Cr^{54} are studied using 13.6-MeV protons, and are compared with the simple Butler theory of stripping reactions. The values of l_n for captured neutrons are obtained for the ground state and several excited states of the final nuclei. Some conclusions are reached regarding possible spins and parities of states of the final nuclei Cr^{51}, Cr^{53}, Cr^{54}, and Cr^{55}.

IN the present work we continue our earlier investigations [1] of stripping reactions in targets containing single isotopes with $A \approx 60$. We have now studied the angular distributions from stripping reactions on the four chromium isotopes Cr^{50}, Cr^{52}, Cr^{53}, and Cr^{54}.

Other workers have studied (d, p) reactions using deuterons up to 21 MeV.[2-5] However, except in [5], all targets were made of natural chromium. Thus in one of the first investigations Schiffer et al [2] studied the gross structure of the proton spectrum from the (d, p) reaction on natural chromium. The angular distributions of protons were compared with the simple Butler theory.

Elwyn and Shull [5] investigated the proton angular distributions from (d, p) on Cr^{52} and Cr^{53} using 10-MeV deuterons. A comparison with the theory yielded values of the orbital angular momentum l_n for neutrons captured into different states of the final nuclei.

Šlaus [3] studied the mechanism of the $Cr^{52}(d, p)Cr^{53}$ reaction with 3.29- and 4.4-MeV deuterons. Although these deuteron energies are far below the Coulomb barrier, the experimental data indicate that direct interactions play an important part.

El Bedewi and Tadros [4] employed magnetic analysis to investigate $Cr^{52}(d, p)Cr^{53}$ with 8.67-MeV deuterons. They compared the angular distributions of nine proton groups with Butler's theory and obtained possible spins and parities for states of the final nucleus Cr^{53}.

The (d, p) reactions on Cr^{50} and Cr^{54} have not been investigated previously. It was therefore of interest to investigate the angular distributions of protons from this reaction on all four chromium isotopes.

1. MEASUREMENT TECHNIQUE

Our work was done at the cyclotron of the Institute of Physics of the Academy of Sciences of the

Table I

Target	Thickness, mg/cm²	Content, %			
		Cr^{50}	Cr^{52}	Cr^{53}	Cr^{54}
Cr^{50}	2,895	87,7	11,1	0,9	0,3
Cr^{52}	3,211	0,2	99,0	0,7	0,1
Cr^{53}	3,790	0,2	13,8	84,3	1.7
Cr^{54}	2,895	0,4	10,9	10,1	78.6

Ukrainian S.S.R., which furnished a 13.6-MeV deuteron beam. The apparatus and measurement technique have been described in [1]. The targets in the form of free thin films 20 mm in diameter were enriched in the chromium isotope to be investigated. Table I gives the target thicknesses and isotopic compositions.

The (d, p) proton angular distributions were obtained at c.m. angles from 7.5° to 100° and are compared with theoretical calculations based on the simple Butler theory.[6]

The indicated experimental errors in the angular distributions were obtained by averaging several measurements, and include statistical errors not greater than 3%, errors of proton-group resolution, errors associated with inaccurate angular positioning, etc. All these errors pertain to measurements of the angular distributions in relative units. The error in the absolute value of the differential (d, p) cross section was ± 50%.

2. RESULTS AND DISCUSSION

Figure 1 shows the (d, p) proton spectra resolved into several groups whose angular distributions were obtained. The different proton groups have been designated with the numerical indices 0, 1, 2 etc. Since the inadequate resolving power of the spectrometer did not always permit good resolution of the proton groups, in determining their areas we assumed Gaussian shapes (the dashed curves) of the spectral lines. Consequently, although in certain instances some proton groups could not be resolved easily, very good agreement was obtained between the angular distributions from different runs in which the proton groups were resolved independently. The angular distributions of the corresponding proton groups are therefore quite reliable.

We shall now discuss briefly the separate results for each reaction.

a) $Cr^{50}(d, p)Cr^{51}$. Figure 2 shows the angular distributions of protons. The angular distributions for the ground state (Fig. 2a) and for the first excited state (Fig. 2b) correspond to separate levels in good agreement with the theoretical curves. Table II gives the characteristics of the levels obtained from an analysis of these data. On the shell model the most probable spin and parity are $7/2^-$ for the ground state and $3/2^-$ for the first excited state. According to the Cr^{51} level scheme [8] the first excited level at 0.75 MeV is followed by a group of excited levels at 1.17, 1.42, and 1.53 MeV. In our experimental work we were unable to resolve these levels separately; therefore we obtained a combined angular distribution for all three levels.

In Fig. 1a this proton group is designated by the number 2 and is seen to consist of at least two groups (2a and 2b) corresponding to the approximate excitation energies 1.2 and 1.5 MeV, respectively. The corresponding angular distribution is shown in Fig. 2. The spectra obtained at different

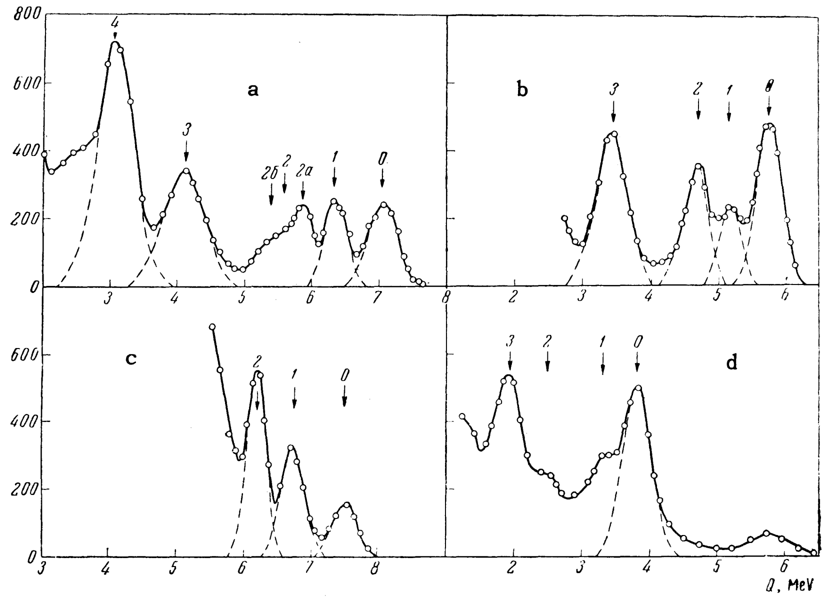

FIG. 1. Proton spectra from the (d, p) reaction on chromium isotopes: a – $Cr^{50}(d, p)Cr^{51}$, $\theta = 30°$; b – $Cr^{52}(d, p)Cr^{53}$, $\theta = 30°$; c – $Cr^{53}(d, p)Cr^{54}$, $\theta = 30°$; d – $Cr^{54}(d, p)Cr^{55}$, $\theta = 40°$.

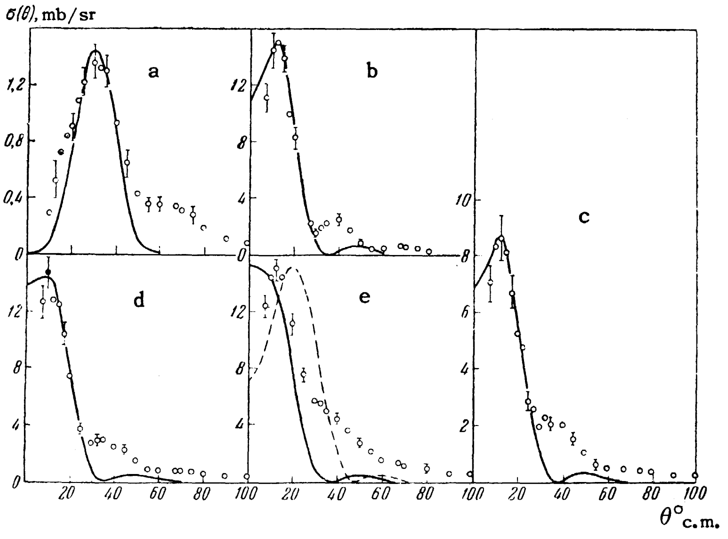

FIG. 2. Angular distributions of protons from $Cr^{50}(d, p)Cr^{51}$. o – experimental points accompanied by Butler theoretical curves. a – $l_n = 3$, $r_0 = 6.19 \times 10^{-13}$ cm; b – $l_n = 1$, $r_0 = 5.8 \times 10^{-13}$ cm; c and d – $l_n = 1$, $r_0 = 5.5 \times 10^{-13}$ cm; e – $l_n = 1$, $r_0 = 5.5 \times 10^{-13}$ cm (continuous curve) and $l_n = 2$, $r_0 = 5.5 \times 10^{-13}$ cm (dashed curve).

Table II

Reaction	Q, MeV	Excitation energy, MeV	Proposed value of l_n	Radius r_0, 10^{-13} cm	Possible spins and parities	Differential cross section at peak, mb/sr	Reduced width $(2J+1)\theta^2$
$Cr^{50}(d, p)Cr^{51}$	7,08	0	3	6.19	$5/2^-, 7/2^-$	1.36	0,054
	6,33	0,75	1	5.8	$1/2^-, 3/2^-$	15.05	0,076
	5,70	1,17	1	5.5	$1/2^-, 3/2^-$	8.57	0,042
		1.42					
		1,53					
	4,16	2.92	1	5,5	$1/2^-, 3/2^-$	14,69	0,055
	3,11	3,97	1	5,5	$1/2^-, 3/2^-$	14.95	0.049
$Cr^{52}(d, p)Cr^{53}$	5,74	0	1	5.5	$1/2^-, 3/2^-$	24.90	0,122
	5,16	0.58	1	5.5	$1/2^-, 3/2^-$	9.38	0.040
	4,73	1,00	3	6,0	$5/2^-, 7/2^-$	1.92	0,054
	3.41	2,33	1	5,5	$1/2^-, 3/2^-$	18.55	0,060
$Cr^{53}(d, p)Cr^{54}$	7,55	0	1	6,28	$0^+, 1^+, 2^+, 3^+$	1,31	0.031
	6,69	0.81	1	5,8	$0^+, 1^+, 2^+, 3^+$	3,76	0,079
	6.26	1,23	1	5,5	$0^+, 1^+, 2^+, 3^+$	3,38	0,072
$Cr^{54}(d, p)Cr^{55}$	3.8	0	1	5,5	$1/2^-, 3/2^-$	24,63	0,084

angles indicate that the given proton groups resulted from the capture of neutrons with different values of l_n. Thus the proton group 2b is very well resolved and gives the highest yield at about 12°, whereas the group 2a is most strongly resolved at 30°. It can therefore be assumed that the group 2a results from a transition with $l_n = 3$, and the group 2b from a transition with $l_n = 1$. This to some degree confirms our angular distribution for both groups taken together as shown in Fig. 2c, where we also have the theoretical curve for $l_n = 1$ and $r_0 = 5.5 \times 10^{-13}$ cm.

The experimental angular distribution is seen to agree with theory for $l_n = 1$. However, there is no perceptible experimental minimum in the range 30–35°, as is usually found in the case of $l_n = 1$ (Fig. 2b). This can be due to the contribution of the second proton group (2b) resulting from a transition with $l_n = 3$.

For the same reaction we obtained two more angular distributions of the proton groups 3 and 4 (Fig. 2d, e) corresponding to excitation energies of the order 2.92 and 3.97 MeV. Since a Cr^{51} level scheme is lacking for this energy region, we cannot state that the corresponding proton groups result from neutron capture into separate levels.

Figure 2 shows the angular distribution for the 2.92-MeV state and the Butler theoretical curve for $l_n = 1$ and $r_0 = 5.5 \times 10^{-13}$ cm. Taking the indicated value $l_n = 1$, we can assign $1/2^-$ or $3/2^-$ to this state.

The angular distribution for the 3.97-MeV state is shown in Fig. 2e, together with the Butler theoretical curves for $l_n = 1$ and 2. The experimental points are seen to lie between the theoretical curves and can hardly be reconciled with either one. In [9] similar difficulties have been pointed out regarding the choice of l_n for states with low Q in analyzing stripping reactions on nuclei of medium atomic weight with 10-MeV deuterons. This is associated with the fact that Butler's theory disregards both the Coulomb and the nuclear reactions between deuterons and nuclear protons. By using the distorted-wave theory [10] in calculating theoretical angular distributions we obtain considerably better agreement with experiment and the elimination of ambiguities regarding the selection of l_n. Thus, as Scott [9] has shown, when the experimental points lie between Butler curves for two adjacent values of l_n, the theoretical curve based on the distorted-wave theory for the lower value of l_n agrees well with the experimental distribution.

We can take $l_n = 1$ for the investigated 3.97-MeV state on the basis of the foregoing discussion. Then the possible spins and parities will be $^1/_2{}^-$ and $^3/_2{}^-$.

b) $Cr^{52}(d, p)Cr^{53}$. The angular distributions of four proton groups from this reaction are shown in Fig. 3 along with the corresponding theoretical curves. Table II gives the orbital angular momenta of neutrons captured into the corresponding states, and the spins and parities of these states.

On the shell model the most probable spin and parity of the Cr^{53} ground state will be $^3/_2{}^-$, with $^5/_2{}^-$ for the second excited state (1.0 MeV). These results are confirmed by data in [4,5].

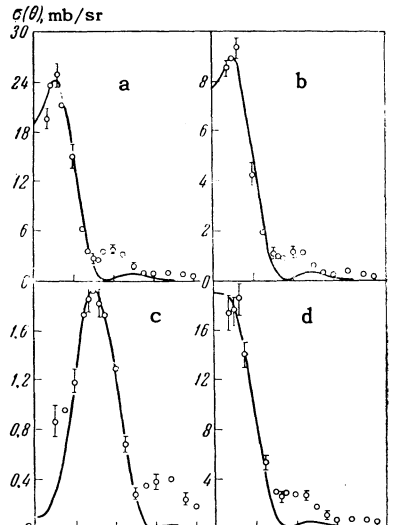

FIG. 3. Angular distributions of proton groups from $Cr^{52}(d, p)Cr^{53}$. o – experimental points; continuous lines – Butler theoretical curves. a, b, and d – $l_n = 1$, $r_0 = 5.5 \times 10^{-13}$ cm; c – $l_n = 3$, $r_0 = 6 \times 10^{-13}$ cm.

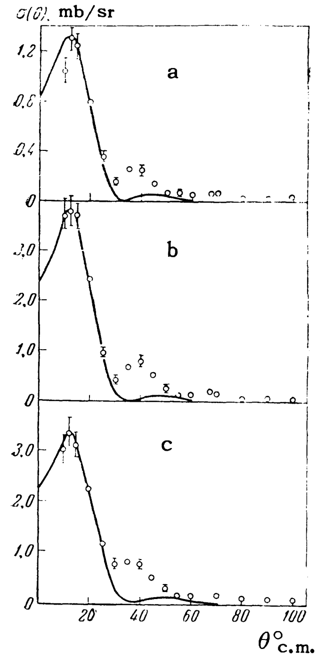

FIG. 4. Angular distributions of protons from $Cr^{53}(d,p)Cr^{54}$. o – experimental points; continuous lines – Butler theoretical curves. a – $l_n = 1$, $r_0 = 6.28 \times 10^{-13}$ cm; b – $l_n = 1$, $r_0 = 5.8 \times 10^{-13}$ cm; c – $l_n = 1$, $r_0 = 5.5 \times 10^{-13}$ cm.

For the first excited Cr^{53} state at 0.58 MeV the possible spin and parity will be $^1/_2{}^-$ or $^3/_2{}^-$. Wilkinson and Sheline [11] have identified this level as a $2p_{1/2}$ state on the basis of relative γ-ray intensities in neutron capture.

c) $Cr^{53}(d, p)Cr^{54}$. Figure 4 shows the proton angular distributions from this reaction and the Butler theoretical curves; $l_n = 1$ was obtained for all angular distributions. Since the target is a spin-$^3/_2{}^-$ even-odd nucleus, the investigated levels must have positive parity and the possible spins are 0, 1, 2, and 3.

The final Cr^{54} nucleus has an even mass and must therefore have a 0^+ ground state. The most probable assignment for the first excited state of Cr^{54} is 2^+. Our values of l_n for all three states agree with those given in [7].

d) $Cr^{54}(d, p)Cr^{55}$. Figure 1d shows the proton spectrum from this reaction. Only two groups (0 and 3) have appreciable intensities; the other two groups (1 and 2) are very weak at the given angle. At other angles the intensity ratio of these groups changes. Since it is very difficult to discriminate all these proton groups and the level

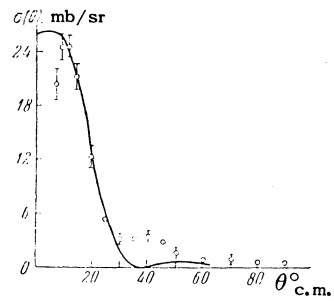

FIG. 5. Angular distribution of protons from $Cr^{54}(d, p)Cr^{55}$. o – experimental points; continuous line – Butler theoretical curve for $l_n = 1$ and $r_0 = 5.5 \times 10^{-13}$ cm.

scheme of Cr^{55} is entirely unknown, we plotted the angular distribution only for the ground-state group; this is shown in Fig. 5 in comparison with the Butler theoretical curve for $l_n = 1$. Since, according to the shell model, in the Cr^{55} ground state the 31st neutron should be captured into the $2p_{3/2}$ shell, the most probable spin and parity assignment for this state will be $3/2^-$, in good agreement with [8].

Regarding the proton group 1 we can only comment about the angular dependence of its intensity. At small angles the group is very weak and almost entirely imperceptible in the tail of the intense ground-state group. The intensity of group 1 rises with increase of the angle, and at 30° is comparable to the group 0 for the ground state. Its intensity again diminishes with further increase of the angle. It is thus suggested that the group results from the capture of neutrons with $l_n = 3$. This agrees with the shell model, according to which the $1f_{5/2}$ level should lie above the $2p_{3/2}$ level. However, final conclusions regarding this state will await an angular distribution based on measurements in which these groups can be resolved.

On the basis of the measured absolute values of the differential cross sections for the investigated (d, p) reactions and the analysis of the angular distributions we employed Butler's theory to calculate the reduced widths $(2J + 1)\theta^2$, where J is the spin of the final-nucleus state. An equation in [12] was used to calculate $(2J + 1)\theta^2$. Table II gives the reduced widths and other characteristics of states in the investigated nuclei.

In conclusion we wish to thank A. P. Klyucharev for providing the enriched targets, and also the crew that was responsible for the uninterrupted operation of the cyclotron.

[1] M. V. Pasechnik and P. G. Ivanitskiĭ, Ukr. fiz. zhurn. (Ukrainian Physics Journal) **6**, 603 (1961).

[2] Schiffer, Lee, Yntema, and Zeidman, Phys. Rev. **110**, 1216 (1958).

[3] Ivo Šlaus, Nuclear Phys. **10**, 457 (1959).

[4] F. A. El Bedewi and S. Tadros, Nuclear Phys. **19**, 604 (1960).

[5] A. J. Elwyn and F. B. Shull, Phys. Rev. **111**, 925 (1958).

[6] Butler, S. T., Nuclear Stripping Reactions (Horowitz Publications, Inc., Sydney), 1957.

[7] M. G. Mayer and J. H. D. Jensen, Elementary Theory of Nuclear Shell Structure (John Wiley and Sons, New York), 1955.

[8] B. S. Dzhelepov and L. K. Peker, Skhemy raspada radioaktivnykh yader (Decay Schemes of Radioactive Nuclei), 1958.

[9] H. D. Scott, Nuclear Phys. **27**, 490 (1961).

[10] W. Tobocman, Phys. Rev. **115**, 98 (1959).

[11] J. R. Wilkinson and R. K. Sheline, Phys. Rev. **99**, 752 (1955).

[12] M. H. Macfarlane and J. B. French, Rev. Modern Phys. **32**, 567 (1960).

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