Levels of Cr^{53} and Cr^{55} from (d,p) Reactions*

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Chromium isotopes Cr^{52}, Cr^{53}, and Cr^{54} have been bombarded with 2.8-MeV deuterons and the resultant protons analyzed with a 16-in. broad-range spectrograph. Comparison of results between 30- and 90-deg exposures corroborated most of the energy levels found. Energy levels are reported in Cr^{55} at 0.246, 0.522, 0.583, 0.881, 1.206, 1.474, 2.020, 2.268, and 2.779 MeV and in Cr^{53} at 0.568, 1.007, 1.297, 2.322, and 2.670 MeV. These are compared with recent experimental results.

INTRODUCTION

NUCLIDES lying in the region of atomic numbers just above "double magic" Ca^{48} are of especial interest owing to the possibility of describing them rather well with relatively simple shell-model considerations.

There are four stable chromium isotopes, Cr^{50}, Cr^{52}, Cr^{53}, and Cr^{54}. Cr^{50}, Cr^{52}, and Cr^{54} are even-even nuclei, with 24 protons and 26, 28, and 30 neutrons, respectively. The (d,p) reaction with Cr^{52} and Cr^{54} leads to Cr^{53} and Cr^{55} which have one and three neutrons in the $p_{3/2}$ shell, respectively. The question arises as to whether the Cr^{55} spectrum will be similar to Cr^{53}, i.e., whether the extra two neutrons in the $p_{3/2}$ level will pair each other off with little net effect on the energy levels of Cr^{55}. Since the energy levels of Cr^{55} had not been studied at all, in fact the ground-state Q value was not known to better than 140 keV, it seemed desirable to explore this nucleus as well as Cr^{53}.

There have been a number of investigations of Cr^{53}. The earliest significant investigation was that of Elwyn and Shull[1] who measured the protons from the $Cr^{52}(d,p)Cr^{53}$ reaction with 70-keV resolution. In 1960, El Bedewi and Tadros[2] measured the energy levels of Cr^{53} with a resolution of 60 keV and made some rough angular-distribution measurements. In 1963, Andrew *et al.*[3] performed a 40-keV energy resolution (d,p) stripping experiment using surface barrier detectors for particle identification. Bardwick[4] and Legg[5] have also examined the level structure of Cr^{53}. Rollefson *et al.*[6] looked at the gamma decay of seven excited states of Cr^{53} using particle/gamma-coincidence techniques. Legg *et al.*[7] measured the angular distribution of the protons at a deuteron bombarding energy of 10 MeV. Sperduto *et al.*[8] have also reported measurements of the energy levels and angular distribution for this reaction. As stated earlier there was essentially no information on Cr^{55} when we did the $Cr^{54}(d,p)Cr^{55}$ experiment. Since we completed the experiment, work has been performed on this reaction by Bjerregard *et al.*[9] and by Bochin *et al.*[10]

EXPERIMENTAL PROCEDURE

The energy levels of some of the chromium isotopes have been looked at by means of the $Cr^{x}(d,p)Cr^{x-1}$ reaction. The targets consist of chromium, about 5 keV thick to 3-MeV deuterons, evaporated on a 7-keV-thick pure gold foil. Targets of natural chromium, Cr^{52}, greater than 99.9% enrichment, Cr^{53}, greater than 95% enrichment, and Cr^{54}, greater than 95% enrichment, were routinely produced with an 85% chance of success. The separated chromium isotopes were procured from the Oak Ridge National Laboratory.

The bombarding deuterons were accelerated in a Van de Graaff electrostatic accelerator to energies from 2.745 to 2.768 MeV for the various exposures. Exposures were made with the broad-range spectrograph similar to the one designed by Browne and Buechner.[11] It has an instrumental energy resolution of 0.1% and covers an energy range of E to 1.3 E in one exposure. Kodak NTA 50-μ nuclear emulsions, 10 in. long, were used and developed according to standard procedures. The targets took as much as 0.18 μA of the 2.56-MeV deuteron beam on a 50×100-mil beam spot before burning off the chromium.

Ten exposures have been made on Cr^{52}, Cr^{53}, and Cr^{54} separated isotopes and natural chromium at 90 and 30 deg.

The identification of nuclei by means of exposures at different angles is successful for the lighter nuclei, but for nuclei in the medium-weight range only a few mass units apart, the shift in energy of the emitted particle becomes comparable to the resolution of the experiment

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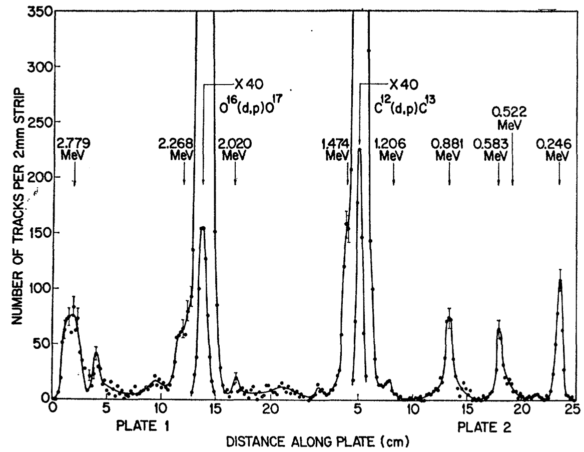

FIG. 1. Proton spectrum for the $Cr^{54}(d,p)Cr^{55}$ reaction at $\theta=30$ deg, showing levels in Cr^{55}, $E_d=2.767$ MeV, separated isotope Cr^{54} target, 3000 μC exposure.

and has to be studied over a large shift in angle to be feasible. For example, the 30-to-90-deg shift for chromium isotopes separated in mass by two units results for this case in approximately a 6-keV shift in energy.

An auxiliary principle used in this experiment for identifying levels due to each of the isotopes and getting additional information on the impurities in the targets is to make targets of each of the separated isotopes and of the natural chromium and run identical exposures on each of them to determine if the difference in the intensity of the peaks was proportional to the degree of purity of the isotopes.

DISCUSSION OF RESULTS

The Q values of the first nine excited states of Cr^{55} are reported in Table I. An absolute error of 15 keV is quoted for the Cr^{55} data and 10 keV for the Cr^{53} data. Cross sections for each level are given in Table II. The principal source of the 60% error in the cross sections is due to uncertainty in the target thickness, which was determined from the elastic scattering peak half-widths and also from the energy degradation of transmitted polonium alphas. Four exposures were made with the Cr^{54} target; the spectrum at 30 deg is shown in Fig. 1 while Fig. 2 presents that at 90 deg. Each figure represents a composite of data from two plates and since the energy scale is not linear with distance along the plate, a discontinuity in energy appears at the plate juncture. Most of the levels were seen on both the 30- and 90-deg exposures as well as by other experimenters. For levels at 0.522, 1.474, 2.020, and 2.268 MeV, however, the level seen at one angle appeared in the exposure at the other of the two angles only as a small perturbation on the tail of a larger peak. The level at 2.779 MeV was observed only at 30 deg and not at 90 deg but has been recently corroborated by Bochin *et al.*[10] Bochin reports levels in Cr^{55} with an uncertainty of about 35 keV, but does not report absolute Q values. Bjerregard *et al.*[9] have also just reported levels in Cr^{55} with an uncertainty of 8 keV.

TABLE II. Differential-cross sections for Cr^{53} and Cr^{55}.

Nuclide	Energy level (MeV)	Differential cross section (mb/sr) At 30°	At 90°
Cr^{53}	0		0.09 ±0.05
	0.568		0.05 ±0.03
	1.007		0.06 ±0.04
	1.297		0.01 ±0.006
Cr^{55}	0.246	0.08 ±0.05	0.016±0.010
	0.522	0.008±0.005	0.006±0.004
	0.583	0.05 ±0.03	0.036±0.021
	0.881	0.07 ±0.04	0.037±0.022
	1.206	0.007±0.004	0.007±0.004
	1.474	0.021±0.013	0.11 ±0.07
	2.020	0.008±0.005	0.037±0.022
	2.268	0.03 ±0.02	0.06 ±0.04
	2.779	0.11 ±0.07	

TABLE I. Energy levels of Cr^{55}.

Present experiment Q (MeV)	Level (MeV)	Bjerregard[a] Level (MeV)	Bochin[b] Level (MeV)
3.785	0.246±0.015	0.248±0.008	0.230±0.035
3.509	0.522±0.015	0.523±0.008	
3.448	0.583±0.015	0.574±0.008	0.600±0.035
3.150	0.881±0.015	0.890±0.008	0.930±0.035
2.815	1.206±0.015		1.200±0.035
2.557	1.474±0.015	1.486±0.008	1.520±0.035
		1.656±0.008	
		1.775±0.008	
		1.979±0.008	
2.011	2.020±0.015	2.023±0.008	2.000±0.035
		2.093±0.008	2.090±0.035
1.763	2.268±0.015	2.275±0.008	2.310±0.035
			2.480±0.035
1.252	2.779±0.015		2.790±0.035

[a] J. H. Bjerregard, P. F. Dahl, O. Hansen, and G. Sidenius, Nucl. Phys. 51, 641 (1964).
[b] V. P. Bochin, K. I. Zherebtsova, V. S. Zolotarev, V. A. Komorov, and L. V. Krasnov, Nucl. Phys. 51, 161 (1964).

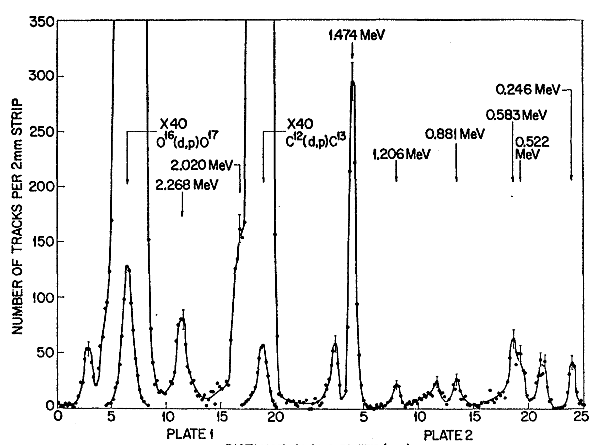

FIG. 2. Proton spectrum for the $Cr^{54}(d,p)Cr^{55}$ reaction at $\theta=90$ deg, showing levels in Cr^{55}, $E_d=2.767$ MeV, separated isotope Cr^{54} target, 3000 μC exposure.

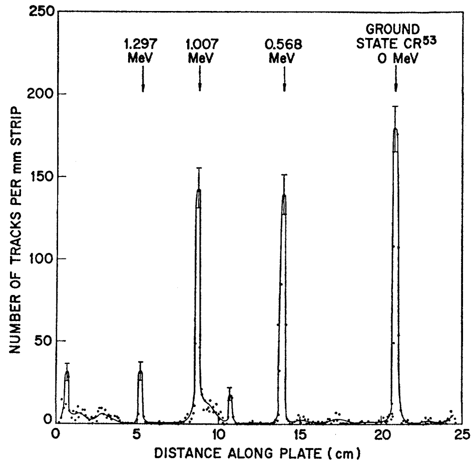

FIG. 3. Proton spectrum for the $Cr^{52}(d,p)Cr^{53}$ reaction at $\theta=90$ deg, showing levels in Cr^{53}, $E_d=2.745$ MeV, natural chromium targets, 2800 μC exposure.

Our Q values agree well with Bjerregard. Bochin's level spacing is also in general agreement to within the uncertainty claimed for the data. The exceptions include the level at 1.211 MeV which we report as well as Bochin but which is not seen by Bjerregard and the level at 2.093 MeV which is seen by Bochin and Bjerregard but not in the present experiment. The three levels at 1.656, 1.775, and 1.979 MeV were reported only by Bjerregard. In the present experiment, several other proton peaks are seen in either Figs. 1 or 2 without further corroboration. Some of these may represent levels in Cr^{55}, but the possibility exists that they may also be as yet unrecognized contaminants.

The Cr^{52} contamination is small since there is no indication in Figs. 1 and 2 of the strong 2.32-MeV level of Cr^{53} which is seen in our Cr^{52} exposures having approximately the same bombarding energy.

TABLE III. Energy levels of Cr^{53}.

Present experiment		Bjerregard[a]	Bochin[b]
Q (MeV)	Level (MeV)	Level (MeV)	Level (MeV)
5.723	0 $\pm$0.010	0 $\pm$0.008	0 $\pm$0.035
5.155	0.568$\pm$0.010	0.565$\pm$0.008	0.570$\pm$0.035
4.716	1.007$\pm$0.010	1.003$\pm$0.008	1.010$\pm$0.035
4.426	1.297$\pm$0.010	1.283$\pm$0.008	
		1.531$\pm$0.008	
		1.968$\pm$0.008	
		2.168$\pm$0.008	
		2.230$\pm$0.008	
3.401	2.322$\pm$0.010	2.319$\pm$0.008	2.310$\pm$0.035
		2.654$\pm$0.008	
3.053	2.670$\pm$0.010	2.667$\pm$0.008	2.690$\pm$0.035

[a] J. H. Bjerregard, P. F. Dahl, O. Hansen, and G. Sidenius, Nucl. Phys. **51**, 641 (1964).
[b] V. P. Bochin, K. I. Zherebtsova, V. S. Zolotarev, V. A. Komorov, and L. V. Krasnov, Nucl. Phys. **51**, 161 (1964).

Exposures were also made of the natural chromium and of the Cr^{52} and Cr^{53} isotopes at 90 deg. A typical exposure taken with a natural chromium target is shown in Fig. 3. The ground-state Q value was determined to be 5.723 MeV. The levels of Cr^{53} are measured to be 0.568, 1.007, 1.297, and 2.322 MeV and a multiplet around 2.67 MeV is observed. These levels were seen in two exposures at 90 deg. Their assignment is in good agreement with Bjerregard and Bochin. (See Table III.) We have several more smaller peaks which have yet to be positively identified. Bochin does not report the level at 1.297 MeV. Bjerregard reports several additional levels which we have observed either only in one exposure or not at all. Bjerregard reports a ground-state Q value of 5.713 MeV.

It will be noted that the peaks of Fig. 3 are only about half the width of those in Figs. 1 and 2. In the exposures of Figs. 1 and 2, an aluminum absorber in front of the emulsions as an elastic-deuteron shield gave rise to the broader peaks of that case.

There is a tentative identification of the 2.609 MeV level ($Q=4.888$ MeV) and a level at 1.809 MeV ($Q=5.588$ MeV) in Cr^{54}. This is based on only one exposure with the separated isotope, Cr^{53}, at 90 deg, and the fact that the levels are reported in the literature.[9,10] Peaks which could be due to levels in Cr^{53} or Cr^{55} were small or nonexistent in this exposure.

One would expect the spectrum of Cr^{54} to be similar to that of Cr^{52} and that of Cr^{55} to be similar to Cr^{53} because the two extra neutrons of the first-named members of each pair of nuclei would tend to couple together. Although Cr^{54} is indeed similar to Cr^{52}, it nevertheless does have an extra level below 2 MeV.[12] The results of our experiment as well as the data of Bjerregard reveal at least four extra levels below 3 MeV in the Cr^{55} spectrum with two of them below 1 MeV. See Tables I and III. These levels could be due to the interactions of the extra neutrons with either the unfilled proton shell or the Ca^{48} core.

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[12] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.).