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GAMMA-RAY DECAY OF LEVELS IN ^{53}Cr

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ABSTRACT

Gamma-ray decay of levels in the stable isotope ^{53}Cr has been studied using $^{53}\text{Cr}(n, n'\gamma)$ reactions for incident neutron energies between threshold and 10 MeV. Of the 65 gamma rays or gamma-ray groups observed for neutron interactions with ^{53}Cr , 50 have been placed or tentatively placed among 34 levels in ^{53}Cr up to an excitation energy of 4.36 MeV. Deduced branching ratios are in reasonable agreement with previous measurements except for decay of the $E_x = 1537\text{-keV}$ level. For the decay of the $E_x = 1537\text{-keV}$ level we are unable to explain variations in the branching ratios of the transition gamma rays as a function of incident neutron energy within the framework of the presently known level structure of ^{53}Cr and suggest the possibility of a second energy level at $E_x = 1537\text{ keV}$.

1. INTRODUCTION

The level structure of the stable nucleus ^{53}Cr has been studied via inelastic nucleon scattering¹⁻⁹ as well as charged-particle reactions,^{1-6,9-14} and gamma-ray transitions among levels have been observed by in-beam spectroscopy methods^{2,8,13-31} and following beta-decay^{32,33} of ^{53}V . Recently, experimental data available through 1983 were compiled and evaluated by Peker³⁴ as part of the Nuclear Data Project. One might expect, therefore, that the low-lying (excitation energy $E_x < 3$ MeV) level structure of ^{53}Cr could be considered as well known. One might also expect that the ^{53}Cr level structure can be satisfactorily described within the theoretical framework of the nuclear shell model. Indeed, reported calculations³⁵⁻⁴⁴ exhibit reasonable agreements with experiment, at least for level excitation energies, E_x , and for calculated spins and parities J^π . (To get good agreement, however, apparently requires more than the usual amount of configuration mixing of chosen basis states.)

We have embarked upon a program⁴⁵ to provide experimental cross sections for gamma rays produced by energetic neutrons (generally $E_n > 0.5$ MeV) interacting with stable nuclei in the mass region $A \sim 60$ for the purpose of providing data for comparisons with, and leading to improvement of, nuclear model calculations.⁴⁶ These calculations require knowledge of the level structure as well as the transition branching ratios of the decay of excited states for many nuclei in this mass region, and such information is deduced from our experimental data. We have measured gamma-ray yields for neutron interactions with ^{53}Cr as a part of this program. In addition to new information about levels in ^{53}Cr we have observed data on yields of transition gamma rays from decay of the presumed well-known low-lying levels in ^{53}Cr at $E_x = 1289$ and 1536 keV which are not in agreement with what should be expected on the basis of current knowledge³⁴ of ^{53}Cr . In this report, we present our experimental results for gamma rays following inelastic scattering in some detail. In addition, plausible, but not definitive, explanations for the observed data will be discussed.

2. EXPERIMENTAL DETAILS

The experimental system has been discussed in some detail in an earlier report.⁴⁵ The salient features are shown schematically in Fig. 1. Starting from the lower-left of this figure, 140-MeV electrons produced by the Oak Ridge Electron Linear Accelerator (ORELA) impinged upon a tantalum target producing bremsstrahlung. Neutrons produced in the tantalum by subsequent photonuclear reactions were guided to the experimental area by an evacuated, 20-m-long flight tube located at 120 deg with respect to the incident electron beam. Collimators were inserted into the flight tube to define the neutron beam to a diameter of 7.3 cm at the sample position. The beam traveled ~ 2 m in air before impinging on the ^{53}Cr sample. A small NE-110 scintillator intercepted $\sim 1\%$ of the incident neutron flux and was used as a beam monitor.

Fig. 1. Schematic representation of the experimental system. The "TWO-DIMENSIONAL DATA STORAGE" unit may be programmed to sort and update >50 4096-channel spectra. The beam monitor is an NE-110 scintillator 0.6 cm diam by 0.6 cm thick mounted on a photomultiplier tube. Experimental details have been reported by Bell et al. (ref. 45).

A large-volume Ge(Li) detector was placed at $D = 0.40$ m from the sample (D is the distance from the center of the sample to the front of the aluminum container housing the detector) at a scattering angle, θ_γ , of 125 deg. This angle was chosen because $P_2(125 \text{ deg}) = 0$ and so one may use the relationship between the total gamma-ray production cross section (i.e., angle-integrated) and the measured differential cross section:

$$\sigma(E_\gamma) \simeq 4\pi d\sigma(\theta_\gamma = 125 \text{ deg})d\omega . \quad (1)$$

Two types of pulses were extracted from the detector electronics. One was for energy analysis using standard very-high resolution pulse-amplitude analyzing equipment (3 μ s time constants for the spectroscopy amplifier). The other pulse was used for fast-timing analysis to determine the flight time of the neutron responsible for the detected gamma ray. The time-of-flight datum was correlated with the energy datum in a data-acquisition computer, which sorted and then stored events on a bulk storage disk pack.

The sample used was Cr_2O_3 encapsulated in a cylindrical nylon container 2.9-cm diam by 6.7-cm height. The total sample mass was ~ 49 gm, and the isotopic enrichment was 95.4% in the ^{53}Cr isotope. The remaining concentrations were 0.3%, 4.1%, and 0.2% for ^{50}Cr , ^{52}Cr , and ^{54}Cr , respectively. The sample was positioned so that the axis of the cylinder was normal to the plane defined by the incident neutron beam and the gamma-ray detector.

It was necessary to determine time-of-flight (hence, incident neutron energy) and gamma-ray pulse-height binning prior to the final (i.e., definitive) measurements. For the latter we chose 4096 channels with a dispersion of ~ 0.9 keV/channel. Rather coarse time-of-flight groupings were required to obtain sufficient pulse-height data for a chosen time-of-flight bin, partly dictated by the known⁴⁵ rapid decline in neutron beam flux for $E_n > 2$ MeV.

Altogether 18 gamma-ray spectra, corresponding to 18 neutron time-of-flight bins, were studied to provide information presented in this report. One of these spectra is exhibited in Figs. 2 and 3. In these figures essentially all peaks corresponding to gamma-ray detection have been identified. Those due to detection of gamma rays following neutron interactions with isotopes other than ^{53}Cr are labelled with the symbol of the responsible isotope.

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Fig. 2. Pulse-height spectrum for 3.2- to 4.0-MeV neutron interactions with the chromium sample. Gamma rays not due to $^{53}\text{Cr}(n, n')^{53}\text{Cr}$ are labelled with the isotope symbol. Neutron inelastic interactions with germanium isotopes result in broad peaks. The experimental dispersion is $\sim 0.9 \text{ keV/channel}$.

Fig. 3. Pulse-height spectrum of Fig. 2 continued to larger E_γ .

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A combination of data reduction techniques involving (1) computer methods (a modified version of the code TPASS⁴⁷) and (2) manual methods was used to extract yields of gamma rays from the spectral data. Gamma-ray attenuation by the sample was computed⁴⁸ using attenuation coefficients in the literature⁴⁹ for oxygen and chromium (the thin-walled nylon container was assumed to be oxygen for this purpose); the largest such correction was $\sim 17\%$ for $E_\gamma = 247$ keV. Multiple scattering effects were estimated by analytical methods and found to be $< 1\%$ for the present experiment. Gamma-ray production cross sections, σ , were deduced from the data. We were able to extract some σ as small as 1 mb; however, for much of the data the lower limit to our sensitivity was ≥ 10 mb. The absolute normalization for σ is presently being checked in a similar series of measurements for a natural chromium sample. Values of σ given in this report should be considered relative, although we doubt that the final values will differ by as much as 10% from values quoted herein.

There are two aspects of the choice of gamma-ray scattering angle, $\theta_\gamma = 125$ deg, that need to be discussed. The first, as mentioned above, is that $P_2[\cos 125^\circ] = 0$, so that to first order, the gamma-ray production cross section, $\sigma(E_\gamma)$ is given by Eq. (1). This equation is exact⁵⁰ if J of the decaying excited state is $\leq 3/2$, and is a good approximation²⁷ for states in ^{53}Cr having larger J .

The other aspect of this choice of θ_γ is the Doppler effect on an observed gamma-ray energy. The Doppler effect is manifest in two ways: (1) variation of observed E_γ because of the variation of the velocity vector of the excited Cr ion in flight which (variation) is observed as a peak broadening in the spectrum, and (2) shift of the mean E_γ of the (broadened) response so that the observed E_γ is not necessarily the true energy of the emitted gamma ray. The latter effect is well known and often used as a basis for level lifetime determination. The measured energy, E_γ^{obs} , is related to the intrinsic energy, E_0 , by the relationship

$$E_\gamma^{obs} = E_0(1 + F(t)\beta_{c.m.} \cos \theta_\gamma) , \quad (2)$$

where $\beta_{c.m.}$ is the scalar velocity of the center of mass in units of c , and $F(t)$ is a function of t , the mean lifetime of the decaying level. The values of $F(t)$ range between 1.0 for $t < 10^{-15}$ s to 0 for $t > 10^{-12}$ s. As far as peak broadening is concerned, one may readily deduce that this broadening is a function of the angular distribution of the recoiling ion. If isotropy in the center-of-mass system of the

angular distribution is assumed for the excited Cr ion (and hence recoiling incident neutron), then the line broadening is independent of θ_γ and the Doppler-broadened line width is given approximately by

$$R \approx E_\gamma \beta_{ion} F(t) , \quad (3)$$

where β_{ion} is the scalar velocity of the ion in the center-of-mass system. This Doppler line width must be combined with the intrinsic resolution of the detection system to obtain the observed resolution, which, in turn, must be known in order to determine if a given peak observed in the raw data could be due to detection of more than one gamma ray.

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The reduced data consist of yields, $\sigma(E_\gamma, E_n)$ obtained for gamma-ray production in ^{53}Cr of discrete-energy gamma rays having energies E_γ by incident neutrons having energies E_n . The E_n for this experiment are values representing chosen energy bins described by the bounds, E_{low} and E_{high} , which were deduced from the flight-time bins. incident-neutron energy bin sizes ranged between 10% and 25% of E_n .

For most of the E_γ we used previously³⁴ determined values which we consider to be "known" to better than the accuracies associated with our gamma-ray energy calibrations; other values of E_γ reported herein were determined by utilizing a nearby difference

$$E_\gamma^{\text{unknown}} = E_\gamma^{\text{known}} + \Delta E_\gamma, \quad (4)$$

where ΔE_γ is based on the known energy dispersion of the experimental system. Uncertainties, dE_γ , assigned to deduced E_γ include uncertainties associated with ΔE_γ of Eq. (4) as well as those due to Doppler effects [Eq. (2)] if the mean lifetime, t , of the decaying level is now known.

Assignments of observed gamma rays as specific transitions among levels of ^{53}Cr were based on (a) prior knowledge³⁴ or (b) agreement of the experimental E_γ with the expected transition energy, E_i , coupled with the experimental incident-neutron threshold. A given observed threshold was, of course, approximate because of the incident-neutron energy bin size; in addition, thresholds for gamma rays due to decay of high spin states tended to be indistinct because of small values of σ near threshold. We were also concerned about the possibility of an incorrect threshold because the decaying excited state had a "long" mean lifetime ($t > 1$ nsec). No such isomeric state has been reported³⁴ for ^{53}Cr , and we do not adduce any long-lived level from our data.

3.1 LEVELS < 2 MEV EXCITATION

Prior experimental data support assignment of nine gamma-ray transitions among six levels in ^{53}Cr ; the adopted³⁴ levels, J^π , mean lifetimes, transitions and branching ratios are shown in Fig. 4. Implied, but not explicit in this figure are results from (γ, γ) , $(p, p'\gamma)$, $(d, p\gamma)$, and (decay β, γ) coincidence

measurements^{2,14,16,17,22,24,31-33} which have helped in defining the placements shown.

Fig. 4. Level structure of ^{53}Cr for excitation energies < 2 MeV, taken from the compilation of Peker (ref. 34). As discussed in the text, the present data have some disagreements with branching ratios given for decay of levels of $E_x = 1289.6$ and 1536.7 keV. The 442.7 -keV transition shown for one transition decay of the 1006.5 -keV level, although reported in ref. 32, was not included in Peker's evaluation.

3.1.1 $E_x = 564.1$ keV

The $E_\gamma = 564.1$ -keV gamma ray is observed strongly for E_n up to ~ 6 MeV, and then its yield lessens somewhat for larger E_n indicating that the $E_x = 564.1$ -keV level is not strongly fed by highly excited states of ^{53}Cr , at least not by those states excited by inelastic neutron scattering. The observed peak in the raw data slightly broadens for larger E_n in reasonable agreement with Doppler broadening for a level having a mean lifetime $t \sim 0.6$ ps.

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3.1.2 $E_x = 1006.5$ keV

A very strong gamma ray corresponding to the ground-state transition is first observed for the incident neutron-energy bin $1.0 \leq E_n \leq 1.2$ MeV. The yield of the observed peak remains large in all spectra for E_n to 10 MeV, and the peak in the raw data remains narrow, consistent with $T > 1$ ps.

Dorikens-Vanpraet et al.,³² in a study of the decay of ^{53}V report a 442.7-keV gamma ray which they assign as the 1006-564 keV transition with a branching ratio of 0.4%. We looked for evidence of this gamma ray in our data. Because the anticipated yield was very small, the five spectra spanning the region of E_n between 1.2 and 4.0 were summed for $430 < E_\gamma < 455$ keV. These data are shown in Fig. 5 compared with an estimate, based on the 0.4% branching ratio,³² of the position and peak shape due to a possible 442.7-keV gamma ray superimposed upon a constant background taken to be 680 counts per channel. Although it is not apparent that the data can support identification of a "peak" corresponding to $E_\gamma = 442.7$ keV (or even $E_\gamma = 442.4$ keV which is the expected transition energy), neither can one rule out a contribution to the spectrum from a 442.7-keV gamma ray. However, a peak having a yield 2.5 times the estimate given by the solid curve in Fig. 5 at $E_\gamma = 442.7$ keV is not observed, and so our data place an upper limit of a 1% branching ratio for this transition if it exists at all.

3.1.3 $E_x = 1289.6$ keV

Both gamma rays shown in Fig. 4 were first observed in the incident neutron energy group $1.2 \leq E_n \leq 1.4$ MeV; the yields for both gamma rays increase rapidly with increasing E_n and remain large as E_n increases to 10 MeV. Our results are almost but not quite in agreement with the evaluated results shown in Fig. 4. In the lower portion of Fig. 6, the ratio of extracted σ for the 283-keV and 1289-keV gamma rays is plotted as a function of increasing E_n . This ratio should be essentially a constant, a feature of multiple-transition decay we observed⁴⁵ in our study of the decay of levels in ^{57}Fe . The deviation from a constant ratio for $3 \leq E_n \leq 6$ MeV we ascribe to a second nearly energy-coincident gamma ray at $E_\gamma \simeq 283$ keV; the most reasonable placement of this second gamma ray is as the $2453 \rightarrow 2172$ keV transition, so that $E_\gamma = 281$ keV. There is some support for this E_γ assignment in the basic spectral data. In the upper portion of Fig. 6 are shown relevant portions of spectral data for five different E_n bins as indicated in the figure. The first two

Fig. 5. Portion of spectral data obtained in the present experiment. The axis of abscissas has been converted to gamma-ray energy for purposes of illustration. The solid curve represents one estimate of the expected response for detection of a possible gamma ray at $E_\gamma = 442.7$ keV shown in Fig. 2 as a possible 1006.5- to 564.1-keV transition.

spectra (from the left) give an indication of the detection system's resolution of ~ 2.2 channels (i.e., ~ 2.0 keV) full width at half maximum (FWHM). The middle spectrum suggests a second peak having $E_\gamma \sim 280$ keV; the integral yield deduced by the peak-extraction routine for the sum of data for E_γ between 279 and 285 keV results in the ratio shown by the solid lines. However, manually fitting a peak centered at $E_\gamma \sim 283$ keV results in a smaller $\sigma(E_\gamma = 283 \text{ keV})$ and hence a smaller ratio, and this smaller ratio is shown by the dashed cross. In the fourth spectrum (for $4.0 \leq E_n \leq 4.9$ MeV) the two peaks are not resolved, but the width of the observed peak definitely exceeds the expected FWHM for a single peak. The σ for the total peak results in the plotted ratio. The spectral data in the fifth spectrum suggest that, as for the spectra for $E_n < 2$ MeV, the 283-keV gamma ray is the primary contribution. Except for E_n near threshold, the ratio data do appear to be essentially constant after correction for the postulated $E_\gamma = 281$ -keV transition.

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Fig. 6. Portions of spectral data for $E_\gamma \sim 283$ keV and ratios of the yields of the two transitions observed for decay of the $E_x = 1289.6$ -keV level following $^{53}\text{Cr}(n, n'\gamma)$ measurements as a function of incident neutron energy between threshold and 10 MeV. The upper portion of the figure exhibits portions of spectral data for five selected incident-neutron bins. As in figure 5, the axis of abscissas for the separate spectra have been converted to gamma-ray energies for illustrative purposes. The lower portion of the figure exhibits the ratio data. The dashed cross for $3.2 \leq E_n \leq 4.0$ MeV indicates the value of the plotted ratio if only the main peak having $281 \leq E_\gamma \leq 285$ keV of the companion spectrum contributes to the yield for detection of a gamma ray having $E_\gamma = "283"$ keV. The horizontal line at ratio ≈ 0.07 represents the adopted value from Peker's compilation (ref. 34).

The ratio value that we obtain agrees well with the accepted value given in Fig. 4 which is indicated in Fig. 6 by the line at 0.07. We do not have an explanation for the much larger ratio shown in Fig. 6 for E_n just greater than threshold. In this lowest E_n bin yields for peaks corresponding to both gamma rays are small but well defined. Possibly the observed ratio near threshold reflects a substantial variation from the assumption leading to Eq. (1) for one or both transitions.

3.1.4 $E_x = 1536.7$ keV

This $J^\pi = 7/2^-$ level is observed with large yields in pick-up reactions^{3,6,9,10} suggesting that the wave function describing this level contains a substantial component of $|(1f_{7/2})_{7/2}^{-1} (2p_{3/2}, 2p_{1/2} \text{ or } 1f_{5/2})_{j=0}^2\rangle$ neutron hole-state configuration.^{43,44} This hole-state configuration is not included as a basis state in most of the calculations cited above and so this level is not predicted by these calculations. On the other hand, the neighboring $J^\pi = 7/2^-$ level at $E_x = 1289.6$ keV is simply described^{4,11,35-37,39} as a phonon-particle configuration, that is, by a $2p_{3/2}$ neutron coupled to the $J^\pi = 2^+$ state of the ^{52}Cr core. There is some configuration mixing between these two $J^\pi = 7/2^-$ states as evidenced by observation, albeit weak, of the $E_x = 1289.5$ -keV state in pick-up reactions as well as weak observations of the $E_x = 1536.7$ -keV state in stripping reactions.

Experimentally, the 1536.7-keV state has proved to be difficult to understand. In the first place, the two measurements of the half life of this level^{23,29} are in disagreement. Both measurements used the $^{50}\text{Ti}(\alpha, n\gamma)^{53}\text{Cr}$ reaction; Engelstein et al.²³ obtained $T_{1/2} = (14.4 \pm 2.5)$ psec while Radford and Poletti²⁹ obtained $T_{1/2} = (23.2 \pm 1.1)$ psec for this level. However, as noted by Auble⁵¹ a value for $T_{1/2} \sim 23$ psec is inconsistent (about a factor of 25 too large) with the measured²⁶ $B(E2) = (9 \pm 1)e^2\text{fm}^4$ for $E_\gamma = 1536$ keV deduced from Coulomb excitation measurements. This measured $B(E2)$ is close to the calculated value (see Löbner⁵² for theoretical methods) of $11.8 e^2\text{fm}^4$. Finally, measured branching^{17,19,22,24,28,30} ratios for the three gamma-ray decay modes are given in Table 1. Major disagreements are evident for the two partial measurements,^{24,30} and minor disagreements, at least in comparison with assigned uncertainties, are evident among the other five experiments.

Our data do not resolve the problem of understanding the decay of this level. Extracted ratios of $\sigma(247 \text{ keV})/\sigma(530 \text{ keV})$ and $\sigma(1537 \text{ keV})/\sigma(530 \text{ keV})$ are shown

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Table 1. Branching ratios for decay of $E_x = 1537$ -keV level of ^{53}Cr

Type of measurement	1537-keV gamma ray	530-keV gamma ray	247-keV gamma ray	Reference
$^{52}\text{Cr}(d, p\gamma)$	11 ± 2	57 ± 2	32 ± 3	17
$^{50}\text{Ti}(\alpha, n\gamma)$	10 ± 1	65 ± 1	25 ± 1	19
$^{50}\text{Ti}(\alpha, n\gamma)$	10	63	27	22
$^{51}\text{V}(^7\text{Li}, \alpha n\gamma)$		(60) ^a	(15) ^a	24
$^{53}\text{Cr}(p, p'\gamma)$	11 ± 1	57 ± 1	32 ± 1	26
$^{53}\text{Cr}(\alpha, \alpha'\gamma)$				
$^{48}\text{Cr}(^9\text{Be}, 4n, \gamma)$	9 ± 2	65 ± 2	26 ± 2	28
$^{52}\text{Cr}(n, \gamma)$	$(44 \pm 7)^b$	$(56 \pm 6)^b$		30

^a $E_\gamma = 1537$ keV not reported. These values are relative to each other.^b $E_\gamma = 247$ keV not reported. These values are relative to each other.

as functions of incident neutron energy in Fig. 7. For comparisons, these ratios from the data given in Fig. 4 are shown by labelled lines. Because the results in Fig. 7 came from computer-extracted cross sections, the spectral data were carefully gone over. The spectral data corresponding to E_γ between 1527 and 1544 keV are exhibited in Fig. 8. Also plotted for comparisons are "estimated responses" for a peak corresponding to $E_\gamma = 1537$ keV based on a 0.14 ratio, the efficiency-corrected yields of the $E_\gamma = 530$ -keV peak, a visually estimated continuum, and the measured detector response at $E_\gamma = 1434$ keV plotted with the peak centroid at $E_\gamma = 1537$ keV. (That is, plotted peaks are not the computer extracted data.) There are several observations that may be made. (1) The yield of the 1537-keV gamma ray for the neutron energy bin $1.73 \text{ MeV} \leq E_n \leq 2.16 \text{ MeV}$ is definitely greater than expected from the adopted ratio, whereas the yield of this gamma ray for the next two larger-energy bins is about that expected. (2) The spectral data for the neutron energy bin $3.2 \text{ MeV} \leq E_n \leq 4.0 \text{ MeV}$ are complex; one cannot be sure if there are contributions due to additional gamma rays having energies $E_\gamma \sim 1530$ and/or ~ 1541 keV. (The computer program did not determine either possibility.) (3) For the neutron energy bin $7.9 \text{ MeV} \leq E_n \leq 9.5 \text{ MeV}$, the spectral data do not indicate any peak at all, hence the zero ratio shown in Fig. 7. Although there is no obvious peak in this spectrum, one cannot mandate a null result; deducing the magnitude of a proposed peak, however, would seem to require a subjective

appraisal of the data. Interestingly, the next higher incident neutron energy bin (the lower right-most spectrum of Fig. 8) does exhibit a peak even with fewer average counts per channel.

Fig. 7. Yield ratios for the three transitions observed for decay of the $E_x = 1536.6$ -keV level following $^{53}\text{Cr}(n, n' \gamma)$ measurements as a function of incident neutron energy between threshold and 11 MeV. The labelled horizontal lines represent the adopted values from Peker's compilation (ref. 34).

Can the results given in Table 1 and those in Figs. 7 and 8 be explained? One must first accept the premise that outright experimental errors are not the sources of the differences given in Table 1 and/or Figs. 7 and 8. Except for the energy bins $E_n = 2.73$ to 2.16 MeV and $E_n = 7.9$ to 9.5 MeV, a subjective appraisal of the spectra of Fig. 8 might lead to the conclusion that the ratio $\sigma(1537 \text{ keV})/\sigma(530 \text{ keV})$ shown in Fig. 7 is essentially constant with a value ~ 0.17 , a value a little larger than but at least approximately consistent with 0.14 , i.e., the adopted ratio.³⁴ Perhaps, then, the ratio data are consistent; the ratio for our smallest E_n bin could reflect a deviation from the assumption leading to Equation (1), and the ratio for the E_n bin of 7.9 to 9.5 MeV may just be a statistical variant. Then the only substantially

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Fig. 8. Portions of spectral data for $1537 \leq E_\gamma \leq 1545$ keV obtained in the present experiment. As in Fig. 5, the axis of abscissas has been converted to gamma-ray energy for illustrative purposes. The dispersion is ~ 0.9 keV/channel. The solid curves are estimated responses for detection of a gamma ray having $E_\gamma = 1536$ keV corresponding to a ground-state transition. The curves include estimated yields for the $E_\gamma = 1536$ -keV gamma ray based upon the measured yield of the $E_\gamma = 530$ -keV gamma ray, the evaluated branching ratios for decay of the $E_x = 1536$ -keV level, and the experimental detection resolution superimposed upon a Compton continuum. The latter was estimated subjectively for the purposes of this illustration. The "peaks" exhibited in this figure are not those determined during the data analysis leading to the ratio determinations exhibited in Fig. 7. Indeed, the computer program did not locate any peaks at all in this gamma-ray energy interval for $7.9 \leq E_n \leq 9.5$ MeV (second spectrum from the right).

discrepant ratio is for the $^{52}\text{Cr}(n, \gamma)$ reaction, and the value for this ratio might be somewhat suspect, since it is not obvious how the $J^\pi = 7/2^-$ level at $E_x = 1537$ keV was populated in the reaction studied.

The substantial variations in the ratio $\sigma(247 \text{ keV})/\sigma(530 \text{ keV})$, as shown in the upper half of Fig. 7, are very puzzling. The pertinent portions of five spectra are exhibited in Fig. 9, and the data are compared with "estimated responses" for a peak corresponding to $E_\gamma = 247$ keV based on a 0.4 ratio, the efficiency-corrected yields of the $E_\gamma = 530$ -keV peak, a visually estimated continuum, and the detector response at $E_\gamma = 247$ keV. For these spectra, the individual data have much smaller uncertainties than for the spectra in Fig. 8. In this case, it seems unreasonable to describe the fluctuations in the observed cross-section ratio as a function of E_n (in Fig. 7) as "random" bearing in mind that the ratio value ought to be essentially a constant independent of E_n . If the observed variations are not random and not due to experimental error, what is their cause?

At present, all that we can say for certain is that we cannot explain the data for the decay of the $E_x = 1537$ keV within the framework of the known level structure of ^{53}Cr , and that there are other experimental discrepancies, e.g., the above-mentioned different measured or deduced values of the level lifetime. In addition, no gamma rays having $E_\gamma \simeq 1537$ keV have been observed for decay of levels of other Cr isotopes or for other $n + ^{53}\text{Cr}$ reaction channels. We, therefore, tentatively propose a new low-lying level in ^{53}Cr at $E_x = (1536.7 \pm 0.9)$ keV. New experiments will be needed to determine if such a level exists.

3.1.5 $E_x = 1973.6$ keV

The two transitions shown in Fig. 4 at $E_\gamma = 1973.6$ keV and $E_\gamma = 684.1$ keV are observed in our data having thresholds consistent with these transition assignments. For the incident-neutron energy bin $2.16 \text{ MeV} \leq E_n \leq 2.59 \text{ MeV}$ $\sigma(684)/\sigma(1974) = 0.13 \pm 0.05$, and for $2.59 \leq E_n \leq 3.18$, this ratio is 0.15 ± 0.02 , both values in good agreement with 0.18 deduced from the adopted³⁴ branching ratios shown in Fig. 4. For $E_n > 3.2$ MeV the spectral peak corresponding to $E_\gamma = 684$ keV appears to be fragmented. However, the cross-section ratio $\sigma(684)/\sigma(1974)$ of 0.15 ± 0.06 for $3.2 \leq E_n \leq 4.0$ MeV is consistent with single gamma-ray contribution.

Fig. 9. Portions of spectra data for $240 \leq E_\gamma \leq 254 \text{ keV}$. The information presented here is similar to that shown in Fig. 8, except now for the $E_\gamma = 247\text{-keV}$ transition. Statistical uncertainties associated with the spectral data indicated for the $4.9 \leq E_n \leq 5.9 \text{ MeV}$ incident-neutron bin are indicative of these uncertainties for the other four spectra.

3.2 LEVELS BETWEEN 2 AND 3 MEV EXCITATION

In this region of excitation energy, Peker³⁴ gives 16 levels. We exhibit 12 levels in Fig. 10, including one for which we did not observe possible decay transitions. Four levels in Peker's compilation,³⁴ at $E_x = (2165 \pm 10)$, (2221 ± 10) , (2715 ± 10) , and 2723 ± 10 keV, are not shown in Fig. 10. These levels are reported in the $^{52}\text{Cr}(d, p)$ experiments.^{1,2} However, no other experiments have located gamma-ray decay transitions for levels at these energies, and the $\Delta E_\gamma = 10$ keV in all cases is sufficient to overlap with other near-lying established levels.

3.2.1 $E_x = 2172.4$ keV

This $J^\pi = 11/2^-$ level is seen weakly² in $^{53}\text{Cr}(p, p')$ measurements, but essentially not seen at all in the various single-nucleon transfer reactions. It is excited rather strongly in the $^{51}\text{V}(\alpha, d)^{53}\text{Cr}$ reaction reported by Kawa et al.¹² These authors suggest that in the phonon-particle model the wave function of this state is dominated by a $2p_{3/2}$ neutron coupled to the $J^\pi = 4^+$ state of the ^{52}Cr core. The measured half lives of the state are discrepant, with Engelstein et al.²³ reporting (4.5 ± 2.1) psec, Poletti et al.²⁴ reporting (31 ± 10) psec, and Radford and Poletti²⁹ reporting (9.3 ± 0.7) psec. The transition gamma ray, having $E_\gamma = 883$ keV, for decay of this level is observed in several of the gamma-ray measurements.^{8,19,22-24,28,29,31}

We observed the 883-keV gamma ray in the lowest energy E_n bin consistent with the threshold for exciting this state, and, as shown in Fig. 11, the gamma-ray production cross section increases with increasing E_n . Also shown on this figure are the results of a compound-nucleus nuclear-model calculation⁵³ of the type $^{53}\text{Cr}(n, n')^{53}\text{Cr}$ using the code TNG⁵⁴ for the direct excitation of this level by neutrons; the calculation does not include level excitation via transitions from decay of more energetic levels in ^{53}Cr . The data emphasize that, in fact, this latter mode of level excitation is dominant for $E_n > 4$ MeV. One may extend this observation by noting that the more-energetic levels decaying via transitions to this state will (most probably) have $J \geq 9/2$ therefore involving orbital angular momentum transfer $L \geq 3$ in the scattering process. The measurements, therefore, give an indication of the amount of neutron excitation of high-spin states for energetic levels in ^{53}Cr .

3.2.2 $E_x = 2233.3$ keV

This $J^\pi = 9/2^-$ level decays via a transition to the $J^\pi = 7/2^-$ "hole" state at $E_x = 1537$ keV. We observed the transition gamma ray at $E_\gamma = 696.5$ keV in

Fig. 10. Level structure of ^{53}Cr for excitation energies $E_x < 3$ MeV. This figure exhibits information obtained partly from Peker's compilation (ref. 34) and partly from the present experiment. The four italicized level energies, three gamma-ray energies, and one J^π are new information from the present experiment. The solid arrows indicate definitely observed transitions, the three dashed arrows indicate transitions previously reported but not confirmed in the present experiment, and the dot-dashed arrows indicate transition gamma rays which may have been detected in the present experiment but for which definitive assignments are uncertain.

Fig. 11. Excitation function for the $E_\gamma = 883$ -keV gamma ray corresponding to the 2172- to 1289-keV transition. The solid curve is a nuclear-model calculation using the TNG code for the neutron inelastic excitation of the $E_x = 2172$ -keV level and does not include (indirect) contributions to the population of this level by transitions following decay of more energetic levels. Clearly this indirect mode of contribution is important for $E_n \geq 3.5$ MeV.

the correct E_n bin for the threshold of excitation of the $E_x = 2233$ -keV level. The excitation function for this gamma ray is qualitatively similar to that for $E_\gamma = 883$ keV discussed in the last subsection. The cross section reaches a maximum of ~ 135 mb at $E_n \sim 7$ MeV. The calculated direct excitation of the level at $E_x = 2233$ keV by neutrons is very similar to that shown in Fig. 11 for the level at $E_x = 2172$ keV; the calculated level excitation agrees with the measured σ_γ for $E_n \leq 4$ MeV.

3.2.3 $E_x = 2320.5$ keV

This $J^\pi = 3.2^-$ level is observed to be strongly excited in the $^{52}\text{Cr}(d,p)$ reaction;^{1,2,5,14} its transition decay gamma ray, at $E_\gamma = 2320.5$ keV, is observed strongly in the $^{52}\text{Cr}(d,p\gamma)$ reaction,^{14,17} the capture reaction $^{52}\text{Cr}(n,\gamma)$ for thermal neutrons,^{18,21} in the $^{50}\text{Ti}(\alpha,n\gamma)$ reaction,¹⁹ and in Coulomb excitation.²⁶ Our

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gamma-ray production cross sections are shown in Fig. 12 along with the TNG nuclear-model $^{53}\text{Cr}(n, n')^{53}\text{Cr}$ calculation.⁵³ This case differs from that shown in Fig. 11: the indications are that there is essentially no population of this level via transitions from decay of more energetic excited states of ^{53}Cr as the incident E_n is increased, at least for $E_n < 10$ MeV. This feature, combined with the single observed decay transition, suggests that the wave function describing this level must be functionally orthogonal to wave functions describing the other ^{53}Cr excited states possibly mixing only with the wave function describing the ^{53}Cr ground state.

Fig. 12. Excitation function for the $E_\gamma = 2321$ -keV gamma ray corresponding to the ground-state decay of a level at $E_x \approx 2321$ keV. For this level indirect excitation is essentially nil, at least for $E_n < 6$ MeV.

3.2.4 $E_x = 2453.1$ keV

According to Peker's evaluation³⁴ this level decays by two transitions, $E_\gamma = 1446.8$ keV to the $J^\pi = 5/2^-$ state at $E_x = 1006.5$ keV and $E_\gamma = 1163.6$ keV to the $J^\pi = 7/2^-$ state at $E_x = 1289.6$ keV, with relative branching ratios of

60:40. These branching ratios are based upon those reported by Carola et al.¹⁷ who give no details of their branching-ratio determination for this level in their report. As discussed above in Sect. 3.1.3, our data indicate a new gamma ray having energy $E_\gamma \simeq 281$ keV with a threshold definitely < 3.2 MeV. The only transition energy, $\Delta E_x = E_x^{(1)} - E_x^{(2)}$, that is within ± 2 keV of this gamma-ray energy is the 2453-keV-to-2172-keV transition. We have placed the $E_\gamma \simeq 281$ -keV gamma ray as this transition rather than postulating a new, heretofore unobserved level. If this placement is correct, then the spin of this state is very probably either $7/2$ or $9/2$, and the parity is almost surely negative. The parity can be deduced from the following argument. If the parity were positive, then $J^\pi = 7/2^+$ or $9/2^+$. If $J^\pi = 7/2^+$ then the $E_\gamma = 281$ -keV transition is M2. However, for an M2 transition having $E_\gamma = 281$ keV and a 15% branching ratio $\Gamma_\gamma/\Gamma_W > 1$ (where Γ_W is the single-particle Weisskopf estimate) unless the mean lifetime of the level $t > 270$ nsec, a sufficiently long enough period that we would have clearly observed its effect as an indistinct threshold in our experiment. Even though the peaks in the spectra are small, they first appear in the correct E_n energy bin for the known threshold for this level. So then $\Gamma_\gamma/\Gamma_W > 1$ which (ratio) exceeds the recommended upper limit (of 1) for an M2 transition. Hence $J^\pi \neq 7/2^+$. If $J^\pi = 9/2^+$ then the $E_\gamma = 1447$ -keV transition is M2. However, for an M2 transition having $E_\gamma = 1447$ keV and a 45% branching ratio $\Gamma_\gamma/\Gamma_W > 1$ unless $t > 225$ psec. If the t were even one-tenth this long, then the spectral peaks in our data would be observed to have a relatively narrow resolution-width given by the detection-system resolution. The observed spectral peaks appear to broaden in accordance with expectations of Eq. (3) for $t < 1$ psec. However, the observed peaks in the raw data corresponding to this gamma ray are small for all E_n , and the channel-to-channel counts/channel have relatively large uncertainties, so we cannot be positive that our data rule out $t > 225$ psec. However, there is another reason to question the possibility of $t > 225$ psec, for then the E1 transition having $E_\gamma = 1164$ keV would appear to be unusually hindered. Both of these considerations taken together make it quite unlikely that $J^\pi = 9/2^+$. Hence, the parity for this level is most likely negative.

3.2.5 $E_x = 2655.8$ keV

Pcker's compilation³⁴ places a level at 2657.0 keV decaying via two gamma-ray transitions, $E_\gamma = 1367.5$ and 1650.7 keV (see Fig. 10). It is apparent that

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the gamma-ray energies and branching ratios were taken from the $^{50}\text{Ti}(\alpha, n\gamma)$ experiment of Carola and Tamboer.¹⁹ The only other experiment to report these gamma rays is the $^{50}\text{Ti}(\alpha, n\gamma)$ experiment of Radford and Poletti.²⁹ We observe both gamma rays in the correct E_n energy bin for the threshold of excitation of this state. However, our energies, E_γ , are somewhat smaller by ~ 1.2 keV than those shown in Fig. 10. We obtain $E_\gamma = (1649.4 \pm 0.5)$ keV and $E_\gamma = (1366.4 \pm 0.5)$ keV and a yield ratio $\sigma(1366)/\sigma(1649) = 0.38 \pm 0.04$ based on data observed for E_n between threshold and 4 MeV. For $E_n > 4$ MeV the spectral peak corresponding to $E_\gamma = 1649$ keV appears to split into two groups with the "new" gamma ray having an energy $E_\gamma \simeq 1651.3$ keV. For $E_n > 5$ MeV, the spectral peak corresponding to $E_\gamma = 1366$ keV becomes too indistinct to reliably extract a yield. In summary, our data indicate that the excitation energy of this level should be $E_x = 2655.8$ keV.

3.2.6 $E_x = 2669.5$ keV

We observe a spectral peak corresponding to $E_\gamma \simeq 2670$ keV in the E_n energy bin corresponding to the threshold for this level. Our energy determination is affected by the Doppler shift [Equation (2)] correction which can't be precisely determined because the mean lifetime t is given only as $t < 7$ fsec.³⁴ Our energy E_γ is consistent with $E_\gamma = 2669.5$ keV with an overall uncertainty of ± 0.8 keV. For $E_n > 5$ MeV, the spectral peak corresponding to this gamma ray cannot be resolved from the continuum data. The other decay gamma ray shown in Fig. 10, at $E_\gamma = 2105.5$ keV, is essentially coincident with the single-escape mode of detection of the known background gamma ray at $E_\gamma = 2614.5$ keV due to neutron interactions with the massive lead shielding surrounding the detector, and we were unable to deduce a yield for this gamma ray, assuming its existence.

3.2.7 $E_x \simeq 2707$ keV (doublet)

Previous experimental measurements suggest two levels having $E_x \sim 2707$ keV, one with large J and the other with small J . The present experiment is the first to confirm this suggestion.

Experiments^{24,28,29} involving population of large spin states in ^{53}Cr (J up to 19/2) report a gamma ray having $E_\gamma = 534$ keV placed as the 2707- to 2173-keV transition with the state at $E_x = 2707$ keV having $J_\pi = 11/2^-$. This gamma ray is separated by only 4 keV from the much more intense $E_\gamma = 530.2$ -keV gamma ray due

to the 1536.6- to 1006.3-keV transition. It is clearly observed, however, and resolved from the peak corresponding to the $E_\gamma = 530.2$ -keV gamma ray for the incident neutron bin having $4.0 \leq E_n \leq 4.9$ MeV, i.e., more than an MeV above the threshold for excitation of a level at $E_x \simeq 2707$ keV. However, the spectrum for $3.2 \leq E_n \leq 4.0$ MeV (see Fig. 2) does indicate an unresolved, and small, contribution on the high-energy side of the spectral peak corresponding to $E_\gamma = 530.2$ keV. Our deduced gamma-ray energy is $E_\gamma = 533.5$ keV, which energy is in excellent agreement with $E_\gamma = 533.49$ keV reported by Warburton et al.²⁸ Therefore, we place our observed gamma ray as the 2706- to 2172-keV transition despite the indistinct threshold determination.

For the "other" excited state at $E_x \simeq 2707$ keV, previous measurements support gamma rays of 2708.0, 2143.9, 1701.7, 734.4, and possibly 387.5 keV. We observe peaks in the spectral data corresponding to gamma rays at approximately all of these energies. However, the gamma rays having $E_\gamma \sim 1702$ and 388 keV are masked by background radiation, and we are unable to be certain, even, that we have observed these transitions. We observe a small peak in the spectral data corresponding to $E_\gamma \simeq 734$ keV for the neutron bin $2.6 \leq E_n \leq 3.2$ MeV. Our deduced energy for the responsible gamma ray is $E_\gamma = (733.5 \pm 0.4)$ keV. For $E_\gamma \simeq 2144$ keV, we observe a well-defined doublet peak in the spectral data for $E_n \geq 3.2$ MeV (see Fig. 3). A "singlet" peak is observed in the spectral data for $2.6 \leq E_n \leq 3.2$ MeV, corresponding to detection of a gamma ray having $E_\gamma^{obs} = (2142.4 \pm 0.5)$ keV. The estimated Doppler correction [from Equation (2)] for this E_γ^{obs} is ~ 0.6 keV, so that the intrinsic gamma-ray energy could be 2143.0 keV. The doublet character of the observed data for $E_n > 3.2$ MeV indicates a separation of ~ 2.8 keV between the two observed gamma-ray energies, with $E_\gamma^{obs} = 2141.1$ keV for the smaller-energy gamma ray. The maximum Doppler correction is ~ 2 keV. Equating this gamma ray with the 2707- to 564-keV transition indicates a level energy $E_x = 2707.1$ keV, assigned to a short mean-lifetime level (corresponding to a large Doppler shift) which decays by 2143.1- and 733.5-keV transitions. From our yield data, $\sigma(734)/\sigma(2143) = 0.7 \pm 0.16$, a value somewhat larger than 0.3 ± 0.1 deduced from branching given in Peker's evaluation.³⁴ Insofar as the previously reported ground-state transition is concerned, we observe a very small yield "peak" (=5 counts) at about the correct position in the spectrum for the neutron bin $2.6 \leq E_n \leq 3.2$ MeV which may correspond to the $E_\gamma = 2707$ -keV ground-state

transition. The observed yield is too small for a reliable assignment; however, if the ground-state transition assignment is assumed; then $\sigma(2707)/\sigma(2143) \simeq 0.18 \pm 0.09$, a value in agreement with 0.24 ± 0.05 in Peker's compilation.³⁴

3.2.8 $E_x = 2771$ keV

A level at about this energy is observed in $^{53}\text{Cr}(p, p')$ reactions^{1,2} but not, apparently, in particle-transfer reactions. We first observe a small peak corresponding to $E_\gamma = 1481.5$ keV in the neutron bin $2.6 \leq E_n \leq 3.2$ MeV which we place as the 2771- to 1290-keV transition. Possibly we may be observing a gamma ray corresponding to the 2771- to 1537-keV transition but the spectral data are not sufficiently definitive for a reliable placement. Similarly, a weak peak is observed which corresponds to a gamma ray having $E_x = 798$ keV for $2.6 \leq E_n \leq 3.2$ MeV which could be the 2771- to 1974-keV transition, but the data are uncertain.

3.2.9 $E_x = 2826.5$ keV

The gamma-ray decay of this state has been observed primarily in experiments emphasizing study of large J states in ^{53}Cr . The $E_\gamma = 593.8$ -keV gamma ray was a little difficult for us to observe since the detector has a substantial response to neutron interactions with the $E_x = 595.8$ -keV excited state of ^{74}Ge in the detector. As a consequence, a definitive peak was not observed in the spectral data for $E_n < 5.9$ MeV. The peak observed in the spectral data for the neutron bin $5.9 \leq E_n \leq 6.9$ MeV corresponds to $E_\gamma^{\text{obs}} = 593.3$ keV. The estimated Doppler shift in energy based upon a mean lifetime of ~ 0.2 psec²⁹ is ~ 0.1 keV. Hence $E_\gamma \simeq 593.4$ keV, in excellent agreement with $E_\gamma = 593.33$ keV reported by Warburton et al.²⁸ Thus, we place this observed gamma ray as the 2827- to 2233-keV transition, despite the lack of observation of this gamma ray at incident-neutron energies $E_n < 5.9$ MeV.

3.2.10 $E_x = 2993$ keV

A level with this excitation energy is reported to be observed in $^{53}\text{Cr}(p, p')$ reactions^{1-3,8} and in $^{52}\text{Cr}(d, p)$ reactions.^{1,2,5,17} The only experiment reporting gamma-ray transitions is the report on measurements of $^{52}\text{Cr}(d, p\gamma)$ by Carola et al.¹⁷ No details concerning the measurements are given in their report. We were not able to determine any yield for a gamma ray having energy $E_\gamma \sim (1987 \pm 10)$ keV from our data. As for $E_\gamma \simeq 1704$, our spectral data for the neutron bin

$3.2 \leq E_n \leq 4.0$ MeV, as shown in Fig. 3, exhibit a small peak (~ 20 counts) corresponding to $E_\gamma^{obs} = 1702.7$ keV superimposed upon the broad detector response to inelastic neutron excitation of the 1708.0-keV level of ^{70}Ge . This gamma ray could also be due to a known $^{206}\text{Pb}(n, n'\gamma)$ reaction resulting in a 1703-keV gamma ray⁵⁶ via neutron scattering in the massive lead shield surrounding the detector. Because of these essentially negative results concerning these two previously reported gamma rays we searched our data for all other possible transitions corresponding to decay of a state having $E_x \simeq 2993$ keV. There was only one observed peak which could correspond to any such transition. For $2.6 \leq E_n \leq 3.2$ MeV a small peak containing ~ 50 counts superimposed upon a continuum of ~ 140 counts/channel was observed corresponding to a gamma-ray energy $E_\gamma \simeq 335$ keV. Also, at the same corresponding gamma-ray energy and for $3.2 \leq E_n \leq 4.0$ MeV a peak containing ~ 40 counts superimposed upon a similar continuum was observed. No definite peak was observed for $E_n > 4.0$ MeV. Possibly this $E_\gamma = 335$ -keV gamma ray corresponds to the 2993- to 2657-keV transition. If so, the excitation energy of the level being investigated would be $E_x = 2656$ keV (from Sect. 3.2.5) + 335 keV = 2991 keV. Our data are such, however, that we are inclined to suggest that the only strong statement that can be made is that this level is very weakly (if at all) excited by neutron scattering. This result is somewhat unexpected, since levels excited by inelastic proton scattering are usually also similarly excited by inelastic neutron scattering.

3.3 LEVELS > 3 MEV EXCITATION

Although a number of experiments^{1-3,5,6,8,9,11,14,16-22,24,28-31} have reported ^{53}Cr levels having $E_x > 3$ MeV, the correspondence of levels seen in different reactions is very uncertain. Even the generally more precise gamma-ray energy measurements^{2,8,14,16-22,24,28-31} do not agree from experiment to experiment as well as one might expect. The present data are moderately uncertain because of the Doppler effects discussed in Section 2. In addition, peak yields are small, partly due to an increase in level density resulting in a smaller yields for exciting individual levels, and partly reflecting an experimental problem, namely the reduction of incident neutron beam flux with increasing neutron energy as mentioned in Section 2. As a consequence, although the spectral data contain evidence for many

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more gamma rays than are presently assigned as transitions among levels of ^{53}Cr , determining reliable assignments has proved to be challenging.

The order of items to be presented in the following discussion, therefore, is somewhat unusual. The first part will deal with reported energy levels (in order of increasing E_x) for which there are reported decay transitions so that one may compare our gamma-ray data with those in the literature. The second part, commencing with subsection 3.3.13, will deal with energy levels (again in order of increasing E_x) observed in charged-particle experiments for which decay transitions have not yet been reported. Placements of some of our observed gamma rays as decay transitions will be discussed. Finally, subsection 3.3.22 will report a proposed new energy level deduced from our data. A summary of our gamma ray placements is exhibited in Fig. 13.

3.3.1 $E_x = 3084.3$ keV

This level has $J^\pi = 15/2^-$ and decays primarily^{13,28} by a 911.8-keV transition to the $E_x = 2172.4$ keV level. Our data show definite evidence for an $E_\gamma = 912$ -keV gamma ray for incident neutron energies $4.9 \leq E_n \leq 5.9$ MeV and $E_n > 5.9$ MeV, with a suggestive peak at about the correct channel for $4.0 \leq E_n \leq 4.9$ MeV. We assign the observed $E_\gamma = 912$ -keV gamma ray to this transition. For $4.9 \leq E_n \leq 5.9$ MeV, the gamma-ray production cross section is (16 ± 8) mb, a bit large when compared with the TNG nuclear-model calculation prediction of $\sigma = 5.0$ mb for direct neutron excitation of this large-spin level. Indirect excitation of this level due to transitions from more energetic states may be contributing.

3.3.2 $E_x = 3138$ keV

A level at about this excitation energy is reported in one (p, p') experiment.¹ Radford and Poletti²⁹ provide a definitive transition, $E_\gamma = 1848$ keV, which they assign as the 3138- to 1290-keV transition. We observe a definite peak in the spectral data corresponding to a gamma-ray energy $E_\gamma \simeq 1844$ keV for $3.2 \leq E_n \leq 4.0$ MeV (see Fig. 3). The peak is a well defined doublet for $4.0 \leq E_n \leq 4.9$ MeV, and a not-so-well defined doublet for $E_n \geq 4.9$ MeV. Analysis of the doublet peak for $4.0 \leq E_n \leq 4.9$ MeV indicates two (separate) gamma rays having energies of (1844 ± 0.6) keV and (1847.5 ± 0.6) keV. The $E_x = 3138$ -keV state has a reported²⁹ mean lifetime, $t = 0.05$ psec, which would imply a partial Doppler shift of ~ 0.9

Fig. 13. Level structure for ^{53}Cr emphasizing levels having excitation energies $3.0 \leq E_x < 4.4$ MeV for which gamma-ray transitions have been deduced from the present data. The implications of the solid arrows, dashed arrows, and dot-dashed arrows is the same as for Fig. 10.

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keV to the intrinsic gamma-ray energy for decay of this level for $E_n \simeq 4.4$ MeV. We take the larger-energy gamma ray as the $E_t = 3137.9$ - to 1289.5-keV transition. The smaller-energy gamma ray will be discussed in subsection 3.3.16.

3.3.3 $E_x = 3179.3$ keV

This level has $J^\pi = 3/2^-$ and has been observed in most reactions. Peker's compilation³⁴ indicates adopted transitions of 3180 keV, 2610 keV, 2170 keV, and 1890 keV. We observed the ground-state transition with a yield of (15 ± 5) mb for the neutron energy bin $3.2 \leq E_n \leq 4.0$ MeV. The observed peak corresponds to $E_\gamma^{obs} = (3177.3 \pm 0.6)$ keV and the maximum Doppler shift [from Eq. (2)] is ~ 2.9 keV, so that our data are consistent with $E_x = 3179.3$ keV and a mean lifetime $t < 0.007$ psec. The 3719- to 564-keV transition has a transition energy, unfortunately, indistinguishable for the well-known 2614.5-keV transition in ^{208}Pb , which we observed as background, and we were unable to delineate the ^{53}Cr transition from the background. The 3179- to 1006-keV transition, at $E_\gamma \approx 2172$ keV, we did not observe. This transition should have a yield³⁴ $\sim 59\%$ of the ground-state transition, implying a production cross section of ≈ 9 mb. In Fig. 14 the spectral data corresponding to $2167 \leq E_\gamma \leq 2177$ are shown along with a curve representing the expected contribution for a gamma ray having $E_\gamma \simeq 2172$ keV, a yield $\simeq 9$ mb, and a peak shape expected for a Doppler broadened peak at this gamma-ray energy. In our opinion, the observed data do not support this particular transition. For $E_\gamma \simeq 1890$ keV, the spectral data are similarly featureless; however, the expected yield³⁴ for the ≈ 1890 -keV transition is $\sim 40\%$ of the yield for the ground-state transition, or $\sigma \sim 6$ mb, a value at about the sensitivity of the measurement.

3.3.4 $E_x = 3243.7$ keV

This high-spin state (J probably $13/2$) has been observed in multi-nucleon transfer reactions^{24,28,29,31} to decay primarily via a 1071.3-keV transition to the $J^\pi = 11/2^-$ level at $E_x = 2172.4$ keV. Our spectral data for $4.0 \leq E_n \leq 4.9$ MeV exhibit a definite peak corresponding to a gamma ray at $E_\gamma \sim 1071$ keV which we assign to this transition.

3.3.5 $E_x = 3264$ keV

This state has $J^\pi = 5/2^+$; and the adopted³⁴ decay transitions have energies of 3262, 2256, and 1725 keV. The gamma ray corresponding to the ground-state

Fig. 14. Portions of spectral data for two gamma-ray energy regions: on the left for $2164 \leq E_\gamma \leq 2178$ keV; on the right for $2245 \leq E_\gamma \leq 2265$. The solid lines indicate peak shapes anticipated for detection of $E_\gamma = 2172$ keV (on the left) and $E_\gamma = 2255$ keV. The magnitudes of the illustrated peaks are based upon yields of gamma rays corresponding to ground-state transitions, evaluated branching ratios, and estimated detector responses for gamma rays having the desired gamma-ray energy.

transition is observed with a comparatively large production cross section, $\sigma = (29 \pm 7)$ mb for $3.2 \leq E_n \leq 4.0$ MeV. The observed peak is broadened, consistent with Doppler broadening for decay of a level with a "short" mean lifetime, t . The observed peak corresponds to $E_\gamma^{obs} \simeq (3261.5 \pm 0.7)$ keV. The estimated Doppler shift for $t = 0.02$ psec is ~ 2.4 keV, giving (3263.9 ± 0.9) keV as the transition energy. For the transition 3264- to 1006-keV, the estimated E_γ^{obs} should be ≈ 2256 keV. In Fig. 14 the spectral data are exhibited along with a curve corresponding to a peak for a gamma ray at $E_\gamma = 2255$ keV, a yield corresponding to the adopted³⁴ 40% yield of the ground-state transition, and a peak shape consistent with Doppler broadening. The data do not unequivocally verify nor negate existence of this transition gamma ray. If the Compton continuum is taken to be 9 counts/channel, one could ascribe a "peak" corresponding to $E_\gamma \sim 2255$ keV of ≈ 15 counts, which in

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turn would yield a cross-section ratio $\sigma(2258)/\sigma(3264) = 0.16 \pm 0.11$. This energy gamma ray, however, could also be due to another transition, e.g., the 4547- to 1289-keV transition. We did observe a peak in the spectral data corresponding to $E_\gamma \simeq 1727$ keV for the neutron energy interval $3.3 \leq E_n \leq 4.0$ MeV. The ratio of yields $\sigma(1727)/\sigma(3264) = 0.36 \pm 0.10$, a value consistent with the adopted value³⁴ of 0.35.

3.3.6 $E_x = 3592.3$ keV

This high-spin, negative parity³¹ state decays via a 765.7-keV transition^{22,24,28,29} to the $J^\pi = 11/2^-$ state at $E_x = 2826.6$ keV. Our data exhibit a comparatively narrow peak corresponding to production of a gamma ray of energy $E_\gamma^{obs} = (766.0 \pm 0.5)$ keV with $\sigma = (9.0 \pm 3.6)$ mb for the neutron interval $4.0 \leq E_n \leq 4.9$ MeV. (For the next larger neutron interval, $4.9 \leq E_n \leq 5.9$ MeV, the observed peak is much broader, and could well be due to detection of two gamma rays.) We place our observed gamma rays as the 3592- to 2827-keV transition.

3.3.7 $E_x = 3616$ keV

This $J^\pi = 1/2^-$ state is seen in a variety of reactions; it decays via a ground-state transition. The most precise measurement of the gamma-ray energy of this transition is (3616.0 ± 0.9) keV by Kopecky et al.²¹ Although the threshold for excitation of this level is 3.68 MeV, we do not observe a peak corresponding to this gamma ray for $E_n < 4.0$ MeV. For the neutron interval $4.0 \leq E_n \leq 4.9$ MeV, a rather broad peak is observed corresponding to detection of a gamma ray having energy $E_\gamma^{obs} = (3615.0 \pm 0.7)$ keV. The deduced cross section is (13 ± 4) mb, and the peak width is consistent with a relatively short mean life time for this level.

3.3.8 $E_x = 3706$ keV

This level is observed in $^{52}\text{Cr}(d,p)$ reactions with angular momentum transfer $\ell = 4$. It has $J^\pi = 9/2^+$, and it decays via an $E_\gamma \simeq 2418$ -keV transition^{14,17,20} to the $E_x = 1289.6$ -keV level. Our data indicate a definite peak corresponding to $E_\gamma \approx 2415$ keV for the neutron interval $4.0 \leq E_n \leq 4.9$ MeV. The peak is broad and appears to be due to detection of at least two gamma rays, one at $E_\gamma^{obs} = 2411.4$ keV and the other at $E_\gamma^{obs} = (2415.6 \pm 0.9)$ keV. This latter gamma ray provides

the dominant contribution to the observed data. We place it as the transition under discussion, namely the $9/2^+ \rightarrow 7/2^-$ transition. The maximum Doppler shift would be ~ 2.5 keV if the level's mean lifetime were very short. Thus, with a conservative uncertainty, the intrinsic gamma-ray energy $E_\gamma = (2416.9 \pm 1.5)$ keV, and so $E_x = (3706.4 \pm 1.5)$ keV. Interestingly, Peker's evaluation³⁴ shows a level at about this E_x with no associated energy given.

3.3.9 $E_x = 3985$ keV

A state at about this excitation energy is reported¹⁷ to decay 25% via a ground-state transition, the remainder via a transition to $E_x = 564$ keV. Our data are insufficient to support or negate existence of these transitions. The best that we can report is that if the 3985- to 564-keV transition gamma ray corresponds to one of two apparent peaks (at $E_\gamma^{obs} \simeq 3407$ and 3411 keV) for the neutron interval $4.0 \leq E_n \leq 4.9$ MeV, then its cross section $\sigma < 10$ mb.

3.3.10 $E_x = 4136$ keV

A level at this energy is reported^{14,17} to have three decay modes: a ground-state transition of 17%, a transition to $E_x = 1006$ keV of 37%, and a transition to $E_x = 2324$ keV of 46%. For the neutron interval $4.0 \leq E_n \leq 4.9$ MeV our spectral data do not exhibit "peaks" corresponding to gamma rays for the transition energies $\simeq 3130$ and 1812 keV. There are peaks in the spectra corresponding to $E_\gamma^{obs} = 3626$ and 3115 keV for this neutron interval, which could be due to the single-escape and double-escape modes of detection of a gamma ray having $E_\gamma^{obs} \simeq 4137$ keV. (The maximum detection energy of this experiment corresponded to $E_\gamma = 3750$ keV, so the full energy 4137-keV peak could not be recorded.) Although we may be observing a 4137-keV gamma ray, it is unlikely that we are observing decay of the level as previously reported.^{14,17}

3.3.11 $E_x = 4233$ keV

A level at $E_x = 4228$ keV is reported¹⁷ to have three decay modes: a transition to $E_x = 1006$ keV of 59%, a transition to $E_x = 1289$ keV of 11%, and a transition into one of the levels having $1655 \leq E_x \leq 2707$ keV for the remainder. We observe a fairly definite, but small-yield peak corresponding to $E_\gamma^{obs} = (3227 \pm 1)$ keV for the neutron interval $4.0 \leq E_n \leq 4.9$ MeV. The cross section for a full-energy peak at

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this observed energy is $\sigma = (8 \pm 3)$ mb. Although no definite peak is discerned in this neutron spectrum corresponding to $E_\gamma = 2943$ keV, a broad bulge corresponding to gamma-ray energies between 2940 and 2948 keV, which might include a contribution for $E_\gamma = 2943$ keV, is observed. For $E_\gamma \approx 1550$ keV, we do observe peaks, somewhat ill-defined, corresponding to $E_\gamma^{obs} \approx 1526$ and 1571 keV which could correspond to 4233- to 2707-keV and/or 4233- to 2670-keV transitions either of which could be the previously reported¹⁷ transition. More than one gamma ray or more than one level could have been involved in the earlier particle-gamma coincidence measurements.

3.3.12 $E_x = 4349.7, 4697.1, \text{ and } 5001.5$ keV

High-precision (in energy) gamma rays are reported by Warburton et al.²⁸ corresponding to decay of high-spin states ($J = 15/2$ to $19/2$) at these three excitation energies. The transition energies are 757.4, 1612.8, and 1917.2 keV, respectively, for decay of levels at $E_x = 4349.7, 4697.1, \text{ and } 5001.5$ keV. Except for a very weak "peak" in the data for the neutron interval $4.9 \leq E_n \leq 5.9$ MeV which could be due to detection of an $E_\gamma \approx 1611$ -keV gamma ray we do not observe these gamma rays.

In summary our data support, or at least do not contradict, most of the previous transition assignments. The major discrepancies are for (1) the 3179- to 1006-keV (Sect. 3.3.3) and (2) the 3261- to 1006-keV (Sect. 3.3.5) transitions. We have no satisfactory explanation for either discrepancy.

Before going into the next subsection, it should be pointed out that most of the definitely observed gamma rays have been placed as transitions among levels already discussed. There are only a few observed but unplaced gamma rays for $E_n < 5$ MeV having cross sections $\sigma > 10$ mb, i.e., large enough to ensure that an observed peak in the spectral data is indeed due to detection of a gamma ray created by a neutron interaction in the sample. There are, as might be expected, a number of "peaks" in the spectral data which could be interpreted as being due to detection of gamma rays having $\sigma < 10$ mb. Our experience with measurements of this kind indicates that such observed "peaks" are sometimes due to detection of background radiation, often of undetermined origin, and are sometimes just statistical fluctuations of the Compton continuum. These possible gamma rays will not be referred to unless a level energy E_x is sufficiently accurately defined so as to

provide a precise transition energy ($\Delta E_t < 1$ keV) for comparison with the energy of a possible gamma ray.

3.3.13 $E_x = 3127$ keV

A level at this energy is reported in one high-resolution $^{53}\text{Cr}(p, p')$ experiment² but not the other.¹ Indeed, this level may well be the $E_x = 3138$ -keV level discussed in subsection 3.3.2. No gamma rays which could be transitions due to decay of a level at about this excitation energy were definitely observed in the present data.

3.3.14 $E_x = 3155$ keV

A level at about this energy is observed in $^{52}\text{Cr}(d, p)$ experiments.^{1,2} There is, however, a level in ^{52}Cr at about this excitation energy which decays via a ground-state transition,⁵⁷ and since the present sample contains $\approx 4\%$ ^{52}Cr , the small peak corresponding to $E_\gamma = 3158$ -keV gamma ray that is evident in the data cannot unambiguously be assigned to a ground-state transition from decay of a level in ^{53}Cr . We searched the data for any indication of a transition corresponding to any other decay transition for a level at this energy with negative results.

3.3.15 $E_x = 3345$ keV

A level is reported at about this energy in $^{53}\text{Cr}(p, p')$ and $^{52}\text{Cr}(d, p)$ reactions.^{1,2,5} Our data exhibit possible, but not definite, peaks corresponding to $E_\gamma = 3345$ and 1371 keV which could be assigned as the 3345-keV to ground-state and 3345- to 1974-keV state transitions, respectively.

3.3.16 $E_x = 3381$ keV

A strongly-excited level is observed in the $^{54}\text{Cr}(^3\text{He}, \alpha)$ reaction⁹ at $E_x = 3.37$ MeV and in the $^{54}\text{Cr}(p, d)$ reaction³ populating $E_x = 3.34$ MeV. (Peker's evaluation³⁴ places this level at $E_x = 3351$ keV.) For both of the measurements, the angular distributions of the outgoing particles agree well with calculated angular distributions for angular momentum transfer $\ell_n = 3$. This evidence supports suggesting that the wave function describing this level contains a substantial component of neutron hole-state configuration discussed in subsection 3.1.4, and, therefore, assigning $J^\pi = 7/2^-$ to this level. We assign the smaller-energy gamma ray of the $E_\gamma = 1845$ keV doublet discussed in subsection 3.3.2 as the 3381- to 1537-keV

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transition, a transition certainly to be expected on the basis of the descriptions of the two levels as neutron-hole states. No conclusive evidence was found in the data corresponding to other possible gamma transitions following decay of this level.

3.3.17 $E_x = 3434.5$ keV

A level at about this energy is observed in inelastic-scattering, stripping, and pick-up reactions.^{1-3,5,9} We assign the larger-energy gamma ray of the $E_\gamma = 2144$ -keV doublet discussed in subsection 3.2.7 as a transition following decay of this level. The observed energy of this gamma ray was incremented by half of the maximum Doppler shift to yield $E_\gamma = (2415.0 \pm 1.5)$ keV, where the assigned uncertainty includes the uncertainty in the Doppler-shift correction due to the lack of knowledge of the mean lifetime of the level. The transition assignment, then, is from a level at $E_x = (3434.5 \pm 1.5)$ keV to $E_x = 1289.6$ keV.

3.3.18 $E_x = 3602$ keV

A level at about this E_x is observed in $^{53}\text{Cr}(p, p')$ reactions.^{1,2} Our data exhibit small "peaks" (of the type discussed at the end of subsection 3.3.12) which could be due to detection of gamma rays corresponding to possible transitions between a level at $E_x \simeq 3602$ keV and any one of the six lowest-energy excited states of ^{53}Cr . We cannot, however, offer a reliable assignment for any of these transitions.

3.3.19 $E_x = 3695$ keV

A level at this energy is observed in $^{53}\text{Cr}(p, p')$ reactions.^{1,2} We observe a definite peak corresponding to detection of a gamma ray having $E_\gamma^{\text{obs}} = (3693.7 \pm 0.9)$ keV for the incident-neutron interval between 4.0 and 4.9 MeV, and having a production cross section $\sigma = (11 \pm 3)$ mb. We assign this gamma ray as a ground-state transition, with a gamma-ray energy (hence level excitation energy, E_x) of $E_\gamma = (3695.4 \pm 1.9)$ keV. On the basis of this comparatively precise value for E_x , the data were studied for other possible transitions. Small, and very uncertain peaks are observed which could be due to detection of gamma rays corresponding to the 3695- to 564-keV, 3695- to 1006-keV, 3695- to 1974-keV, and/or 3695- to 2453-keV transitions. There is no evidence to support gamma-ray transitions populating energy levels $E_x = 1289, 1537, 2172$, or 2233 keV, nor for other possible smaller-energy transitions.

3.3.20 $E_x = 4192$ keV

There are nine excited states observed in $^{53}\text{Cr}(p, p')$ reactions^{1,2} having excitation energies $3.75 < E_x < 4.2$ MeV; five of these are reported in $^{52}\text{Cr}(d, p)$ measurements.^{1,2} One of these, at $E_x = 4136$ keV, was discussed in subsection 3.3.10. For seven of these levels, we observe peaks in the data which could be due to detection of gamma rays corresponding to possible transitions following decay of these levels, but any specific assignment is very uncertain. For $E_x = 4192$ keV, however, a transition assignment 4192 to 564 keV can be made with some confidence. A relatively strongly excited state at $E_x = 4189$ keV is reported¹ for the $^{53}\text{Cr}(p, p')$ reaction. A level at $E_x = 4187$ keV is proposed by Kopecky et al.³⁰ from resonant neutron capture measurements. These authors report a primary transition of 3754 keV populating a level at $E_x = 4187$ keV, but they do not observe a 4187-keV ground-state transition, nor report the decay mode of this level. We observe a definite peak in our data due to detection of a gamma ray having $E_\gamma^{obs} = 3626$ keV having $\sigma = (9 \pm 3)$ mb for the incident neutron bin $4.0 \leq E_n \leq 4.9$ MeV. [It appears that a gamma ray of this energy is recorded, but not identified, in the capture spectrum published by Kopecky et al.³⁰] Because the mean lifetime of the excited state is not known, a correction of about 50% of the maximum computer Doppler shift was applied to the E_γ^{obs} . The uncertainty in this procedure was taken to be the correction applied. Considering that there are only three energetically available transitions for this gamma ray (viz. 3628 keV to ground, 4192 to 564 keV, and 4634 to 1006 keV) and considering the other experimental information, the choice of the 4192- to 564-keV transition seems quite reliable. If this placement is correct, the excitation energy, E_x , will be (4192 ± 3) keV depending upon the mean lifetime of the level. Evidence for other possible transitions was sought in our data, and the only positive result is a peak that could be due to detection of the $E_\gamma \simeq 3186$ -keV gamma ray associated with the 4192- to 1006-keV transition. This latter assignment is very tentative, based as it is upon a "peak" containing (5 ± 3) counts.

3.3.21 $E_x = 4361$ keV

A relatively strongly excited level is observed at this excitation energy in the $^{53}\text{Cr}(p, p')$ reaction.¹ We observe a definite and somewhat broad peak due to detection of a gamma ray having $E_\gamma^{obs} \simeq (3069 \pm 1)$ keV for the incident neutron bin

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$4.0 \leq E_n \leq 4.9$ MeV. The gamma-ray production cross section for this neutron energy bin is $\sigma = (8 \pm 3)$ mb. The peak yield more than doubles (and the peak further broadens) for the $4.9 \leq E_n \leq 5.9$ MeV neutron bin. In this higher-energy neutron bin the data could well include detection of a second gamma ray having similar energy. The peak width for $4.0 \leq E_n \leq 4.9$ MeV suggests that the responsible level has a very short mean lifetime, so that correction due to the entire Doppler shift in gamma-ray energy should be applied. This correction will result in an intrinsic gamma-ray energy $E_\gamma = (3072 \pm 2)$ keV. We assign this gamma ray as the 4361- to 1289-keV transition, although it could possibly be a transition from a previously unobserved excited state populating some other ^{53}Cr excited state.

Summarizing at this point in the discussion, the data were studied to try to deduce reliable transition placements for decay of previously reported excited states in ^{53}Cr . One can determine a large number of plausible transitions but with substantial uncertainties. Most of the remaining observed but unplaced gamma rays will be discussed in subsection 3.4. Of this set of gamma rays, there is one that can be assigned almost unambiguously as a transition following decay of a level not previously reported for ^{53}Cr .

3.3.22 $E_x = (3172 \pm 3)$ keV

The peak corresponding to $E_\gamma = 3177$ keV (subsection 3.3.3) for the incident-neutron bin $3.2 \leq E_n \leq 4.0$ MeV (see Fig. 3) exhibits a definite, but not quite resolved, lower-energy contribution that appears to be due to detection of a gamma ray having $E_\gamma^{\text{obs}} = (3170 \pm 2)$ keV. The maximum Doppler shift is ~ 3 keV for a gamma ray at this energy, and as done above for several other gamma rays in the absence of knowledge of the responsible level's mean lifetime, half of the maximum is taken for the Doppler shift. The observed data, then, are due to a gamma ray having energy $E_\gamma = (3172 \pm 3)$ keV and having a production cross section $\sigma = (6.6 \pm 3.3)$ mb. Energetically this gamma ray could correspond to either a ground-state transition or a 3734- or 564-keV transition. If it were the latter, then a substantial correction would have been applied to the cross section, since only that portion of the neutron flux between $E_n = 3.80$ MeV (the threshold for $E_x = 3734$ keV) and $E_n = 4.0$ MeV would be responsible for excitation and subsequent decay of a level at this excitation energy. The corrected production cross section would be $\sigma \geq 35$ mb, a rather large value. Such a strongly excited level should result in the $E_\gamma = 3172$ -keV

gamma ray being easily observed in the next more energetic incident-neutron bin $4.0 \leq E_n \leq 4.9$ MeV. The observed peak yield in this larger E_n bin, however, is less than half the peak yield for $3.2 \leq E_n \leq 4.0$ MeV bin. Thus, the assignment of this gamma ray as a 3734- to 564-keV transition seems unlikely. We assign it as the 3172-keV to ground-state transition, establishing a level at $E_x = (3172 \pm 3)$ keV.

3.4 UNASSIGNED OBSERVED GAMMA RAYS

In the previous sections about 50 observed gamma rays have been placed, or tentatively placed, among 34 levels of ^{53}Cr , and 5 previously reported transitions could not be confirmed. As mentioned in the second paragraph of subsection 3.3.12, nearly all of the large-yield gamma rays have been assigned to transitions among ^{53}Cr excited states. There is, in fact, only one gamma ray, at $E_\gamma \simeq 1143$ keV, having a yield of >30 mb at any incident neutron energy, that is unplaced, and the peak corresponding to detection of this gamma ray is broad and very likely due to detection of two gamma rays. The spectral data support very probable assignments to 14 other gamma rays. Measured observed energies and production cross sections are given in Table 2. One should be alert, however, to the possibilities that these gamma rays may not be due to $^{53}\text{Cr}(n, n'\gamma)$ reactions. At larger incident neutron energies, for example, gamma rays are observed which are due to neutron reactions with ^{16}O in the sample.

Table 2. Observed gamma rays not assigned by transitions among levels of ^{53}Cr

E_γ^{obs} (keV)	σ (mb)	Incident neutron bin (MeV)
964.0 ± 0.6	11.8 ± 4.8	4.0 – 4.9
1111.0 ± 0.7	15.4 ± 5.4	4.0 – 4.9
1132.1 ± 0.8	10.6 ± 4.1	3.2 – 4.0
1132.1 ± 0.8	14.2 ± 5.4	4.0 – 4.9
1142.7 ± 0.9^a	19.7 ± 6.6	3.2 – 4.0
1142.7 ± 0.9^a	41.8 ± 8.1	4.0 – 4.9
1142.7 ± 0.9^a	36.7 ± 8.6	4.9 – 5.9
2294.6 ± 1.0	10.4 ± 4.5	4.9 – 5.9
2394.5 ± 2.0	8.9 ± 3.3	3.2 – 4.0
2411.4 ± 1.3^b	12.3 ± 4.6	3.2 – 4.0
2419.6 ± 1.5	6.6 ± 3.3	4.0 – 4.0
2422.9 ± 1.1	13.4 ± 4.1	3.2 – 4.0
2422.9 ± 1.1	18.6 ± 4.1	4.0 – 4.9
2472.2 ± 1.3	8.6 ± 3.5	4.0 – 4.9
3044.0 ± 2.0	7.6 ± 3.3	4.0 – 4.9
3115.1 ± 1.1	6.8 ± 2.4	4.0 – 4.9
3211.3 ± 1.1	6.0 ± 2.4	4.0 – 4.9
3588 ± 3	9.4 ± 3.1	4.0 – 4.9
3595 ± 3	9.4 ± 3.1	4.0 – 4.9

^aMay be due to detection of two gamma rays of energies $E_\gamma \simeq 1141$ and 1143 keV.

^bPeak is broad and may include data for a second gamma ray at energy $E_\gamma \simeq 2408$ keV. For the incident neutron bin $4.0 \leq E_n \leq 4.9$ MeV, this gamma ray is not resolved from the more intense $E_\gamma = 2415$ keV gamma ray.

4. CONCLUDING REMARKS

The level structure of ^{53}Cr is not readily understood in terms of comparatively simple models, for example, the weak-coupling model.⁵⁸ Indeed, rather more sophisticated models³⁵⁻⁴⁴ are required, and even most of these appear to be incomplete as they do not include the neutron hole-state configuration discussed in subsection 3.1.4.

Our data do not make the task of theoretical understanding much easier. The only general observation we have is that levels described by wave functions containing a substantial component of neutron hole-state configuration (as discussed in subsection 3.1.4) decay directly or indirectly through the $E_x = 1536.7$ -keV level, and all other large-spin states decay directly or indirectly through the $E_x = 1289.6$ -keV state. The present data have helped to clarify the status of the $E_x = 2453$ -keV level as well as provide a definite separation of the doublet at $E_x \sim 2706$ keV. New information on decay transitions for $E_x > 3$ MeV has also been provided. On the other hand, our data clearly do not support earlier reports of several gamma rays, and our results concerning the decay transitions of the level at $E_x = 1536.7$ keV are certainly perplexing. Our tentative suggestion, that of a second level at $E_x \sim 1537$ keV, should be taken in the context in which it is offered. Regarding the level structure for E_x between 3 and 3.7 MeV, it seems certain that there are additional levels, even though these are not reported in e.g., $^{53}\text{Cr}(p, p')$ reactions;^{1,2} for $E_x > 3.7$ MeV we were able to provide some definitive assignments for transitions due to decay of levels previously reported.

One goal discussed in the Introduction has been met, and that is the goal to provide experimental cross sections for comparisons with predictions of nuclear-model calculations. Examples of calculational results are exhibited in Figs. 11 and 12 and further calculations have been reported.⁵⁹ Clearly additional experimental work is required to understand even the low-lying level structure of ^{53}Cr . In particular, explanations are needed for the apparent discrepant data on the decay of the $E_x = 1537$ -keV level.

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