strahlung measurement[16] is not correct and that the value of 0.89 Mev determined from the $Fe^{57}(p,n)Co^{57}$ reaction[17] should be adopted.

Mn^{57} Decay

The decay of this nucleus to the $\frac{5}{2}-$ second-excited state and the $\frac{3}{2}-$ third-excited state establishes Mn^{57} to be $\frac{3}{2}-$ or $\frac{5}{2}-$. From the coupling behavior of individual nucleons in the $(f_{7/2})^{-3}$ configuration found in neighboring nuclei, the higher spin is considered to be more probable. The $\log ft$ values for the various decay modes cannot be determined until the strength of the branch to the $\frac{3}{2}-$ first-excited state is measured.

ACKNOWLEDGMENTS

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Coincidence Studies of the Thermal Neutron Capture Gamma Rays of Chromium*

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The gamma-ray cascades which follow thermal neutron capture in chromium have been investigated by means of the measurement of coincidences between gamma rays detected by a three-crystal pair spectrometer and a single NaI crystal. Samples of normal chromium and chromium enriched in Cr^{50} and Cr^{53} were used. The following assignments of gamma rays to individual isotopes have been made. Cr^{51}: 8.499, 7.36, 6.34, 6.12, 5.46, and 5.18 Mev; Cr^{53}: 7.929, 7.36, 5.61, and 5.26 Mev; Cr^{54}: 9.716, 8.881, 7.097, 6.872, 6.644, 6.31, 6.00, and 4.83 Mev. A number of features of the de-excitation of the energy levels populated by these transitions are established.

INTRODUCTION

THERE are four stable isotopes of chromium, three of which contribute appreciably to the total thermal neutron capture cross section. The abundances,[1] cross sections,[1] and contributions of these isotopes to the total cross section are listed in Table I.

The thermal neutron capture gamma rays of normal chromium have been studied by Kinsey and Bartholomew[2] with the aid of a pair spectrometer, by Groshev and co-workers[3] with the aid of a Compton recoil spectrometer, and by Braid[4] and Reier and Shamos[5] with the use of scintillation techniques. The results of these four groups are summarized in Table II.

TABLE I. Properties of the chromium isotopes.

Isotope	Abundance (percent)[a]	Capture cross section (10^{-24} cm^2)[a]	Contribution to cross section (percent)
Cr^{50}	4.31	17.0	23.6
Cr^{52}	83.76	0.76	20.4
Cr^{53}	9.55	18.2	55.8
Cr^{54}	2.38	<0.3	<0.3

[a] See reference 1.

Because of the contributions of three isotopes to the capture-gamma-ray spectrum of chromium, it has not previously been possible to assign with certainty more than a few of these gamma rays to individual isotopes of chromium, despite the existence of other information from studies of nuclear reactions and the decay of radioactive nuclei. In the present experiment the capture gamma rays produced in samples enriched in Cr^{50} and Cr^{53} and normal chromium placed in a thermal neutron beam have been investigated with the use of a three-crystal pair spectrometer in coincidence with a single scintillation detector. By this method most of the known capture gamma rays of chromium have

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[1] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), 2nd ed.
[2] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953). The measured energies of individual high-energy gamma rays reported in this reference have been adopted in the present discussion.
[3] L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, *Atlas of γ-Ray Spectra from Radiative Capture of Thermal Neutrons* (translation. Pergamon Press, London, New York, 1959).
[4] T. H. Braid, Phys. Rev. **102**, 1109 (1956).
[5] M. Reier, and M. H. Shamos, Phys. Rev. **100**, 1302 (1955).

TABLE II. Thermal neutron capture gamma rays of chromium previously reported. Intensities indicated are per 100 neutrons captured. Errors in the last digit of the measured gamma-ray energies are indicated in parentheses.

Emitting isotope (present assignment)	Kinsey and Bartholomew[a] E_γ(Mev)	I_γ	Groshev *et al.*[b] E_γ(Mev)	I_γ	Braid[c] E_γ(Mev)	I_γ	Reier and Shamos[d] E_γ(Mev)
Cr^{54}	9.716(7)	7	9.72(2)	7			
Cr^{54}	8.881(7)	19	8.88(2)	20			
Cr^{51}	8.499(7)	7	8.49(2)	9			
Cr^{53}	7.929(8)	8	7.93(2)	11			
	7.67(2)	0.2					
	7.54(2)	0.2					
Cr^{51}, Cr^{53}	7.364(7)	3					
	7.21(2)	0.2					
Cr^{54}	7.097(6)	2.6	7.09(2)	3.4			
probably Cr^{54}	6.872(8)	0.6	6.88(3)	1			
Cr^{54}	6.644(6)	3.0	6.65(2)	4.2			
Cr^{51}, Cr^{54}	6.358(7)	0.3	6.35(3)	0.8			
Cr^{53} ?	6.26(2)	0.9					
Cr^{51}	6.12(1)	0.7	6.14(3)	0.9			
Cr^{54}	6.00(1)	1	6.00(3)	1.6			
Cr^{53}	5.61(1)	2	5.60(2)	2.1			
Cr^{51}			5.45(3)	0.8			
Cr^{51}, Cr^{53}	5.26(2)	1	5.25(3)	0.9			
			4.90(3)	1.4			
Cr^{54}	4.83(1)	0.6	4.80(3)	0.6			
Cr^{54}	3.72(2)	0.5	3.70(2)	1.4			
partially Cr^{51}			3.02(3)	2	3.04(3)	4	
Cr^{53}, Cr^{54}			2.32(2)	2	2.28(3)	10	2.13(5)
Cr^{51}			1.88(2)	2	1.84(3)	6	
Cr^{54}			1.75(2)	2			
							1.07(6)
Cr^{54}			0.840(15)	20	0.83(3)	40	0.815(16)
Cr^{51}			0.75(2)	3			0.740(20)
Cr^{53}					0.52(3)	2	

[a] See reference 2. [b] See reference 3. [c] See reference 4. [d] See reference 5.

been assigned to individual isotopes and properties of the energy levels populated have been established.

Previously existing information on the energy levels of the chromium isotopes formed in thermal neutron capture is summarized below.

Cr^{51}

The level scheme of Cr^{51}, which includes both previously existing information and the present results, is shown in Fig. 1. The spin and parity of the ground state have been determined as $\frac{7}{2}-$ by Bunker and Starner[6] from the decay of Cr^{51} to V^{51}. Energy levels at 0.775, 1.165, 1.420, and 1.530 Mev were established by Stelson, Preston, and Goodman[7] from the $V^{51}(p,n)Cr^{51}$ reaction. Ballini, Cassagnon, Levi and Papineau,[8] utilizing the same reaction and time of flight techniques, have reported energies of 0.75 and 1.15 Mev for the first two levels. Recently, in a study of the decay of Mn^{51} to Cr^{51}, Nozawa, Yamamoto, Yoshizawa, and Koh[9] have observed gamma rays with energies of 0.74 and 1.17 Mev, corresponding to the first two excited states of Cr^{51}. On the basis of the binding energy of the last neutron in Cr^{51}, Kinsey and Bartholomew[2] have proposed that the 8.499-Mev capture gamma ray originates in this isotope, proceeding from the state formed by thermal neutron capture to the 0.775-Mev level.

Cr^{53}

The level scheme of Cr^{53} is shown in Fig. 2. All of the levels, save for the one at 1.29 Mev, were established in studies of the $Cr^{52}(d,p)Cr^{53}$ reaction by McFarland, Bretscher, and Shull.[10] The existence of all of these levels with the exception of that at 3.20 Mev, which is designated by a dashed line in Fig. 2, was confirmed by El Bedewi and Tadros,[11] also in an investigation of the $Cr^{52}(d,p)Cr^{53}$ reaction. No capture gamma ray corresponding to a transition to a level at 3.2 Mev in Cr^{53} has been observed (cf. Table II).

The values shown for l_n, the orbital angular momentum of the captured neutron in the (d,p) reaction, are from the work of Elwyn and Shull[12] and El Bedewi and Tadros.[11]

The three levels at 0.56, 1.01, and 1.29 Mev were

[6] M. E. Bunker and J. W. Starner, Phys. Rev. **97**, 1272 (1955).
[7] P. H. Stelson, W. M. Preston, and C. Goodman, Phys. Rev. **80**, 287 (1950).
[8] R. Ballini, Y. Cassagnon, G. Levi, and L. Papineau, Compt. rend. **251**, 947 (1960).
[9] M. Nozawa, H. Yamamoto, Y. Yoshizawa, and Y. Koh, J. Phys. Soc. Japan **15**, 2137 (1960).
[10] C. E. McFarland, M. M. Bretscher, and F. B. Shull, Phys. Rev. **89**, 892(A) (1953).
[11] F. A. El Bedewi and S. Tadros, Nuclear Phys. **19**, 604 (1960).
[12] A. J. Elwyn and F. B. Shull, Bull. Am. Phys. Soc. **1**, 281 (1956); Phys. Rev. **111**, 925 (1958).

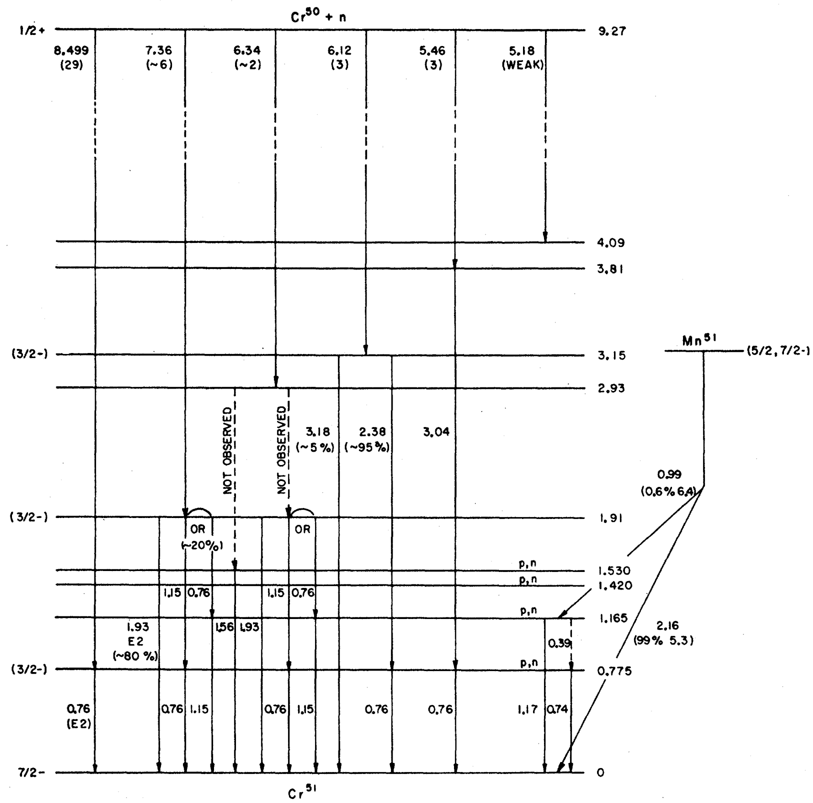

FIG. 1. Level scheme of Cr^{51}. The energies of the primary capture gamma rays are taken from reference 2, or in the case of new gamma rays, from the present results. Their indicated intensities are those of reference 2, which were expressed in units of photons emitted per 100 neutrons captured in normal chromium, renormalized to photons per 100 neutrons captured in Cr^{50}. The levels established in nuclear reaction studies are indicated by the symbol (p,n). The level energies given are those obtained in nuclear reactions. The energies of the remaining levels are obtained by subtracting the energies of the primary gamma rays from the neutron binding energy. For the decay of Mn^{51} to Cr^{51} the maximum positron energies, branching ratios, and $\log ft$ values are shown.

also observed in the inelastic scattering of protons on separated isotopes of chromium by Porter, Van Patter, Rothman, and Mandeville.[13] In addition, this group reported the appearance of gamma rays with these three energies in the inelastic scattering of neutrons from normal chromium.

A 1.00-Mev gamma ray has been observed in the decay of V^{53} to Cr^{53} by Schardt and Dropesky.[14]

According to the shell model,[15] the ground state, with $l_n=1$ and a measured spin of $\frac{3}{2}$, is considered to be the single-particle $p_{\frac{3}{2}}$ state, and the 1.01-Mev level, with $l_n=3$, is considered to be the single-particle $f_{\frac{5}{2}}$ state.

Cr^{54}

The level scheme of Cr^{54} is shown in Fig. 3. Energy levels established in nuclear reaction experiments[11–13] are indicated in Fig. 3 by the symbols (d,p) or (p,p') and the appropriate l_n values.

The energy levels at 1.31 and 1.23 Mev, designated by dashed lines, were attributed to Cr^{54} by Elwyn and Shull[12] and El Bedewi and Tadros[11] in their studies of (d,p) reactions. The latter proposed on the basis of these levels that the 8.499-Mev capture gamma ray originates in Cr^{54}.

The first excited state at 0.84 Mev is populated in the decay of[16] Mn^{54} and has also been reached by Coulomb excitation.[17]

Schardt and Dropesky[14] observed gamma rays with energies of 0.84, 0.99, and 2.21 Mev in the decay of V^{54} and proposed the existence of levels in Cr^{54} at 1.82 and 4.04 Mev in addition to the 0.84-Mev level. Both the observed properties of the decay of V^{54} and the nonappearance of the 1.82- and 4.04-Mev levels of Cr^{54} in nuclear reactions and in neutron capture suggest that these two levels have high spins.

On the basis of a difference of 0.835 Mev in the energies of the 9.716- and 8.881-Mev gamma rays, Kinsey and Bartholomew[2] proposed that they represent transitions to the ground state and first excited state, respectively, of Cr^{54}. This was confirmed by Trumpy,[18] who determined the angular correlation of the 8.881–0.84 Mev cascade and the circular polarization of the 9.716- and 8.881-Mev gamma rays following the capture of polarized neutrons, establishing the spins of the levels and multipole orders of the transitions in the 8.881–0.84 Mev cascade as 1(1)2(2)0 and both the 9.716- and 8.881-Mev gamma rays as $E1$.

[13] W. C. Porter, D. M. Van Patter, M. A. Rothman, and C. E. Mandeville, Phys. Rev. **112**, 468 (1958).

[14] A. W. Schardt and B. J. Dropesky, Bull. Am. Phys. Soc. **1**, 162 (1956).

[15] B. J. Raz, Bull. Am. Phys. Soc. **1**, 336 (1956).

[16] M. Deutsch and L. G. Elliott, Phys. Rev. **65**, 211 (1944).

[17] D. S. Andreev, A. P. Grinberg, G. M. Gusinskii, K. I. Erokhina, and I.Kh. Lemberg, Izvestiya Akad. Nauk (U.S.S.R.), Ser. Fiz. **24**, 1474 (1960).

[18] G. Trumpy, Nuclear Phys. **2**, 664 (1956).

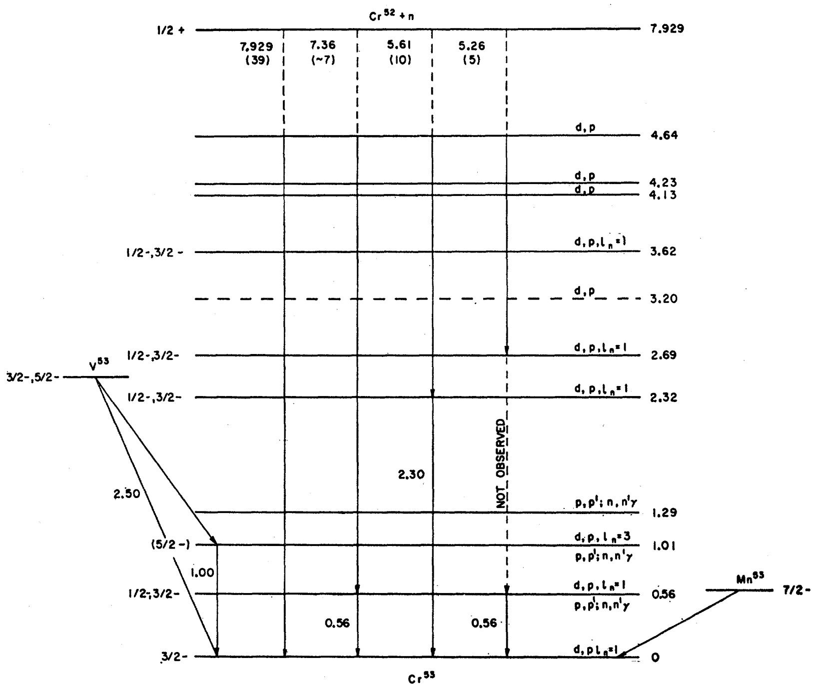

FIG. 2. Level scheme of Cr^{53}. Information is indicated in the same way as in Fig. 1.

EXPERIMENTAL PROCEDURE

The essential features of the present experiment are the same as in earlier work.[19] Recent modifications of the apparatus have been described elsewhere.[20] Certain aspects of the performance of the apparatus, however, which are characteristic of the experiment, affect the nature of the results obtained and their interpretation. These will be treated briefly here.

Capture gamma rays are produced in a target placed in an external beam of thermal neutrons from the Brookhaven Graphite Research Reactor. Coincidences are measured between high-energy gamma rays detected by a three-crystal pair spectrometer and lower energy gamma rays detected by a single NaI crystal of appropriate size—in the present instance $1\frac{1}{2}\times 1$ or 3×3 inches. The pulse heights of both coincident gamma rays are recorded by a two-dimensional, 2048 (32×64) channel pulse-height analyzer.[21] Ordinarily the region of interest of the pair spectrometer spectrum is recorded on the 32-channel axis of the analyzer and the output of the single detector, on the 64-channel axis. Thus, in a single run, 32 spectra (64 channels each) of low-energy gamma rays coincident with individual channels of the pair spectrometer spectrum are obtained.

The employment of the pair spectrometer in the coincidence measurements has the evident advantage that only one peak is present in the spectrum for each gamma ray, so that the spectrum of gamma rays coincident with a given pair spectrometer peak represents in effect the pattern of de-excitation of the particular level populated by the high-energy gamma ray. In contrast, if a single crystal were used for this purpose, the photopeaks of successive gamma rays would be superimposed upon the single and double escape peaks and the Compton distributions of higher energy gamma rays, and correspondingly the coincident spectra would have a more complicated character. However, the three-crystal pair spectrometer has an extremely low efficiency, so that when it is used for coincidence measurements, the conditions of the experiment are dominated by the necessity for a useful coincidence counting rate, typically 40 to 120 events per min distributed among the 2048 channels of the pulse-height analyzer. This is realized only by placing the scintillators close to the target and by permitting high counting rates in the individual detectors, with a consequent sacrifice of the performance attainable in other scintillation arrangements. With the high counting rates, which range up to 5×10^4/sec in the single 3×3-in. detector, stabilization of the photomultipliers is essential. A slight broadening of photopeaks from the pileup of pulses is unavoidable.

Effects of the compact geometry and of the massive shielding necessary for a scintillation experiment at the face of a reactor must be taken into account: Lead x rays, a backscatter peak at $\sim$0.25 Mev, and 0.511-Mev annihilation radiation are prominent features of the low-energy spectrum. Gamma-ray cascades exhibit sum peaks with intensities typically 3 to 4% of that of the higher energy gamma ray in the cascade. In the pair spectrometer spectrum the strong capture gamma

[19] R. E. Segel, Phys. Rev. **111**, 1620 (1958); **113**, 844 (1959).
[20] N. F. Fiebiger, W. R. Kane, and R. E. Segel, Phys. Rev. (to be published).
[21] R. L. Chase, Brookhaven National Laboratory, Report No. 3838, 1958 (unpublished).

rays of lead (7.38 Mev) and aluminum (7.72 Mev) appear as weak background peaks arising from the capture of scattered neutrons in the apparatus. In addition, the pair spectrometer peaks are not symmetrical, having a low-energy tail which extends as a weak, continuous background to rather low energies. This tail arises from several instrumental effects. Gamma rays may suffer small losses of energy through small-angle Compton scattering before being detected. This effect ordinarily does not appear in the customary use of three-crystal pair spectrometers, where the source to detector distance is usually greater and the gamma rays are collimated. For higher energy gamma rays, the escape of bremsstrahlung and electrons from the middle crystal of the pair spectrometer also contributes to the low-energy tails of the lines. As a result of these effects, lower energy peaks in the pair spectrometer spectrum are superimposed upon a background of counts arising from higher energy gamma rays, and consequently the spectra coincident with lower energy peaks in the pair spectrometer spectrum will also contain a background of "extraneous" peaks coincident with higher energy pair spectrometer peaks. This interference, however, is many times smaller than that which would arise from the escape peaks and Compton distribution if a single crystal were used as a detector for the high-energy gamma rays. It is enhanced in the case of chromium, however, by the fact that the highest energy capture gamma rays are also the strongest.

Targets of natural chromium and of chromium enriched in Cr^{50} and Cr^{53} were used in the present investigation. Their properties are listed in Table III.

TABLE III. Properties of chromium targets.

Target	Chemical state	Weight (g)	Isotopic composition (percent) Cr^{50}	Cr^{52}	Cr^{53}	Cr^{54}
Natural Cr	Metal	3.48	Natural (see Table I)			
Cr^{50}	Cr_2O_3	1.895	90.4	8.7	1.0	<0.2
Cr^{53}	Cr_2O_3	1.461	0.1	4.3	95.3	0.4

Because of the small thermal neutron capture cross sections of Cr^{52} and Cr^{54} it was not worthwhile to use targets enriched in these isotopes.

In the present investigation of chromium, where only a few of the capture gamma rays have previously been assigned to individual isotopes, high- and low-energy singles spectra of the samples enriched in Cr^{50} and Cr^{53} also proved useful in determining the origin of a number of gamma rays.

RESULTS

Cr^{51}

The pair spectrometer of Cr^{51} is shown in Fig. 4.

The highest peak corresponds to the expected 8.499-Mev gamma ray, which populates the first excited state of Cr^{51}. In accord with earlier results,[2] no ground-state transition was observed.

The second peak corresponds to a gamma ray with an energy of 7.36 Mev. The appearance of this gamma ray in Cr^{51} was completely unexpected, for the 7.364-

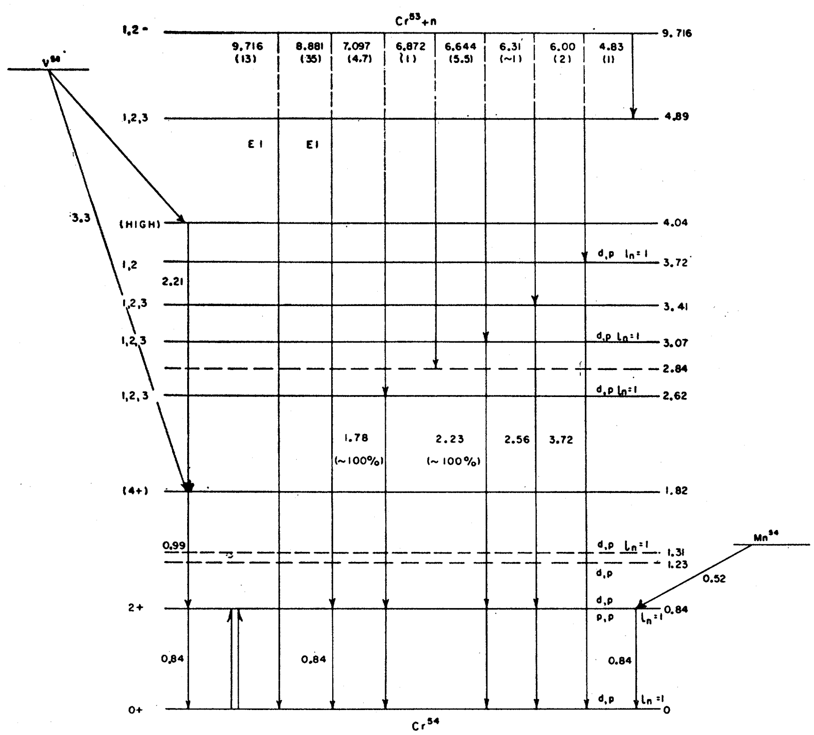

FIG. 3. Level scheme of Cr^{54}. Information is indicated in the same way as in Fig. 1.

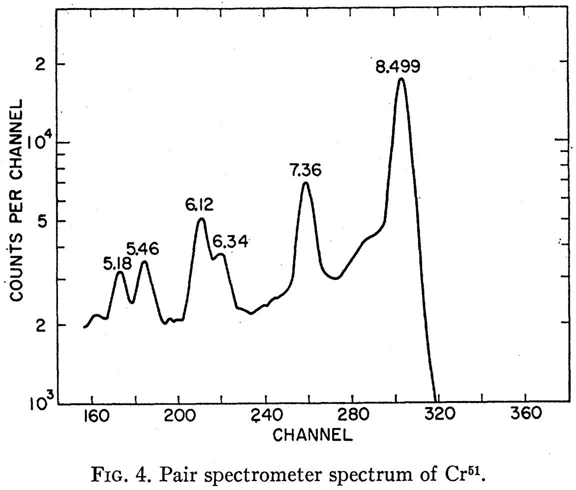

FIG. 4. Pair spectrometer spectrum of Cr^{51}.

Mev gamma ray found by Kinsey and Bartholomew had previously been assigned to Cr^{53} because its energy fits closely the difference between the neutron binding energy, 7.929 Mev, and the energy of the first excited state, 0.56 Mev.[3] As will be shown in the next section, a gamma ray of this energy indeed originates in Cr^{53}. In the pair spectrometer spectrum of Cr^{51} the ratio of intensities of the 7.36- and 8.499-Mev gamma rays is 1:5. From this ratio and the intensities of 3 and 7%, respectively, reported for these two gamma rays in the spectrum of normal chromium by Kinsey and Bartholomew[2] (cf. Table II), we deduce that Cr^{51} and Cr^{53} make approximately equal contributions to the total intensity of the 7.364-Mev capture gamma ray of normal chromium.

The next incompletely resolved doublet of peaks corresponds to gamma-ray energies of 6.12 and 6.34 Mev. These are identified with the reported 6.12- and 6.358-Mev gamma rays of normal chromium.[2]

The measured energies of the two lower peaks in the spectrum are 5.46 and 5.18 Mev, respectively. No gamma ray in the vicinity of 5.46 Mev was observed by Kinsey and Bartholomew[2]; however Groshev *et al.*[3] reported the existence of a 5.45-Mev gamma ray. The peak observed here is tentatively identified with the latter. The only known gamma ray in the vicinity of 5.18 Mev is that whose energy was reported at 5.26 Mev by Kinsey and Bartholomew and 5.25 Mev by Groshev *et al.* It will be shown in the next section that a strong gamma ray of this energy originates in Cr^{53}. In spectra of normal chromium this gamma ray would be expected to obscure the weaker 5.18-Mev gamma ray of Cr^{51} found here. We therefore conclude that the 5.18-Mev gamma ray represents a previously unobserved transition in Cr^{51}.

The low-energy gamma rays of Cr^{51} in the region from 0.07 to 2.6 Mev, detected by a single $1\frac{1}{2}\times 1$-inch NaI crystal, are shown in Fig. 5. The singles spectrum is displayed in part (a) of Fig. 5. When a similar spectrum is taken in twofold coincidence with high-energy gamma rays detected by the middle crystal of the pair spectrometer, a considerable reduction in background ensues. While this may no longer reproduce accurately the original intensity distribution of the low-energy gamma rays, it nevertheless is useful in identifying these gamma rays and in measuring their energies. Such a spectrum is shown in Part (b) of Fig. 5. In addition to the backscatter peak and the ubiquitous 0.511-Mev annihilation radiation, peaks appear with energies of 0.76, 1.15, 1.90, and 2.35 Mev. The shoulder on the high-energy side of the 0.76-Mev peak is attributed to the strong 0.84-Mev gamma ray of Cr^{54}. (Approximately 1% of the neutron capture events in the sample enriched in Cr^{50} occurred in residual Cr^{53}.)

The results of the measurement of coincidences between high-energy gamma rays detected by the pair spectrometer and low-energy gamma rays detected by a single 3×3-inch NaI crystal are presented in Fig. 6 and in Table IV and are incorporated in Fig. 1.

The spectrum coincident with the 8.499-Mev transition consists of a single peak at 0.76 Mev. This is the expected result, in accord with the original assignment of the 8.499-Mev gamma ray to Cr^{51} as a transition to the first excited state.[2]

The spectrum coincident with the 7.36-Mev transition, which must populate a level at 1.91 Mev, contains peaks with measured energies of 0.76, 1.15, and 1.93 Mev. These evidently represent a two-step cascade and a ground-state transition. The order of the transitions in the cascade is uncertain, for in the existing level scheme the 1.91-Mev level could de-excite either by a 1.14-Mev transition to the 0.775-Mev level or by a 0.75-Mev transition to the 1.165-Mev level, or by both. Both of these possibilities are shown in Fig. 1.

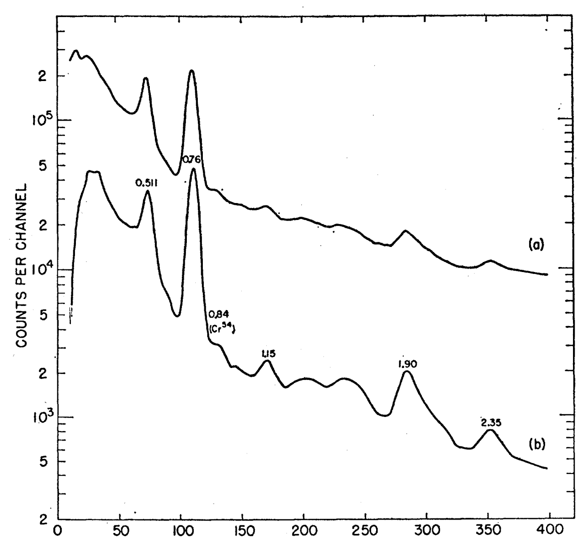

FIG. 5. Spectra of low-energy gamma rays of Cr^{51} from 0.07 to 2.6 Mev detected by a $1\frac{1}{2}\times 1$-inch NaI crystal. (a) Singles spectrum. (b) Spectrum in coincidence with high-energy gamma rays detected by a single NaI crystal.

From the intensity ratio of the 1.93- and 1.15-Mev peaks the branching of the direct transition is $\sim$80%, and of the cascade, $\sim$20%.

As the 6.34- and 6.12-Mev peaks in the pair spectrometer spectrum are incompletely resolved from one another, the spectra in coincidence with them yield only qualitative results. The spectrum coincident mainly with the 6.34-Mev transition, which populates a level at 2.93 Mev, contains peaks with measured energies of 0.76, 1.15, 1.56, 1.95, and 2.38 Mev, and possibly additional, unresolved peaks in the region from 1.0 to 1.5 Mev. The peak at 2.38 Mev is strongly coincident with the 6.12-Mev transition. Its appearance in the spectrum coincident with the 6.34-Mev peak appears to arise entirely from the overlap of the 6.34- and 6.12-Mev peaks. The 1.56-Mev peak, however, is coincident only with the 6.34-Mev transition. The 1.15- and 1.95-Mev peaks appear to arise partly from coincidences with the tail of the 7.36-Mev peak and partly from actual coincidences with the 6.34-Mev transition. A 2.93-Mev ground-state transition was not observed; an upper limit of $\frac{1}{3}$ of the intensity of the 1.56-Mev gamma ray is set on its intensity.

The complete picture of the de-excitation of the 2.93-Mev level is not clear from these results. A 1.56-Mev transition can be placed in the existing level scheme only as a ground-state transition from the 1.530-Mev level. The observed intensities of the 1.15- and 1.95-Mev peaks suggest that the 1.91-Mev level also is populated by the decay of the 2.93-Mev level. However, direct transitions of 1.38 and 1.00 Mev from the 2.93-Mev level to the 1.56- and 1.91-Mev levels are not apparent in the coincident spectrum.

The spectrum coincident with the 6.12-Mev transition, which populates a level at 3.15 Mev, contains peaks with measured energies of 0.76, 1.95, 2.38, and 3.18 Mev. The 1.95-Mev peak appears to arise only from overlap of the 6.12- and 6.34-Mev peaks and background from the 7.36-Mev peak in the pair spectrometer spectrum. The 3.18- and 2.38-Mev gamma rays evidently correspond to transitions from the 3.15-Mev level to the ground state and 0.775-Mev first excited state. An appreciable part ($\sim$4% of the intensity of the 2.38-Mev peak) of the 3.18-Mev peak

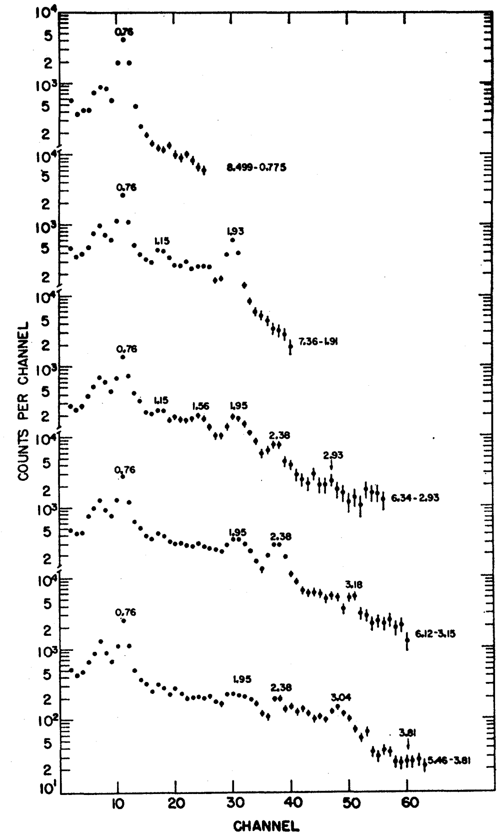

FIG. 6. Low-energy rays of Cr^{51} detected by a 3×3-inch NaI crystal in coincidence with high-energy gamma rays detected by a pair spectrometer. The primary-gamma-ray energy and level populated are indicated for each spectrum.

is actually due to the summing of the 0.76- and 2.38-Mev gamma rays. When this is subtracted, the relative intensities of the 2.38- and 3.18-Mev transitions are $\sim$95 and $\sim$5%, respectively.

The spectrum coincident with the 5.46-Mev transition, which populates a level at 3.81 Mev contains peaks with measured energies of 0.76 and 3.04 Mev which evidently constitute a cascade from the 3.81-Mev level. A 3.81-Mev ground-state transition was not observed; an upper limit of $\frac{1}{4}$ of the intensity of the

TABLE IV. Results of the measurement of coincidences in Cr^{51} between high-energy gamma rays detected by a pair spectrometer and low-energy gamma rays detected by a single 3×3-inch NaI crystal. All energies are in Mev.

Primary transition	Level populated	Coincident spectrum
8.499	0.775	0.76
7.36	1.91	0.76,[a] 1.15 ($\sim$20%), 1.93 ($\sim$80%)
6.34	2.93	0.76,[a] 1.15, 1.56, 1.95
		(2.38—overlap from 6.12)
		(2.93—not observed, $I_{2.93}<\frac{1}{3}I_{1.56}$)
6.12	3.15	0.76,[a] (1.95—overlap and background)
		2.38 ($\sim$95%), 3.18 ($\sim$5%)
5.46	3.81	0.76,[a] (1.95 and 2.38—overlap and background)
		3.04, (3.81—not observed, $I_{3.81}<\frac{1}{4}I_{3.04}$)
5.18	4.09	complex, no strong ground-state transition

[a] Coincidences of the 0.76-Mev gamma ray with background from strong higher energy peaks prevented an accurate determination of its relative intensity in this spectrum.

3.04-Mev gamma ray is set on its intensity. In addition, peaks are also observed at 1.95 and 2.38 Mev which are attributed to background from the 6.12-Mev transition.

The spectrum coincident with the 5.18-Mev transition, which populates a level at 4.09 Mev, is complex, with no prominent peaks. It indicates, however, that the de-excitation of the 4.09-Mev level takes place chiefly by transitions other than a direct transition to the ground state.

Cr^{53}

Because the capture gamma rays of Cr^{53} were obtained only from a target of normal chromium, only the coincidence results provided new information on transitions in Cr^{53}. These are presented in Fig. 7 and in Table V and are incorporated in Fig. 2.

The 7.929-Mev peak, which is a prominent feature of the pair spectrometer spectrum of normal chromium did not appear in the pair spectrometer spectra of Cr^{51} or Cr^{54}, and was not found to be in coincidence with any low-energy gamma ray. This confirms the assignment of the 7.929-Mev transition as the ground-state transition in Cr^{53}.[2]

The low-energy spectrum coincident with the 7.364-Mev transition contains peaks at 0.56, 0.76, 1.15, and 1.93 Mev. As was shown in the last section, the 0.76, 1.15, and 1.93-Mev gamma rays originate in Cr^{51}. The appearance of an additional peak at 0.56 Mev in normal chromium indicates that there is also a 7.36-Mev transition in Cr^{53}, which as previously expected,[3] proceeds to the first excited state of 0.56 Mev. The relative intensities of the peaks in the coincident spectrum support the conclusion reached in the last section that approximately half of the 7.36-Mev gamma rays originate in Cr^{51} and half in Cr^{52}.

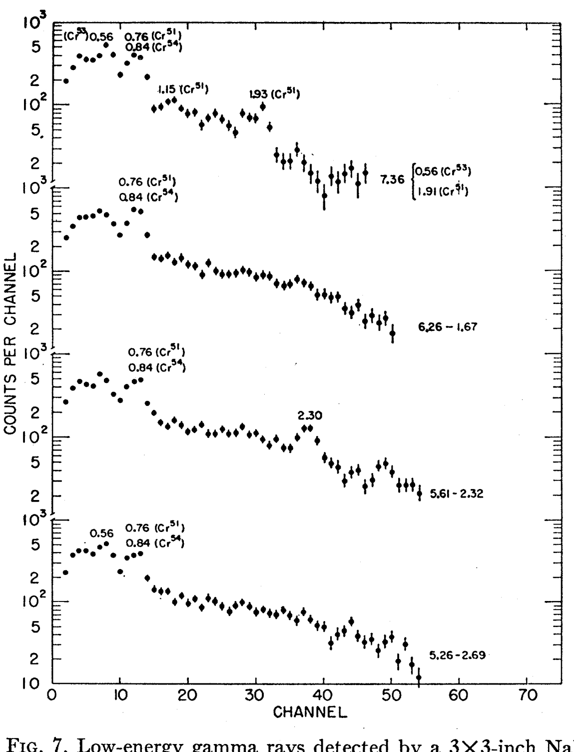

FIG. 7. Low-energy gamma rays detected by a 3×3-inch NaI crystal in coincidence with high-energy gamma rays of Cr^{53} (in a sample of normal chromium) detected by a pair spectrometer. The primary-gamma-ray energy and level populated are indicated for each spectrum.

TABLE V. Results of the measurement of coincidences in normal chromium between high-energy gamma rays of Cr^{53} detected by a pair spectrometer and low-energy gamma rays detected by a single 3×3-inch NaI crystal. All energies are in Mev.

Primary transition	Level populated	Coincident spectrum
7.929	0	...
7.36	0.56 (Cr^{53}), 1.91 (Cr^{51})	0.56, 0.76, 1.15 1.93
6.26	1.67 ?	...
5.61	2.32	2.30
5.26	2.69	0.56, complex

Of the gamma rays reported by Kinsey and Bartholomew, only one with an intensity greater than 0.2 per 100 neutron capture events remains unobserved here. This is the 6.26-Mev gamma ray with a reported intensity of 0.9 per 100 neutron capture events.[2] It is noteworthy that the results of Kinsey and Bartholomew[2] and Groshev *et al.*[3] on the high-energy gamma rays of chromium disagree with respect to the 6.26-Mev gamma ray. The former report an intensity of 0.9 for this gamma ray and 0.3 for a gamma ray at 6.358 Mev. The spectrum published by the latter group shows no peak in the vicinity of 6.26 Mev and a peak at 6.35 Mev corresponding to an intensity of 0.8. In the present work the sum of the intensities of the 6.34-Mev gamma ray found in Cr^{51} and a 6.31-Mev gamma ray in Cr^{54} (see the next section) is in accord with the results of Groshev *et al.*

Our results show clearly that a 6.26-Mev gamma ray with the intensity given by Kinsey and Bartholomew does not originate in Cr^{51} or Cr^{54}. If this transition originated in Cr^{53} it would populate a level at 1.67 Mev. However, no level at 1.67 Mev in Cr^{53} has been found in nuclear reaction studies, while all of the primary capture gamma rays assigned here to Cr^{53} populate levels which are observed in (d,p) reactions.

The low-energy spectrum coincident with a possible 6.26-Mev transition in normal chromium is shown in Fig. 7. No features attributable to Cr^{53} appear in this spectrum. It may be compared with the next spectrum in Fig. 7, which shows the coincidence of the 5.61- and 2.30-Mev gamma rays of Cr^{53}, where the intensity of the 5.61-Mev transition is approximately twice that reported by Kinsey and Bartholomew for the 6.26-Mev transition, and the 5.61- and 2.30-Mev transitions are fully coincident. If a 6.26-Mev transition with the reported intensity originated in Cr^{53}, populating a level at 1.67 Mev, a strong transition from this level to the ground state or first excited state would be apparent in the coincident spectrum. A more complicated decay

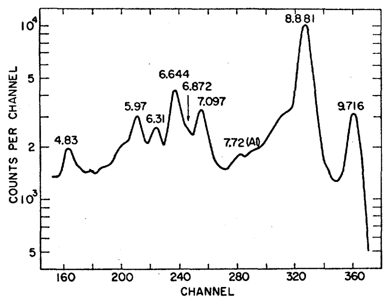

FIG. 8. Pair spectrometer spectrum of Cr^{54}.

of this level to several lower-lying levels, however, in which the total transition intensity were divided among several gamma rays might still be consistent with the present results.

The 5.61-Mev transition is expected to originate in Cr^{53} because it has the proper energy to populate a level at 2.32 Mev established from nuclear reaction studies. As indicated above, the spectrum coincident with the 5.61-Mev transition contains a single peak with a measured energy of 2.30 Mev. This evidently represents the ground-state transition from the 2.32-Mev level.

The 5.26-Mev transition also is expected to originate in Cr^{53}, because it has the proper energy to populate a level at 2.69 Mev established from nuclear reaction studies. In the spectrum coincident with the 5.26-Mev transition a strong 0.56-Mev peak appears, confirming the assignment of this transition to Cr^{53}. No other peaks are seen above a more or less continuous spectrum, indicating that there is no strong ground-state transition from the 2.69-Mev level and that it probably has a complex pattern of de-excitation. Gamma rays coincident with the weaker 5.18-Mev transition in Cr^{51} also contribute to the observed spectrum.

Cr^{54}

The pair spectrometer spectrum of Cr^{54} is shown in Fig. 8. The four highest energy peaks correspond to the 9.716, 8.881, 7.097, and 6.644-Mev gamma rays, which are expected to originate in Cr^{54}, proceeding to the ground state and to three levels established in nuclear reaction studies. The measured energies of the three lower peaks in the spectrum are 6.31, 5.97, and 4.83 Mev, respectively. Kinsey and Bartholomew[2] reported a gamma ray with an energy of 6.358 Mev, and Groshev *et al.*,[3] 6.35 Mev. On the basis of our results this actually represents two gamma rays, the 6.34-Mev gamma ray of Cr^{51} and the 6.31-Mev gamma ray of Cr^{54}. The peak with a measured energy of 5.97 Mev evidently corresponds to the 6.00-Mev gamma ray observed by both Kinsey and Bartholomew and Groshev *et al.* Corresponding to the peak with a measured energy of 4.83 Mev, Kinsey and Bartholomew observed a single gamma ray with an energy of 4.83 Mev, and Groshev *et al.*, two gamma rays with energies of 4.80 and 4.90 Mev and relative intensities of 0.6 and 1.4, respectively. In the spectrum of Fig. 8 a shoulder appears on the upper side of the 4.83-Mev peak at approximately the position of a 4.9-Mev peak, but in contrast with the results of Groshev *et al.* it is much weaker than the 4.83-Mev peak itself. As these energies are approximately half of the neutron binding energy, an individual gamma ray in this energy range can either populate a level at 4.8–4.9 Mev or represent a ground-state transition from the same level, and accordingly two gamma rays in this energy range could represent a two-step cascade from the state formed in neutron capture to the ground state, with the order of the cascade undetermined. Coincidence results presented later in this section indicate that the 4.83-Mev transition is coincident with the 0.84-Mev transition from the first excited state and therefore is probably a transition from the state formed in neutron capture to a level at 4.89 Mev.

The 6.644-Mev peak also displays a shoulder on its high-energy side. This corresponds in energy and intensity to the 6.872-Mev gamma ray of normal chromium.[2] This gamma ray definitely does not originate in Cr^{51}. If it originated in Cr^{53} it would populate a level at 1.057 Mev. A level in Cr^{53} at 1.01 Mev is known to exist, but it has $l_n=3$ and therefore almost certainly would not be populated by a primary transition. On the other hand, the assignment of the 6.872-Mev transition to Cr^{54} requires the placing of a new energy level of 2.84 Mev. We conclude, however, that this is the most probable assignment.

The low-energy gamma rays of Cr^{54} in the region from 0.07 to 2.6 Mev, detected by a single $1\frac{1}{2}\times 1$-inch NaI crystal, are shown in Fig. 9. The singles spectrum is displayed in Part (a) of Fig. 9 and the spectrum

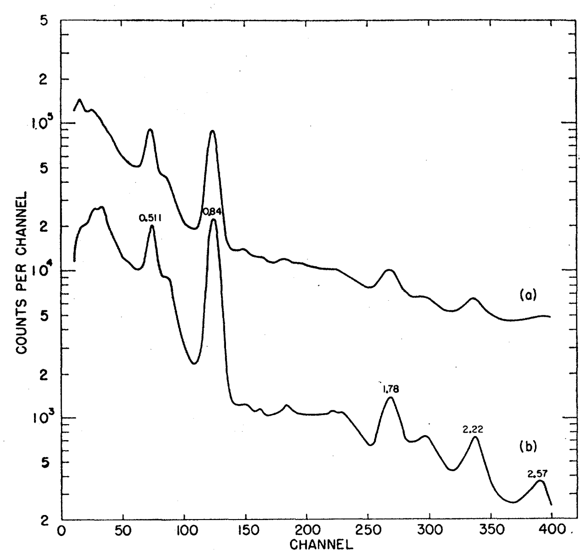

FIG. 9. Spectra of low-energy gamma rays of Cr^{54} from 0.07 to 2.6 Mev detected by a $1\frac{1}{2}\times 1$-inch NaI crystal. (a) Singles spectrum. (b) Spectrum in coincidence with high-energy gamma rays detected by a single NaI crystal.

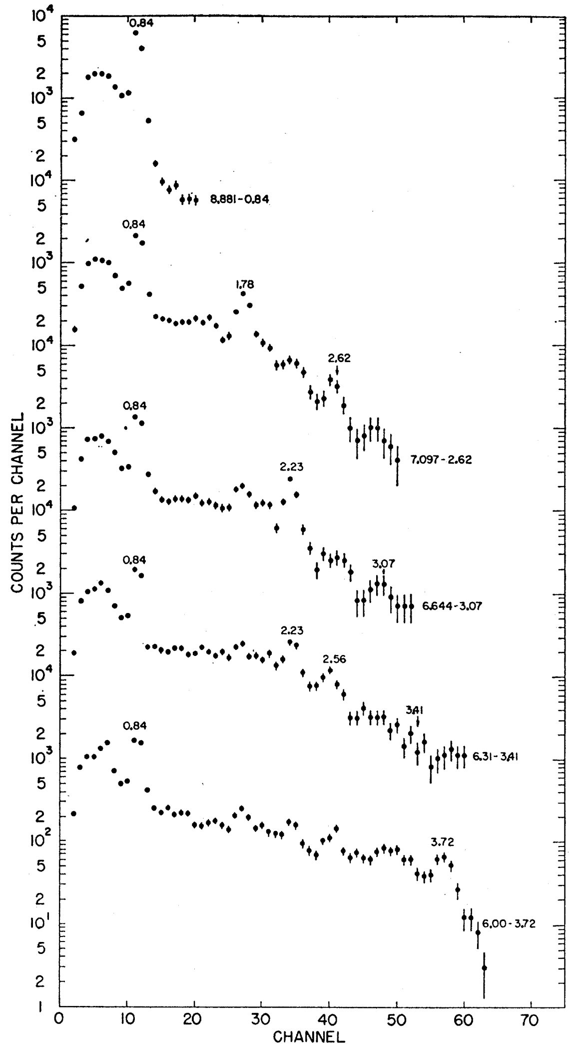

FIG. 10. Low-energy gamma rays of Cr^{54} detected by a 3×3-inch NaI crystal in coincidence with high-energy gamma rays detected by a pair spectrometer. The primary gamma-ray energy and level populated are indicated for each spectrum.

coincident with high-energy gamma rays detected by the middle crystal of the pair spectrometer in Part (b). In addition to the backscatter peak and 0.511-Mev annihilation radiation, peaks appear with energies of 0.84, 1.78, 2.22, and 2.57 Mev.

The results of the measurement of coincidences between high-energy gamma rays detected by the pair spectrometer and low-energy gamma rays detected by a single 3×3-inch NaI crystal are presented in Fig. 10 and in Table VI, and incorporated in Fig. 3.

As expected, there are no gamma rays coincident with the 9.716-Mev ground-state transition and only the 0.84-Mev gamma ray is coincident with the 8.881-Mev transition to the first excited state.

Transitions to levels believed to exist in Cr^{54} at 1.23 and 1.31 Mev from studies of (d,p) reactions[11,12] were not observed. A transition to the 1.83-Mev level, which was established in studies of the decay of V^{54},[14] was also not observed, in accord with a probable spin assignment of 4 for this level.

The spectrum coincident with the 7.097-Mev transition, which populates a level at 2.62 Mev, contains chiefly a 1.78–0.84 Mev cascade. The peak corresponding to the 2.62-Mev crossover transition is slightly more intense than the expected sum peak, but the excess intensity is not sufficient statistically to establish the existence of the crossover transition. An upper limit of 7% is set on the intensity of this transition relative to the intensity of the cascade.

The spectrum coincident with the 6.644-Mev transition which populates a level at 3.07 Mev, contains a 2.23–0.84 Mev cascade. The peak corresponding to the 3.07-Mev crossover transition has the intensity of the expected sum peak. An upper limit of 5% is placed on the relative intensity of this transition.

The spectrum coincident with the weak 6.31-Mev peak, which represents a transition to a level at 3.41 Mev, is complicated by overlap with the stronger 6.664- and 6.00-Mev peaks. In this spectrum, however, in addition to such peaks, a new peak appears with a measured energy of 2.56 Mev. In the existing level scheme this can only be a cascade transition from the level at 3.41 Mev to the 0.84-Mev first excited state. No 3.41-Mev crossover transition was observed. An upper limit of 20% is placed on its intensity.

The most prominent peak in the spectrum coincident with the 6.00-Mev transition, which populates a level at 3.72 Mev, is that corresponding to the ground-state transition. This is evidently the principal mode of de-excitation of this level. The background of "extraneous"

TABLE VI. Results of the measurement of coincidences in Cr^{54} between high-energy gamma rays detected by a pair spectrometer and low-energy gamma rays detected by a single 3×3-inch NaI crystal. All energies are in Mev.

Primary transition	Level populated	Coincident spectrum
9.716	0	...
8.881	0.84	0.84
7.097	2.62	0.84,[a] 1.78, 2.62 (not established, $I_{2.62}<7\%$ of $I_{1.78}$)
6.644	3.07	0.84,[a] 2.23 (~100%), 3.07 (not observed, $I_{3.07}<5\%$ of $I_{2.23}$)
6.31	3.41	0.84,[a] 2.56, 3.41 (not observed, $I_{3.41}<20\%$ of $I_{2.56}$)
6.00	3.72	3.72 (strong)
4.83	4.89 ?	0.84,[a] complex

[a] Coincidences of the 0.84-Mev gamma ray with background from strong, high-energy peaks prevented an accurate determination of its relative intensity in this spectrum.

peaks, described earlier, which represent low-energy gamma rays coincident with background from peaks in the pair spectrometer spectrum above 6.00 Mev, becomes so large here, however, that the presence of weak, lower energy gamma rays in coincidence with the 6.00-Mev transition cannot be ruled out.

No transition associated with the 4.04-Mev level populated in the decay of V^{54} [14] was observed, consistent with a probable high spin for this level.

The spectrum coincident with the 4.83-Mev transition is complex. The only definite feature of this spectrum is an enhancement of the 0.84-Mev gamma ray. This indicates, however, as mentioned earlier, that the 4.83-Mev transition does not proceed to the ground state of Cr^{54}, and therefore probably represents a primary transition from the state formed in neutron capture to a level at 4.89 Mev.

DISCUSSION

Cr^{51}

The present work confirms the assignment of the 8.499-Mev transition to Cr^{51} and establishes in addition the five new primary transitions and levels at 1.91, 2.93, 3.15, 3.81, and 4.09 Mev shown in Fig. 1. The three levels at 1.165, 1.420, and 1.530 Mev previously established from the $V^{51}(p,n)$ reaction[7,8] do not appear to be populated by direct transitions following thermal neutron capture. While the presently available information is not sufficient to determine uniquely the spins and parities of the levels of Cr^{51}, certain assignments appear highly probable. From the systematics of capture-gamma-ray transition probabilities it is known that the great majority of strong, high-energy transitions have dipole character, chiefly $E1$. Furthermore, in the region near $A\sim 55$ the energy of the $3s$ single-particle level is close to the neutron binding energy, so that strong $E1$ transitions are expected to occur between the state formed in neutron capture and low-lying p states of the residual nucleus.[22] Experimentally, capture-gamma-ray spectra in this region are characterized by exceptionally intense transitions to low-lying levels.

If dipole character is postulated for the primary transitions in Cr^{51}, then the levels populated must have spins of $\frac{1}{2}$ or $\frac{3}{2}$. If the spin of the 0.775-Mev level were $\frac{1}{2}$, then the transition from it to the $\frac{7}{2}-$ ground state would have $E3$ or $M3$ character. But for either of these possibilities the single-particle lifetime is several orders of magnitude greater than the resolving time of the coincidence apparatus used to detect the coincidence of the 8.499- and 0.76-Mev transitions, and hence this coincidence would not have been observed. Thus the 0.775-Mev level probably has spin $\frac{3}{2}$. If the parity of this level were even, the ground-state transition from it would have $M2$ character, with a single-particle lifetime of $\sim 10^{-8}$ sec, so that this possibility cannot be ruled out on the basis of the coincidence results. (The resolving time of the coincidence apparatus was set at 5×10^{-8} sec.) However, there is evidence from studies of nuclear reactions[12] (see the discussion of Cr^{54}) that the orbital angular momentum l_n of the last neutron is equal to 1 for the 0.775-Mev level, indicating odd parity. This is in accord with the assumed $E1$ character of the 8.499-Mev transition. We therefore conclude that it is highly probable that the spin and parity of the 0.775-Mev level are $\frac{3}{2}-$, and hence that the ground-state transition from it is a pure $F2$ transition. This is the result expected from shell-model considerations.

The 1.91- and 3.15-Mev levels also are populated by transitions from the $\frac{1}{2}+$ state formed by neutron capture and de-excite in turn both to the $\frac{7}{2}-$ ground state and to an intermediate level. Spin and parity assignments of $\frac{1}{2}\pm$ or $\frac{3}{2}+$ for the 1.91- or 3.15-Mev levels would require that the ground-state transitions be $E3$, $M3$, or $M2$, respectively, while the cascade transitions could be $E1$ or $M1$. In this event it is unlikely that the direct transition would be observed. A $\frac{3}{2}-$ spin and parity for the 1.91- and 3.15-Mev levels thus appears probable.

Recently, the radiations accompanying the decay of 44-minute Mn^{51} to Cr^{51} have been investigated.[9] In addition to intense annihilation radiation, weak gamma rays with energies of 0.74 and 1.17 Mev were observed. These were interpreted as ground-state transitions from the first two excited states of Cr^{51} following the decay of Mn^{51} to these two levels. In view of the spin and parity of $\frac{3}{2}-$ for the first excited state of Cr^{51} arrived at here, however, this interpretation presents difficulties. The logft values obtained for the decay of Mn^{51} to the ground state and first excited state of Cr^{51} are 5.3 and 7.3, respectively. Clearly, the ground-state transition is allowed, giving a spin and parity of $\frac{5}{2}-$ or $\frac{7}{2}-$ for Mn^{51}. For the first of these possibilities the decay of Mn^{51} to the first excited state of Cr^{51} would also be allowed, and for the second possibility second forbidden. In either case a logft value of 7.3 appears unlikely. On the other hand, the second excited state of Cr^{51} has a probable spin of $\frac{5}{2}$ or greater, for it is not populated by a direct transition following neutron capture, so that the decay of Mn^{51} to this level would probably be allowed. It therefore is more plausible that Mn^{51} decays to this level rather than to the first excited state of Cr^{51} and that the latter level is populated by a cascade transition. This is shown in Fig. 1. If this is the case, a logft of 6.4 follows for the electron capture transition to the 1.165-Mev level. The cascade transition between the first two excited states of Cr^{51} would have an energy of 0.39 Mev. In the gamma-ray spectra of Mn^{51} presented in reference 9 there is strong background in this energy region, approximately two orders of magnitude greater than the expected height of the 0.39-Mev peak, so that it probably would not have been detected.

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[22] J. P. Schiffer, L. L. Lee, Jr., J. L. Yntema, and B. Zeidman, *Proceedings International Congress on Nuclear Physics*, Paris, July 7–12, 1958 (Dunod, Paris, 1959), p. 536.

Cr^{53}

The present work confirms the assignment to Cr^{53} of the four transitions shown in Fig. 2 previously postulated from the results of nuclear reaction studies.[10–13] However, the discovery here of a strong 7.36-Mev gamma ray originating in Cr^{51} requires that the total intensity of the 7.368-Mev capture gamma ray of normal chromium be divided approximately equally between Cr^{51} and Cr^{53} and not attributed entirely to Cr^{53}, as previously proposed.

Cr^{54}

The information obtained on Cr^{54} is shown in Fig. 3. The levels populated by the high-energy transitions assigned to this isotope have all been established in nuclear reactions[11–13] with the exception of the 2.84, 3.41, and 4.89-Mev levels.

No evidence appears in the present work for a level in Cr^{54} in the vicinity of 1.2–1.3 Mev. From the systematics of the energy levels of even nuclei in this region a level at this energy is regarded as rather unlikely.[13] The existence of a level of this energy has been postulated by Elwyn and Shull,[12] who observed a proton group with $l_n=1$ in the (d,p) reaction on chromium enriched in Cr^{53} corresponding to a Q value of 6.24 Mev, and by El Bedewi and Tadros[11] who observed a similar group in the (d,p) reaction on normal chromium with a Q value of 6.26 Mev. On this basis, the 8.499-Mev capture gamma ray of normal chromium was assigned as a transition to this level in Cr^{54}. It has been demonstrated here, however, that the 8.499-Mev gamma ray represents a transition to the first excited state of Cr^{51} at 0.775 Mev. If the (d,p) reaction in question is assumed to be $Cr^{50}(d,p)Cr^{51}$, the Q value of El Bedewi and Tadros implies the excitation of a level in Cr^{51} at 0.78 Mev, in close agreement with the energy of the first excited state. The appearance of a proton group corresponding to the same Q value in the work of Elwyn and Shull,[12] however, where chromium enriched to 90.1% in Cr^{53} and 9.3% in Cr^{52} was used, remains unexplained. The value of $l_n=1$ obtained by the latter for the level in question is consistent with the probable $\frac{3}{2}-$ character of the first excited state of Cr^{51}.

The free-vibration model,[23] applicable to even-even nuclei with a number of nucleons outside of closed shells, predicts the existence of 0+—2+—4+ triplets of levels at an energy $\sim$2.2 times the energy of the first 2+ state. A number of examples of this have now been found. The 1.82-Mev level of Cr^{54}, with a probable spin and parity of 4+, has an energy 2.19 times the energy of the first 2+ state. Although Cr^{54} has only two neutrons outside of the 28-neutron shell, it is of interest to determine if a second 2+ state and perhaps a 0+ state exist in the vicinity of the 1.82-Mev level. Indeed, no evidence for such levels appears in our results. From the pair spectrometer spectrum of Cr^{54} an upper limit of 0.5% per neutron captured in Cr^{54} may be set on the intensity of any primary transition to new levels in the vicinity of 1.82 Mev.

ACKNOWLEDGMENTS

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[23] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).