

ELECTROMAGNETIC PROPERTIES OF ^{53}Cr

T. P. G. CAROLA and J. G. TAMBOER

Fysisch Laboratorium, Rijksuniversiteit, Utrecht, Netherlands

Received 27 January 1972

Abstract: Lifetimes, excitation energies, decay modes and spins of ^{53}Cr levels with $E_x < 3.3$ MeV, have been determined in the $^{50}\text{Ti}(\alpha, n\gamma)^{53}\text{Cr}$ reaction. Previous tentative $J^\pi = \frac{7}{2}^-$ assignments to the 1.29 and 1.54 MeV levels have been confirmed. New spins and parity assignments are $J^\pi = \frac{5}{2}^-$ and $\frac{3}{2}^-$ for the 1.97 and 2.71 MeV respectively. Multipole mixing ratios are given for many of the observed transitions. The measured lifetimes of 12 levels are compared with recent shell-model and intermediate coupling model calculations.

E

NUCLEAR REACTION $^{50}\text{Ti}(\alpha, n\gamma)$; $E = 4.9\text{--}6.0$ MeV; measured $\sigma(E; E_\gamma, \theta_\gamma)$, $E_\gamma(\theta)$, DSA. ^{53}Cr deduced levels, $T_{\frac{1}{2}}$, γ -branching ratios, J , δ . Enriched target.

1. Introduction

In the last few years, several theoretical treatments of the nucleus ^{53}Cr have been published, which were mainly concerned with reproducing the level structure and spectroscopic factors $^{1-3}$). Recently, a more complete study of ^{53}Cr and ^{55}Fe based on the shell model and the intermediate coupling model proved to be rather successful in describing the electromagnetic properties of ^{55}Fe [refs. $^4, ^5$]. For ^{53}Cr , a comparison as extensive as for ^{55}Fe was not possible. Only a few mixing ratios were known from a (d, p γ) experiment 6), and lifetime information was quite scarce. The lifetime of the 2.32 MeV state was known from nuclear resonance fluorescence 7), and lower limits had been obtained for the lifetimes of the first and second excited states from a (p, p' γ) experiment 6).

This paper describes the determination of lifetimes, spins, excitation energies and branching ratios of several levels of ^{53}Cr , and mixing ratios of de-excitation γ -rays. The experimental data are compared with both shell-model and intermediate coupling model calculations.

2. Experimental method and data analysis

2.1. EXPERIMENTAL METHOD

Alpha particles were accelerated with the Utrecht 6 MV tandem Van de Graaff generator to energies ranging from 4.9 to 6.0 MeV. The Ti target, 83.2 % enriched in ^{50}Ti , was thick enough to stop the beam completely as well as the recoiling Cr ions. Two Ge(Li) detectors were used in these measurements. In a first series of runs, the

detector had an active volume of 36 cm^3 and a resolution of 4 keV FWHM at $E_\gamma = 1.33 \text{ MeV}$. Later, a detector with an active volume of 60 cm^3 and a resolution of 2.8 keV was also used. The detectors were placed at 14 cm from the target.

Runs at different bombarding energies with the γ -ray detector placed at 90° and 55° yielded accurate determination of excitation energies and branching ratios. For the energy calibration, γ -rays from ^{22}Na , ^{60}Co and ^{88}Y sources were simultaneously recorded.

Most of the γ -ray transitions to be expected were known from previous work. Possible new transitions were accepted on the basis of the following criteria: appearance of the γ -ray as the energy is increased above the threshold of the level under study, consistency in the branching ratios measured at different bombarding energies and in the $F(\tau_m)$ values if the level decays with different branches.

For the γ -ray angular distributions, spectra were recorded at angles $\theta = 20^\circ$, 30° , 45° , 55° , 60° and 90° , relative to the incoming beam direction. The γ -ray intensities were normalized on the intensity of the strong 564 keV γ -ray from the decay of the first excited state ($J^\pi = \frac{1}{2}^-$) of ^{53}Cr . The angular distributions thus obtained were fitted to a Legendre polynomial expansion $W(\theta) = a_0\{1 + a_2P_2(\cos \theta) + a_4P_4(\cos \theta)\}$. For the Doppler-shift measurements, the peak positions of the γ -ray spectra were determined from first-moment calculations after subtraction of a linear background.

2.2. DATA ANALYSIS

In order to correct for target thickness, an average bombarding energy, \bar{E}_α , was calculated for each bombarding energy. The target was considered to be made of thin layers. The α -particle energy in the i th layer, E_i , was determined⁸⁾, and \bar{E}_α was calculated from the relation:

$$\bar{E}_\alpha = \sum_i E_i T_{il} / (\sum_i T_{il}),$$

where T_{il} represents the penetrability and l the orbital angular momentum of the α -particle.

2.2.1. Lifetime measurements. The theoretical $F(\tau_m)$ values were computed according to the nuclear stopping approximation of Blaugrund¹³⁾, and the stopping theory of Lindhard, Scharff and Schiøtt¹⁴⁾. The electronic stopping parameter¹⁴⁾ ξ_e , extracted from experimental data on the slowing down of various ions in carbon¹⁵⁾, was found to be $\xi_e = 1.75 + 4 v/c$ for Cr ions. As the results of Ormrod *et al.*²⁷⁾ indicate that ξ_e is independent of Z , it was assumed that this value also holds for Cr ions in Ti.

There is some uncertainty in the value of the recoiling ion velocity along the Z -axis, $v_Z(0)$, as a result of the outgoing neutron distribution in the c.m. system. Following Warburton *et al.*¹⁶⁾, a conservative estimate can be obtained from the relationship:

$$\langle v_Z(0) \rangle \approx v_{\text{c.m.}}(1 \pm 0.33 \gamma^{-1}),$$

where γ^{-1} is the ratio of the velocity of the ^{53}Cr nucleus in the c.m. system to the speed of the c.m. in the lab system. In this experiment, the correction was of the order of 8 % in the worst case.

The error in τ_m was determined from the statistical uncertainty in $F_{\text{exp}}(\tau_m)$ and the uncertainty in $\langle v_z(0) \rangle$. The total error was computed by quadratically adding to the statistical error, the error due to an assumed uncertainty of 20 % in ξ_c .

2.2.2. Angular distributions. The angular distributions were compared with the results of the compound nuclear statistical model of Sheldon ⁹⁾ for various spin sequences and multipolarity mixings. In this model, the population parameters of the decaying level are calculated with a statistical distribution for the states being populated in the compound nucleus. The $^{50}\text{Ti}(\alpha, n\gamma)^{53}\text{Cr}$ reaction is endothermic ($Q = -1.791$ MeV) and the outgoing (unobserved) neutrons have a low energy, i.e. they are expected to be predominantly S-wave. The states of the residual nucleus should therefore remain strongly aligned. All the contributing incoming partial waves are nevertheless taken into account in the calculations.

The α -particle transmission coefficients needed for the program MANDY ⁹⁾ were extracted from the tables of Huizenga and Igo ¹⁰⁾. These coefficients were essentially the same as those computed from the optical model of Davison ¹¹⁾. The optical-model parameters of Rosen ¹²⁾ were used to calculate the neutron transmission coefficients. The proton channel was not taken into account. The $^{50}\text{Ti}(\alpha, p)^{53}\text{V}$ reaction has a low Q -value (-4.14 MeV) and, experimentally, no evidence was found for proton emission. This can be explained by comparing the proton and neutron penetrabilities for $E_\alpha \approx 6$ MeV, the former being negligible compared to the latter.

In some cases, it has been necessary to correct for cascade feeding competing with direct feeding of a given state. The resulting corrections were small.

3. Experimental results

3.1. EXCITATION ENERGIES AND DECAY SCHEME

It was found that γ -rays from a given ^{53}Cr level could only be observed in the γ -ray spectra if E_α was at least 300 keV above the threshold for production of the level. A typical γ -ray spectrum is shown in fig. 1. Most of the γ -rays originate from ^{53}Cr , with weak contributions from competing reactions and natural background.

The averages of excitation energies measured at different bombarding energies are listed in table 1 and compared with previous results. According to the previous (d, $p\gamma$) work ⁶⁾, the 2.23 MeV state decays entirely to the 1.54 MeV state with a 690 keV γ -ray. This transition was masked by the broad 693 keV γ -ray resulting from neutron inelastic scattering on ^{72}Ge . The $E_x = 2.77, 2.83$ and 3.15 MeV states were weakly excited so that the γ -ray decay was not observed.

The results of the branching ratio measurements are summarized in fig. 2. There is generally good agreement with previous determinations ¹⁷⁾. In many cases, the present branching ratios have a smaller error.

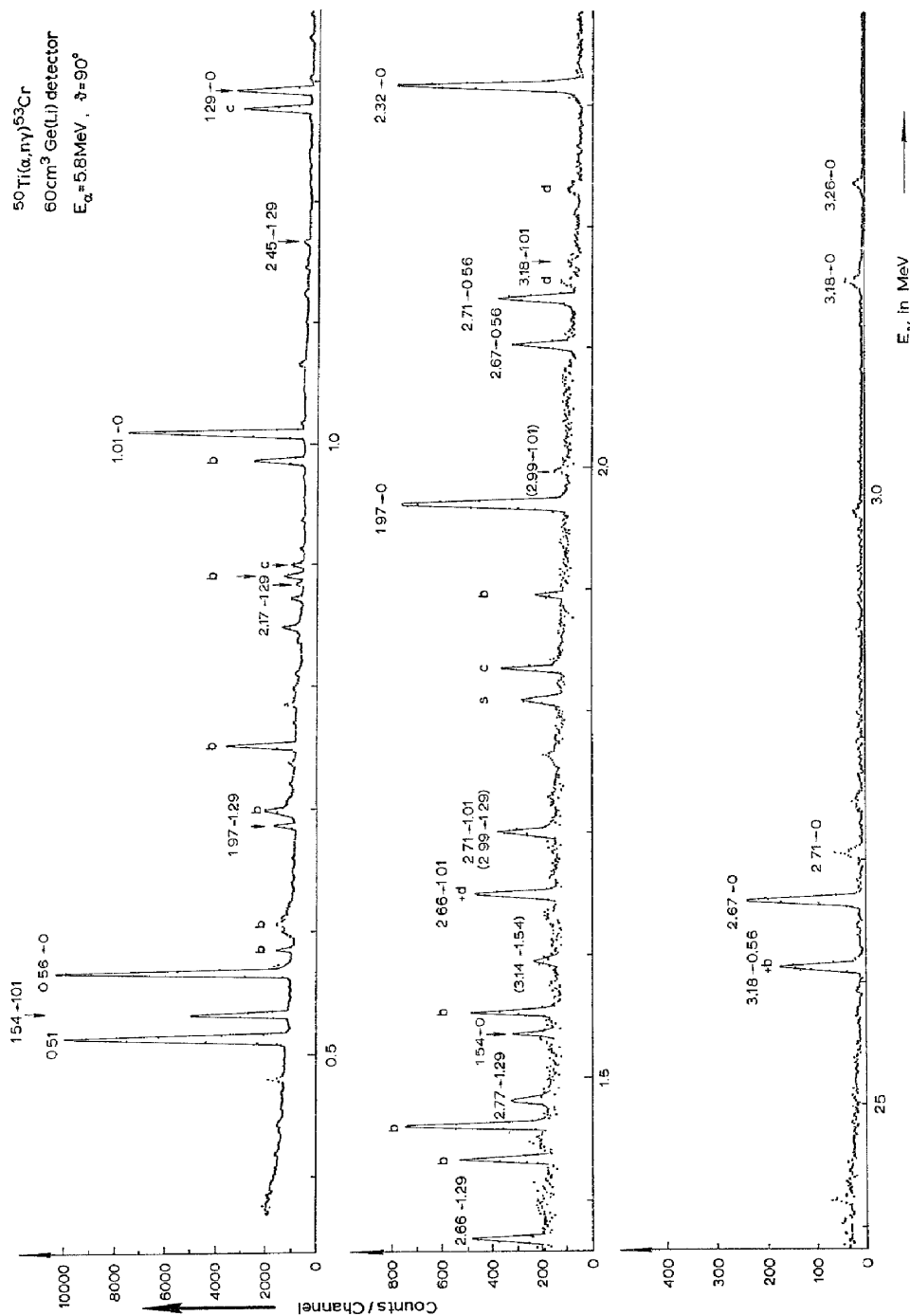


Fig. 1. A typical γ -ray spectrum obtained at a bombarding energy of 5.8 MeV. Only transitions in ^{53}Cr have been indicated. Single- and double-escape peaks are labeled (s) and (d), respectively. Peaks originating from calibration sources and from contaminants or natural background are labeled (c) and (b), respectively.

TABLE 1
Excitation energies of ^{53}Cr levels

Present work E_x (keV)	Ref. ¹⁸⁾ E_x (keV)	Ref. ²³⁾ E_x (keV)	Refs. ^{6, 17)} E_x (keV)	Present work E_x (keV)	Ref. ¹⁷⁾ E_x (keV)
564.07 \pm 0.11	564.2 \pm 0.4	563.6 \pm 0.3	564.1 \pm 0.2	2708.0 \pm 0.6	2711 \pm 5
1006.28 \pm 0.13		1006.0 \pm 0.3	1006.0 \pm 0.2		2775 \pm 5
1289.5 \pm 0.2		1289.1 \pm 0.3	1287 \pm 1		2826 \pm 5
1536.5 \pm 0.2			1539 \pm 4	2993 \pm 2	2995 \pm 4
1973.6 \pm 0.2			1973 \pm 4	3083.2 \pm 0.8	3085 \pm 7
2172.2 \pm 0.5			2171 \pm 5	3138 \pm 2	3132 \pm 5
			2233 \pm 5		3153 \pm 7
2320.5 \pm 0.5	2320.3 \pm 0.4		2321 \pm 5	3179.3 \pm 1.0	3186 \pm 4
2453.1 \pm 1.0			2455 \pm 5		(3244 \pm 7)
2657.0 \pm 0.3			2661 \pm 5	3261 \pm 2	3268 \pm 4
2669.6 \pm 0.6	2669.2 \pm 0.4		2670.4 \pm 1.0		

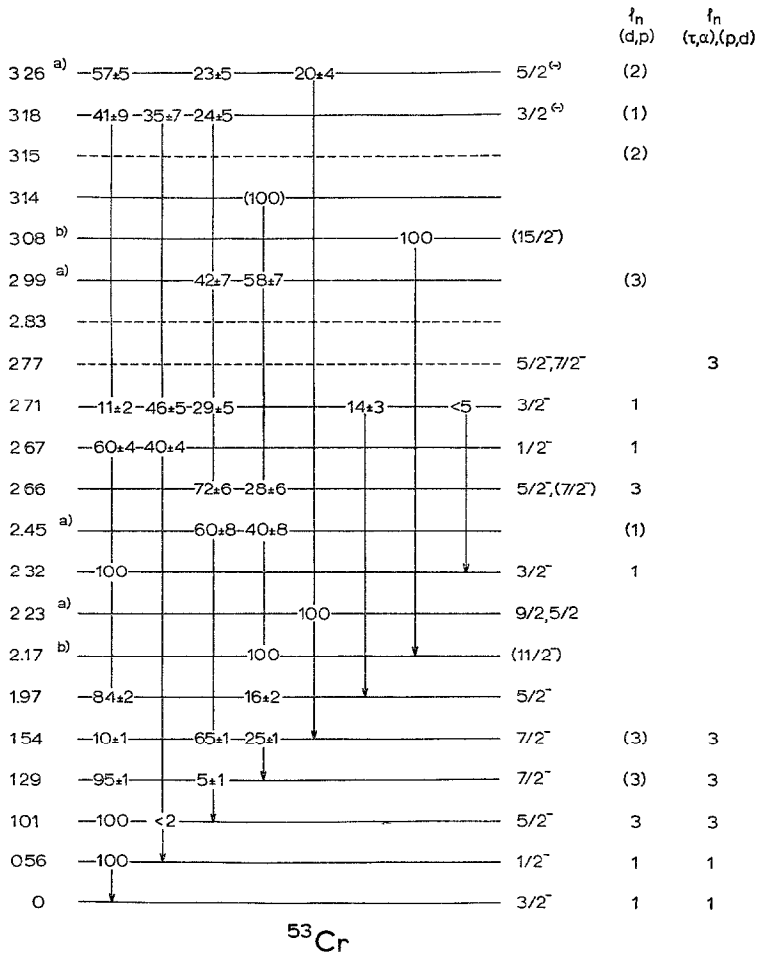


Fig. 2. Level scheme for ^{53}Cr below 3.3 MeV excitation. The branching ratios are from this work except for levels labeled (a) which are from ref. ⁶⁾, and labeled (b) which are from ref. ²⁴⁾. l_n values are from ref. ¹⁷⁾. The states not excited in this experiment are represented by a dotted line. Excitation energies are in MeV. For spins and parities, see text.

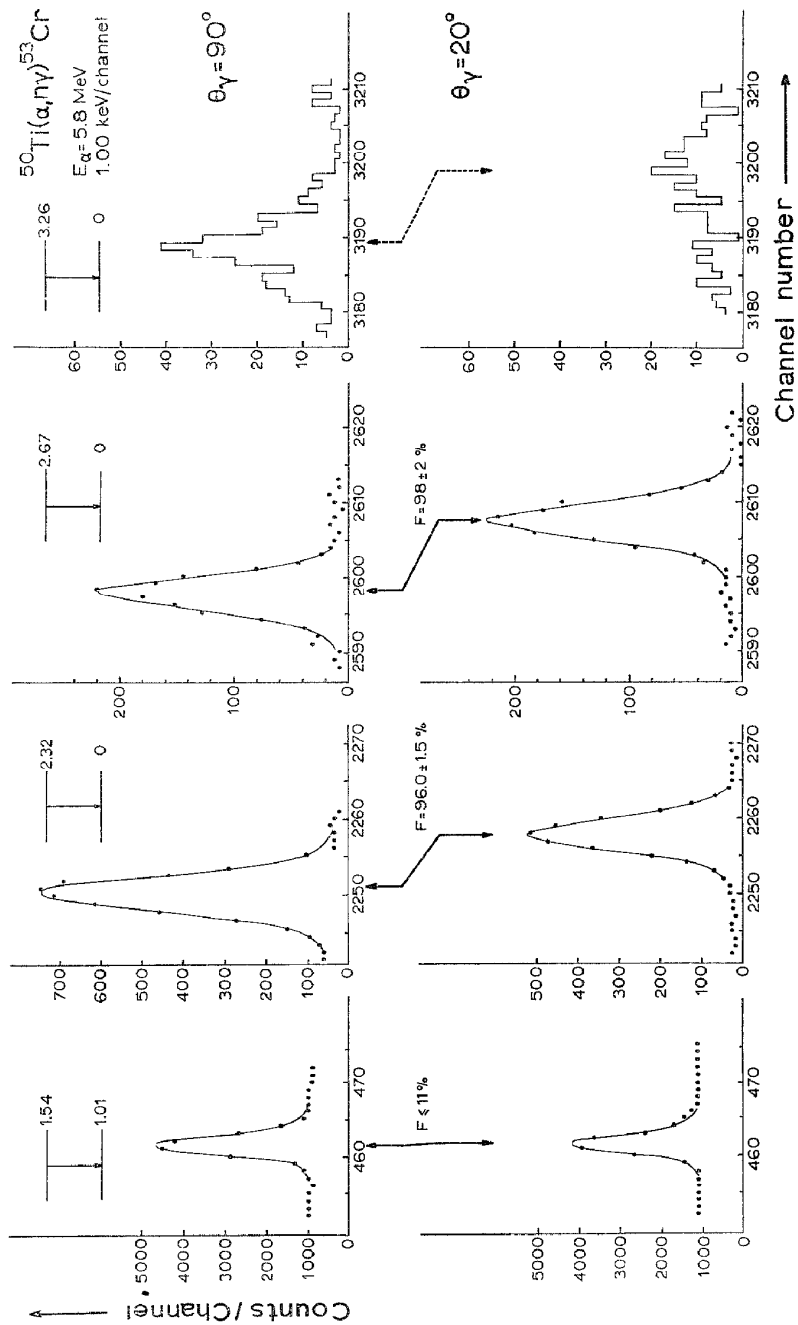


Fig. 3. Typical γ -ray peaks measured at 20° and 90° to the beam axis.

3.2. LIFETIME MEASUREMENTS

Typical γ -ray peaks obtained at $E_\alpha = 5.8$ MeV are shown in fig. 3. The measured energy shifts of all the γ -rays studied were linear in $\cos \theta$ well within the experimental error. The measured attenuation factors and deduced lifetimes are listed in table 2. As a result of the $1.54 \rightarrow 1.29$ MeV cascade feeding, only a lower limit on the mean life of the 1.29 MeV state could be obtained. As the 1.01 MeV level was excited through the 1.54 and 1.29 MeV states, its mean life could not be measured.

TABLE 2
Lifetimes of ^{53}Cr levels

E_{xi} (MeV)	E_{xf} (MeV)	$F(\tau_m)(\text{in } \%)$			τ_m (fs)
		$E_\alpha = 5.25$ MeV	$E_\alpha = 5.6$ MeV	$E_\alpha = 5.8$ MeV	
0.56	0	16 ± 4			900 ± 350
1.29	0	$> 4.5^a$			< 3500
1.54	1.01	< 18	< 7	< 11	> 1200
1.97	0	67 ± 9	67 ± 4	67 ± 2^b	100 ± 25
	1.29		88 ± 19	77 ± 14	
2.17	1.29			< 17	> 800
2.32	0	97 ± 5	98 ± 5	96.0 ± 1.5	11 ± 5
2.66	1.01		108 ± 9	103 ± 6	< 45
	1.29		99 ± 13	93 ± 8	
2.67	0		93 ± 5	98 ± 2	< 10
	0.56		97 ± 10	97 ± 3	
2.71	0		106 ± 13	93 ± 5	
	0.56			95 ± 3	14 ± 9
	1.97			89 ± 15	
3.08	2.17			< 38	> 300
3.18	0			100 ± 4	< 10
	0.56			100 ± 4	
3.26	0			96 ± 6	< 30

^a) Corrected for 8 % cascade feeding from the 1.54 MeV state.

^b) Corrected for 6.5 % cascade feeding from the 2.71 MeV state.

3.3. ANGULAR DISTRIBUTIONS

Gamma-ray angular distributions were measured for most of the levels below $E_x = 3.5$ MeV. The resulting Legendre polynomial expansion coefficients corrected for finite size geometry are listed in table 3. The spin assignments and the extracted values of the mixing ratios δ are summarized in table 4. The errors in the mixing ratios correspond to the standard deviation ¹⁹). The phase convention of Rose and Brink ²⁸) is used. For the low-lying states, it was necessary to correct for cascade feeding, which in the worst case ($1.01 \rightarrow 0$ MeV transition) amounted to almost 40 % of the total feeding. The final results were hardly affected by these corrections (see e.g. fig. 4). On the basis of the new information on lifetimes and branching ratios,

TABLE 3

A summary of Legendre polynomial coefficients fitted to the angular distributions of transitions observed in the $^{50}\text{Ti}(\alpha, n\gamma)^{53}\text{Cr}$ reaction at different bombarding energies

E_{xi} (MeV)	E_{xf} (MeV)	E_{α} (MeV)	$\bar{E}_{\alpha}-E_{\text{tresh.}}$ (MeV)	a_2	a_4	χ_{\min}^2			
						$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{7}{2}$
1.01	0	5.60	2.37	0.09 ± 0.02	0.02 ± 0.02			2.5	96
		5.80	2.57	0.14 ± 0.02	-0.01 ± 0.02			1.4	58
1.29	0	5.80	2.27	0.29 ± 0.01	-0.11 ± 0.02			14	3
	1.01	5.80	2.27	-0.23 ± 0.06	0.00 ± 0.08			0.15	0.12
1.54	1.01	5.25	1.45	-0.40 ± 0.07	0.06 ± 0.07			1.4	0.2
		5.80	2.00	-0.23 ± 0.03	-0.02 ± 0.03			2.8	2.5
	1.29	5.60	1.80	0.43 ± 0.04	-0.15 ± 0.05			15	1.8
		5.80	2.00	0.36 ± 0.03	0.00 ± 0.04			5	0.1
1.97	0	5.60	1.33	0.39 ± 0.04	0.11 ± 0.05		2.9	0.8	6
		5.80	1.53	0.31 ± 0.03	0.07 ± 0.03		3.7	1.1	20
	1.29	5.80	1.53	-0.23 ± 0.06	0.02 ± 0.08		16	0.8	1.2
2.32	0	5.80	1.15	0.09 ± 0.04	0.02 ± 0.04	11.8	3.2		
2.67	0	5.80	0.78	0.00 ± 0.05	0.02 ± 0.06	0.1	0.1		
2.71	0	5.80	0.72	-0.21 ± 0.09	-0.03 ± 0.12	3.3	1.2		
	0.56	5.80	0.72	-0.16 ± 0.04	0.05 ± 0.05	7.3	1.3		
3.18	0	5.80	0.22	0.47 ± 0.13	-0.03 ± 0.16		2.2	2.5	4.4
3.26	0	5.80	0.14	-0.90 ± 0.13	0.35 ± 0.17		2.6	0.16	24

The values corresponding to the minimum χ^2 resulting from the fits to the angular distributions are also given.

^{a)} The χ_{\min}^2 are written in italics when they result in a unique spin assignment; the known I_{π} values are taken into account if necessary.

TABLE 4

Summary of spin assignments and of mixing ratios as determined from the present work

E_{xi} (MeV)	J^{π}	E_{xf} (MeV)	J^{π}	Mixing ratio δ	
				this work	previous work ^{a)}
1.01	$\frac{5}{2}^{-}$	0	$\frac{3}{2}^{-}$	-0.34 ± 0.04	-0.27 ± 0.09 -0.31
1.29	$\frac{7}{2}^{-}$	0	$\frac{3}{2}^{-}$	0.00 ± 0.04	0.00 ± 0.16
		1.01	$\frac{5}{2}^{-}$	0.00 ± 0.05	0.3 ± 0.3
1.54	$\frac{7}{2}^{-}$	1.01	$\frac{5}{2}^{-}$	0.03 ± 0.02	
		1.29	$\frac{7}{2}^{-}$	-0.08 ± 0.09	
1.97	$\frac{5}{2}^{-}$	0	$\frac{3}{2}^{-}$	-0.48 ± 0.10 ; $-4.7^{+1.2}_{-2.5}$	
		1.29	$\frac{7}{2}^{-}$	-0.23 ± 0.13	
2.32	$\frac{3}{2}^{-}$	0	$\frac{3}{2}^{-}$	0.11 ± 0.07	0.11 ± 0.03 ^{b)} ; 9 ± 3 ^{b)}
2.66	$(\frac{3}{2}^{-})$	1.01	$\frac{3}{2}^{-}$	-0.07 ± 0.08	
	$(\frac{7}{2}^{-})$		$\frac{3}{2}^{-}$	-0.38 ± 0.06	
	$(\frac{5}{2}^{-})$		$\frac{7}{2}^{-}$	-0.35 ± 0.12	
	$(\frac{7}{2}^{-})$			1.0 ± 0.4	
2.71	$\frac{3}{2}^{-}$	0	$\frac{3}{2}^{-}$	$0.5 < \delta < 5$	
		0.56	$\frac{1}{2}^{-}$	-0.13 ± 0.10 ; 2.4 ± 0.8	
3.18	$\frac{3}{2}^{-(-)}$	0	$\frac{3}{2}^{-}$	0.00 ± 0.07 ; $-3.7^{+0.4}_{-1.4}$	
3.26	$\frac{3}{2}^{-(-)}$	0	$\frac{3}{2}^{-}$	0.22 ± 0.09 ; 1.5 ± 0.3	$0.06 < \delta < 1.8$

^{a)} Ref. ⁶⁾, unless indicated otherwise.

^{b)} Ref. ²²⁾.

alternate values of δ were discarded when yielding $B(E2)$ strengths of more than 50 W.u. As will be seen in sect. 4, this limit is conservative.

In table 4, the present values of δ are compared with the values previously known from (d, p γ) work ⁶). All values agree within the experimental error, and in most cases, the range of possible values of δ is smaller in the present work.

Besides agreement with spin assignments determined in previous work ^{6, 17, 24}) new information has been obtained. The $J = \frac{7}{2}$ assignment to the 1.29 and 1.54 MeV

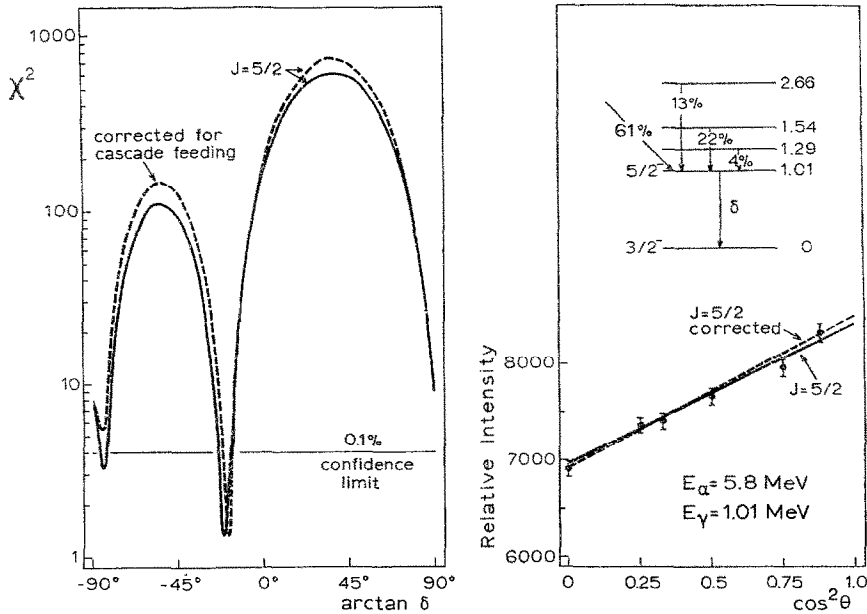


Fig. 4. Angular distributions and χ^2 plots for the ground state transition from the 1.01 MeV state, showing the influence of multiple cascade feeding.

states was considered as tentative, being based on the J -dependence of particle angular distributions in (p, d) [ref. ²⁵)] and (τ , α) [ref. ²⁹)] experiments. These assignments have been confirmed in the present work (see table 3).

Prior to this work, the spin and parity of the 1.97 MeV state were unknown. This state decays 84 % to the ($\frac{3}{2}^-$) ground state and 16 % to the 1.29 MeV ($\frac{7}{2}^-$) state. From the angular distributions of the 1974 and 685 keV γ -rays a unique spin assignment, $J = \frac{5}{2}$, was obtained (see fig. 5).

Of particular interest is the triplet at $E_x = 2.7$ MeV, identified as $E_x = 2.657$ MeV ($I_n = 3$), 2.669 MeV ($I_n = 1$) and 2.708 MeV ($I_n = 1$) [ref. ¹⁷]]. On the basis of a large stripping strength as opposed to a small pick-up strength, a value $J^\pi = \frac{5}{2}^-$ is preferred for the lowest state ¹⁷). In this study, it has not been possible to assign an unambiguous J -value to this weakly excited state. The angular distributions of the

2669 and 2105 keV γ -rays from the decay of the 2.67 MeV state to the ground state and the first excited state, respectively, were isotropic within the experimental error which suggests $J^\pi = \frac{1}{2}^-$ although the value $J^\pi = \frac{3}{2}^-$ cannot be ruled out. However,

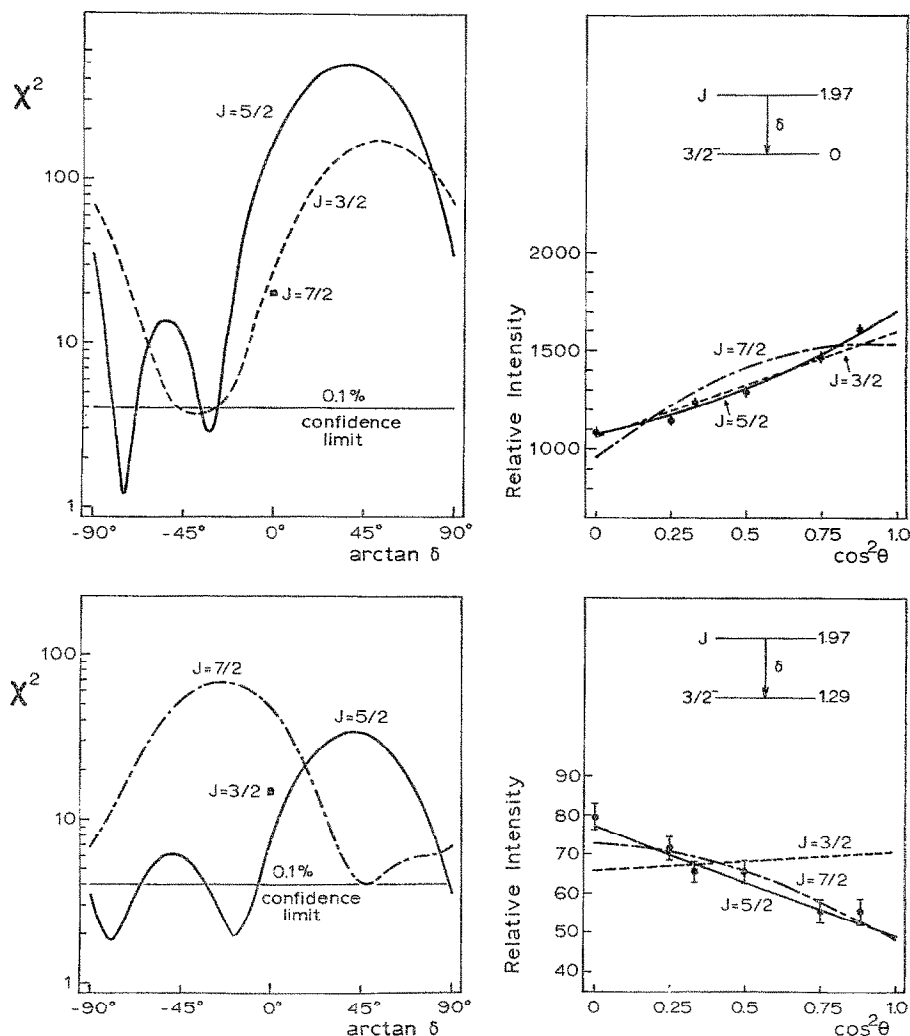


Fig. 5. Angular distributions and χ^2 plots for transitions de-exciting the 1.97 MeV state.

from the recent (n, γ) polarization work of Kopecký *et al.*¹⁸⁾, this state has definitely been assigned $J^\pi = \frac{1}{2}^-$. The 2.71 MeV state decays mainly to the 0.56 MeV ($\frac{1}{2}^-$) state. The angular distribution of the 2144 keV γ -ray yields a unique $J = \frac{3}{2}$ assignment as shown in fig. 6.

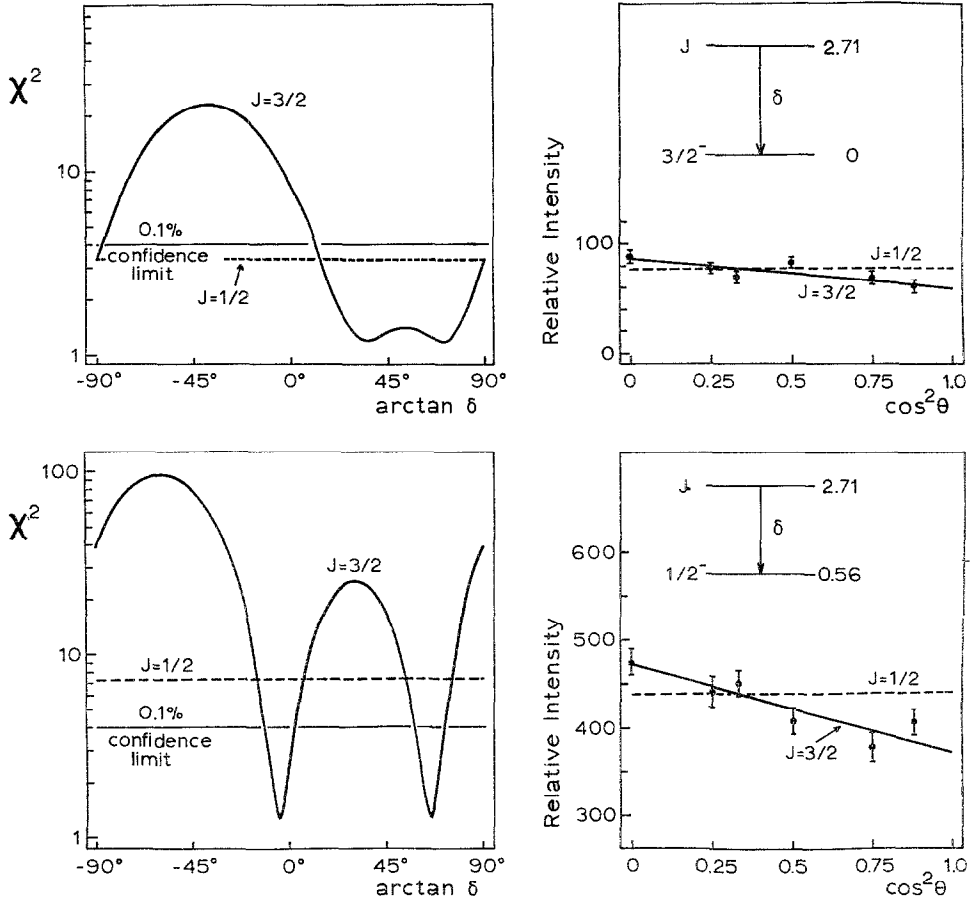


Fig. 6. Angular distributions and χ^2 plots for transitions de-exciting the 2.71 MeV state.

4. Discussion

In table 5, the lifetimes measured in this work are compared with previous measurements and with the theoretical calculations of Carola and Ohnuma⁴). In the shell-model calculations, effective charges $e_{\text{eff}} = 1.0e$ were used for both proton and neutron to calculate $B(E2)$ values. Some lifetimes have been calculated from unpublished intermediate coupling model wave functions obtained in these calculations. No effective charge was used with the intermediate coupling model.

The 1.97 MeV state has been assigned $J = \frac{5}{2}$ in the experiment. Positive parity would result in unrealistic strengths of ≈ 150 W.u. for the M2 component of the ground state transition, and ≈ 1500 W.u. for the M2 component of the $1.97 \rightarrow 1.29$ MeV transition. The 1.97 MeV state then is in fact, the $J^\pi = \frac{5}{2}^-$ state long expected on the basis of theoretical calculations^{1-4, 20}). Its lifetime is correctly calculated with

TABLE 5
Comparison of calculated and measured lifetimes of ^{53}Cr levels

E_x (MeV)	J^π	$\tau_m(\text{fs})$; experiment		$\tau_m(\text{fs})$; theory	
		previous work	this work	shell model ^{d)}	int. coupling ^{e)}
0.56	$\frac{1}{2}^-$	> 500 ^{a)}	900 ± 350	300	160
1.01	$\frac{5}{2}^-$	> 1000 ^{a)}		8500	4300
1.29	$\frac{7}{2}^-$	1600 ± 200 ^{b)}	< 3500	1500	1100
1.54	$\frac{7}{2}^-$	900 ± 400 ^{b)}	> 1200		
1.97	$\frac{5}{2}^-$		100 ± 25	40	94
2.17	$(\frac{11}{2})^-$		> 800		8000
2.32	$\frac{9}{2}^-$	6 ± 2 ^{c)}	11 ± 5	15	24
2.66	$(\frac{9}{2})^-$		< 45		30
2.67	$\frac{1}{2}^-$		< 10		37
2.71	$\frac{3}{2}^-$		14 ± 9		33

^{a)} Ref. ⁶⁾.

^{b)} Calculated from $B(E2)$ values published in ref. ¹⁷⁾.

^{c)} From ref. ⁷⁾, corrected for the J -value of the 2.32 MeV level.

^{d)} Ref. ⁴⁾.

^{e)} From ref. ⁴⁾, and from unpublished wave functions, see sect. 4.

the intermediate coupling model, whereas the shell-model estimate is faster by a factor ≈ 2 .

There are two possible ranges of δ for the $1.97 \rightarrow 0$ MeV transition. One yields $B(E2)$ strengths of ≈ 4 W.u., the other of ≈ 20 W.u. If one compares with the theoretical calculations ⁴⁾, the lower value is preferred and $\delta = 0.48 \pm 0.10$ results in an M1 strength of 0.030 ± 0.015 W.u. and in an E2 strength of 4 ± 2 W.u. The same arguments apply for the $2.32 \rightarrow 0$ MeV transition. From all the data now available, the preferred value of δ is 0.11 ± 0.03 which results in an M1 strength of 0.23 ± 0.10 W.u. and an E2 strength of 1.5 ± 1.1 W.u. This result is in agreement with the fact that the 2.32 MeV state is weakly excited in inelastic scattering experiments ^{25, 26)}.

A tentative $I_n = 2$ value was assigned by Rao *et al.* ²¹⁾ to the weak stripping state at $E_x = 3.26$ MeV. The lowest limit of δ for the ground state transition would yield an M2 strength larger than 3 W.u. if the parity were even. This suggests odd parity for this state.

Inelastic scattering experiments on ^{53}Cr have been reported ^{25, 26)} and they show that the 0.56 ($\frac{1}{2}^-$), 1.01 ($\frac{5}{2}^-$), 1.29 ($\frac{7}{2}^-$) and 1.97 ($\frac{5}{2}^-$) MeV states are strongly excited and decay to the ground state with enhanced E2 transitions, with strengths of the order of ≈ 20 , ≈ 4 , ≈ 5 and ≈ 4 W.u., respectively, estimated from previously published data ¹⁷⁾ and from this work. This enhancement is explained by the important one-phonon amplitude in their wave functions calculated with the intermediate coupling model ⁴⁾. The theoretical values are in agreement with the experimental results.

The assistance and advice of Dr. N. R. Roberson in the early stages of this work is gratefully acknowledged. We wish to thank Dr. I. Mauritzson for his help in collecting the data and Mr. C. Davis for running some preliminary calculations with his program TRENDY. We also thank Prof. A. M. Hoogenboom and Dr. P. W. M. Glaudemans for their interest in this work, Prof. P. M. Endt, Dr. C. van der Leun and Dr. G. van Middelkoop for many valuable discussions and for their critical reading of the manuscript.

This investigation was partly supported by the joint program of the Stichting voor Fundamenteel Onderzoek der Materie and the Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek.

References

- 1) K. Ramavataram, Phys. Rev. **132** (1963) 2255
- 2) J. Vervier, Nucl. Phys. **78** (1966) 497
- 3) H. Ohnuma, Nucl. Phys. **88** (1966) 273
- 4) T. P. G. Carola and H. Ohnuma, Nucl. Phys. **A165** (1971) 259
- 5) B. C. Robertson, T. P. G. Carola, D. M. Sheppard and W. C. Olsen, Nucl. Phys. **A160** (1971) 137
- 6) T. P. G. Carola *et al.*, Nucl. Phys. **A144** (1970) 53
- 7) E. C. Booth, C. Chasan and K. A. Wright, Nucl. Phys. **57** (1964) 303
- 8) C. F. Williamson, J. P. Boujot and J. Picard, CEN Saclay, report CEA R 3042 (1966)
- 9) E. Sheldon, Rev. Mod. Phys. **35** (1963) 795;
E. Sheldon and R. M. Strang, Comp. Phys. Comm. **1** (1969) 35
- 10) J. R. Huizenga and G. J. Igo, Argonne National Laboratory report ANL 6373 (1961)
- 11) N. E. Davison, Univ. of Alberta report no. 8 (1969)
- 12) L. Rosen, Proc. 2nd Int. Symp. on polarization phenomena of nucleons, ed. P. Huber and H. Schaffer (Birkhauser Verlag, Basel, 1966)
- 13) A. E. Blaugrund, Nucl. Phys. **88** (1966) 501
- 14) J. Lindhard, M. Scharff and H. E. Schiøtt, Mat. Fys. Medd. Dan. Vid. Selsk. **33** (1963) no. 14
- 15) P. Hvelplund and B. Fastrup, Phys. Rev. **165** (1968) 408
- 16) E. K. Warburton, J. W. Olness and A. R. Poletti, Phys. Rev. **160** (1967) 938
- 17) R. L. Auble and M. N. Rao, Nucl. Data **B3** (1970) 5, 6-127
- 18) J. Kopecký, K. Abrahams and F. Stecher-Rasmussen, Nucl. Phys., to be published
- 19) M. J. A. de Voigt, J. Grootenhuis, J. B. van Meurs and C. van der Leun, Nucl. Phys. **A170** (1971) 467
- 20) R. J. Philpott and W. W. True, Phys. Rev. **C2** (1970) 512
- 21) M. N. Rao, J. Rapaport, A. Sperduto and D. L. Smith, Nucl. Phys. **A121** (1968) 1
- 22) G. A. Bartholomew and M. R. Gunye, Can. J. Phys. **43** (1965) 1128
- 23) L. Dorikens-Vanpraet, M. Dorikens and J. Demuyne, Z. Phys. **241** (1971) 459
- 24) W. Gulholmer and Z. Sawa, Research Inst. for Phys., Stockholm, progr. report 1970;
Z. Sawa, private communication
- 25) C. A. Whitten, Phys. Rev. **156** (1967) 1228
- 26) J. R. Meriwether *et al.*, Phys. Rev. **146** (1966) 804
- 27) J. H. Ormrod, J. R. MacDonald and H. E. Duckworth, Can. J. Phys. **43** (1965) 275
- 28) H. J. Rose and D. M. Brink, Rev. Mod. Phys. **39** (1967) 306
- 29) P. David, H. H. Duhm, R. Bock and R. Stock, Nucl. Phys. **A128** (1969) 47