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STRUCTURE OF ^{51}Cr VIA ^{48}Ti(^{4}He, nγ) AND ^{51}V(p, nγ) PROMPT γ-RAY SPECTROMETRY

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Abstract: The level structure of ^{51}Cr has been studied in some detail via prompt γ-ray energy and intensity measurements utilizing a NaI(Tl)-Ge(Li) anti-Compton spectrometer and a 511–γ–511 escape peak spectrometer via the ^{51}V(p, nγ) reaction with proton energies in the range 2.6–6.0 MeV and via the ^{48}Ti(^{4}He, nγ) reaction with ^{4}He^{++} energies in the range 12.0–15.0 MeV. Many of the γ-rays associated with levels in ^{51}Cr were identified with the (^{4}He, nγ) or the (p, nγ) reaction by means of nγ coincidence measurements employing an organic phosphor as the fast neutron detector and a Ge(Li) γ-ray detector. Characterization of many levels populated in the (p, nγ) reaction was achieved by means of thresholds for individual γ-rays obtained from measurement of excitation functions of individual γ-rays and from the $\gamma\gamma$ coincidence relationships established in on-beam $\gamma\gamma$ coincidence measurements in the ^{51}V(p, nγ) reaction at $E_p = 5.0$ MeV employing a NaI(Tl) and a Ge(Li) detector. It was thus established that 39 levels in ^{51}Cr are populated in these reactions. The levels at 2255.7, 2385.6, 2767.1 and 3001.6 or 3004.1 keV which were observed in these experiments have not been reported previously. The rest of the levels studied in this work have been studied previously by means of (d, p), (p, d) and (n_{th}, γ) reactions. With the exception of the first six levels, the levels reported here have not been reported previously in the (p, nγ) or the (^{4}He, nγ) reactions. For the levels below 2704 keV in ^{51}Cr branching ratios for deexcitation of these levels by γ-decay were obtained by averaging the measured angular correlation of each γ-ray about the beam direction. The new γ-ray information from the present study was used in conjunction with the results of previously reported (d, p) reaction studies to make definite J^{π} assignments to many stripping levels in ^{51}Cr and to place limits to the J^{π} values for many levels which were reported earlier to exhibit proton angular distribution patterns from the (d, p) reaction non-characteristic of a stripping reaction. In this work a number of γ-rays were assigned to deexcite levels in ^{51}V that are populated via the ^{51}V(p, p$'\gamma$) and ^{48}Ti(^{4}He, pγ) reactions and which were found to compete to a small extent with the (p, nγ) and (^{4}He, nγ) reactions. A tentative decay scheme for the deexcitation of levels in ^{51}V is offered. The level structure of ^{51}Cr and of ^{51}V is compared with previously reported results of the Coriolis coupling model for the $f_{\frac{7}{2}}$ shell and good qualitative agreement in the level ordering is found.

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NUCLEAR REACTIONS ^{48}Ti(^{4}He, nγ) and ^{48}Ti(^{4}He, pγ), $E = 12.0$–15.0 MeV; measured E_γ, I_γ, nγ-coin. ^{51}V(p, nγ) and ^{51}V(p, p$'\gamma$), $E = 2.3$–6.0 MeV; measured E_γ, I_γ, nγ-coin, $\gamma\gamma$-coin, 511–γ–511 coin. $Q(E_\gamma)$, $I_\gamma(\theta)$. ^{51}Cr deduced levels, J, π, γ-branching ^{51}V deduced levels, J, π. Enriched targets; NaI(Tl), Ge(Li), NE-213 liquid scintillator detectors; NaI(Tl)-Ge(Li) anti-Compton, NaI(Tl)-Ge(Li)-NaI(Tl) 3-crystal pairescape spectrometers.

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1. Introduction

The levels in ^{51}Cr are accessible for excitation by a variety of nuclear reactions and as a result of this they have been extensively studied in recent years. The levels in ^{51}Cr have been studied via the stripping reaction ^{50}Cr(d, p)^{51}Cr by many investigators [1-8]. Level energies with the smallest errors have been reported by Macgregor and Brown [5] and by Robertshaw *et al.* [8]. Angular distributions have been reported by Pasechnik *et al.* [1], Bochin *et al.* [2], Alty *et al.* [4], Lee and Schiffer [6], Siemssen *et al.* [7] and Robertshaw *et al.* [8]. Spectroscopic factors from the (d, p) data have been reported by Bochin *et al.* [2], by Alty *et al.* [4] and by Robertshaw *et al.* [8]. The levels in ^{51}Cr have been studied also via the pick-up reaction ^{52}Cr(p, d)^{51}Cr by a number of investigators [9-13] and angular distributions for a number of excited states have been reported by Sherr *et al.* [10] and by Whitten *et al.* [13]. Other pick-up reaction studies include the ^{52}Cr(d, t)^{51}Cr work of Zeidman *et al.* [14] and the ^{52}Cr(^{3}He, α)^{51}Cr work of Bachner *et al.* [15]. The levels in ^{51}Cr have been further investigated via the ^{51}V(p, n)^{51}Cr reaction by numerous workers [refs. [16-24]]. The neutron threshold results of Stelson *et al.* [16], of Ferguson and Paul [17], of Ballini *et al.* [18], and the γ-ray work from the ^{51}V(p, nγ)^{51}Cr reaction of Ballini *et al.* [18] and of Lobkowicz *et al.* [19] have been summarized by Way *et al.* [25]. A study of some angular distributions of γ-rays from the ^{51}V(p, nγ)^{51}Cr reaction has been reported by Iyengar *et al.* [24]. Another mode of excitation which provided considerable information about the levels in ^{51}Cr is the radiative capture of thermal neutrons and such studies have been reported by several workers [26-29]. The most definite of these studies is the work of Bartholomew *et al.* [28] who have employed a Ge(Li) detector in their γ-ray measurements.

The level structure in ^{51}Cr has been compared [8] with the predictions of an extended shell-model theory for the 1f$_{\frac{7}{2}}$ shell as formulated by McCullen, Bayman and Zamick [30] with a noted disagreement between theory and experiment. Further comparisons of the experimental level spectrum for ^{51}Cr have been made [8] with the predictions of a Coriolis coupling model as discussed by Malik and Scholz [31]. It is interesting to note that the latter model predicts low-lying $\frac{9}{2}^-$ and $\frac{11}{2}^-$ levels in ^{51}Cr which had not been definitely assigned experimentally.

The γ-decay properties of the levels in ^{51}Cr have not been investigated in detail by high resolution techniques. The present investigation was undertaken in an effort to further develop the techniques for detailed spectrometric studies through measurement of prompt γ-rays from nuclear reactions with high resolution Ge(Li) detectors. For a given target system the reactions that can be conveniently and reliably studied by means of γ-ray spectrometry are those that have the largest relative cross section. In the case of ^{51}Cr two reactions were found most suitable and these are ^{51}V(p, nγ)^{51}Cr and ^{48}Ti(^{4}He, nγ)^{51}Cr. The assignment of many γ-rays in a level scheme for ^{51}Cr was greatly facilitated by means of measurements of excitation functions of individual γ-rays observed by the (p, nγ) reaction. The assignment of many γ-rays to ^{51}Cr was also based on γ-ray spectra obtained with a Ge(Li) detector in coincidence with pulses from fast neutrons recorded in a NE-213 scintillator. Neutron-gamma coincidence spectra were obtained from the ^{51}V(p, nγ) and the ^{48}Ti(^{4}He, nγ) reactions. The assignment of γ-rays to the decay of levels with excitation up to $\approx$ 3.3 MeV was also based on $\gamma\gamma$ coincidence relationships which were established in this work. Seventy-seven γ-rays have been characterized and assigned to deexcite 39 levels in ^{51}Cr. Branching ratios for γ-rays deexciting 7 levels in ^{51}Cr have been obtained by averaging the angular correlation of each γ-ray measured with respect to the direction of the beam. The γ-ray correlations employed for the determination of the branching ratios will be presented separately in a future communication, as they are beyond the scope of the present paper.

2. Experimental procedures

The Washington University cyclotron, a 137 cm sector focused variable energy machine, was used to provide the 12.0–15.0 MeV ^{4}He ion beams and the 3.0–7.0 MeV proton beams required. The experimental arrangement employed is shown in fig. 1. The external beam passes through a first set of focusing quadrupole magnets and a set of steering magnets and then is clipped by a set of slits. The beam finally passes through the switching magnet (A in fig. 1) and then through a last set of focusing quadrupole magnets (B in fig. 1) and enters a miniature 7.0 cm scattering chamber (C or D in fig. 1). The energy spread of the beams used (FWHM) was $\approx$ 0.5 % of the incident energy. The beam currents employed varied between 1–200 nA. The miniature scattering chamber was employed for some of the experiments as a Faraday cup which was connected to a beam current integrator. In other experiments the beam was monitored by means of a Si surface barrier detector which was used to record elastic scattering events. In this arrangement the beam passed through a 4.0 mm lead collimator and then through the target and finally stopped in lead. For the energies employed in these experiments nuclear reactions in Pb that produced γ-rays (other than Pb X-rays) could not be detected.

2.1. TARGET PREPARATION

The targets employed in the ^{48}Ti(^{4}He, nγ) studies were self-supporting foils (2.0 mg/cm^{2}) of titanium enriched to 99.8 % in mass 48. The enriched material was obtained from the Oak Ridge National Laboratory. The targets employed in the ^{51}V(p, nγ) studies were self-supporting foils (4–7 mg/cm^{2}) of high purity natural vanadium metal (99.76 % in mass 51). Both the titanium and vanadium target foils were prepared by rolling the metals.

2.2. DETECTION EQUIPMENT AND METHODS OF COUNTING

For γ-ray counting both NaI(Tl) and Ge(Li) detectors were employed. The NaI(Tl) detector was an integrally mounted 7.6×7.6 cm crystal and the Ge(Li) detector was a five-sided cylindrical lithium-drifted Ge crystal with an active volume of 29 cm^3 and a typical resolution (FWHM) of 2.8 keV for the 1332 keV line of ^{60}Co. This detector

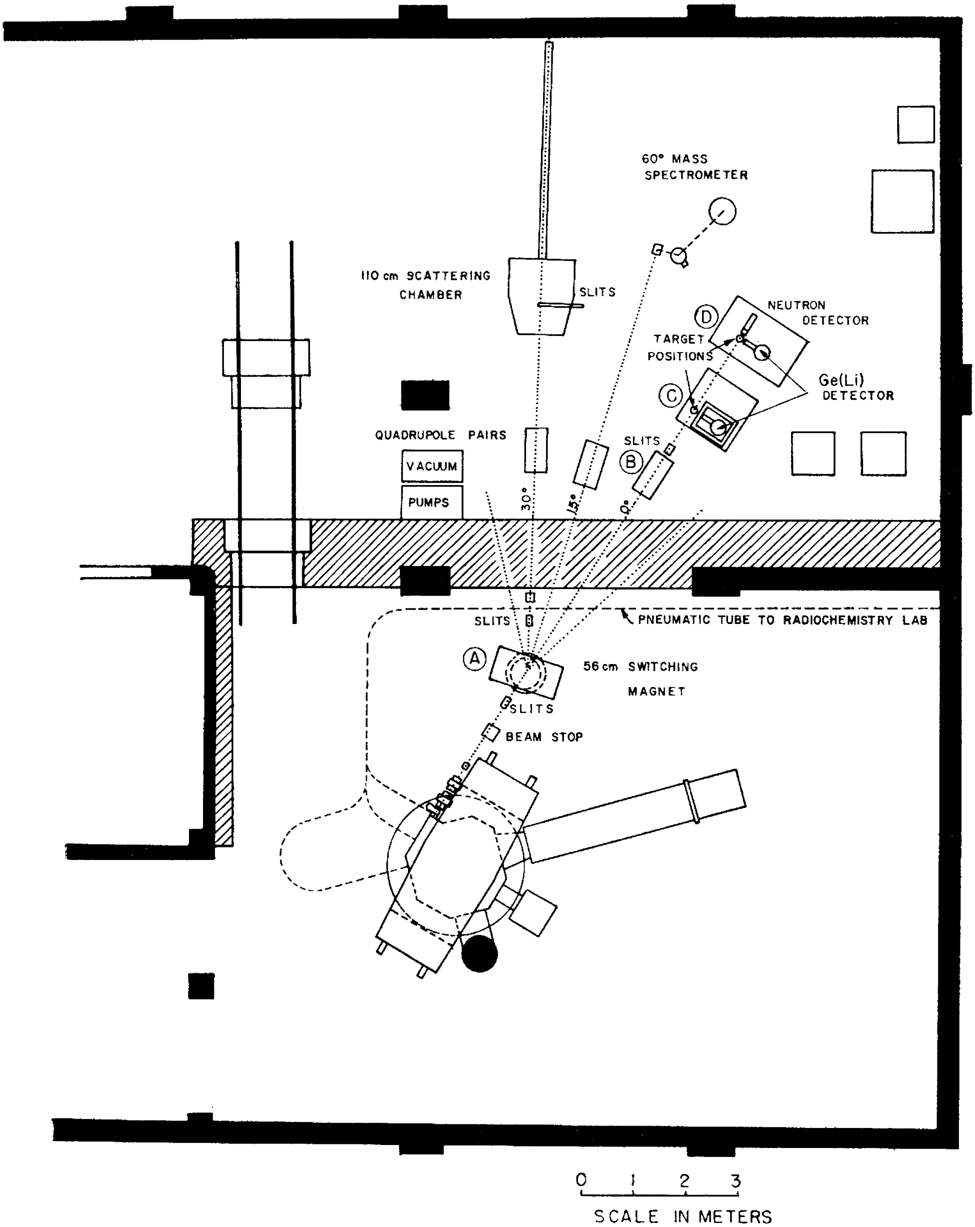


Fig. 1. Schematic drawing showing the floor arrangement of the cyclotron vault and the experimental area. A = 56 cm switching magnet for sending the beam along the 0°, 15° and 30° beam pipes; B = quadrupole focusing magnets, C and D target positions.

was mounted in an anti-Compton arrangement with a 19.0 cm diameter by 12.7 cm long annular NaI(Tl) detector. The annular NaI(Tl) detector was split into optically isolated quadrants and it could be operated as a 511–γ–511 peak escape three-crystal coincidence spectrometer. A full description of this system and its calibration was given elsewhere [32]. The entire spectrometer and its lead shield were mounted on an angular correlation table which allowed measurements to be taken between 0°–90° with respect to the beam. For precision γ-ray energy measurements the spectrometer was positioned at 90° with respect to the beam in order to minimize the distortion of the γ-peaks due to Doppler shift and broadening. For the nγ coincidence measurements the Ge(Li) was used without the Compton suppression in order to maximize the solid angle. For these nγ coincidence measurements the Ge(Li) was positioned at 120° with respect to the beam at a distance of 4.0 cm from the target.

For fast neutron counting, a 5.1 × 5.1 cm cylinder consisting of fast organic phosphor NE-213 was used as the detector. This was coupled to an RCA 8575 photomultiplier tube which was connected to an Ortec Model No. 264 photomultiplier base equipped with a timing discriminator and preamplifier. Standard techniques of discrimination by pulse shape were employed. This allowed us to discard the γ-pulses in the neutron detector. Prior to each experiment the pulse shape discrimination system was checked with a ^{256}Cf source by recording the pulses from the γ-rays and the fast neutrons. Most conveniently one displays (Δt) the time difference between the start and the zero cross-over of the linear signal versus the amplitude of the linear signal in a 64 × 64-channel two-parameter configuration. This allows for minor adjustments that eliminate most of the amplitude dependence of the timing signals. Thus, the spread in timing (FWHM) of the γ-ray pulses was typically $\approx$ 3.1 nsec and of the neutron pulses $\approx$ 5.0 nsec with a peak-to-peak separation of $\approx$ 15 nsec. This system allowed complete (> 95 %) elimination of the γ-pulses even at counting rates as high as 10^4 c/sec. In the present experiments neutrons with energy up to 7 MeV were analyzed. This γ-ray discrimination could be easily achieved for a dynamic range of neutron pulses covering the energy range 0.5–10 MeV.

The pulses from the Ge(Li) detector were amplified through a Tennelec TC-135 preamplifier followed by a Tennelec TC-200 linear amplifier and a Tennelec TC-biased amplifier and stretcher.

For pulse-height analysis a Nuclear Data Model No. 161 4096-channel two-parameter pulse-height analyzer was used. The analyzer was equipped with buffer tape and a read search control unit. In many experiments 4096-channel Compton suppressed spectra were recorded directly in the memory of the analyzer. In several other experiments Compton suppressed spectra and 511–γ–511 escape peak spectra were recorded simultaneously each in a 2048-channel resolution. For the nγ coincidence measurements two-parameter spectra were recorded with the neutron energy pulses in a 128-channel resolution and the Ge(Li) pulses in a 2048-channel resolution. A block diagram of the circuitry employed in the nγ coincidence measurements is shown in fig. 2. For the energies employed in these experiments the period between beam bursts ranged between 100–140 nsec, while the width of each beam burst is $\approx$ 4 nsec. The reactions of interest in this work have high cross sections compared to the competing reactions. This allows one to operate at low enough beam currents so that on the average no more than one γ-ray producing event occurs per beam burst. Under these conditions and with the neutron and γ-ray detectors positioned at 3.0 and 4.0 cm from the target $n\gamma$ coincidence events could be accumulated at a rate of

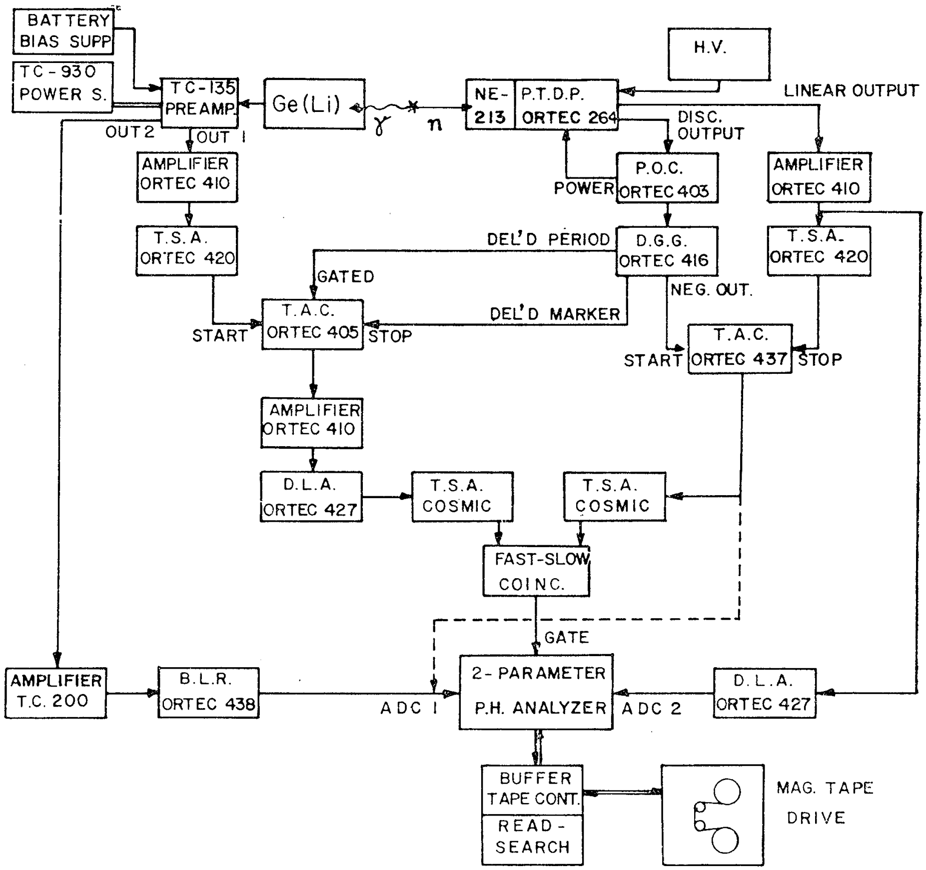


Fig. 2. Block diagram of the electronics circuitry employed in the $n\gamma$ (or $\gamma\gamma$) coincidence experiments between fast neutrons and prompt γ-rays. Some abbreviations have been used: (TSA = timing single channel analyzer, TAC = time-to-amplitude converter, PTDP = photomultiplier tube timing discriminator and preamplifier, POC = pick-off control unit, DGG = delay and gate generator, BLR = base line restorer, DLA = delay line amplifier).

20–50 c/sec with random events not exceeding the limit of 10 % of the total coincidence rate. It should be noted that due to the pulsed character of the cyclotron beam the random rate cannot be decreased without improvement in the timing resolution below $\approx$ 4 nsec. Under the present experimental conditions the limitation in timing was due to the five-sided coaxial Ge(Li) detector used. Thus the prompt coincidence peak has a width at 1/100 height of $\approx$ 70 nsec for γ-rays corresponding to the energy range of 80–3000 keV. This allowed complete rejection of the random events in the satellite bursts. Another serious limitation is the loss of resolution in the coincidence spectra due to high Ge(Li) singles rate. In the present experiments some loss in energy resolution was observed at singles rates > 3000 c/sec.

For $\gamma\gamma$ coincidence measurements a 7.6×7.6 cm NaI(Tl) and a 29 cm^3 Ge(Li) were employed. The NaI(Tl) detector was positioned at $\approx$ 10 cm from the target at an angle of $\approx$ 120° with respect to the beam. To reduce the Compton background in the NaI(Tl) detector a collimator was employed that limited the γ-flux to the cone subtended by the target and the back face of the NaI(Tl) detector. The Ge(Li) was positioned at $\approx$ 4.0 cm from the target also at an angle of $\approx$ 120° with respect to the beam. The coincidence circuitry employed was that shown in fig. 2 except that the NE-213 scintillator was replaced by the NaI(Tl) detector and the pulse shape discrimination section was bypassed. Coincidence measurements were performed at E_p = 5.0 MeV and the coincidence rate obtained under these conditions was $\approx$ 60 c/sec. The random coincidence events under these conditions were determined to be $(9 \pm 3)\%$ of the total coincidence rate. The timing resolution (1/100 height) was $\approx$ 70 nsec and adequately separated the random events originating from the neighbouring beam bursts.

3. Experimental results

Singles measurements of the γ-rays emitted in the 12.5 and 15.0 MeV ^{4}He ion bombardment of ^{48}Ti have been taken under Compton suppression at 90° relative to the beam direction. Due to target thickness the beam energy in these experiments covered the ranges 12.0–12.5 and 14.5–15.0 MeV. The large excitation energy provided by the (^{4}He, n) reaction ($Q = -2.683$ MeV) at these projectile energies complicates the γ-ray spectra due to the large number of emitted γ-rays. Fig. 3 shows a typical Compton suppressed spectrum obtained in a 12.5 MeV bombardment of ^{48}Ti. The background from the large number of unresolved γ-rays appears as a "continuum". Spectra taken at E = 15.0 MeV did not exhibit any new structure. The spectrum of fig. 3 includes the γ-rays from the reactions ^{48}Ti(^{4}He, p)^{51}V and ^{48}Ti(^{4}He, $\alpha'\gamma$) (peaks labelled V and Ti, respectively). These γ-rays comprise only a small fraction of the total γ-ray intensity as it is shown below. Under the present experimental conditions there were several sources of background radiations. Firstly, the γ-radiations from induced short-lived radioactivity in the target were determined by pulsing the low-level rf supply of the master oscillator. Thus spectra were taken with the beam on for 400 msec followed by a beam off period of 400 msec and routing the two 2048-channel spectra in the two halves of the 4096-channel pulse-height analyzer. The contribution from radioactivity was thus found negligible. Secondly, the background of the present arrangement with the beam on but without the target was measured for the same amount of integrated beam current and was also found negligible. Finally, the most important background radiation was found to have

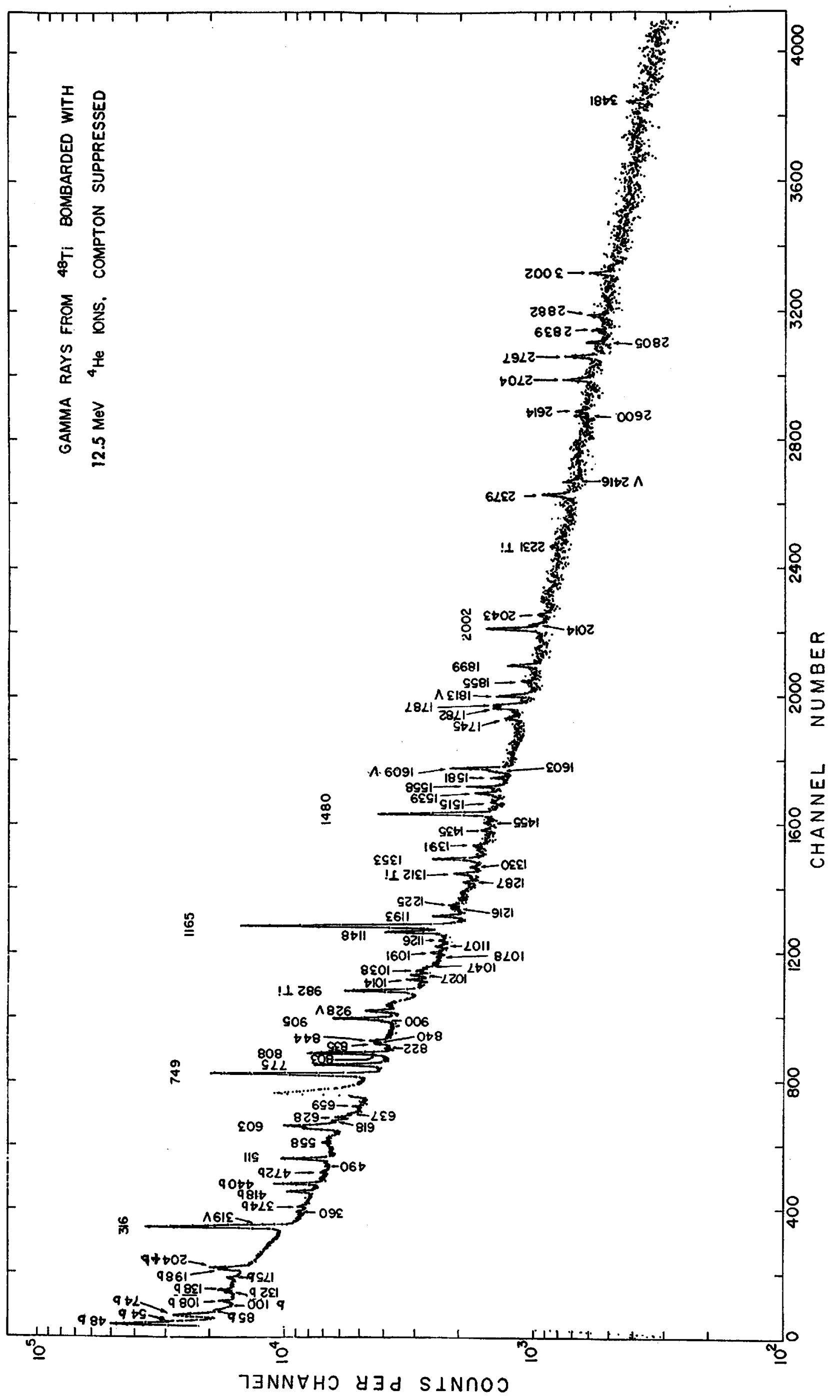


Fig. 3. Compton-suppressed spectrum of the singles γ-rays emitted in the 12.0 MeV ^{4}He ion bombardment of ^{48}Ti. The delayed and background γ-rays have not been subtracted. Peaks labelled b are associated with the background; peaks labelled V are associated with the ^{48}Ti(^{4}He, pγ) reaction; and peaks labelled Ti are associated with the ^{48}Ti(^{4}He, $\alpha'\gamma$) reaction.

originated from nuclear reactions and radioactivity induced by the fast neutrons in the materials surrounding the Ge(Li) detector. These interfering γ-rays originate from (n, n′γ) reactions in the various Ge isotopes, in the ^{23}Na and ^{127}I of the NaI(Tl) annulus and to a much smaller extent from radioactivity induced by (n, γ) reactions

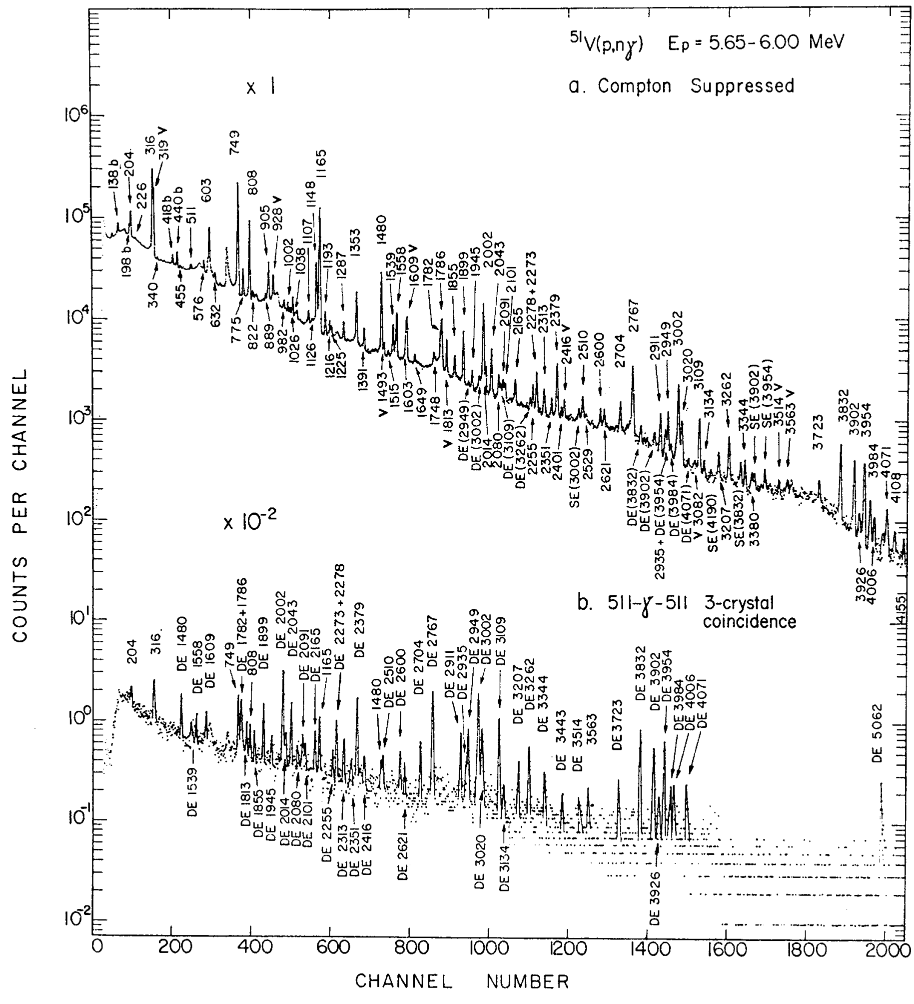


Fig. 4. Spectra of the prompt γ-rays from the 6.0 MeV proton bombardment of ^{51}V. The upper part (a) shows the Compton suppressed spectrum; peaks labelled b are associated with the background, while peaks labelled V are associated with the ^{51}V(p, p′γ) reaction. The lower part (b) is the 511–γ–511 pair-escape 3-crystal coincidence spectrum recorded simultaneously with the upper spectrum (a).

in the same materials. These γ-rays were identified as extraneous by performing singles measurements with 3 and 5 cm of lead absorber between the target and the detector. These extraneous γ-rays were enhanced in intensity relative to the γ-rays from the reactions in the target and were easily identified.

TABLE 1

Energy and intensity of the γ-rays from ^{51}Cr following the ^{51}V(p, nγ) reaction at $E_p = 6.0$ MeV and the ^{48}Ti(^{4}He, nγ) reaction at $E_\alpha = 12.5$ MeV

Transition	E_γ measured (keV)		E_γ from scheme [a] (keV)		I_γ (90°) from (p, nγ)		Effective threshold E_p+Q (MeV)		Observed in nγ coincidence
6 → 4	204.0	*8*	204.5	*4*	1.9	*4* [d]	1.6	*1*	204.0 [b,c]
25 → 18	296.0	*7*	296.2	*5*	0.04	*2*			
5 → 3	315.6	*3*	315.8	*2*	32.7	*33*	1.50	5	315.6 [b,c]
27 → 18	432.0	*7*	432.9	*5*	0.21	*6*			
15 → 10	454.8	*5*	454.6	*4*	0.35	*6*	3.0	*5*	
17 → 11	510.8	*3*	510.5	*4*	1.18	*9*	3.1	*3*	510.8 [b]
4 → 2	575.6	*1*	575.6	*3*	2.05	*16*	1.60	*15*	575.6 [b,c]
4 → 1	603.4	*4*	603.8	*3*	15.9	*13* [d]	1.60	*10*	603.4 [b,c]
1 → 0	749.0	*1*	749.0	*1*	100		0.95	*5*	749.0 [b,c]
9 → 5	775.4	*3*	775.4	*3*	7.0	*4*	2.5	*2*	775.4 [b]
6 → 1	807.9	*1*	808.3	*3*	42.4	*25* [d]	1.55	*10*	807.9 [b,c]
11 → 6	822.3	*3*	822.3	*4*	1.56	*20*	2.6	*2*	
17 → 8	888.7	*2*	888.7	*4*	1.91	*17*	>3.0		
11 → 5	899.9	*5*	899.3	*3*	2.8	*6*	2.5	*2*	
12 → 6	905.3	*2*	905.3	*3*	12.4	*14*	2.5	*2*	905.3 [b]
21 → 8	1002.7	*4*	1002.6	*4*	1.98	*18*	3.3	*3*	
11 → 4	1026.7	*2*	1026.8	*4*	4.3	*4*	2.6	*2*	1026.7 [b]
31 → 17	1037.7	*11*	1038.2	*10*	0.25	*11*	3.8	*4*	1037.7 [b]
23 → 8	1107.3	*2*	1107.5	*4*	2.4	3	3.2	*3*	1107.3 [b]
13 → 6	1147.9	*3*	1146.3	*5*	14	*3*	2.5	*2*	1147.9 [b,c]
10 → 3	1147.9	*3*	1148.0	*2*	12	*3*			1147.9 [b,c]
3 → 0	1164.5	*1*	1164.5	*1*	113	*7*	1.30	*15*	1164.5 [b,c]
11 → 3	1215.5	*5*	1215.1	*2*	2.2	*2*	2.6	*2*	
13 → 5	1224.7	*3*	1223.3	*5*	1.4	*2*	2.8	2	
15 → 5	1287.2	*4*	1286.8	*4*	3.7	*2*	2.8	*2*	
4 → 0	1353.3	*2*	1352.8	*3*	13.5	*8*	1.45	*10*	1353.3 [b,c]
19 → 6	1391.3	*2*	1391.4	*4*	3.3	*3*	3.0	*3*	1391.3 [b]
29 → 11	1453.4	*15*	1451.7	*5*	0.28	*10*			
5 → 0	1480.3	*2*	1480.3	*2*	30.4	*18*	1.6	*1*	1480.3 [b,c]
13 → 3	1538.8	*3*	1539.1	*4*	6.9	*4*	2.8	*2*	1538.8 [b]
6 → 0	1557.6	*2*	1557.3	*3*	10.9	*7*	1.70	*15*	1557.6 [b,c]
15 → 3	1603.4	*5*	1602.7	*3*	3.3	*5*	2.75	*15*	
26 → 6	1649.8	*5*	1649.9	*5*	1.2	*2*	3.4	*3*	
18 → 3	1747.7	*9*	1746.5	*4*	1.7	*2*	3.0	*2*	
23 → 4	1755.7	*7*	1756.2	*5*	0.20	*4*	3.0	*3*	
24 → 4	1782.2	*3* [e]	1781.8	*5*	<5.6	*12*	3.2	*3*	1782.2 [b]
26 → 5	1782.2	*3* [e]	1781.3	*5*	<5.6	*12*	3.2	*3*	1782.2 [b]
27 → 6	1787.4	*3*	1786.6	*5*	10.9	*17*	3.2	*3*	1787.4 [b]
25 → 4	1854.6	*3*	1854.4	*5*	2.2	*4*	3.0	*3*	1854.6 [b]
7 → 0	1899.3	*3*	1899.3	*3*	9.2	*6*	2.0	*2*	1899.3 [b,c]
23 → 3	1944.6	*2*	1944.5	*3*	1.8	*2*	3.4	*4*	
8 → 0	2001.5	*2*	2001.5	*2*	28	*2*	2.1	*1*	2001.5 [b,c]
14 → 1	2013.6	*5*	2013.6	*5*	3.0	*2*	3.0	4	
25 → 3	2042.5	*7*	2042.7	*4*	6.9	*4*	3.2	*2*	
16 → 1	2080.0	*4*	2080.0	*4*	2.1	*3*			
28 → 6	2164.6	*8*	2164.8	*8*	2.5	*2*	3.7	*3*	
21 → 1	2255.1	*3*	2255.1	*3*	2.2	*2*	3.4	*3*	

TABLE 1
(continued)

Transition	E_γ measured (keV)		E_γ from scheme [a] (keV)		I_γ (90°) from (p, nγ)		Effective threshold E_p+Q (MeV)		Observed in nγ coincidence
29 → 6	2273.6	*3*	2274.0	*5*	3.3	*4*	3.8	*3*	
10 → 0	2312.5	*2*	2312.5	*2*	2.8	*2*	2.4	*2*	
29 → 5	2350.5	*6*	2351.0	*5*	1.4	*1*			
11 → 0	2379.3	*2*	2379.6	*2*	7.0	*4*	2.6	*2*	
31 → 5	2448.9	*10* [e]	2448.0	*10*	0.21	*7* [d]			
34 → 6	2448.9	10 [e]	2449.0	*7*	0.21	*7* [d]			
32 → 4	2600.4	*4*	2601.2	*6*	1.1	*1*			
13 → 0	2703.6	*6*	2703.6	*4*	2.2	*2* [d]	2.9	*4*	
15 → 0	2767.1	*2*	2767.1	*3*	9.2	*6* [d]	2.9	*3*	
18 → 0	2910.9	*2*	2911.0	*3*	2.5	*2*	3.1	*3*	
19 → 0	2948.8	*2*	2948.7	*2*	2.1	*3*	3.0	*3*	
20 → 0	3001.6	*3*	3001.6	*3*	8.0	*5*	3.2	*3*	
22 → 0	3020.3	*2*	3020.3	*2*	2.7	*3*	3.2	*3*	
23 → 0	3109.0	*4*	3109.0	*3*	2.7	*2*	3.4	*4*	
24 → 0	3134.0	*7*	3134.6	*4*	0.35	*7*	3.8	*5*	
25 → 0	3207.3	*7*	3207.2	*4*	0.77	*8*	3.4	*4*	
26 → 0	3261.6	*2*	3261.7	*4*	1.9	2 [d]	3.4	*4*	
27 → 0	3343.6	*4*	3343.9	*4*	0.72	*9*	3.5	*4*	
28 → 0	3722.7	*15*	3722.1	*8*	0.26	*5*			
29 → 0	3831.6	*3*	3831.3	*4*	2.4	*2*			
30 → 0	3901.9	*3*	3901.9	*3*	1.7	*1*			
31 → 0	3926	*2*	3928.3	*10*	0.18	*6*			
32 → 0	3954.4	*6*	3954.0	*5*	1.6	*1*			
33 → 0	3984.3	*13*	3984.3	*13*	0.41	*10*			
34 → 0	4006.4	*9*	4006.3	*6*	0.21	*4*			
35 → 0	4071	*2*	4071	*2*	0.48	*10*			
36 → 0	4108	*2*	4108	*2*	0.10	*6*			
37 → 0	4155	*3*	4155	*3*	0.09	*4*			
38 → 0	4190	*3*	4190	*3*	0.20	*7*			
39 → 0	4273	*4*	4273	*4*	0.09	*5*			

Summary of the neutron γ-ray coincidence relationships and of the effective thresholds from the (p, nγ) reaction.

[a]) This is the transition energy deduced from the proposed level scheme for ^{51}Cr. The level energies are weighted averages of energy sums as given in table 5.

[b]) Observed in coincidence with neutron pulses from the (^{4}He, nγ) reaction at 12.5 MeV.

[c]) Observed in coincidence with neutron pulses of $E_n \geqq 1.3$ MeV from the (p, nγ) reaction at 5.0 MeV.

[d]) Gamma ray also assigned in the ^{51}V decay scheme from the (p, p′γ) reaction; only a small fraction of the intensity given is believed to be associated with the (p, p′γ) reaction.

[e]) Transition that can be assigned in two places in the scheme.

Fig. 4a shows a Compton suppressed spectrum of the singles γ-rays emitted at 90° with respect to the beam in the 6.0 MeV proton bombardment of ^{51}V. In fig. 4b is shown the three-crystal coincidence 511–γ–511 escape peak spectrum recorded simultaneously with the above Compton suppressed spectrum. At this bombarding energy levels in ^{51}Cr up to $\approx$ 4350 keV can be excited by the (p, nγ) reaction. Although a large number of γ-rays is observed in the spectra of fig. 4, it is interesting to note that these spectra have noticeably pronounced line structure compared to the spectra from the (^{4}He, nγ) reaction (fig. 3). Again, the competing ^{51}V(p, p'γ) reaction was shown to be responsible for only a small fraction of the observed γ-ray intensity. The energy and intensity of the γ-rays that are believed to originate from ^{51}Cr

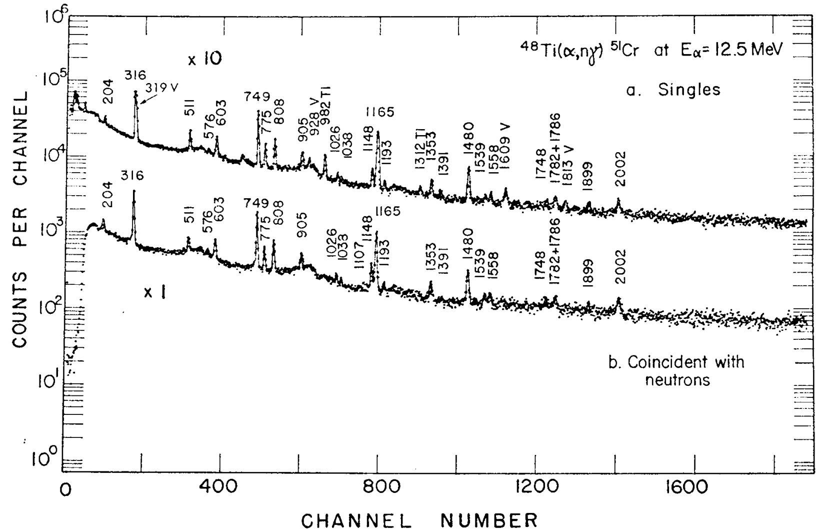


Fig. 5. Typical spectrum of the γ-rays in coincidence with fast neutrons from the ^{48}Ti(^{4}He, nγ) reaction at 12.5 MeV. The upper spectrum (a) is a singles spectrum taken with the same gain for purposes of easy comparison. The lower spectrum (b) is taken in coincidence with neutrons. Note that the peaks labelled V and Ti in the upper spectrum are not seen in the coincidence spectrum and have been assigned to the (^{4}He, pγ) and (^{4}He, $\alpha'\gamma$) reactions, respectively.

excited by the (^{4}He, nγ) and (p, nγ) reaction in ^{48}Ti and ^{51}V, respectively, are summarized in table 1. Column 1 of table 1 gives the level numbers specifying each transition in ^{51}Cr as established in this work. The energies given in column 2 of table 1 are weighted averages from Compton suppressed singles spectra taken at 90° with respect to the beam from two (^{4}He, nγ) experiments at E = 12.5 MeV and two (p, nγ) experiments at E_p = 6.0 MeV, and from one 511–γ–511 coincidence (p, nγ) experiment at E_p = 6.0 MeV taken at 90° to the beam. The energies given in column 3 of table 1 are the transition energies obtained from the proposed level scheme by difference between level energies, which in turn have been obtained as weighted averages of the proper energy sum of observed γ-rays leading to those levels. The intensities given in column 4 of table 1 are weighted averages from the three above mentioned (p, nγ) experiments at E_p = 6.0 MeV with the spectra taken at 90° with respect to the beam. Column 6 of table 1 summarizes the nγ coincidence information obtained in this work. Fig. 5b shows a typical spectrum of the γ-rays obtained in coincidence with neutron pulses from the ^{48}Ti(^{4}He, nγ) reaction at 12.5 MeV. For comparison a singles spectrum with slightly better statistics is shown in fig. 5a. Notice that the peaks at 319, 928, 1609 and 1813 keV, and the peaks at 982 and 1312 keV originating from the reactions ^{48}Ti(^{4}He, pγ) and ^{48}Ti(^{4}He, $\alpha'\gamma$), respectively, are absent from the coincidence spectrum. In fig. 6b we show a typical spectrum of the γ-rays in coincidence with neutrons from the ^{51}V(p, nγ) reaction at 5.0 MeV. In this spectrum the lower level discriminator for the neutron detector was set to reject neutron pulses corresponding to $E_n \leqq 1.3$ MeV. For comparison a singles spectrum

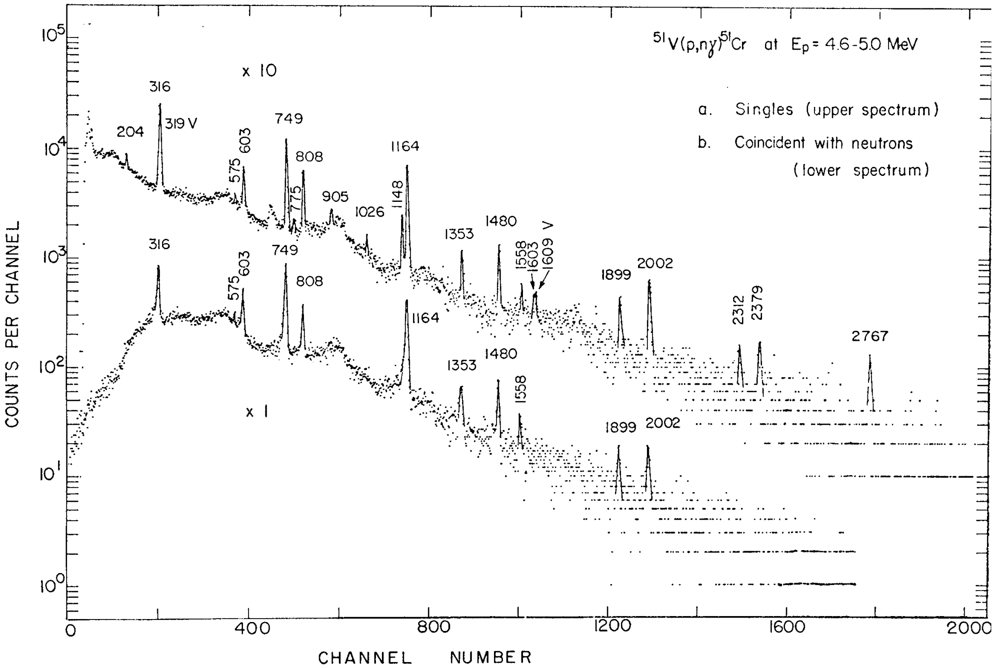


Fig. 6. Typical spectrum of the γ-rays in coincidence with neutron pulses with $E_n \geqq 1.3$ MeV from the ^{51}V(p, nγ) reaction at $E_p = 5.0$ MeV. The upper spectrum is a typical singles spectrum taken under the same gain for purposes of comparison. The lower spectrum is taken in coincidence with the neutrons. Note that the peaks labelled V as well as those at 775, 905, 1026, 1148, 1603, 2312, 2379 and 2767 keV are not seen in the coincidence spectrum as they originate from levels not populated by neutrons of $E_n > 1.3$ MeV. The 204 keV γ-ray is not seen in coincidence due to the high discriminator setting for the Ge(Li) detector.

taken under the same conditions is shown in fig. 6a. Notice again that the peaks at 319, 1609 keV from ^{51}V(p, p$'\gamma$) are not observed in the coincidence spectrum. Absent from the coincidence spectrum also are the peaks at 905, 1026, 1148, 1603, 2312, 2379 and 2767 keV (figs. 6a, b) indicating that these γ-rays are coincident with neutrons with energies below 1.3 MeV, thus originating from levels lying higher than 1.9 MeV in excitation.

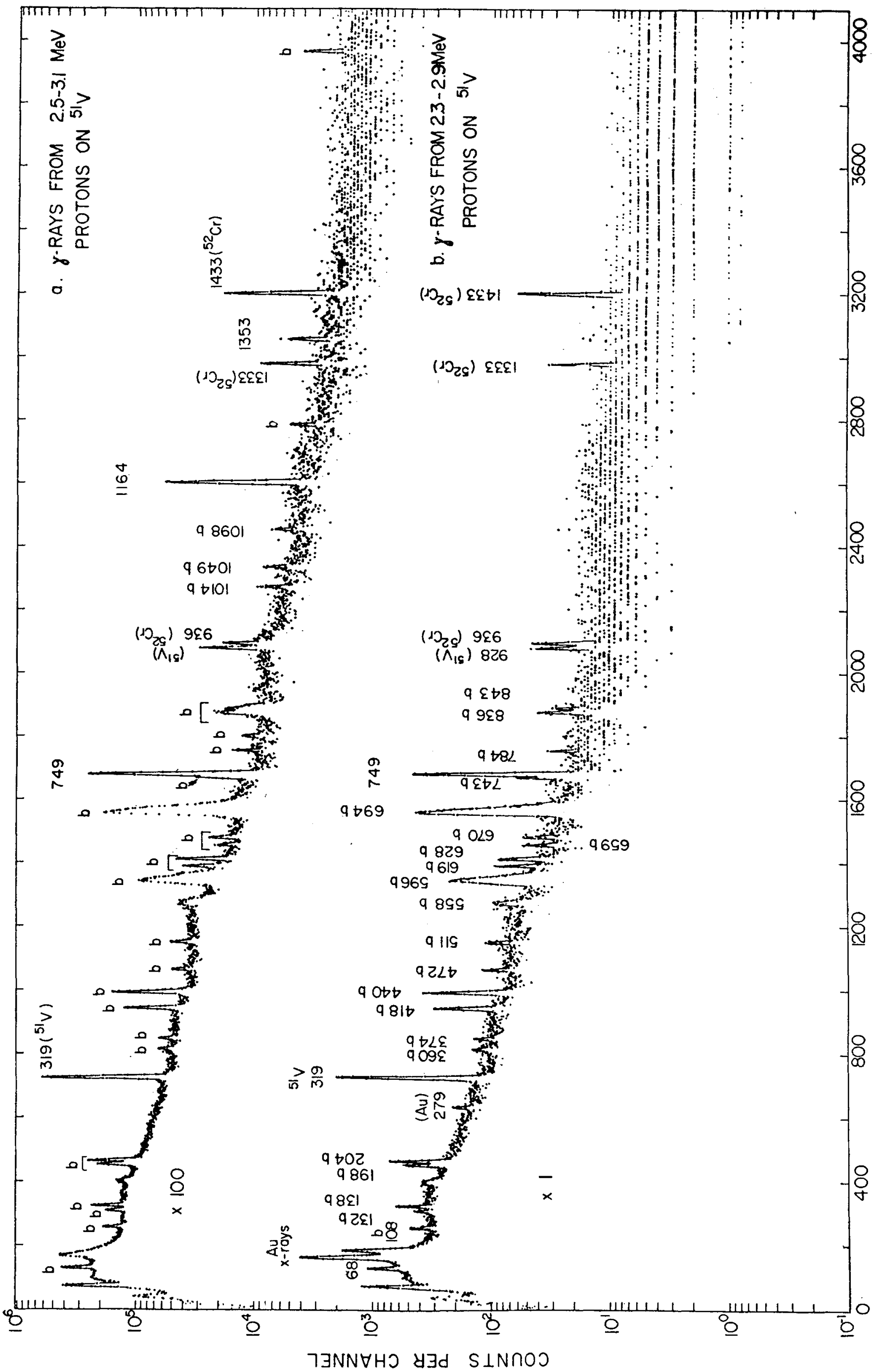


Fig. 7. Compton suppressed γ-ray spectra taken at the indicated proton bombarding energies on ^{51}V. At the lower bombarding energy (b) only the 749 keV γ-ray comes from the (p, nγ) reaction. In the upper spectrum the 1164 and 1353 keV γ-rays are also seen. Note the relatively large number of γ-rays labelled b which are due to background radiations. Peaks labelled ^{51}V are from (p, p′γ) and those labelled ^{52}Cr are believed to be due to the ^{51}V(p, γ) reaction.

In order to facilitate the assignment of the γ-rays in the ^{51}Cr scheme, excitation functions of individual γ-rays were determined by taking spectra at twelve proton bombarding energies covering the range 2.66 to 7.00 MeV. In fig. 7 we show two

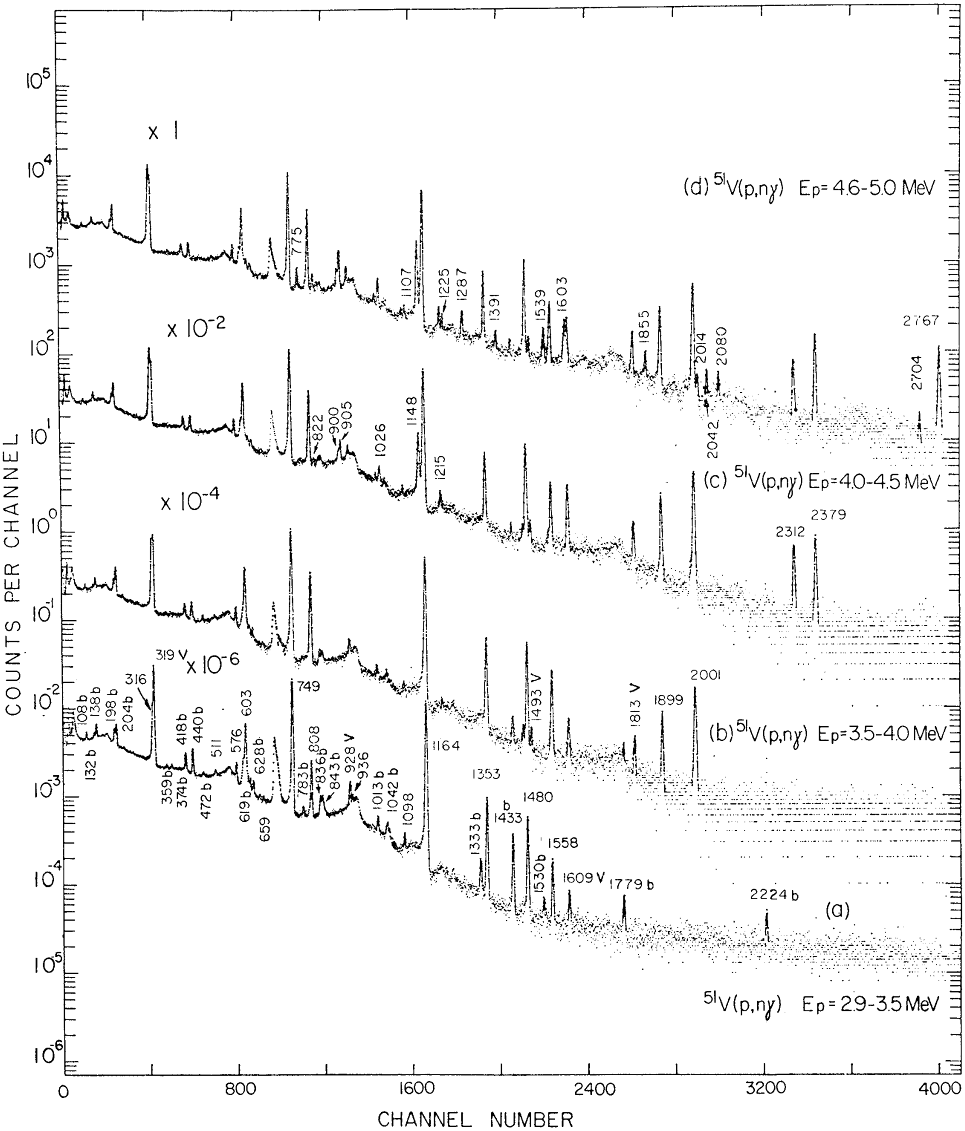


Fig. 8. Typical Compton-suppressed γ-ray spectra from ^{51}V(p, nγ) taken at the indicated bombardment energies. As the energy is increased from (a) to (d) new γ-rays appear due to excitation of higher-lying levels in ^{51}Cr and ^{51}V. In each spectrum only the new γ-rays are labelled with their energies. Note that the interference from the background radiations marked with b becomes relatively unimportant with increasing energy due to the larger increase in cross section for the reactions of interest. Peaks labelled V were assigned to the (p, p′γ) reaction.

spectra taken of $E_p = 2.9$ and 3.1 MeV. At the lower energy only the 749.0 keV γ-ray from ^{51}Cr is observed (fig. 7b) and at the higher energy 1164.5 keV γ-ray is also seen (fig. 7a). The other γ-rays seen in fig. 7 are due to competing reactions and background radiations. In fig. 8 we show spectra taken at four consecutively higher bombarding energies. From these measurements it was found that the yield of each γ-ray is rapidly increasing with bombarding energy.

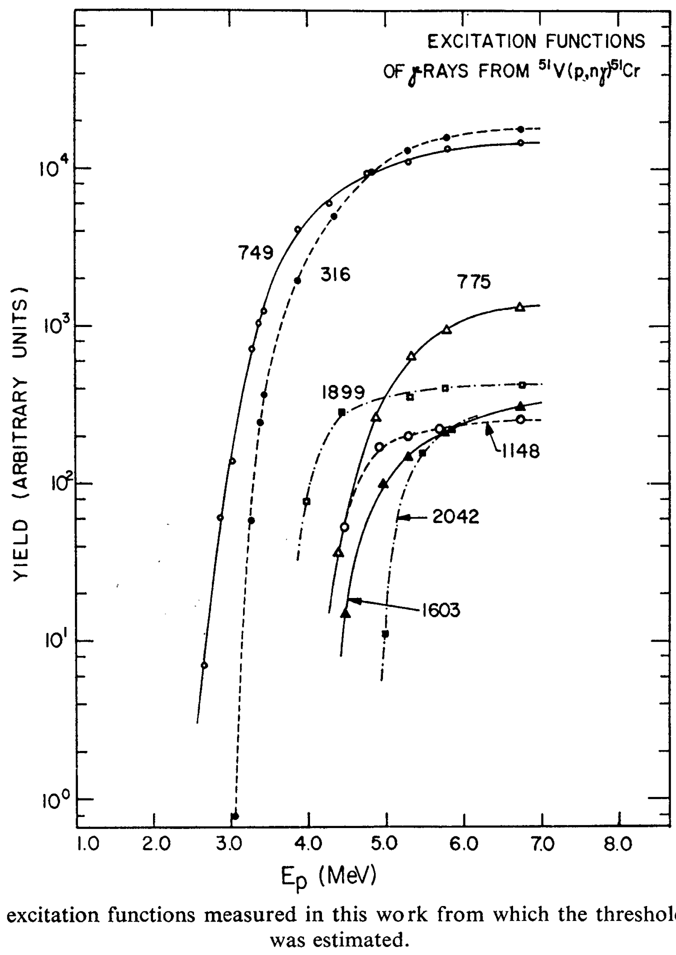


Fig. 9. Typical excitation functions measured in this work from which the threshold of each γ-ray was estimated.

A set of typical excitation functions of individual γ-rays is displayed in fig. 9. From such excitation functions it was possible to estimate the threshold for the production of many of the γ-rays and the results are summarized in the fifth column of table 1.

In order to make definite assignments of the observed γ-rays to the levels in ^{51}Cr populated in these reactions, a $\gamma\gamma$ coincidence experiment was performed following the ^{51}Cr level excitation by the (p, nγ) reaction at $E_p = 5.0$ MeV. In this experiment the coincidence events were accumulated in a two-parameter 128 × 2048-channel configuration for the NaI × Ge(Li) axes, respectively. Both axes covered approximately the same energy range of 30–3100 keV. In order to minimize the number of illustrations required to support the proposed level assignments, we have integrated

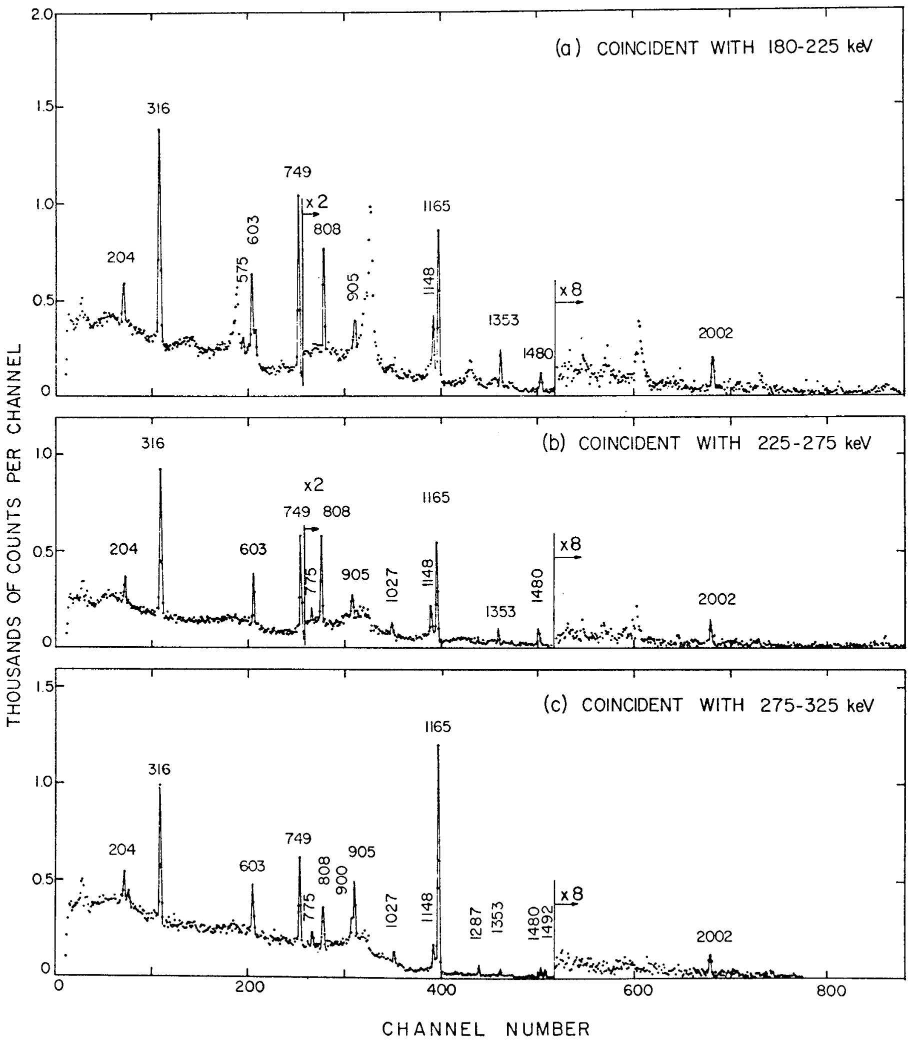


Fig. 10. Spectra of the γ-rays from the 5.0 MeV proton bombardment of ^{51}V taken with a 29 cm^3 Ge(Li) detector in coincidence with the indicated regions in the NaI(Tl) spectrum.

the Ge(Li) spectra every two channels and the NaI(Tl) axis every four or eight channels to obtain the coincidence spectra shown in figs. 10–13. The established $\gamma\gamma$ coincidence relationships are summarized in table 2.

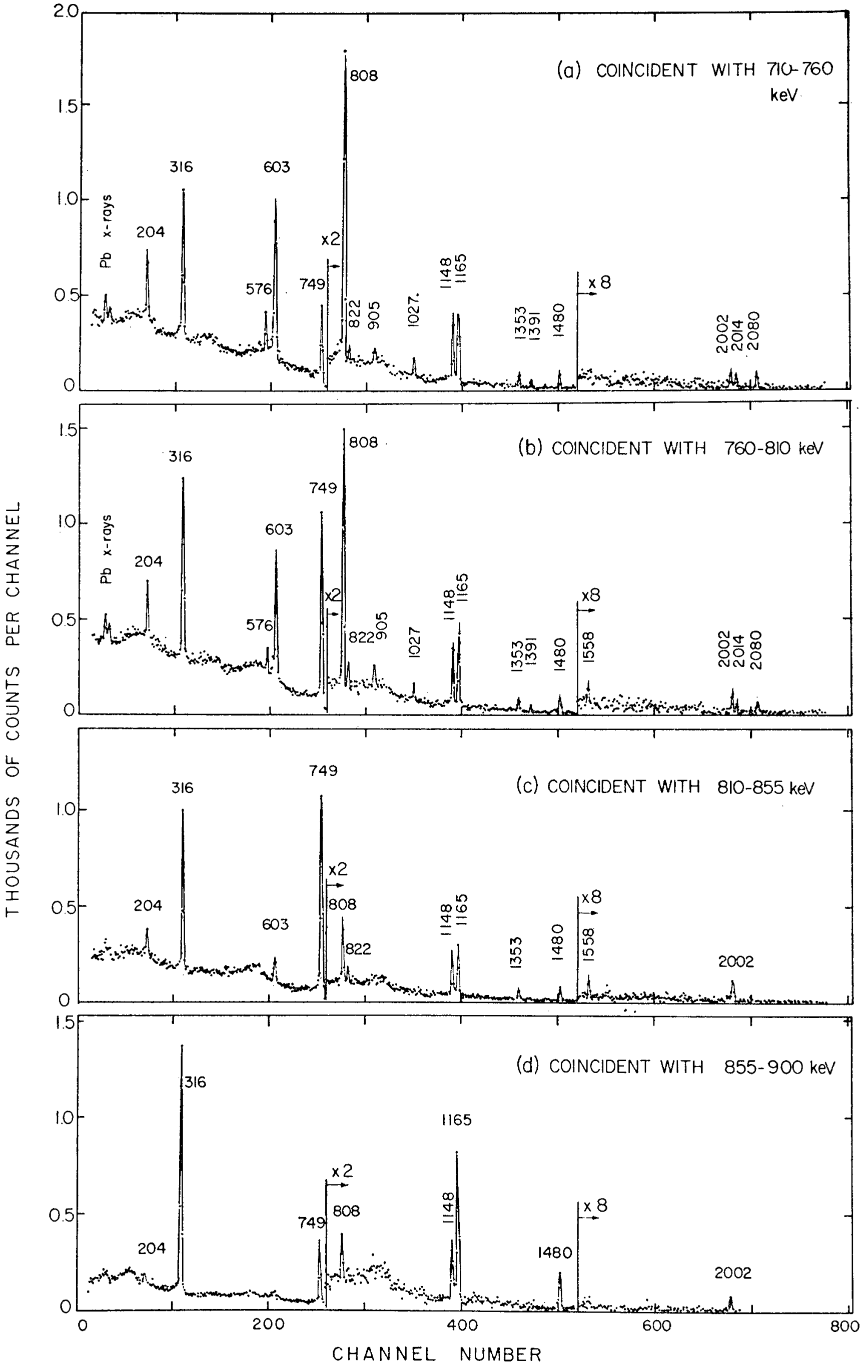


Fig. 11. See caption to fig. 10.

Branching ratios for the deexcitation of the levels in ^{51}Cr up to 2704 keV were determined from measurements of the angular distributions of the γ-rays relative to

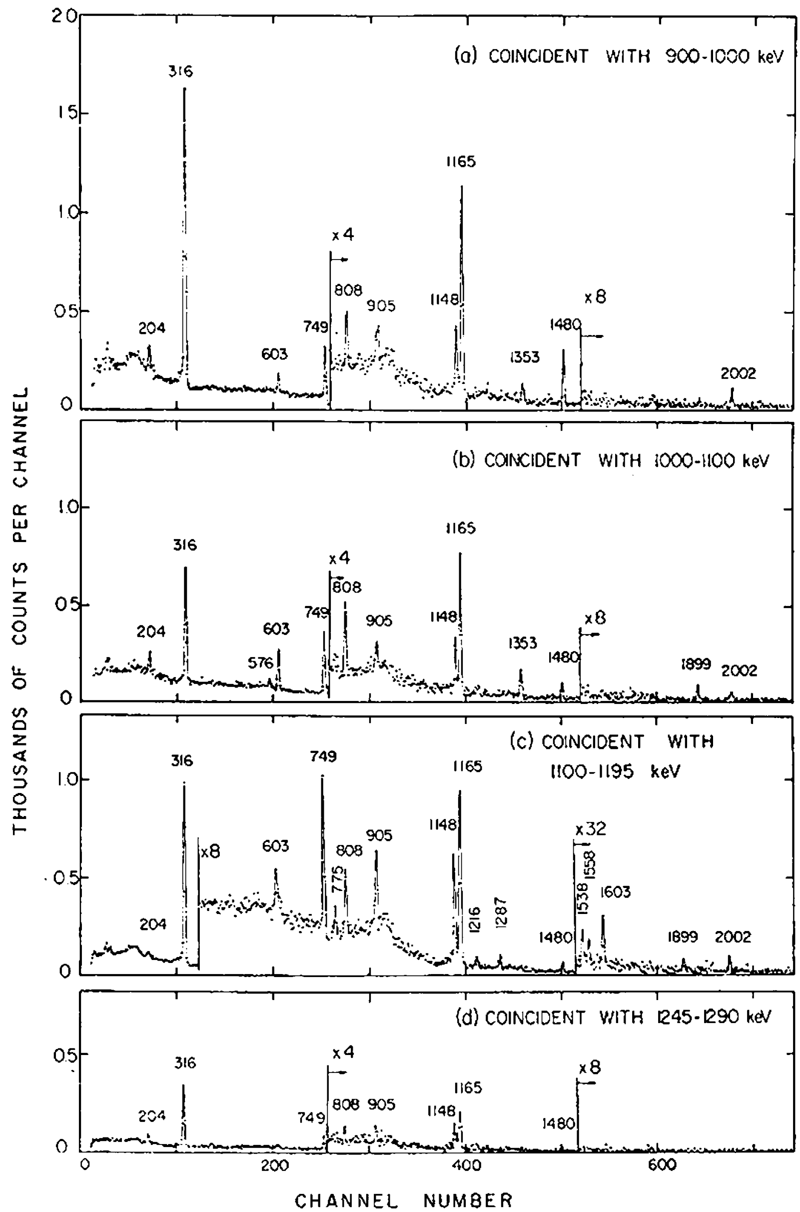


Fig. 12. See caption to fig. 10.

the beam direction and the results are summarized in table 3. Experiments were performed at 4.0 MeV and 6.0 MeV bombarding energies. In these experiments the beam was monitored by observing the elastically scattered protons with a Si(Li) or surface barrier Si detector positioned at 90°.

Finally, from the present study 17 γ-rays could be assigned to the decay of levels in ^{51}V excited by the ^{51}V(p, p$'\gamma$) or the ^{48}Ti(^{4}He, pγ) reactions. These transitions,

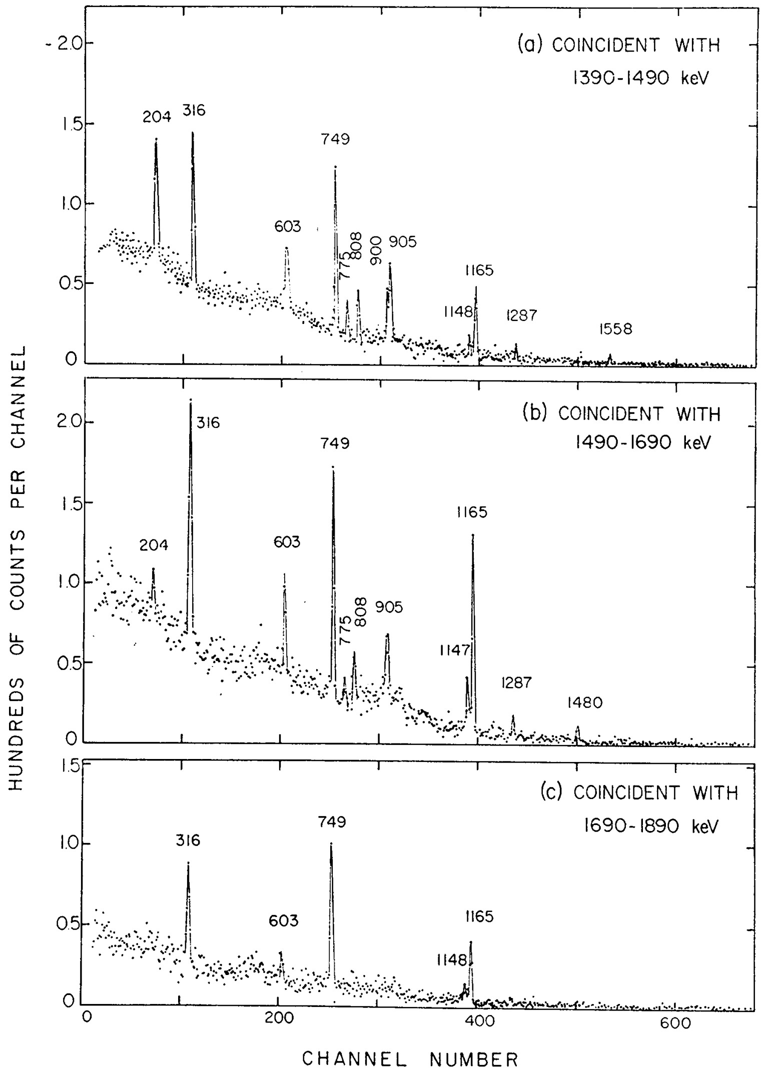


Fig. 13. See caption to fig. 10.

together with the transitions observed from other probable sources of background are summarized in table 4. It should be mentioned that the γ-rays labelled c) in column 3 of table 4 have also been assigned as possible transitions in ^{51}Cr. The last column

TABLE 2

Summary of the observed $\gamma\gamma$ coincidence relationships in the decay of levels in ^{51}Cr populated in the ^{51}V(p, nγ) reaction at $E_p = 5.0$ MeV

Fig. no.	Energy in NaI axis (keV)	γ-rays in the NaI gate (keV)	γ-rays seen in the Ge(Li) coincidence spectrum [a] (keV)
10a	180–225	204	576, 603, 749, 1353
10c	275–325	316, 319 [b]	775, 900, 905, 1165, 1287
[c]	515–610	576, 603	204, 749, 1027
11a	710–760	749, 775	204, 576, 603, 808, 822, 1027, 1391, 1480, 1014, 2080
11b	760–810	749, 775, 808	204, 316, 576, 603, 749, 808, 822, 1027, 1391, 1480, 2014, 2080
11c	810–855	775, 808, 822	204, 316, 603, 749, 808, 822, 1353, 1391, 1480, 1558
11d	855–900	900, 905	316, 1165, 1480
12a	900–1000	900, 905, 1027	316, 603, 749, 1165, 1353, 1480
12b	1000–1100	1027, 1107	576, 603, 1353
12c	1100–1195	1107, 1148, 1165	204, 316, 775, 808, 900, 905, 1148, 1165, 1216, 1287, 1538, 1558, 1603
12d	1245–1290	1216, 1225, 1287	316, 1165, 1480
[c]	1290–1385	1225, 1287, 1353, 1391	204, 216, 749, 808, 1026, 1165, 1480, 1558
13a	1390–1490	1353, 1391, 1480	204, 316, 749, 775, 808, 900, 905, 1558
13b	1490–1690	1480, 1493, 1539 1558, 1603	316, 749, 775, 900, 905, 1147, 1165, 1287, 1353, 1480
13c	1690–1890	1756, 1782, 1855, 1899	749, 1165

[a]) Only γ-rays identified with levels in ^{51}Cr are listed. Coincidences with γ-rays in ^{51}V from (p, p′γ) are not included here. [b]) From decay in ^{51}V. [c]) Not displayed in a figure.

TABLE 3

Summary of the branching ratios for the decay of some of the levels in ^{51}Cr. Values obtained by averaging correlations $I_\gamma(\theta)$ measured at ten angles from (p, nγ) at $E_p = 4.0$ MeV

E_{level} (keV)	E_γ (keV)	Branching (%)
776.2	27.2	>99.7
	776.2	< 0.3
1352.8	575.6	9.0±0.3
	603.4	56.3±1.2
	1353.3	34.6±0.8
1480.3	315.6	48.1±1.1
	1480.3	51.9±1.5
1557.3	204.0	5.1±0.1
	807.9	79.4±2.0
	1557.6	15.5±0.3
2312.4	1147.9	89.0±6.0
	2312.5	11.0±3.0
2379.6	822.3	12.3±1.5
	899.9	17.9±2.4
	1026.7	23.8±1.5
	1215.5	12.8±0.9
	2379.3	35.9±2.0
2703.6 [a])	1147.9	49.1±5.1
	1224.7	9.9±1.5
	1538.8	30.1±2.0
	2703.6	10.9±0.9

[a]) From (p, nγ) data at $E_p = 6.0$ MeV.

in table 4 lists five γ-rays that have been identified with transitions in ^{48}Ti from inelastic excitation.

TABLE 4

Summary of the observed γ-rays from background and from the ^{51}V(p, p$'\gamma$), ^{48}Ti(^{4}He, pγ) and ^{48}Ti(^{4}He, $\alpha'\gamma$) reactions

Background γ-rays E_γ (keV)		E_γ (keV) ^{51}V(p, p$'\gamma$) [a]		I_γ from ^{51}V(p, p$'\gamma$) [b]		E_γ (keV) ^{48}Ti(^{4}He, $\alpha'\gamma$)	
54		204.0	8	[c]		982.2	1
67.8	5	319.3	4	170	20	1312	1
74		603.4	4	[c]		1435.2	1
85.0	5	609.0	8	23	10	2415	2
108.3	8	807.9	1	[c]		2231	2
132.0	8	928.3	1	100			
138.4	7	1492.7	6	12	1		
158.1	7	1609.3	2	31	5		
171.7	10	1813.4	3	34	2		
198.0	8	2415.6	3	9.5	24		
204	1	2558.0	7	1.7	5		
360.1	7	2703.6	6	[c]			
374.4	4	2767.2	3	[c]			
417.8	3	3082.2	10	1.0	4		
439.8	3	3261.6	2	[c]			
536.5	7	3380.0	10	5.3	11		
558.0	4	3513.9	7	0.6	3		
563.0	2	3562.2	7	0.4	2		
596	2	3582.5	7	0.4	2		
618.7	6						
659.0	3						
743	2						
784	2						
802.8	5						
835.9	5						
843.2	6						
991.0	7						
1014.0	5						
1049.0	4						
1063.2	7						
1089.0	7						
1125.6	5						
1174.5	5						
1779	2						
2224	2						

[a]) Energies determined from the (p, p$'\gamma$) and (^{4}He, pγ) reactions.

[b]) Intensities obtained from the (p, p$'\gamma$) reaction at $E_p = 6.0$ MeV with the detector at 90° relative to the beam.

[c]) Gamma ray also assigned in the ^{51}Cr level scheme from the (p, nγ) reaction. The γ-peaks were not resolved and intensities could not be estimated. It is believed that only a small part of each γ-peak is associated with the (p, p$'\gamma$) reaction.

4. Construction of the ^{51}Cr and ^{51}V decay schemes

On the basis of the evidence obtained in this work it is found that a large majority of the γ-rays observed are associated with the decay of levels in ^{51}Cr. The proposed decay scheme for ^{51}Cr is shown in fig. 14 and the energy levels deduced from this work are compared with previous results in table 5. Column 1 in table 5 gives the level number, column 2 gives each level energy from this work obtained as weighted average of the sum of the energies of the γ-rays leaving that level, column 3 gives the level energies from ref. [8]), column 4 gives the difference of level energies from this work and ref. [8]) with a marked average difference of $\approx$ 5 keV, columns 5 and 6 give the l_n and J^π values from ref. [8]), and the last column gives the J^π assignments deduced from this work.

A tentative decay scheme for the levels in ^{51}V is also proposed and it is discussed below.

The arguments that lead to these assignments are summarized below.

4.1. LEVEL AND J^π ASSIGNMENTS IN ^{51}Cr

The total angular momentum of the ground state of ^{51}Cr has been measured by atomic beam methods [34]) and was found to be $\frac{7}{2}$. The parity of the ground state is negative as deduced from the $l_n = 3$ value for the orbital angular momentum of the transferred neutron in the (d, p) reaction as observed by Robertshaw *et al.* [8]).

4.1.1. *The levels at* 749.0 *and* 777.2 keV: These are the first two excited states in ^{51}Cr and from (d, p) reaction studies [8]) they are established to have $l_n = 1$ for the transferred orbital angular momentum by the neutron. These two states were observed by Bartholomew *et al.* [28]) to be directly populated in approximately equal intensity in the decay of the $\frac{1}{2}^+$ 9261 keV resonance state from the ^{50}Cr(n$_{th}$, γ) capture. On the basis of their angular correlation work, Bartholomew *et al.* [28]) have assigned the 749.0 and 777.2 keV levels as $\frac{3}{2}^-$ and $\frac{1}{2}^-$, respectively. The same authors find that the 777.2 level deexcites essentially via a 28.2 keV transition to the 749.0 and from their result on the 749.0 to the 777.2 keV intensity ratio we calculate the fraction of decay by a 777.2 keV transition to be $\leqq$ 0.006. In the present experiments we have observed two γ-rays at 749.0 and 775.4 keV which in the (p, nγ) reaction have effective thresholds (E_p+Q) at 0.95$\pm$0.05 and 2.5$\pm$0.2 MeV, respectively. The high effective threshold observed for the 775.4 keV γ-ray cannot be explained by a reduction in cross section due to centrifugal barrier effects in the ^{51}V(p, n) reaction, as the orbital angular momentum transferred is only 2 or 3 $\hbar$ units. A Hauser-Feshbach calculation for this level supports this argument [see also ref. [21])]. This indicates that the 775.4 keV γ-ray observed here depopulates a level at higher excitation. The population of the 777.2 keV level in the (p, n) reaction, at least indirectly, is established by the observed coincidence of the 575.6 keV γ-ray with the 204.0 and 749.0 keV γ-rays (fig. 11a). The latter coincidence proceeds via the unobserved 28.2 keV transition to the 749.0 keV level. These observations are now consistent with the observation by Bauer *et al.* [33]) of a delayed component with $t_{\frac{1}{2}}$ = 10.8 nsec for the 0.75 MeV γ-ray from the

TABLE 5

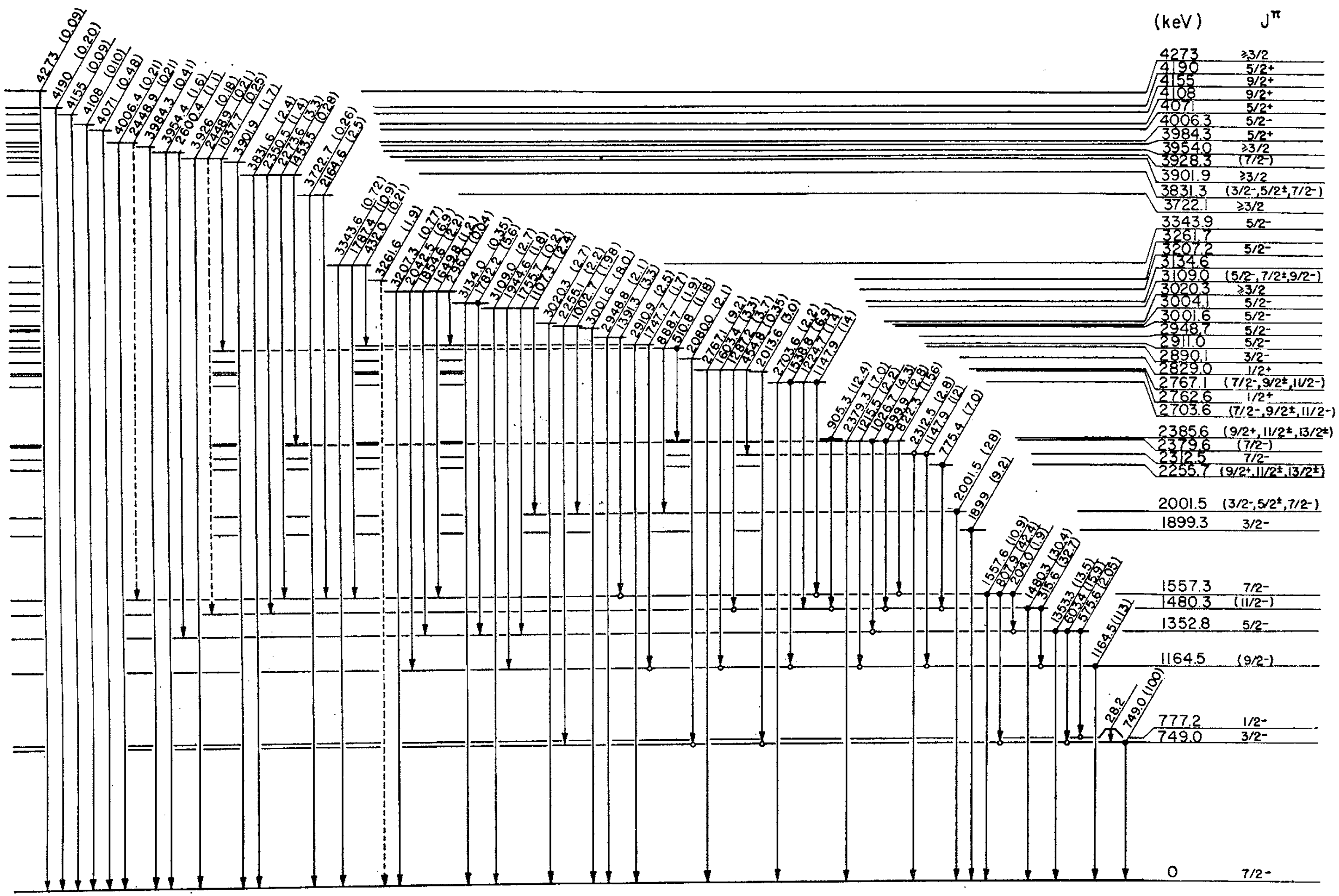
Summary of the levels in ^{51}Cr populated in the ^{48}Ti(^{4}He, nγ) and ^{51}V(p, nγ) reactions

Level no.	This work (keV)	(d, p) from ref. [8] (keV) [a]	Difference this work and ref. [8] (keV)	l_n ref. [8]	J^π assigned from J-dependence ref. [8]	J^π this work
0	0	0	0	3	$\frac{7}{2}^-$	$\frac{7}{2}^-$
1	749.0 *1*	748	+1.0	1	$\frac{3}{2}^-$	$\frac{3}{2}^-$
2	777.2 *2*	775	+2.2	1	$\frac{1}{2}^-$	$\frac{1}{2}^-$
3	1164.5 *1*	1159	+5.5	[b]		$(\frac{9}{2}^-)$
4	1352.8 *3*	1346	+6.8	3	$\frac{5}{2}^-$	$\frac{5}{2}^-$
5	1480.3 *2*	1476	+4.3	[b]		$(\frac{11}{2}^-)$
6	1557.3 *3*	1552	+5.3	3	$(\frac{5}{2}^-, \frac{7}{2}^-)$	$\frac{7}{2}^-$
7	1899.3 *3*	1895	+4.3	1	$\frac{3}{2}^-$	$\frac{3}{2}^-$
8	2001.5 *2*	1998	+3.5	[b]		$\frac{3}{2}^-, \frac{5}{2}^\pm, \frac{7}{2}^-$
9	2255.7 *2*					$\frac{9}{2}^+, \frac{11}{2}^\pm, \frac{13}{2}^\pm$
10	2312.5 *2*	2313	−0.6	(3)	$(\frac{5}{2}^-)$	$\frac{7}{2}^-$
11	2379.6 *2*	2382	−0.4	[b]		$(\frac{7}{2}^-)$
12	2385.6 *3*		+3.6	[b]		$\frac{9}{2}^+, \frac{11}{2}^\pm, \frac{13}{2}^\pm$
13	2703.6 *4*	2705	−1.4	[b]		$\frac{7}{2}^-, \frac{9}{2}^\pm, \frac{11}{2}^-$
14	2762.6 *5*	2761	+1.6	0	$\frac{1}{2}^+$	$\frac{1}{2}^+$
15	2767.1 *3*		+6.1			$\frac{7}{2}^-, \frac{9}{2}^\pm, \frac{11}{2}^-$
16	2829.0 *4*	2825	+4.0	0	$\frac{1}{2}^+$	$\frac{1}{2}^+$

17	2890.1	*3*	2887	+3.1	1	$\frac{3}{2}^-$	$\frac{3}{2}^-$
18	2911.0	*3*	2907	+4.0	3	$\frac{5}{2}^-$	$\frac{5}{2}^-$
19	2948.7	*2*	2946	+2.7	3	$\frac{5}{2}^-$	$\frac{5}{2}^-$
20	3001.6	*3*	} 2999	} +2.6	} 3	} $\frac{5}{2}^-$	$\frac{5}{2}^-$
21	3004.1	*3*		+5.1			$\frac{5}{2}^-$
22	3020.3	*2*	3016	+4.3			$\geqq\frac{3}{2}$
23	3109.0	*3*	3108	+1.0	[b]		$\frac{5}{2}^-, \frac{7}{2}^\pm, \frac{9}{2}^-$
24	3134.6	*4*	3124	+10.6			
25	3207.2	*4*	3204	+3.4	3	$\frac{5}{2}^-$	$\frac{5}{2}^-$
26	3261.7	*4*	3261	+0.7	[b]		
27	3343.9	*4*	3352	−8.1	3	$\frac{5}{2}^-$	$\frac{5}{2}^-$
28	3722.1	*8*	3719	+3.1	0	$\frac{1}{2}^+$	$\geqq\frac{3}{2}$
29	3831.3	*4*	3827	+4.3	[b]		$\frac{3}{2}^-, \frac{5}{2}^\pm, \frac{7}{2}^-$
30	3901.9	*3*	3897	+4.9			$\geqq\frac{3}{2}$
31	3928.3	*10*	3926	+2.3			$(\frac{7}{2}^-)$
32	3954.0	*5*	3947	+7.0			$\frac{3}{2}^-, \frac{5}{2}^\pm, \frac{7}{2}^\pm, \frac{9}{2}^-$
33	3984.3	*13*	3979	+5.3	2	$\frac{5}{2}^+$	$\frac{5}{2}^+$
34	4006.3	*6*	4000	+6.3	3	$\frac{5}{2}^-$	$\frac{5}{2}^-$
35	4071	*2*	4070	+1.0	2	$\frac{5}{2}^+$	$\frac{5}{2}^+$
36	4108	*2*	4099	+9.0	4	$\frac{9}{2}^+$	$\frac{9}{2}^+$
37	4155	*3*	4158	−3.0	4	$\frac{9}{2}^+$	$\frac{9}{2}^+$
38	4190	*3*	4192	−2.0	2	$\frac{5}{2}^+$	$\frac{5}{2}^+$
39	4273	*4*	4283	−10.0	0	$\frac{1}{2}^+$	$\geqq\frac{3}{2}$

[a]) For levels 0 through 32 estimated uncertainty ±8 keV and through 40 estimated uncertainty ±10 keV.

[b]) The proton angular distribution was measured but exhibited a pattern which is not characteristic of a stripping reaction.



$^{51}_{24}Cr_{27}$

Fig. 14. Proposed decay scheme for ^{51}Cr following excitation via the ^{51}V(p, nγ) reaction with $E_p = 2.9-6.0$ MeV and via the ^{48}Ti(^{4}He, nγ) reaction at $E_\alpha = 12.5$ MeV. The relative intensities given in parentheses were obtained in the ^{51}V(p, nγ) reaction at $E_p = 6.0$ MeV with the detector at 90° to the beam and they have not been corrected for correlation effects. The intensities obtained after correction due to correlation effects for levels up to 2703.6 keV were not drastically different as it is seen from the branching ratios of table 3. Open circles indicate observed $\gamma\gamma$ coincidence relationships and the closed circles indicate observed nγ coincidence relationships.

^{51}V(p, nγ) reaction at $E_p = 5.5$ MeV, which is attributed to the 28.2 keV M1 transition to the 749.0 keV level. Recent results on the decay of ^{51}Mn indicate [35]) that the 749.0 keV level is not populated substantially by an 807.9 keV transition, as such a γ-ray was not observed in the ^{51}Mn decay.

4.1.2. *The* 1164.5 keV *level.* This level was observed in the (d, p) reaction [8]), but the proton angular distribution showed a pattern which is not characteristic of a stripping reaction. The 1164.5 keV γ-ray was observed to have an effective threshold of 1.30 ± 0.15 MeV and it was seen in coincidence with neutron pulses both in the (^{4}He, nγ) and (p, nγ) reaction (figs. 5, 6). The 1164.5 keV level appears to decay exclusively to the ground state. This is substantiated by the fact that the 1164.5 keV γ-ray was observed in coincidence with the 315.6, 1147.9, 1538.8 and 1603.4 keV γ-rays (figs. 10c, 12c) and not with the 749.0 keV γ-ray (figs. 11a, b). Upper limits of 0.3 and 0.6 can be placed for the intensity of the 387.3 and 415.5 keV transitions to the 777.2 and 749.0 keV levels, respectively. This evidence together with the fact that no positive parity states are expected to lie low here favors a $\frac{9}{2}^-$ or $\frac{11}{2}^-$ assignment to this level. As is discussed below, however, two levels at 2911.0 and 3207.2 keV which have been assigned as $\frac{5}{2}^-$ were observed to populate this 1164.5 keV level. This information makes the $\frac{11}{2}^-$ value for this level very unlikely, leaving the $\frac{9}{2}^-$ value as the most probable one.

4.1.3. *The* 1352.8 keV *level.* This level has been assigned an $l_n = 3$ value from the (d, p) reaction [3, 5, 8]) and has also been reported to be populated in the ^{51}V(p, n) reaction [17, 21]). These findings are confirmed in this work by the observation of γ-rays at 575.6, 603.4 and 1353.3 keV with effective thresholds 1.60 ± 0.15, 1.6 ± 0.1 and 1.45 ± 0.10 MeV, respectively. These three γ-rays were seen in coincidence with neutrons from the (^{4}He, nγ) and (p, nγ) reactions (figs. 5, 6) and were assigned to deexcite the 1352.8 keV level. A small but undetermined fraction of the 603.4 keV peak intensity has been assigned to deexcite a level at 2415.6 keV in ^{51}V on the basis of energy difference and $\gamma\gamma$ coincidence information. This was substantiated also by the fact that the ground state transition from that level in ^{51}V is not observed below $E_p = 5.5$ MeV (compare figs. 8d and 4). The 1352.8 keV level in ^{51}Cr is further firmly confirmed by the observed strong coincidence of the 575.6 and 603.4 keV γ-rays with the 749.0 keV γ-ray (figs. 11a, b) at $E_p = 5.0$ MeV. Bartholomew *et al.* [28]) in their ^{50}Cr(n_{th}, γ) study reported the population of a level at 1361 keV via a 1532 keV transition from a level at 2893 keV. If this 1361 keV level is the same as the 1352.8 keV level observed in this work, then the latter mentioned authors fail to observe the strong 603.4 and 575.4 keV branches from that level. The rather strong 2376 keV γ-ray observed in a spectrum shown in ref. [28]) has a double escape peak at 1354 keV and such a peak which should be observed in fig. 2 of ref. [28]) has not been so labelled. Furthermore, if the 2893 keV level reported by Bartholomew *et al.* [28]) is the same as the 2890.1 keV from this work then we note that no 1532 keV transition is observed to deexcite this level. Alty *et al.* [4]) and Robertshaw *et al.* [8]) have assigned the 1352.8 keV level as $\frac{5}{2}^-$ on the basis of a *J*-dependence of the proton angular distribution.

The present γ-ray information supports this $\frac{5}{2}^-$ assignment over the alternative $\frac{7}{2}^-$ because the 1352.8 keV level was observed to populate the $\frac{1}{2}^-$ level at 777.2 keV via the 575.6 keV transition.

4.1.4. *The* 1480.3 keV *level.* This level has been observed in the (d, p) reaction [8]) and in the (p, d) reaction [13]) but like the 1164.5 keV level the observed proton angular distribution pattern is not characteristic of a stripping reaction. Two γ-rays at 315.6 and 1480.3 keV have been observed in this study to have effective thresholds of 1.50 ± 0.05 and 1.6 ± 0.1 MeV, respectively. These γ-rays were also observed in coincidence with neutrons from both the (^{4}He, nγ) and (p, nγ) reactions (figs. 5, 6) and have been assigned to deexcite the 1480.3 keV level. This is also confirmed by the observed coincidence of the 315.6 keV γ-ray with the 1164.5 keV γ-ray, but not the 749.0 keV γ-ray. No other γ-ray deexciting this level was observed. The exclusive decay of this level to the $\frac{7}{2}^-$ ground state and the $\frac{9}{2}^-$ level at 1164.5 keV is in disagreement with the decay to the ground and the 1352.8 keV level proposed by Lobkowicz *et al.* [19]). The mode of decay of this 1480.3 keV level is indicative of a high J^π value of $\frac{9}{2}^-$ or $\frac{11}{2}^-$ for this level. A lower than $\frac{9}{2}^-$ value would have resulted in a 731.3 keV transition to the $\frac{3}{2}^-$ 749.0 keV level to be observed. An upper limit of 0.005 for a branching by a 731.3 keV γ-ray can be placed from the present data. A definite choice between the $\frac{9}{2}^-$ and $\frac{11}{2}^-$ values is difficult with the present evidence. Two arguments, however, in favor of the $\frac{11}{2}^-$ value can be given. Firstly, as is discussed below, numerous levels at higher excitation have been assigned as $\frac{5}{2}^-$ and none of these was observed to decay to this 1480.3 keV level; this is to be contrasted with the $\frac{9}{2}^-$ state at 1164.5 keV which is strongly populated by two such levels. Secondly, the branching ratios for the 315.6 and 1480.3 keV transitions were calculated using single proton estimates with the result (M1, 316)/(E2, 1480) = 4.1 or (M1, 316)/(M1, 1480) = 9.7×10^{-3}; these should be compared with the experimental value of 0.93 ± 0.05 obtained from table 3. This result favors an $\frac{11}{2}^-$ assignment to the 1480.3 keV level, which requires an E2 transition to the ground state.

4.1.5. *The* 1557.3 keV *level.* This level has been observed in the (d, p) reaction [4,8]) to have an $l_n = 3$. Alty *et al.* [4]) have assigned this level as $\frac{7}{2}^-$ on the basis of *J*-dependence in the proton angular distribution. Whitten and McIntyre [13]), however, suggested a $\frac{5}{2}^-$ value on the basis of their (p, d) study. This level has been also reported to be populated in the (p, n) reaction [19,20]). Lobkowicz and Marmier [19]) have assigned this 1557.3 keV level to deexcite to the 1352.8 and 749.0 keV levels and possibly to the ground state. In the present experiments three γ-rays at 204.0, 807.9 and 1557.6 keV were observed to have effective thresholds of 1.6 ± 0.1, 1.55 ± 0.10 and 1.70 ± 0.15 MeV, respectively. These three γ-rays were observed in coincidence with neutron pulses from the (^{4}He, nγ) and (p, nγ) reactions (figs. 5, 6), and were assigned to deexcite a level at 1557.3 keV. Furthermore, the 204.0 and 807.9 keV γ-rays were observed in strong coincidence with the 1353.3 and 749.0 keV γ-rays, respectively (figs. 10a, 13a and 11a). A small fraction of the 204.0 keV γ-ray appears to deexcite a level at 1813.4 keV in ^{51}V and this is supported by an observed weak coincidence of the 204.0 keV peak with the 1609 keV γ-ray (fig. 13b). A very weak γ-ray at 783.0 keV was observed with an effective threshold of 1.5 ± 0.2 MeV and could be a candidate for a transition to the 777.2 keV level. However, a γ-ray of this energy was observed in the background at lower bombarding energies and this makes the assignment uncertain. The present γ-ray information is sufficient to assign this 1557.3 keV level as $\frac{7}{2}^-$, since it is observed to decay only to the $(\frac{5}{2}^-)$ 1352.8 and $(\frac{3}{2}^-)$ 749.0 keV levels and to the $\frac{7}{2}^-$ ground state but not to the $(\frac{1}{2}^-)$ 777.2 keV level.

4.1.6. *The* 1899.3 keV *level*. This level has been observed in (d, p) studies [4,8] to have $l_n = 1$. As is discussed by Robertshaw *et al.* [8]) this level was assigned on the basis of J-dependence as $\frac{3}{2}^-$ by Lee and Schiffer [6]) for $E_d = 10$ MeV and as $\frac{1}{2}^-$ by Alty *et al.* [4]) for $E_d = 9.15$ MeV. The angular correlation work of Bartholomew *et al.* [28]) has unambiguously assigned this level as $\frac{3}{2}^-$. In this present study we find that only one γ-ray at 1899.3 keV with an effective threshold of 2.0 ± 0.2 MeV deexcites this level. A γ-ray at 1149 keV which was reported by Bartholomew *et al.* [28]) to deexcite this 1849.3 keV level is not observed here. A doublet at 1148 keV was observed in our spectra obtained at $E_p = 4.5$ MeV but not at $E_p = 4.0$ MeV (see figs. 8b, c), while the 1899.3 keV γ-ray is observed at $E_p = 4.0$ MeV. This assignment is further substantiated by the fact that both the 1147.9 and 1899.3 keV γ-rays were observed in coincidence with neutrons in the (^{4}He, nγ) reaction (fig. 5). However, when the lower level discriminator is raised to discriminate against neutrons below 1.3 MeV the 1148 keV doublet is not observed in the coincidence spectrum, while the 1899.3 keV γ-rays remains in coincidence (fig. 6). No other γ-ray was observed that could deexcite this level. The strong decay of this 1899.3 keV level to the $\frac{7}{2}^-$ ground state excludes the $\frac{1}{2}^-$ as a possibility in agreement with the previous conclusion [28]).

4.1.7. *The* 2001.5 keV *level*. This level has been observed in the (d, p) reaction [8]) but its angular distribution is not characteristic of a stripping reaction. This level was also reported in the (p, d) reaction [13]) but no l_n value was reported. In the present study we find a γ-ray at 2001.5 keV with an effective threshold of 2.1 ± 0.1 MeV. This γ-ray was also seen in coincidence with the neutron pulses (figs. 5, 6). No other γ-ray was observed in this work that could deexcite this 2001.5 keV level. This level, however, is strongly populated in the decay of the $\frac{3}{2}^-$ level at 2890.1 keV. This information allows us to limit the J^π value of this level to $\frac{3}{2}^-$, $\frac{5}{2}^\pm$ or $\frac{7}{2}^-$.

4.1.8. *The* 2312.5 keV *level*. From the (d, p) and (p, d) reaction work [4,8,13]) this level has been assigned to have $l_n = 3$. In the present work two γ-rays at 1147.9 and 2312.5 keV were observed with effective thresholds of 2.5 ± 0.2 and 2.4 ± 0.2 MeV, respectively. Both these γ-rays were observed in coincidence with neutrons from the (^{4}He, nγ) reaction (see also discussion on the level at 1899.3 keV). The 1147.9 keV γ-ray was observed in coincidence with the 1164.5 keV γ-ray (fig. 12c). A γ-ray at 1147.5 ± 1.0 keV is observed in coincidence with the 807.9 and 1557.6 keV γ-rays (figs. 11b, 11c and 13b) thus indicating that the peak at 1147.9 keV is an unresolved doublet. The intensity of the 1147.9 keV γ-ray deexciting the 2312.5 keV level given in table 1 was estimated from the coincidence spectrum shown in fig. 12c where the intensity of the 1147.9 keV peak is measured relative to the 315.6 keV peak and compared to the intensity of these peaks in the singles spectrum. The fact that this level decays only to the $\frac{9}{2}^-$ 1164.5 keV level and the $\frac{7}{2}^-$ ground state with a branching ratio of 8.1 ± 2.5 (see table 3) helps eliminate the $\frac{5}{2}^-$ possibility. A $\frac{5}{2}^-$ value for the 2312.5 keV level would require an E2 character for the 1147.9 keV transition and this gives from single proton estimates (E2, 1148)/(E2, 2313) = 3.0×10^{-2} or (E2, 1148)/(M1, 2313) = 1.7×10^{-4}, values that differ from experiment by at least three orders of magnitude.

4.1.9. *The levels at* 2255.7 *and* 2385.6 keV. These two levels have not been reported earlier. The two γ-rays at 775.4 and 905.3 keV have been observed in this work to have an effective threshold of 2.5 ± 0.2. Both of these γ-rays were observed in coincidence with neutrons from the (^{4}He, nγ) reaction (fig. 5), but in the coincidence spectrum with neutrons from the (p, nγ) reaction at 5.0 MeV they were not seen in coincidence with neutrons of kinetic energy > 1.3 MeV. Both of these γ-rays were further observed in strong coincidence with the 315.6 and 1480.3 keV γ-rays (figs. 10c and 13a). This evidence unambiguously establishes levels at 2255.7 and 2385.6 keV. Since these two levels were observed to decay only to the $\frac{11}{2}^-$ level at 1480.3 keV and they are not populated in the decay of any of the higher lying levels, their J-value is limited to $> \frac{7}{2}$. Since these levels are substantially populated in both the (^{4}He, nγ) and (p, nγ) reactions, a $\frac{7}{2}^-$ or $\frac{9}{2}^-$ assignment for either of these levels should have resulted in an observable decay at least to the $\frac{7}{2}^-$ ground state. An upper limit of 0.04 for the branching to the ground state from each of these two levels can be placed from the present data, and this makes the $\frac{7}{2}^-$ or $\frac{9}{2}^-$ values unlikely for these levels thus leaving $\frac{9}{2}^+$, $\frac{11}{2}^\pm$ or $\frac{13}{2}^\pm$ as possibilities.

4.1.10. *The* 2379.5 keV *level.* This level has also been observed in the (d, p) reaction [8]) but with no stripping pattern. The γ-rays at 822.3, 899.9, 1026.7, 1215.5 and 2379.3 keV have effective thresholds between 2.5–2.6 MeV in the (p, nγ) reaction and were assigned to deexcite this level. Most of these γ-rays are weak and consequently only the 1026.7 and possibly the 899.9 keV γ-rays were observed in coincidence with the neutrons from the (^{4}He, nγ) reaction. This level is, however, firmly established by the observed coincidences of the 822.3, 899.9, 1026.7 and 1215.5 keV γ-rays with the 807.9, 1480.3, 603.4 and 1164.5 keV γ-rays, respectively (figs. 11b, c, 13a, 12a, b, c). This level decays to populate states below with J^π values ranging from $\frac{5}{2}^-$ to $\frac{11}{2}^-$. This information is sufficient to limit the most probable value of J^π to $\frac{7}{2}^-$ or $\frac{9}{2}^-$ for this level. Furthermore, the $\frac{5}{2}^-$ level at 2890.1 keV decays to this level thus limiting the most probable J^π value to $\frac{7}{2}^-$.

4.1.11. *The* 2703.6 keV *level.* This level was reported in the (d, p) reaction studies [3,8]) but no l_n value was assigned. From the present experiments γ-rays at 1147.9, 1224.7, 1538.8 and 2703.6 keV were assigned to deexcite this level. Of these γ-rays the latter three have effective thresholds at 2.8 ± 0.2, 2.8 ± 0.2 and 2.9 ± 0.4, respectively. The 1538.8 keV γ-ray was observed in coincidence with neutron pulses from the (^{4}He, nγ) reaction (fig. 5) and with the 1164.5 keV γ-ray (figs. 12c, d). The observation that the 1147.9 keV peak is a doublet was discussed in connection with the 2312.4 keV level assignment. These results firmly establish the 2703.6 keV level and indicate that it decays to levels below which have been assigned J^π values greater than or equal to $\frac{7}{2}^-$. This information suggests $\frac{7}{2}^-$, $\frac{9}{2}^\pm$ or $\frac{11}{2}^-$ as the most probable assignment for this level.

4.1.12. *The levels at* 2762.6 *and* 2767.1 keV. A level near these energies was was reported in the (d, p) reaction studies [3,8,10]) and the (p, d) and (^{3}He, α) reaction studies [9,10,12,15]) and it was assigned as $\frac{1}{2}^+$. It should be pointed out that the proton angular distribution from the (d, p) reaction [8]) exhibits indeed the characteristic $l_n = 0$ peaking at 0° but also shows substantial cross section at the backward angles in a pattern reminiscent of the non-stripping reactions observed for many other high spin states. A γ-ray at 2013.6 keV is observed in the (p, nγ) reaction with an effective threshold of 3.2$\pm$0.4 MeV. This γ-ray was observed in coincidence only with the 749.0 keV γ-ray (figs. 11a, b). This information establishes a level at 2762.6 keV which should be identified with the $\frac{1}{2}^+$ 2761 keV level from the (d, p) work [8]). No other γ-ray that could deexcite this level was observed and this is consistent with the $\frac{1}{2}^+$ assignment as it would require an E1 transition to the $\frac{3}{2}^-$ 749.0 keV level.

A second level only 4.5 keV higher is observed to be populated substantially in the (^{4}He, nγ) and (p, nγ) reactions. The following four γ-rays at 454.8, 1287.2, 1603.4 and 2767.1 keV have been observed with effective thresholds of 3.0$\pm$0.5, 2.8$\pm$0.2, 2.75$\pm$0.15 and 2.9$\pm$0.3 MeV, respectively. These γ-rays were rather weak to be observed in coincidence with neutrons. However, the 1287.2 and the 1603.4 keV γ-rays were observed in coincidence with the 315.6, 1480.3 and the 1164.5 keV γ-rays, respectively (figs. 10c, 13b and 12c). This information firmly establishes the 2767.1 keV level. The fact that this level decays only to levels with J^π values of $\frac{7}{2}^-$, $\frac{9}{2}^-$ and $\frac{11}{2}^-$ below is used to limit its J^π assignment to $\frac{7}{2}^-$, $\frac{9}{2}^\pm$ or $\frac{11}{2}^-$.

4.1.13. *The* 2829.0 keV *level.* This level was reported from the (d, p) study [8]) to have $l_n = 0$ which would require a J^π value of $\frac{1}{2}^+$ for this level. The rather weak γ-ray at 2080.0 keV was observed in coincidence only with the 749.0 keV γ-ray and this is consistent with an E1 transition to the $\frac{3}{2}^-$ state at 749.0 keV.

4.1.14. *The* 2890.1 keV *level.* A level at this energy has been observed with an $l_n = 1$ in the (d, p) reaction [8]). The two γ-rays at 510.8 and 888.7 keV have effective thresholds 3.5$\pm$0.2 and >3.0 MeV, respectively. The 510.8 keV γ-ray was observed in prompt coincidence with neutrons from the (^{4}He, nγ) reaction and this makes it unlikely to be due to annihilation radiation. By energy difference we have assigned these two γ-rays to deexcite the 2890.1 keV level and populate the ($\frac{7}{2}^-$, $\frac{9}{2}^-$) level at 2379.6 keV and the 2001.5 keV level. If this assignment is indeed correct then the observed decay to the 2379.6 keV level can be used to assign the 2890.1 keV level as $\frac{5}{2}^-$ and limit the J^π value for the 2379.6 keV level to $\frac{7}{2}^-$ only.

4.1.15. *The levels at* 2911.0, 2948.7, 3001.6, 3004.1, 3207.2, 3343.9 *and* 4006.3 keV.

Levels at these energies have been observed in the (d, p) reaction and they have been assigned as ($\frac{5}{2}^-$) by Robertshaw *et al.* [8]) on the basis of the *J*-dependence of the observed $l_n = 3$ proton angular distribution. Of these levels, the first two are established on the basis of (i) observed coincidences of the 1164.5 keV γ-ray with possibly the 1747.7 keV γ-ray (fig. 13c) and of the 1391.3 keV γ-ray with the 807.9 and 749.0 keV γ-rays (figs. 11a, b), and (ii) observed cross-over transitions to the ground state.

The three γ-rays at 1002.7, 2255.1 and 3001.6 keV have effective thresholds in the (p, nγ) reaction at 3.3 ± 0.3, 3.4 ± 0.3 and 3.2 ± 0.3 MeV, respectively. This evidence suggests that the 2999 ± 8 keV level observed in the (d, p) reaction is a doublet consisting of two levels at 3001.6 and 3004.1 keV. These two levels decay to the ground state and to the 749.0 and 2001.5 keV levels, respectively. This information is consistent with the $l_n = 3$ character of this "doublet" and possibly $\frac{5}{2}^-$, as assignments.

A level at 3207.2 keV is firmly established by the fact that: (i) the γ-rays at 1649.8, 1854.6, 2042.5 and 3207.3 keV have observed effective (p, nγ) thresholds at 3.4 ± 0.3, 3.0 ± 0.3, 3.2 ± 0.2 and 3.4 ± 0.4 MeV, respectively; (ii) these four γ-rays and the 296.0 keV γ-ray can be assigned with good energy agreement to populate the levels at 1557.3, 1352.8, 1164.5 keV, the ground state and the level at 2911.0 keV, respectively.

The level at 3343.9 keV is established by the fact that: (i) the γ-rays at 1787.4 and 3343.6 keV have effective (p, nγ) thresholds at 3.2 ± 0.3 and 3.5 ± 0.4 MeV, respectively; (ii) the 1787.4 keV γ-ray was observed in coincidence with neutrons from the (^{4}He, nγ) reaction; and (iii) the 432.0, 1787.4 and 3343.6 keV γ-rays can be assigned by good energy agreement to populate the levels at 2911.0, 1557.3 keV and the ground state, respectively.

The 4006.3 keV level is established from the fact that the 4006.4 keV γ-ray was observed in the (p, nγ) reaction at $E_p = 6.0$ MeV. At this bombarding energy the 4006.4 keV γ-ray can only populate the ground state, as the maximum excitation energy in ^{51}Cr that can be reached with $E_p = 6.0$ MeV is only 4290 keV. The weak γ-ray at 2448.9 keV could by energy agreement be assigned to deexcite the 4006.3 or the 3928.3 keV levels in ^{51}Cr or even a 2767.2 keV level in ^{51}V.

Of these seven levels that have been assigned [8]) as ($\frac{5}{2}^-$) the 2948.7, 3001.6, 3004.6, 3343.9 and 4006.3 keV levels populate $\frac{3}{2}^-$, $\frac{5}{2}^-$ or $\frac{7}{2}^-$ levels below and this observation is consistent with the $\frac{5}{2}^-$ assignment to these levels. As we mentioned earlier the 1557.3 keV level is $\frac{7}{2}^-$ as this now indicates that the total occupancy strength for the $1f_{\frac{7}{2}}$ orbital measured in the (d, p) reaction [8]) is divided between the ground state $\frac{7}{2}^-$ and this 1557.3 keV state. This argument strongly suggests that the other $l_n = 3$ levels in ^{51}Cr are indeed [8]) $\frac{5}{2}^-$. The levels of this type at 2911.0 and 3207.2 keV are observed to populate the ($\frac{9}{2}$ or $\frac{11}{2}^-$) level at 1174.5 keV as well as other $\frac{5}{2}^-$ and $\frac{7}{2}^-$ levels below. This evidence now favors strongly the $\frac{9}{2}^-$ value as the most probable one for the 1164.5 keV level.

4.1.16. *The* 3020.3 keV *level.* This level was observed in the (d, p) reaction [8]) but no l_n value was assigned. Here a 3020.3 keV γ-ray with an effective (p, nγ) threshold of 3.2±0.3 MeV was observed and it is the only γ-ray seen to deexcite this level. The very broad limits $(\frac{3}{2}–\frac{11}{2})^-$ or $(\frac{5}{2}–\frac{9}{2})^+$ for J^π can be placed for this level.

4.1.17. *The* 3109.0 keV *level.* This level was observed in the (d, p) reaction [3,8] but a non-stripping pattern for the proton angular distribution was reported [8]. Four γ-rays at 1107.3, 1755.7, 1944.6 and 3109.0 keV have been observed in the (p, nγ) reaction with effective thresholds at 3.2±0.3, 3.0±0.3, 3.4±0.4 and 3.4±0.4 MeV, respectively. This information and the good energy agreement for the population of levels at 2001.5, 1352.8, 1164.5 keV and the ground state by the above four γ-rays establish the level at 3109.0 keV firmly. Since this level decays to levels with J^π of $\frac{5}{2}^-$, $\frac{7}{2}^-$ and $\frac{9}{2}^-$ below, its J^π value can be limited to $\frac{5}{2}^-$, $\frac{7}{2}^\pm$ or $\frac{9}{2}^-$.

4.1.18. *Possible levels at* 3134.6 *and* 3261.7 keV. Levels at these energies were reported in the (d, p) reaction [3,5,8] but with no l_n assignment. In the present study the γ-rays at 1782.2, 3134.0 and 3261.6 keV were observed with effective (p, nγ) thresholds of 3.2±0.3, 3.8±0.5 and 3.4±0.4 MeV, respectively. The 1782.2 keV γ-ray was also seen in coincidence with neutrons from the (^{4}He, nγ) reaction (fig. 5). This information suggests that these two levels are populated in the (p, nγ) and (^{4}He, nγ) reactions. However, the 1782.2 keV γ-ray by energy difference could be assigned to deexcite either of these two levels. Furthermore, the 3261.7 keV γ-ray could be assigned to deexcite a level at this energy in ^{51}V. In view of these uncertainties we have tentatively assigned the population of the 3261.7 keV level in ^{51}Cr and have indicated the transition to the ground state by a dashed arrow in fig. 14.

4.1.19. *The levels at* 3722.1, 3831.3, 3928.3 *and* 3954.0 keV. These four levels have been observed in the (d, p) reaction [8]. Four γ-rays at 3722.7, 3831.6, 3926 and 3954.4 keV were observed in the (p, nγ) reaction at E_p = 6.0 MeV. For this bombardment energy these γ-rays have sufficiently high enough energy that they can only populate the ground state. Additional γ-rays at 2164.6, 1453.5, 2273.6, 2350.5, 1037.7 and 2448.9 keV have been observed with effective thresholds higher than 3.7 MeV and these have been assigned by energy difference to deexcite these levels as shown in fig. 14. The 2448.9 keV γ-ray can be accommodated to deexcite the 3928.3 or the 4006.3 keV level with good energy agreement and this is indicated in fig. 14 by the dashed arrows.

The 3722.1 keV level has been assigned [8] an l_n = 0. It should be pointed out that this level was only weakly excited in the (d, p) reaction [8] and the l_n = 0 assignment cannot be made with certainty. From this work it was seen that this 3722.1 keV level populates the $\frac{7}{2}^-$ ground and 1557.3 keV levels indicating a J^π value of $\frac{3}{2}^-$, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, $\frac{9}{2}^\pm$ or $\frac{11}{2}^-$ but not $\frac{1}{2}^+$.

The level at 3831.3 keV deexcites to populate levels below with J^π ranging from $\frac{3}{2}^-$ to $\frac{7}{2}^-$. This evidence is sufficient to limit the J^π value for this level to $\frac{3}{2}^-$, $\frac{5}{2}^\pm$ or $\frac{7}{2}^-$.

The 3928.3 keV level in addition to the ground state appears to populate the $\frac{3}{2}^-$ level at 2890.1 keV and conceivably the $\frac{11}{2}^-$ level at 1480.3 keV. If this is indeed the case then its J^π value can be limited to $(\frac{7}{2}^-)$.

The 3954.0 keV level has been observed to populate the ground and the $\frac{5}{2}^-$ 1352.8 keV level. This limits its J^π value to $\frac{3}{2}^-$, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$ or $\frac{9}{2}^-$.

4.1.20. *The levels at* 3901.9, 3984.3, 4071, 4108, 4155, 4190 *and* 4273 keV. These levels have been previously seen in the (d, p) reaction [8]. Here γ-rays at these energies have been observed in the (p, nγ) reaction at E_p = 6.0 MeV, and are of high enough energy that they can populate only the ground state. No other γ-ray that could de-excite any of these levels was observed.

The levels at 3984.3, 4071 and 4190 keV were observed to have l_n = 2 and were assigned as $\frac{5}{2}^+$ by Robertshaw *et al.* [8]). These three levels were observed to decay

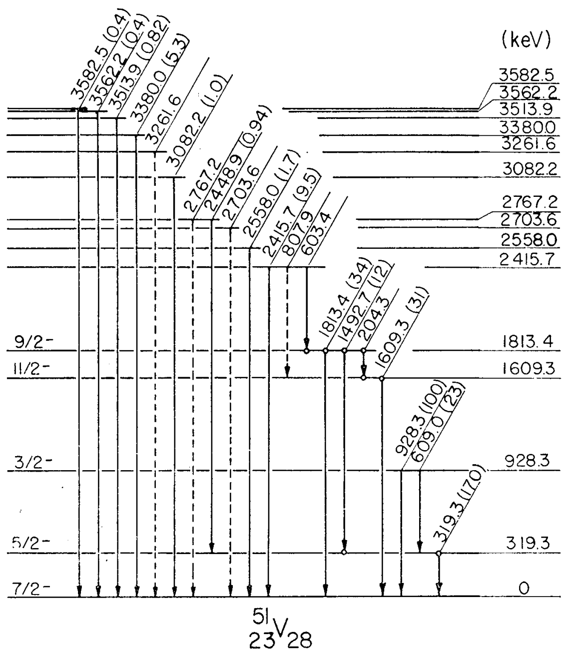


Fig. 15. Proposed decay scheme for ^{51}V following excitation via the ^{51}V(p, p'γ) reaction with E_p = 2.9–6.0 MeV and via the ^{48}Ti(^{4}He, pγ) reaction at E_α = 12.5 MeV. The relative intensities given in parentheses are only estimates obtained from the ^{51}V(p, p'γ) reaction at E_p = 6.0 MeV with the detector at 90° to the beam. The large number of γ-rays from the ^{51}V(p, nγ) reaction prevents the characterization of many γ-rays expected to deexcite known levels in ^{51}V. The open circles indicate some evidence for $\gamma\gamma$ coincidence relationships.

to the $\frac{7}{2}^-$ ground state which is in agreement with the $\frac{5}{2}^+$ assignment and excludes the $\frac{3}{2}^+$ as a possibility.

The levels at 4108 and 4155 keV have been observed by Robertshaw *et al.* [8]) to have l_n = 4 and were assigned as $\frac{9}{2}^+$. These levels were observed to decay to the $\frac{7}{2}^-$ ground state, which is consistent with the $\frac{9}{2}^+$ assignment but this evidence is not sufficient to exclude the $\frac{7}{2}^+$ as a possibility.

The level at 3901.9 keV was observed to decay only to the $\frac{7}{2}^-$ ground state and its J^π value can be limited to $\frac{3}{2}^-$, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, $\frac{9}{2}^\pm$ or $\frac{11}{2}^-$.

Finally, a level at 4283 keV was assigned by Robertshaw *et al.* [8]) an $l_n = 0$, although the fit of the $l_n = 0$ DWBA distribution to the data was rather poor. If this level is the same as the 4273 keV level observed in the (p, nγ) reaction, then its J^π value can be limited to $\frac{3}{2}^-$, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, $\frac{9}{2}^\pm$ or $\frac{11}{2}^-$ as it decays to the $\frac{7}{2}^-$ ground state, and this disagrees with the $l_n = 0$ assignment [8]).

4.2. LEVEL AND J^π ASSIGNMENTS IN ^{51}V

The level structure of ^{51}V has been recently investigated via inelastic proton scattering at $E_p = 6.0$, 7.0 and 7.4 MeV by Buechner *et al.* [36]) and at $E_p = 6.51$ MeV by Mazari *et al.* [37]). In the latter experiments Mazari *et al.* [37]) reported 35 levels up to 4122 keV in excitation in ^{51}V. More recently Barrows *et al.* [38]) studied the levels in ^{51}V by means of the (n, n$'\gamma$) reaction at $E_n = 1.0$–3.1 MeV, and DeLopez *et al.* [39]) have investigated the ^{50}V(d, p)^{51}V reaction at $E_d = 6.5$ MeV and reported 86 levels up to 6648 keV of excitation.

In the present experiments relatively few γ-rays were observed from the (p, p$'\gamma$) reaction because of the large cross section from the competing (p, nγ) reaction. The present γ-ray information was used in conjunction with previous knowledge on the level structure from the particle work to construct a tentative decay scheme which is shown in fig. 15. The arguments for this decay scheme are summarized below.

The ground state of ^{51}V has an angular momentum of $\frac{7}{2}$ as determined by atomic beam experiments [34]) and its parity is negative as it is populated by an $l_n = 3$ transfer in the (d, p) reaction [39]).

4.2.1. *The* 319.3 keV *level.* This first excited state in ^{51}V is well established from the (p, p$'$) work [36,37]) and from the (d, p) study [39]) where it is seen with an $l_n = 3$ and with no doubt it is $\frac{5}{2}^-$. In the present experiments its excitation by (p, p$'\gamma$) at $E_p = 2.1$–6.0 MeV was evidenced by the observed 319.3 keV γ-ray.

4.2.2. *The* 928.3 keV *level.* This level is also well established by the (p, p$'$) and (d, p) studies [37–39]) and it has been assigned [39]) as $\frac{3}{2}^-$. This level was reported to deexcite via γ-transitions at 610 and 930 keV to the 319.3 keV and ground state. This observation is confirmed from the present experiments. The two γ-rays at 609 and 928.3 keV were assigned to deexcite this level. A good measurement of the energy and intensity of the 609 keV γ-ray is prevented by the strong 603.4 keV γ-ray which appears at approximately the same proton bombarding energy. The 928.3 keV γ-ray was also observed in the ^{48}Ti(^{4}He, pγ)^{51}V reaction and it was not seen in coincidence with neutrons.

4.2.3. *The* 1609.3 keV *level.* This level is well established from the (p, p$'$) and (d, p) reaction work [37–39]). The (d, p) reaction study shows $l_n = 1$ for this level which is found to decay exclusively to the $\frac{7}{2}^-$ ground state, and this is consistent with an $\frac{11}{2}^-$ assignment [see also ref. [39])]. The 1609.3 keV γ-ray appeared both in the ^{51}V(p, p$'\gamma$) and ^{48}Ti(^{4}He, pγ) reactions and it was not seen in coincidence with the neutrons (figs. 5 and 6).

4.2.4. *The* 1813.4 keV *level.* This level was observed in the (p, p$'$) and (d, p) reactions [37-39]) and in the $^{50}V(n_{th}, \gamma)$ study of Schwager [40]) who reported a 1490 keV γ-ray in coincidence with the 320 keV γ-ray. This information is confirmed here from the observed coincidence of the 1492.7 keV γ-ray with the 275–325 keV window of the NaI detector from the (p, p'γ) reaction at $E_p = 5.0$ MeV (fig. 10c). A weak coincidence at 204 keV was also observed in the 1590–1690 keV window in the NaI(Tl) detector (fig. 13b) and this suggests that this level deexcites also by a weak 204 keV γ-ray to populate the 1609.3 keV level. This mode of decay is consistent with the $\frac{9}{2}^-$ assignment for this level [39,40]).

4.2.5. *The* 2415.7 keV *level*. This level has been observed both in the (p, p') and (d, p) reaction studies [37-39]) but no l_n value was reported. A rather weak γ-ray at 2415.7 keV has been observed both in the (p, p'γ) reaction at $E_p = 6.0$ MeV and in the (^{4}He, pγ) reaction at $E = 12.5$ MeV. Two additional γ-rays at 603.4 and 807.9 keV that could deexcite this level coincide in energy with such transitions assigned in ^{51}Cr. A weak coincidence of a 603 keV γ-ray was observed in the 1490–1690 and 1690–1890 keV windows in NaI(Tl) indicating that a small but undetermined fraction of the 603.4 keV γ-peaks populates the 1813.4 keV level in ^{51}V. The decay properties of this level suggest a J^π assignment of $\frac{5}{2}^-, \frac{7}{2}^-, \frac{9}{2}^-$ or $\frac{11}{2}^-$.

4.2.6. *The levels at* 2558.0, 3082.2, 3380.0, 3513.9, 3562.2 *and* 3582.5 keV. Levels at these energies were observed in the (p, p') reaction [37,38]). In the present work γ-rays at these energies were observed at $E_p = 6.0$ MeV. As no such levels have been observed in ^{51}Cr we have assigned tentatively these transitions to populate the ground state in ^{51}V. No other γ-rays that could deexcite these levels were observed.

4.2.7. *Tentative levels at* 2703.6, 2767.2 *and* 3261.6 keV. Levels at approximately these energies were reported [8,37,38]) in ^{51}Cr and in ^{51}V and this makes the assignment of at least the weakest of these transitions uncertain. The 2703.6 and 2767.2 keV γ-rays have been assigned to deexcite primarily the well established levels at these energies in ^{51}Cr, although a fraction of their intensity could be attributed to ^{51}V. The 3261.6 keV γ-ray is too weak for a certain assignment in either the ^{51}Cr or ^{51}V in view of the fact that no additional supporting transitions that could deexcite this 3261.6 keV level in ^{51}Cr or in ^{51}V were observed. The 2448.9 keV γ-ray could on energy agreement deexcite the 2767.2 keV level in ^{51}V but also two other levels at 3928.3 and 4006.3 keV in ^{51}Cr.

5. Comparison with nuclear models

The $^{51}_{24}Cr_{27}$ nucleus in the framework of the simple spherical shell model is described by neutrons and protons in an $(f_{\frac{7}{2}})^n$ configuration outside an inert $^{40}_{20}Ca_{20}$ core (for example $[^{40}Ca+\pi(f_{\frac{7}{2}})^4_{J_1}\,\nu(f_{\frac{7}{2}})^6_{J_2}]_J$). Recently McCullen, Bayman and Zamick [30]) (hereafter abbreviated MBZ) have performed extensive shell-model calculations for nuclei filling the $1f_{\frac{7}{2}}$ shell in which they have considered the possible coupling of $\pi(f_{\frac{7}{2}})^n$ protons and $\nu(f_{\frac{7}{2}})^m$ neutrons under the two-body residual interactions extracted from the energy spectra of the $^{42}_{20}Ca_{22}$, $^{50}_{22}Ti_{28}$ and $^{42}_{21}Sc_{21}$ nuclei. The MBZ treatment successfully accounted for the level structure of many $1f_{\frac{7}{2}}$ nuclei, including ^{51}V. There are, however, a few cases of apparent disagreement of the calculated spectrum with experiment and these include ^{51}Cr. As was also pointed out by McCullen *et al.* [30]) and by Robertshaw *et al.* [8]) the low-lying doublet ($\frac{3}{2}^-$) and ($\frac{1}{2}^-$) at 749.0 and 777.2 keV is not reproduced by the MBZ calculation and has been attributed by these authors to $p_{\frac{3}{2}}$ mixing. From this work we have assigned more definite J^π values to a number

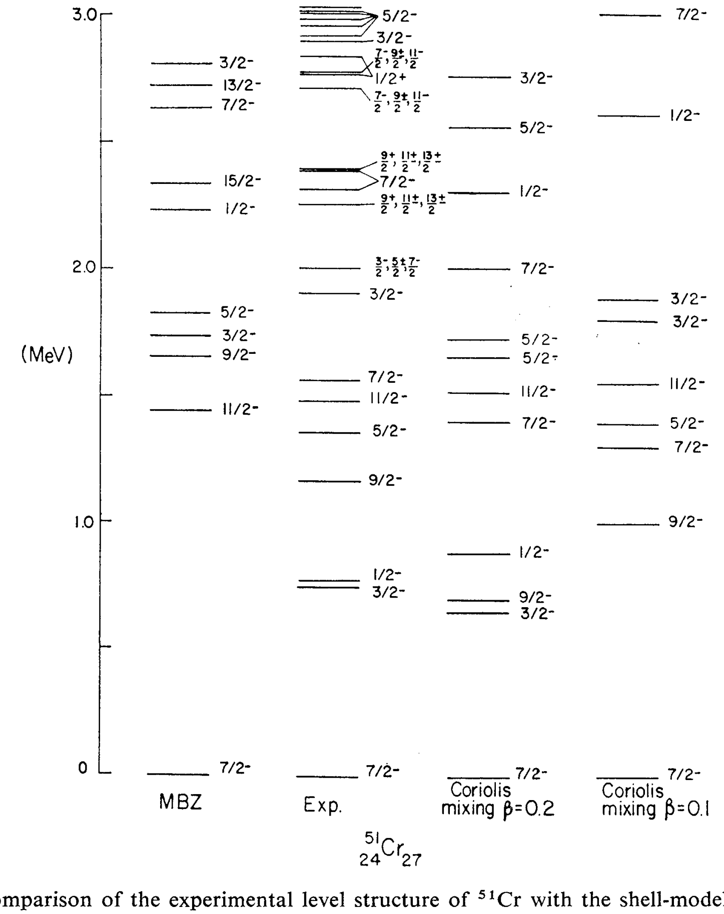


Fig. 16. Comparison of the experimental level structure of ^{51}Cr with the shell-model calculations of McCullen *et al.* [30]) (MBZ) and with the results of Malik and Scholz [31]) on the Coriolis coupling model with a deformation of $\beta = 0.2$ and $\beta = 0.1$. Good qualitative agreement is seen with the Coriolis coupling scheme with $\beta = 0.2$.

of levels in ^{51}Cr and with this and the addition of a few new levels in ^{51}Cr more meaningful comparisons with the theoretical models are now possible. Thus the levels at 1164.5 and 1480.3 are most likely $\frac{9}{2}^-$ and $\frac{11}{2}^-$, respectively, and these are compared with the $\frac{11}{2}^-$ and $\frac{9}{2}^-$ predicted by MBZ at 1440 and 1550 keV. The present experimental level spectrum is compared in fig. 16 with the calculations of MBZ. Below 3004 keV there are 21 excited states while the MBZ theory on the basis of only $(1f_{\frac{7}{2}})^n$ proton and neutron configurations predicts only 9 states in ^{51}Cr. Candidates for the possible $\frac{13}{2}^-$ level are the 2255.7 or 2385.6 keV levels.

More recently Malik and Scholz [31]) (abbreviated as MS) have applied the collective model of Bohr and Mottelson with strong Coriolis coupling between rotational bands to nuclei in the $1f_{\frac{7}{2}}$ shell. In this treatment the rotational motion of the deformed core is coupled to the motion of only the last odd particle. The single-particle motion is described as in the Nilsson model in terms of the deformation of the average

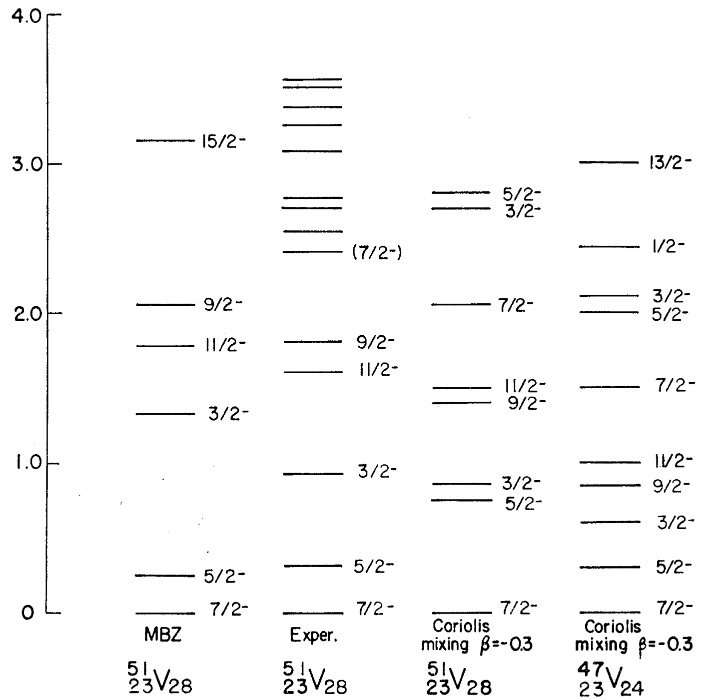


Fig. 17. Comparison of the experimental level structure of ^{51}V with the MBZ theory and the Coriolis coupling model. Both the MBZ theory and the Coriolis coupling scheme with $\beta = -0.3$ give good qualitative agreement with experiment.

potential. The band mixing due to the Coriolis interaction is treated as a perturbation and level spectra are calculated for a series of values of β, the deformation parameter. This model appears to explain quite satisfactorily the levels of many of the $1f_{\frac{7}{2}}$ nuclei In fig. 16 we show the level spectrum calculated with $\beta = 0.2$ as given in ref. [8]) by an apparently improved MBZ calculation. In the same figure is shown the level spectrum calculated by MS for $\beta = 0.1$. This Coriolis mixing model appears to account rather well for the low-lying $\frac{3}{2}^-$ and $\frac{1}{2}^-$ doublet, and for the correct order of the $\frac{9}{2}^-$ and $\frac{11}{2}^-$ levels. It is worthwhile pointing out, however, that the calculated level spectrum changes rather drastically with the deformation parameter β. This is seen in fig. 16 from the calculated spectra for $\beta = 0.1$ and 0.2. Although this model accounts rather well for the few lower-lying states in ^{51}Cr it still does not account for the large number of states observed experimentally.

In fig. 17 we show for comparison the calculated level spectra for ^{51}V according to MBZ and MS for $\beta = -0.3$. The MBZ theory appears to account rather well for the level spacing of the lower energy levels. Here in ^{51}V the Coriolis coupling model requires a prolate deformation with $\beta = -0.3$ and it does not give a significantly better fit to the data. For comparison in fig. 17 we also show the $^{47}_{23}V_{24}$ level spectrum calculated by MS for $\beta = -0.3$.

From the comparisons of the ^{51}Cr and ^{51}V levels and of levels in other nuclei in the $1f_{\frac{7}{2}}$ shell [31]) with the Coriolis coupling model it is apparent that further improvement in the available experimental data is required before definite conclusions about the trends of the sign of deformation with the structure of the $1f_{\frac{7}{2}}$ nuclei can be made.

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