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Study of analogue states in ^{52}Cr through proton capture by ^{51}V

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Abstract. γ-Ray yield function has been studied for the proton capture by vanadium in the proton energy range 720–1300 keV. Isobaric analogues of low lying states in ^{52}V have been identified. At two resonances the γ-decay and γ-ray angular distributions have been obtained and the branching ratios and the multipole mixing ratios have been deduced. The analogue-antianalogue M1 transition in ^{52}Cr is found to be strongly hindered as in other $f_{7/2}$ nuclei. The Q-value obtained for this reaction is $(10500 \pm 2\cdot 8)$ keV and the Coulomb displacement energy is $(8\cdot 06 \pm 0\cdot 01)$ MeV. An upper limit of 2 meV has been obtained for the α- decay strength of the $11\cdot 395$ MeV state in ^{52}Cr.

Keywords. Ge(Li) detector; nuclear levels; resonance strengths; gamma spectrum; branching ratios; isobaric analogue states.

1. Introduction

Isobaric analogue states (IAS) often appear as strong resonances in (p, γ) reactions because both Γ_p and Γ_γ are large in such reactions. This reaction is particularly useful for location of IAS in the energy region below 2 MeV where proton penetrabilities are so low that the observation of resonance proton scattering is not readily achieved. This paper reports the study of resonant capture of protons by ^{51}V in the proton energy interval 720–1300 keV. Preliminary results in the range 720–950 keV have already been reported (Iyengar *et al* 1973). This reaction has been previously studied in this energy region by Teranishi and Furubayashi (1966) and Ahmed *et al* (1972) who determined the resonance energies only. The present experiment was conducted with better beam resolution to determine the resonance energies more accurately. The γ-decay of two analogue states have also been studied. During the course of this experiment Faini *et al* (1973) reported an investigation of this reaction in the energy range 745–820 keV. The resonance energies assigned by them correspond closely to our assignments. Previous studies of electromagnetic transition in the $1f_{7/2}$ nuclei (Vingiani and Ricci 1971) have failed to reveal strong M1 transitions between analogue-antianalogue states; present results indicate that such strong M1 transitions are also lacking in ^{52}Cr.

2. Experimental details

2.1.1. *γ-ray yield function:* The experiment was performed with a proton beam of 3·4 μA from the 1 MV Cockroft-Walton accelerator at this Institute in the energy range 720–950 keV and with the mass-3 (H_2H^+) beam of 0·6 μA from 5·5 MV Van de Graaff accelerator at BARC, Bombay, in the proton energy range 900–1300 keV. As proton current from this Van de Graaff accelerator at these energies was too low for pursuit of experimental investigations we resorted to the use of molecular beams. The mass-3 beam (at thrice the desired proton energy) was preferred to the mass-2 (H_2^+) beam (at twice the energy) as it was more abundant. The energy resolution in the lower energy region was about 1·5 keV at 1 MeV.

The targets were prepared by evaporating in vacuum, turnings of natural vanadium of high chemical purity (99·95%) from a heated tungsten filament on to ultrasonically cleaned tantalum backings. The beam was focussed to a spot of size 2 mm × [illegible] mm with the help of magnetic quadrupole lenses. No cooling of the target was found necessary. This also helped to keep the carbon deposition on the target to a minimum.

In the proton energy range 720–950 keV, the γ-ray yield function was obtained with the help of two NaI(Tl) detectors, one 10·2 cm by 10·2 cm and the other 10·2 cm by 12·7 cm placed on either side of the target tube at 90° to the direction of incident beam. The entire assembly was surrounded by a plastic scintillation detector which was viewed by four fast 12·7 cm dia. photomultipliers. The pulses from the two NaI(Tl) detectors were mixed in a summing circuit and were anticoincidence gated by the plastic scintillator pulses. The assembly is shown schematically in figure 1. The anticoincidence assembly (used for obtaining the yield function) helped to reduce the background in the γ-ray energy range

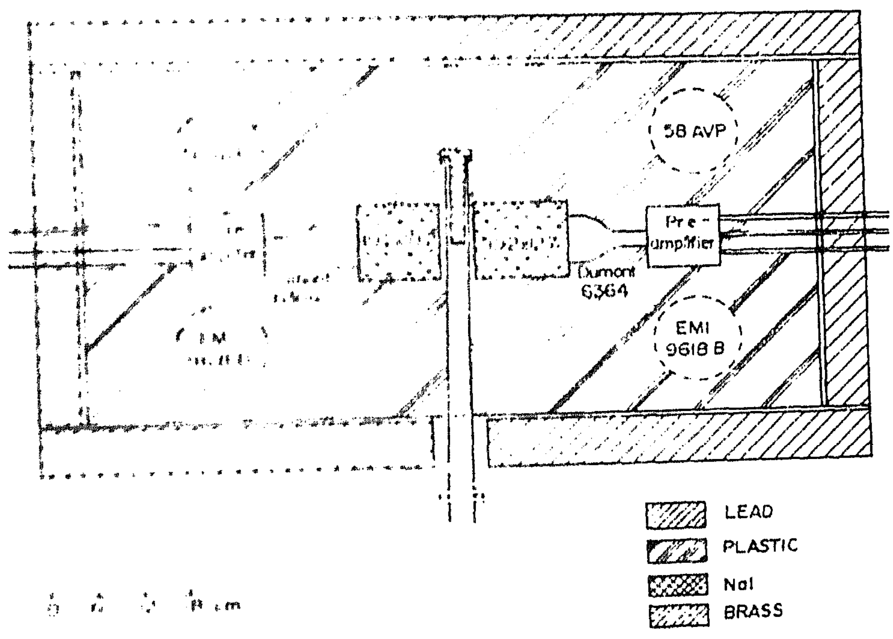

Figure 1. NaI(Tl)-plastic scintillator anticoincidence assembly used for obtaining γ-ray yield functions.

3-13 MeV by a factor of five. The yield function was also obtained with γ-rays in the energy interval 8–13 MeV. Both thin ($\sim$3 keV) and thick ($\sim$15 keV) targets were used under identical detector conditions and the target thickness for the thin target was determined from the ratio of the area under the thin target yield to the step in the thick target yield (Gove 1959). The accelerator energy was calibrated with the help of resonances in $^{27}Al(p, \gamma)^{28}Si$ reaction at 633, 774 and 923 keV and the 872 keV resonance in $^{19}F(p, \alpha\gamma)^{16}O$ reaction.

The yield function in the proton energy range 900–1300 keV was obtained with a single 12·7 cm by 12·7 cm NaI(Tl) detector surrounded by 5 cm thick lead shielding. The detector was placed at an angle of 90° to the direction of incident beam at a distance of 5 cm from the target. The target thickness was about 10 keV. The accelerator energy was calibrated with the resonance at 992 keV in $^{27}Al(p, \gamma)^{28}Si$ reaction.

2.1.2. *Identification of analogue states*—The energy required for the proton to excite the ground state analogue is given by the relation

$$Q_p + E_p(\mathrm{cm}) = \triangle E_c + E_\beta - 0{\cdot}782 \text{ in MeV}$$

where $\triangle E_c$ is the Coulomb energy difference, E_β, the end point energy for β-decay of the parent analogue state and Q_p the Q-value for the reaction. The value 0·782 MeV is the mass difference between the neutron and the hydrogen atom. Since Coulomb forces are of long range nature, they are not very sensitive to the details of nuclear structure. Thus, we expect $\triangle E_c$ to be nearly the same for all pairs of analogue states in the nuclei under consideration. This is a great aid in the identification of the analogue states. Also because of their large Γ_p and Γ_γ values they would appear as quite strong resonances in the yield function.

2.2. *γ-decay of analogue states*

A Ge (Li) detector of 27 cm³ active volume was used to obtain the γ-spectra at the resonances. The spectra were taken at 90° to eliminate Doppler shifts. A computer program was used to calculate the centroids of the γ-ray peaks in the spectra and the area under each peak. γ-rays from radioactive sources and from the decay of the 992 keV resonance in $^{27}Al(p, \gamma)^{28}Si$ were used for the energy calibration of the 4096 channel pulse height analyser. The relative efficiency of this detector was also determined with the help of γ-rays from the same resonance. For the measurement of the thick target yield of the 912 keV resonance and the γ-decay at 55° another Ge(Li) detector of 20 cm³ active volume was used whose absolute efficiency was determined by comparison with a 7·6 cm × 7·6 cm NaI(Tl) detector.

2.3. *Angular distribution of γ-rays*

Since the γ-ray intensities were very poor, angular distributions were obtained only for the strongest γ-ray transition at two resonances. The data were collected at 0°, 31°, 55°, 70° and 90°, with the detector set at a distance of 8 cm from the target. The data were accumulated at each angle for a total period of 12 hr in three sub-runs of 4 hr each. The collected charge for each angle was $\approx$ 0·1 C. A 7·6 cm × 7·6 cm NaI(Tl) detector at 90° was used to monitor the reaction yield during the angular distribution measurements. The data were fitted with the theoretical expression (Erne 1966)

$$W(\theta) = \sum_k A_k Q_k \zeta_{k0} P_k(\cos\theta) \tag{1}$$

where A_k are the correlation coefficients involving the multipole mixing ratio δ and ζ_{k0} are the statistical tensors involving the channel spin mixing ratio δ_s and the orbital mixing ratio δ_l. P_k are the Legendre polynomials and Q_k are the solid angle correction factors. The Q_k were taken from Roy and Iyengar (1974). For the 912 keV resonance the angular distribution of the cascade γ-ray following the primary transition was also obtained so as to determine the mixing ratio uniquely. The mixing ratio for the cascade γ-transition and the J^π values of the bound states were taken from Rapaport (1970). For an assumed spin of the resonant state arctan x was incremented in steps of 3° over the range −90° to +90°. ζ_{20}/ζ_{00} was treated as a parameter and for each assumed value of ζ_{20}/ζ_{00}, the angular distribution of the primary and the cascade γ-rays was fitted simultaneously. The quality of each fit was summarised by

$$\chi^2 = \frac{1}{n} \sum_i (Y(\theta_i) - W(\theta_i))^2/(DY(\theta_i))^2 \tag{2}$$

where Y and W represent the experimental and theoretical yields respectively, DY the error in the experimental yield and n the number of degrees of freedom. The minimum of χ^2 yielded the required values of δ and ζ_{20}/ζ_{00}.

2.4 *α-decay*

Due to the large Coulomb barrier and the isospin forbiddenness, the α-decay width is expected to be very small. Recent experiments (Szabo *et al* 1972, Somogyi *et al* 1968) have proved the usefulness of plastic track detectors for the measurement of low yield reactions. Plastic track detector (cellulose nitrate) was used to detect the α-decay of the analogue state at 11·395 MeV. A thick target of V ($\sim$ 15 keV) on carbon backing was employed for this purpose. The plastic detector in the shape of a rectangular strip was made to cover an angular region 20°–170° at a distance of 10 cm from the target. The plastic was etched in an etching solution (150 g NaOH + 120 g KOH + 45 g $KMnO_4$ in 900 ml H_2O) at 50° C for about 40 min. The strength of the solution and the time required for the etching were optimised to bring out the etch pits due to α's prominently by developing the tracks due to α-particles from the reaction $^{19}F(p, \alpha)^{16}O$ at 872 keV proton energy.

3. Results and discussion

3.1. *Resonance energies*

The yield curves for γ-rays in the energy range 3–13 MeV obtained in this experiment are shown in figure 2. The peaks seen in the yield function are labelled by the numbers in parenthesis along with corresponding proton energies. The yield function for γ-rays in the energy range 8–13 MeV shows similar structures. The peaks at 784, 912 and 1210 keV can be clearly identified as analogues of the second, fourth and fifth excited states of ^{52}V respectively from the constant energy difference between these and the corresponding analogues. For the ground state analogue we have two candidates in peaks seen at 766 keV and 773 keV. Faini *et al* (1973) have identified the peak at 773 keV as the ground state analogue by

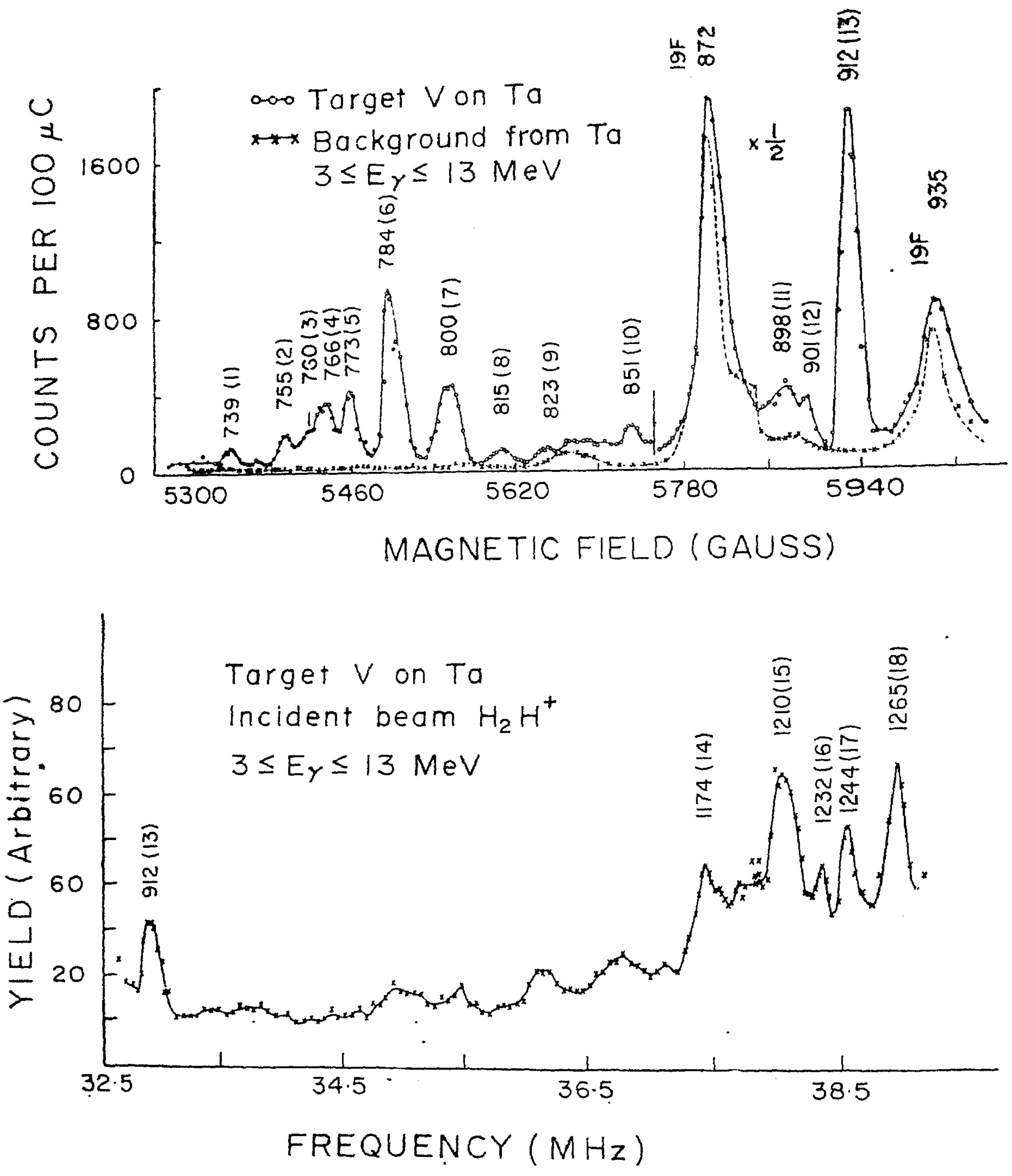

Figure 2. γ-ray yield function for the $^{51}V(p, \gamma)^{52}Cr$ reaction. The abscissa in the 720–950 keV region is the magnetic field measured with a rotating coil gaussmeter. In the 900–1300 keV region it is the NMR frequency corresponding to the proton signal used for measuring the magnetic field. The peaks due to ^{19}F in the background run occur at a lower energy than in the run with the V target. The reason for this is the different amounts of ^{19}F present as contaminant in the two runs. Peaks are shifted from their actual position to the higher energy side by half the target thickness in case of thin targets (Gove 1959).

Table 1. Resonances observed in the $^{51}V(p, \gamma)^{52}Cr$ reaction. The energies assigned to the resonance are accurate to ± [illegible] keV. For the excitation energies in ^{52}Cr, the Q-value for the reaction is assumed to be 10·500 MeV

Identification number from fig. (a)	E_p (lab) keV	E_p (lab) keV	E_x in ^{52}Cr MeV	Corresponding IAS in ^{52}V	Strength function $(2J+1)\,\Gamma_p\Gamma_\gamma/\Gamma$ eV
1	739		11·225		0·03±0·01
2	755		11·241		
3	760		11·247		
4	766	766	11·252	g.s.	0·05±0·02
5	773	774	11·259		0·06±0·01
6	784	784	11·269	0·023	0·13±0·03
7	800	800	11·286		0·06±0·02
8	815		11·300		
9	828		11·313		
10	851		11·335		
11	895		11·378		
12	901		11·384		
13	912	912	11·395	0·148	0·58±0·10
14	1174		11·651		0·84±0·24
15	1210	1210	11·687	0·437	3·01±0·78
16	1232		11·708		0·56±0·16
17	1244		11·720		1·18±0·34
18	1265		11·741		1·52±0·43

(a) Present experiment.
(b) Teranishi and Furubayashi (1966), Ahmed *et al* (1973), Faini *et al* (1973).

comparing the σ part of the M1 decay with the *ft* value of the Gamow-Teller part of the β-decay of the parent state. The resonances observed in this experiment along with their strength functions are presented in table 1.

3.2. *Decay schemes and Q-value*

3.2.1. *The resonance at* 912 *keV*—Four γ-rays have been identified to arise from the decay of the analogue state formed at the proton energy of 912 keV to bound states in ^{52}Cr. A partial spectrum showing the regions where peaks due to γ-rays appear is shown in figure 3. The resonant level is found to have the strongest decay to the 2·370 MeV (4_1^+) level. Two weaker transitions could also be easily identified to lead to the 3·414 MeV (3^+, 4^+) level and the 3·617 MeV (5^+) level. The other strong transition has been assigned to lead to a level at 5·563 MeV by matching the excitation energy of the resonant state with the sum of the

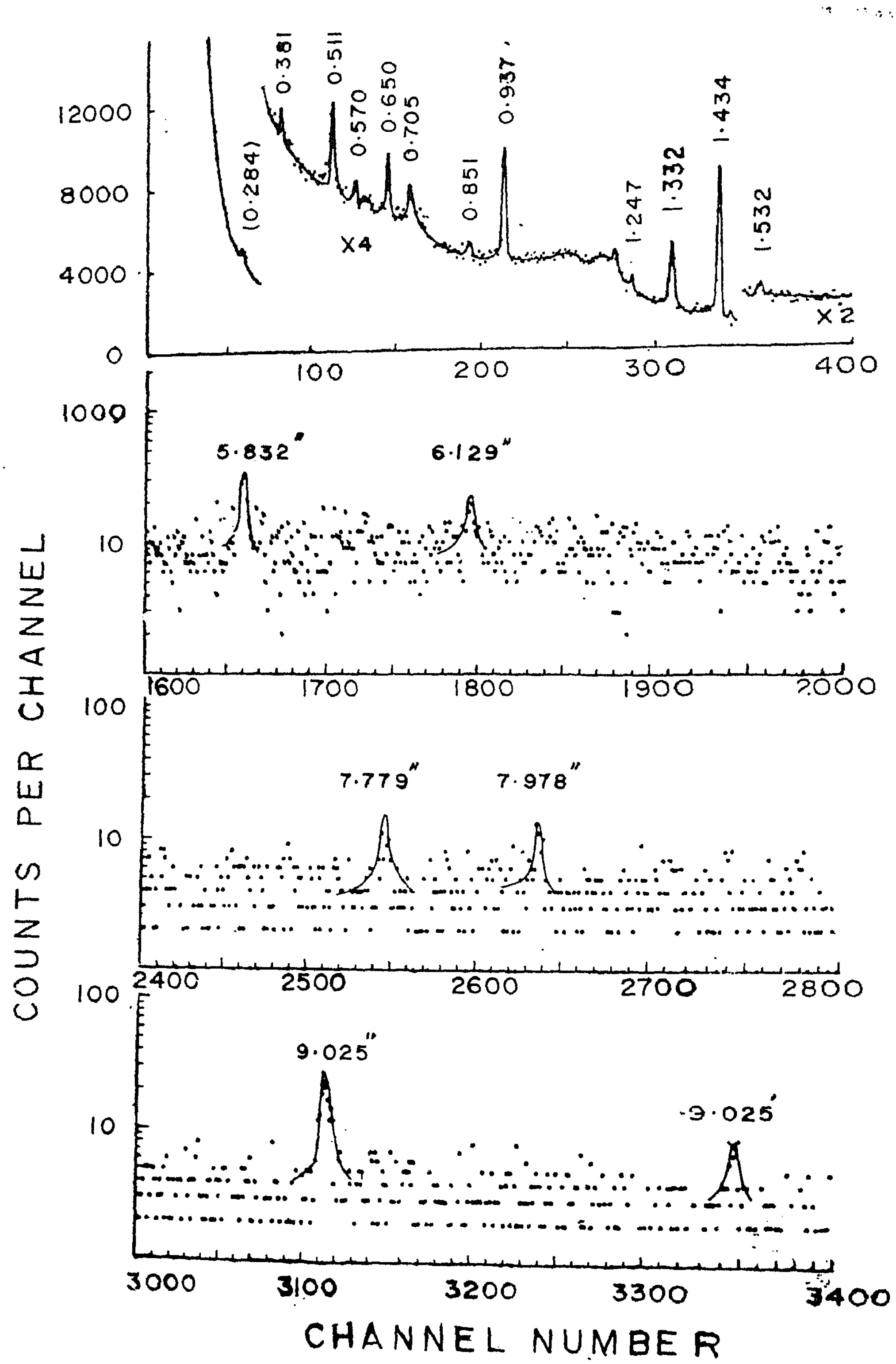

Figure 3. Partial γ-ray spectrum for the decay of the 912 keV resonance. The energy dispersion in the range $E_\gamma < 1 \cdot 7$ MeV is 4·2 keV per channel and in the higher energy region $E_\gamma > 1 \cdot 7$ MeV it is 2·2 keV per channel.

energies of primary and secondary γ-rays. Although many levels are known to exist in ^{52}Cr in the neighbourhood of this energy (Rapaport 1970), it is difficult to identify it with any of them. The decay scheme along with the branching ratios obtained at 55° is shown in figure 4. The excitation energy for this state is determined to be 11·395 MeV from the γ-ray energies. From this value and the proton energy in the centre of mass system corresponding to the resonance we deduce the Q-value for this reaction to be 10500 ± 2·8 keV. This result is in agreement with the value 10500·8 ± 3·8 keV appearing in the 1964 mass tables (Mattuch *et al* 1965).

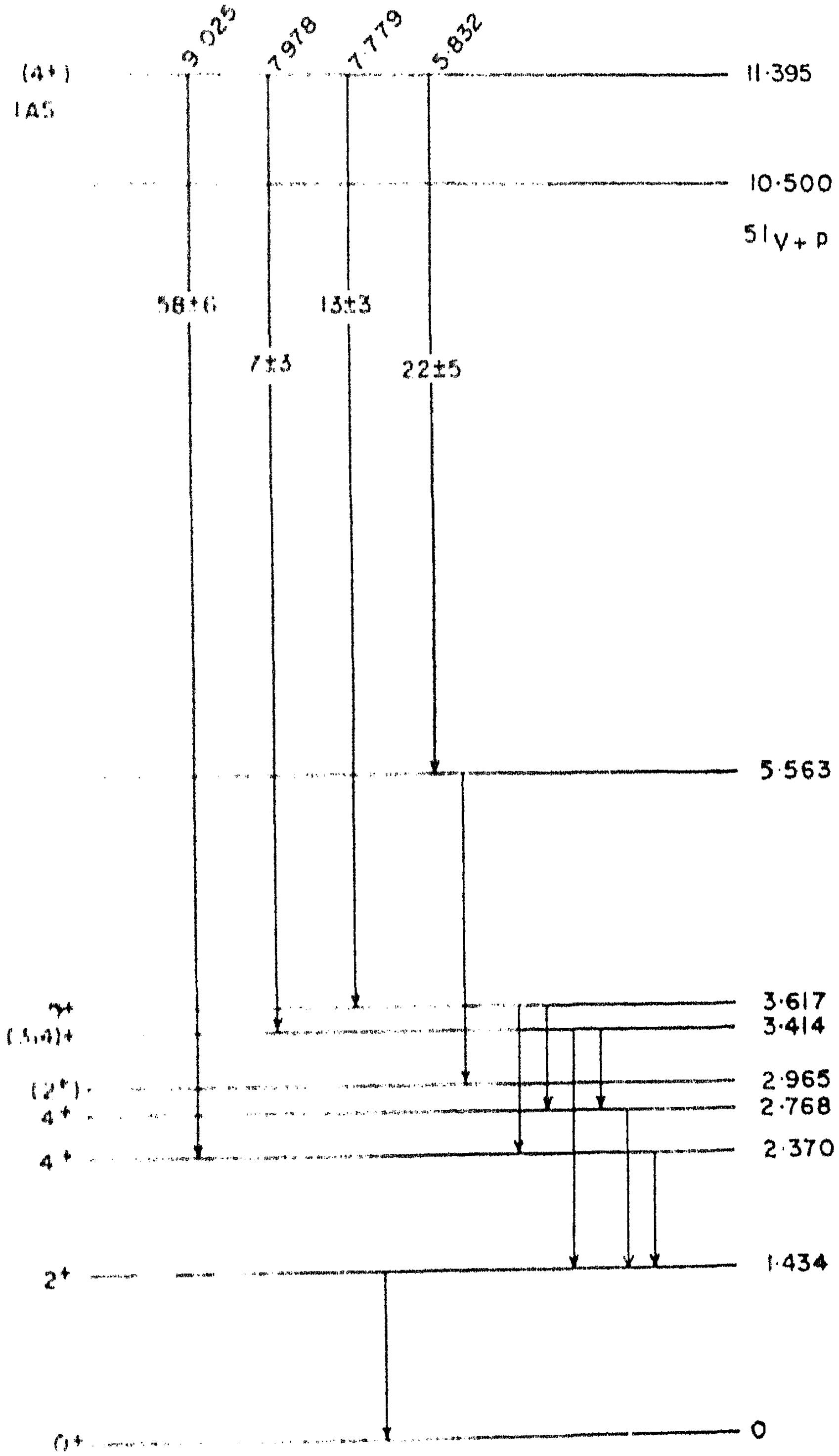

Figure 4. Decay scheme for the 912 keV resonance indicating γ-ray energies and branching ratios. Only the cascade γ-rays observed in this study are shown. The values assigned for the energy of the γ-rays is accurate to ± 2 keV. The energy of the bound states in ^{52}Cr and their J^{π} values are taken from Rapaport (1970).

3.2.2. *The resonance at* 1210 *keV*.—Six γ-rays can be identified to arise from the decay of the analogue state formed at the proton energy of 1210 keV. The strongest γ-ray having about 54% of the branching is due to the transition to the 1·434 MeV (2_1^+) level. Other weaker transitions lead to the 2·370 MeV (4_1^+), 2·965 MeV (2_2^+), 4·742 MeV (0^+) levels. Previous reports (Rapaport 1970) indicate a J^π value of (2^+, 3^+) for the parent analogue state. Since we observe the decay of the resonant state to the 4·742 MeV (0^+) level the J^π value of 2^+ is more likely. Two new levels at 5·054 MeV and 5·446 MeV need to be assigned to account

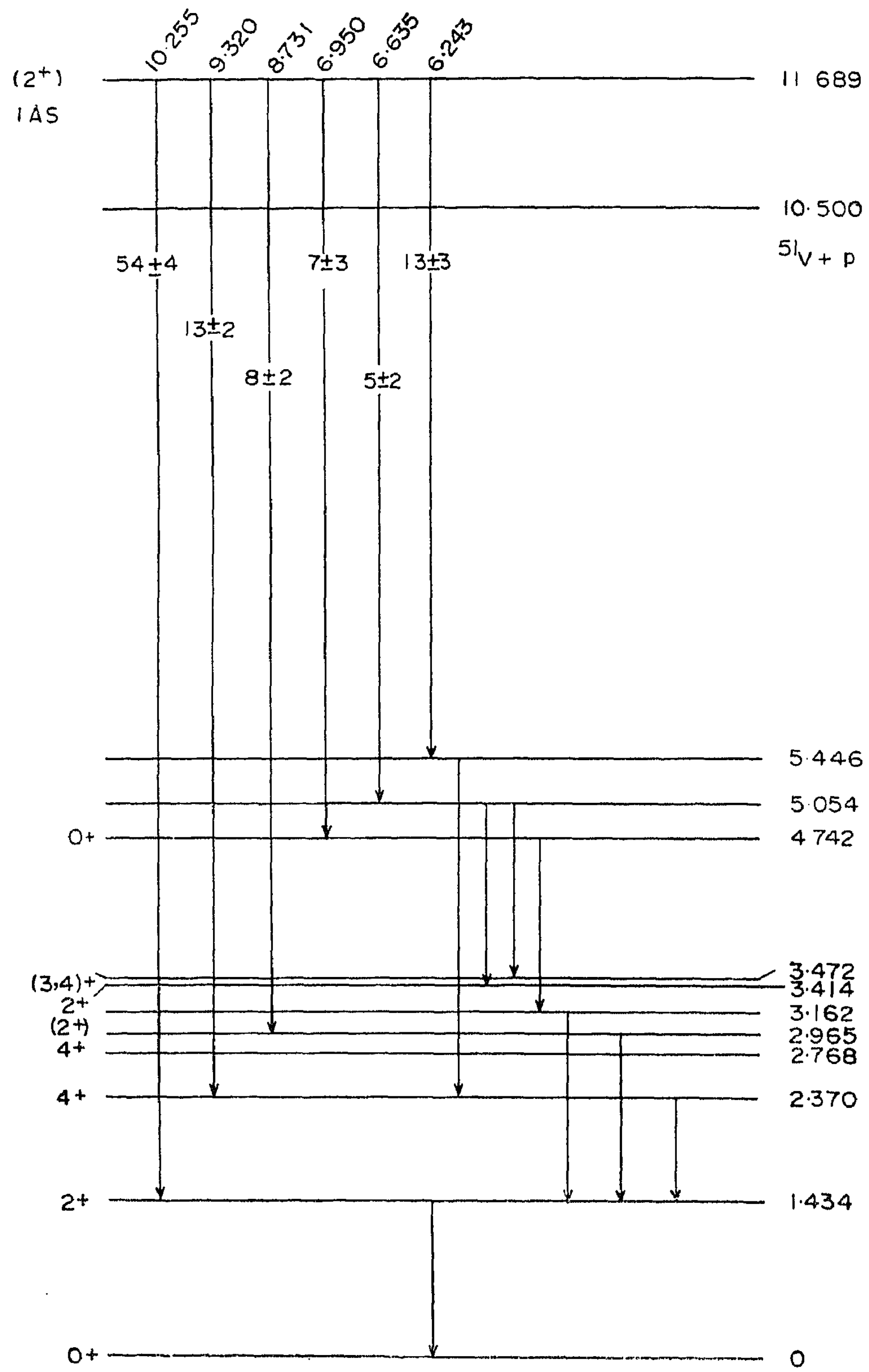

Figure 5. Decay scheme for the 1210 keV resonance with γ-ray energies and branching ratios. Only the cascade γ-rays observed in this study are shown.

for the observed γ-rays. For each of the primary γ-rays, cascade γ-rays have been identified. The decay scheme for this resonant state along with the branching ratios obtained at 55° is shown in figure 5. The excitation energy for this state is determined from the γ-ray energies to be 11·689 MeV.

3.3. *Angular distribution and mixing ratios*

Both the J^π values 3^+, 4^+ for the 11·395 MeV state fit well (χ^2 lower than 0·1% limit) the angular distribution ($a_2/a_0 = -0{\cdot}38 \pm 0{\cdot}10$) of the γ-ray arising from the transition of the resonant state to the 2·370 MeV state. Previous reports (Archer and Kennett 1967, Van Assche *et al* 1966) indicate a J^π value of 4^+ for this resonant state. Since this state decays more strongly to the 4_1^+ level than to the lower 2_1^+ level, it appears that its J^π value is more likely 4^+ than 3^+. For the J^π assignment 4^+ to the resonant state we obtain a value of $-0{\cdot}5 \pm 0{\cdot}2$ for the multipole mixing ratio and a value of 0·63 for the channel spin mixture (assuming no orbital angular momentum mixture).

For the transition between the 11·689 MeV state (2^+) and the 1·434 MeV state (2_1^+) the angular distribution is found to be isotropic ($a_2/a_0 = 0{\cdot}00 \pm 0{\cdot}10$). For $l = 1$ case only one channel spin, *i.e.*, 3 can occur.

3.4. *Transition probabilities*

In the analogue resonances we excite the analogue of the low-lying states in the parent nuclei, which are expected to have a sizable single particle strength. This property will also be reflected in the large spectroscopic factors obtained in (d, p) reactions on the target nuclei. In medium-weight nuclei, the observed values of Γ_p are in the range of several tens of eV whereas Γ_γ is of the order of one eV. Hence, we can assume $\Gamma_p \approx \Gamma$. In such cases the resonance strength $(2J+1)$ $\Gamma_p\Gamma_\gamma/\Gamma$ reduces to $(2J+1)\ \Gamma_\gamma$. Using this we find the γ-widths for the 11·395 and 11·689 MeV states to be ($0{\cdot}064 \pm 0{\cdot}010$) eV and ($0{\cdot}60 \pm 0{\cdot}15$) eV, respectively. For the γ-ray arising due to the transition between the 11·395 MeV level and the 2·370 MeV level, we then find the following reduced transition probabilities:

$$B\,(M1) = (1{\cdot}4 \pm 0{\cdot}7) \times 10^{-3}\ \text{W.u.}$$

and

$$B\,(E2) = (0{\cdot}027 \pm 0{\cdot}013)\ \text{W.u.}$$

As in other f-p shell nuclei, here also we find that the M1 transition is strongly hindered.

3.5. *Coulomb displacement energy*

The semi-empirical formula for Coulomb energy displacement (Anderson *et al* 1965) is

$$\triangle E_c = (1{\cdot}444 \pm 0{\cdot}005)\,(\bar{Z}/A^{1/3}) - (1{\cdot}13 \pm 0{\cdot}04)$$

where $\bar{Z}$ is the average of the initial and final Z values of the nuclei considered. For ^{52}V–^{52}Cr, this formula predicts $\triangle E_c = (7{\cdot}96 \pm 0{\cdot}07)$ MeV. Using the excitation energies of the resonances obtained in this experiment and the end point

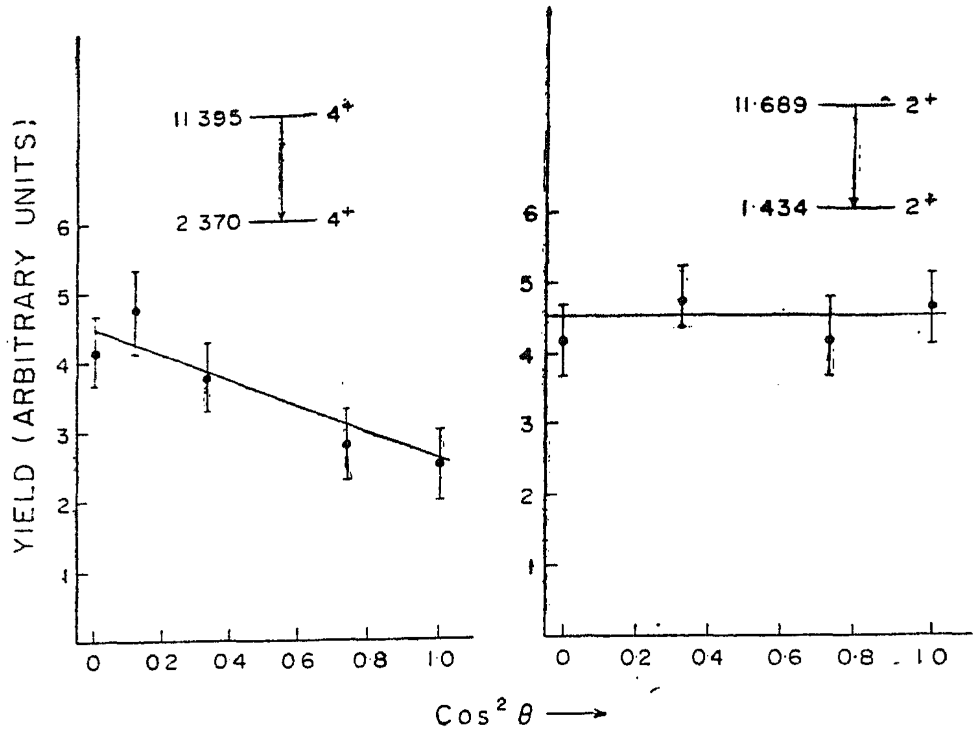

Figure 6. Angular distributions of γ-rays arising from (*a*) the transition between the 912 keV resonance and the $2\cdot370$ MeV level, and (*b*) the transition between the 1210 keV resonance and the $1\cdot434$ MeV level. The yield of the high energy γ-rays is normalised with respect to the isotropic yield of the $10\cdot759$ MeV γ-ray from the 992 keV resonance in $^{27}Al(p, \gamma)^{28}Si$ reaction.

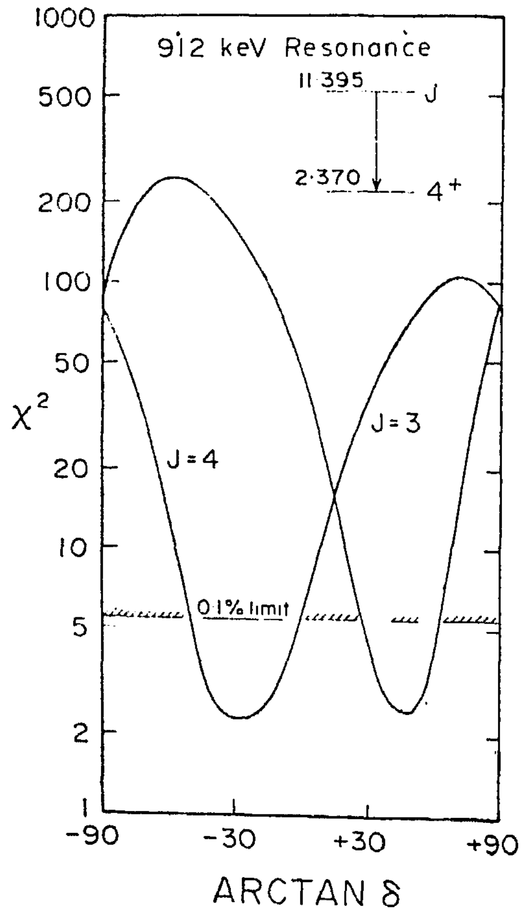

Figure 7. Plot of χ^2 *versus* arctan δ for the fitting of angular distribution at the 912 keV resonance.

energy of the β-decay ($E = 3\cdot974$ MeV) (Lederer *et al* 1967), we deduce $\triangle E_c = (8\cdot06 \pm 0\cdot01)$ MeV. This agrees well with previously reported values ($8\cdot075 \pm 0\cdot020$) MeV (Teranishi and Furubayashi 1966) and ($8\cdot04 \pm 0\cdot01$) MeV (Ahmed *et al* 1973).

3.6. *α-decay*

An exposure with plastic track detector was made on the 912 keV resonance and another at an energy 5 keV below the resonance. The exposure at the lower energy gave the contribution from the non-resonant decay and other contaminants. The difference in the α-yields from these two exposures was found to be insignificant. We estimate from these data the upper limit for the strength function for this resonance, *viz.*, $(2J+1)\,\Gamma_p\Gamma_\alpha/\Gamma$ as 2×10^{-3} eV.

Note added in proof :

A further analysis of the gamma decay of the resonance at 1210 keV reveals a gamma transition to the 3·472 MeV level previously known through (p, p′) reaction in ^{52}Cr. The subsequent cascade gamma rays arising from the decay of the 3·472 MeV level to the 1·434 MeV and 2·768 MeV levels have also been identified. The corrected branching ratios (in percentages) for the gamma decay of the 1210 KeV resonance to the various levels are as follows:

1·434 MeV (50 ± 4), 2·370 MeV (12 ± 2), 2·965 MeV (8 ± 2), 3·472 MeV (9 ± 3), 4·742 MeV (6 ± 2), 5·054 MeV (4 ± 2) and 5·446 MeV (11 ± 3).

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