ROTATIONAL BANDS IN SOME ODD MASS $1f_{7/2}$ NUCLEI

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The properties of ^{45}Sc, ^{45}Ti, ^{51}Cr and ^{55}Fe were probed with proton beam of energies ranging from 3.5 MeV to 5.0 MeV using Chandigarh Variable Energy Cyclotron. Doppler Shift Attenuation (DSA) technique was adopted to deduce the lifetime of excited states. The spin of levels and mixing ratio of γ-transitions were deduced from the analysis of γ-ray angular distribution data. Most of the states in these nuclei were found to follow $J(J+1)$ rule and the transition probability B(E2) of γ-rays, from these levels, were found to be enhanced over single particle estimates. The existence of several rotational bands is therefore suggested in these odd mass $1f_{1/2}$ nuclei. Apart from this, some new information regarding lifetimes and mixing ratios has been obtained for these nuclei.

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1. Introduction

It was pointed out by Maurenzig [1] that the positive parity states in some $1f_{7/2}$ nuclei can be organized as the members of rotational bands. Toulemonde et al. [2], on the basis of the experimental results proposed a $K = 3/2^+$ band in ^{45}Sc. Styczen et al. [3] carried out band mixing calculations to reproduce these rotational bands in odd mass nuclei of Sc, Ti and V. Dhar et al. [4, 5] predicted the bands of states in odd mass isotopes of Ti in the framework of deformed configuration mixing shell model calculations. Several negative parity bands have also been identified in $1f_{7/2}$ region. A possibility of a $K = 1/2^-$ band in ^{51}Cr was pointed out by Szoghy et al. [6]. Later, it was confirmed by Kasagi and Ohnuma [7]. Thus there is an ample evidence for the existence of band structure in $1f_{7/2}$ region. The present work is an attempt to investigate the possible rotational bands in ^{45}Sc, ^{45}Ti, ^{51}Cr and ^{55}Fe nuclei. As a result of the present study, we have been able to propose several new bands of states in these nuclei.

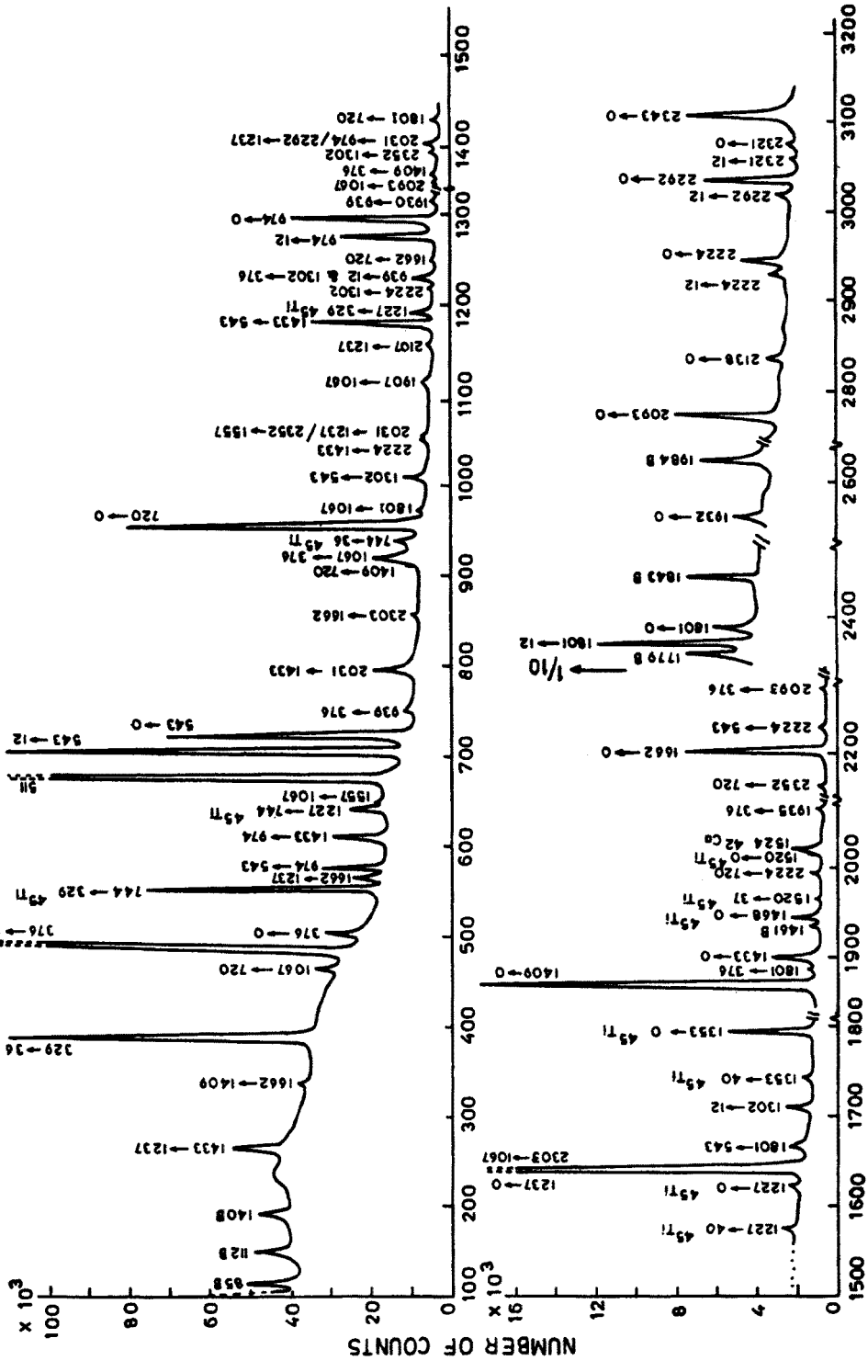


Fig. 1. Gamma ray spectrum due to ^{45}Sc (p, Xγ) reactions, (where X = p or n) at the proton energy E_p = 4.4 MeV at 90° w.r.t. the incident beam direction

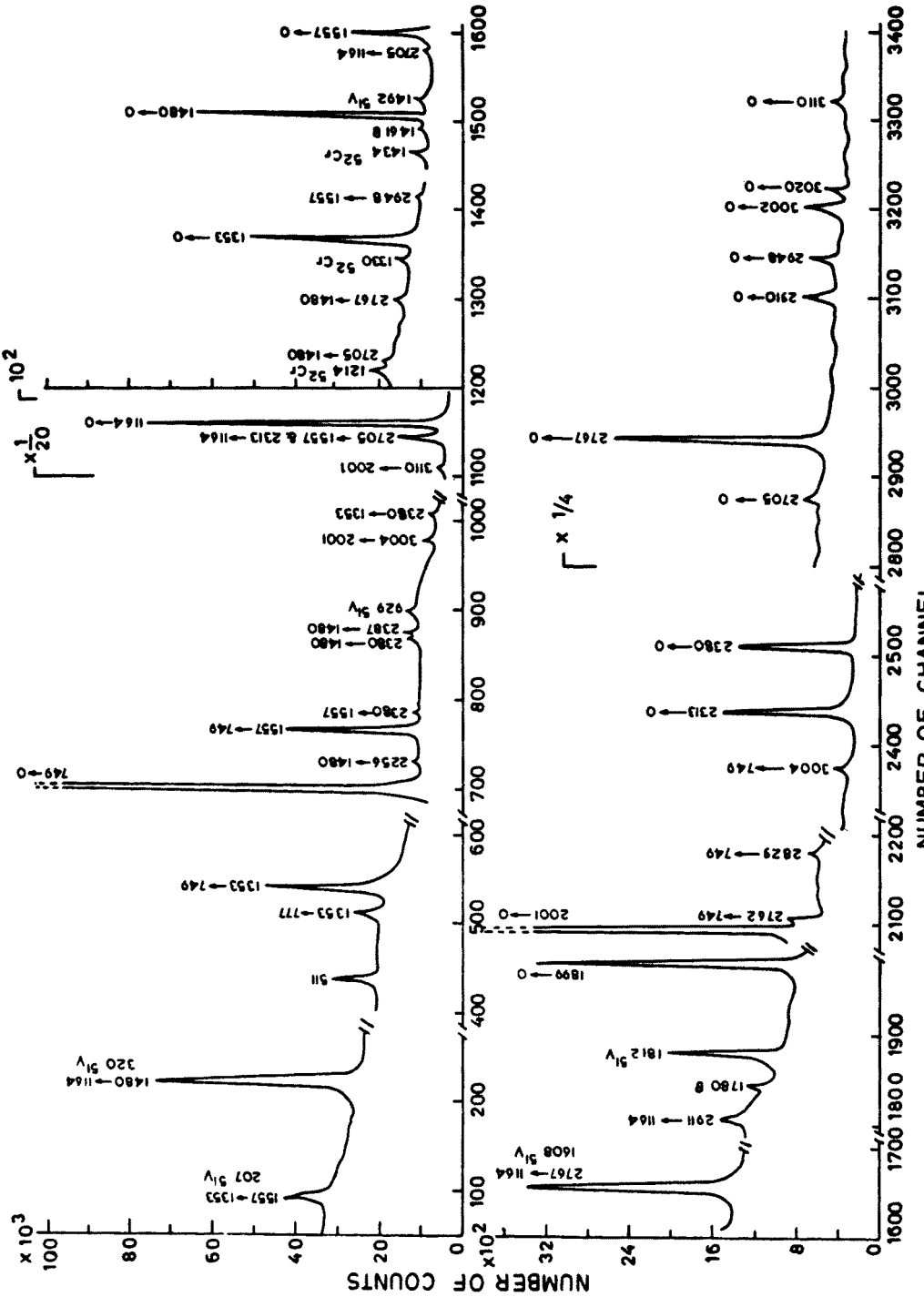


Fig. 2. Gamma ray spectrum due to ^{51}V (p, nγ) reaction at the proton energy E_p = 5.0 MeV at 90° w.r.t. the incident beam direction

2. Experiment

Proton beams of energies ranging from 3.5 MeV to 5.0 MeV were used to excite the various states of the nuclei under consideration. The experimental arrangement has already been described elsewhere [8]. The resulting γ-ray spectra due to the bombardment of proton beam on ^{45}Sc, ^{51}V and ^{55}Mn targets are shown in Figs. 1, 2 and 3 respectively. The nuclear levels in ^{45}Sc, ^{45}Ti, ^{51}Cr and ^{55}Fe were observed following the ^{45}Sc(p, p'γ), ^{45}Sc(p, nγ), ^{51}V(p, nγ) and ^{55}Mn(p, nγ) reactions respectively. The partial decay schemes

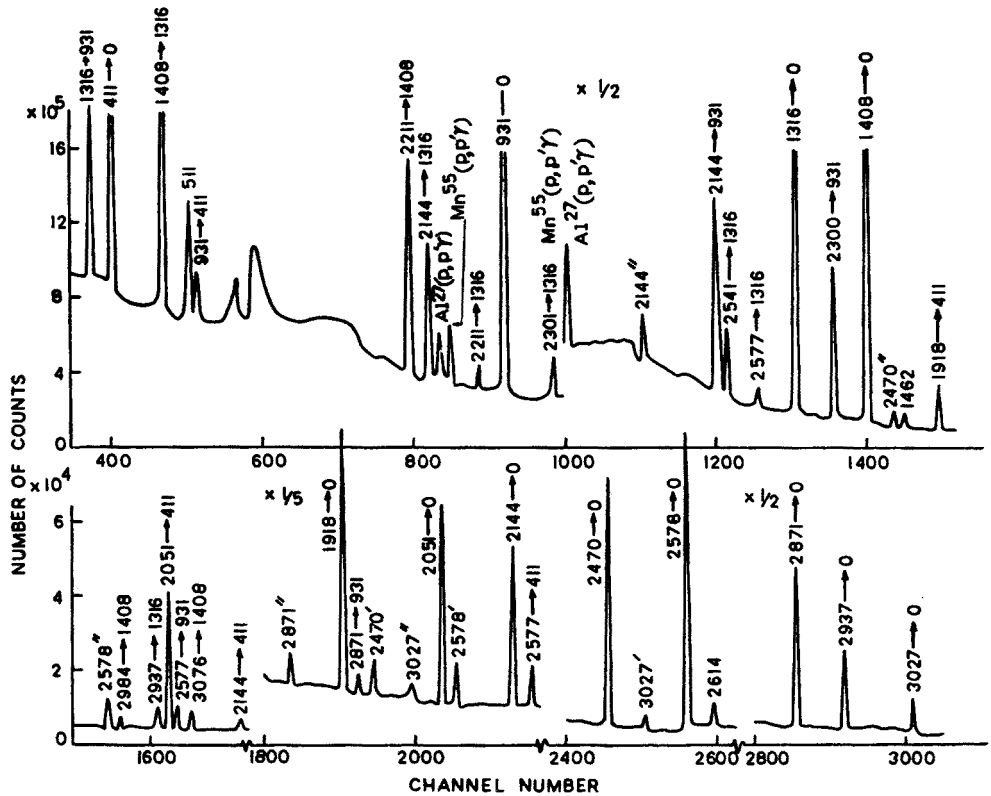


Fig. 3. Gamma ray spectrum due to ^{55}Mn (p, nγ) reaction at the proton energy E_p = 4.2 MeV at 90 w.r.t. the incident beam direction. The peaks marked with dash and double dash are the first and second escape peaks respectively

of respective nuclei observed in the present experiments are shown in Figs. 4 to 7. The targets employed were self-supporting foils (1 to 2 mg/cm^2) of spectroscopically pure Sc, V and Mn. A check on the shift in gain of amplifier was made periodically by observing photopeaks due to the radioactive sources and due to the normal background.

Radioactive sources ^{166m}Ho, ^{152}Eu, ^{133}Ba, ^{75}Se, ^{60}Co and ^{56}Co were used to provide the relative photopeak efficiency and energy calibration. The energy and area of different peaks in the spectrum were calculated with the computer code SAMPO [9].

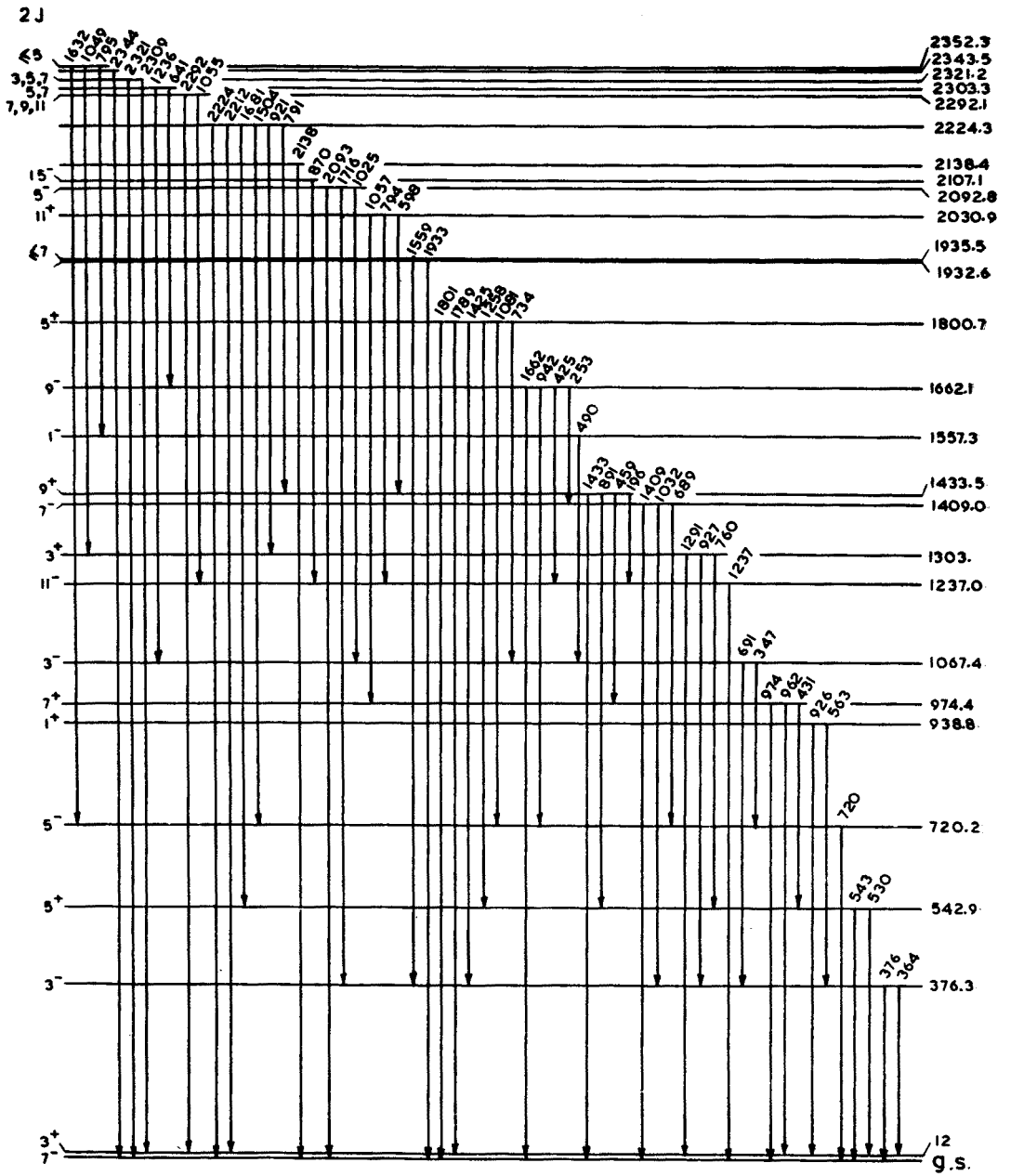


Fig. 4. Partial decay scheme of ^{45}Sc observed in the present experiment. Spin values given are $2J$ and level energies are in keV

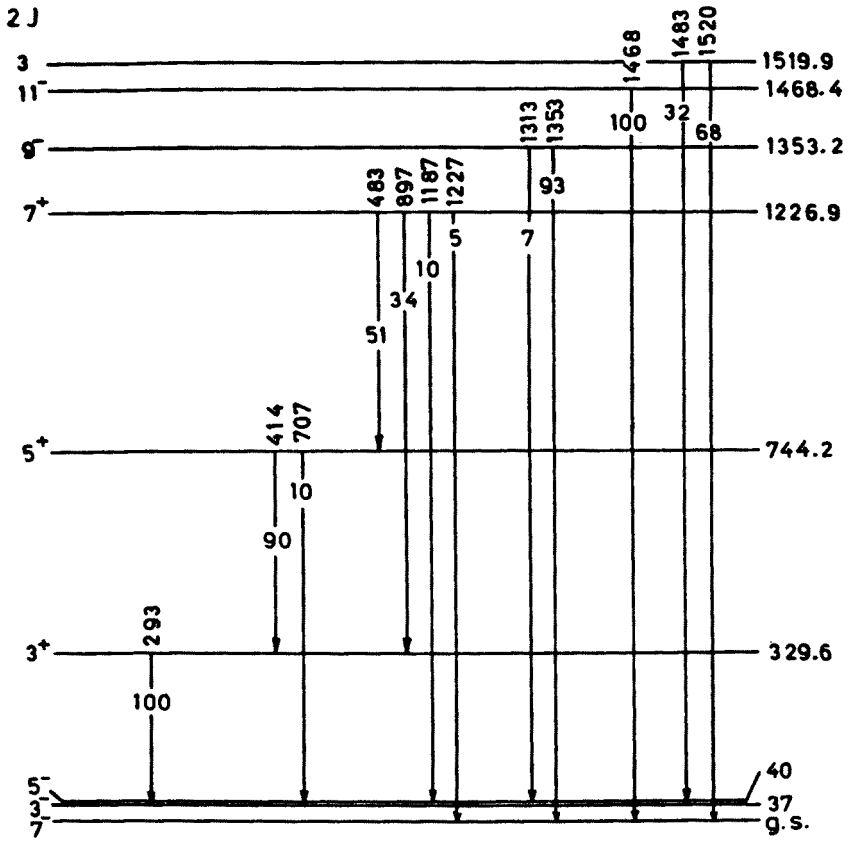


Fig. 5. Partial decay scheme of ^{45}Ti observed in the present experiment + spin values are given as $2J$ and energies in keV

3. *Lifetime measurements*

Mean lifetimes were determined for many transitions using DSA method from the singles γ-ray spectra recorded at different angles between 0° to 90°. The centroids of few photopeaks at different angles are plotted against cos θ as shown in Fig. 8. The straight line in the figure represents the least squares fit to the experimental data. The experimental values of $F(\tau)$ were calculated from the slope of the straight line. As the beam energy was almost near threshold for most of the levels, the recoiling nucleus could move only in a small forward cone. At these low bombarding energies, the (p, n) reaction is predominantly compound nucleus, therefore, this would lead to a symmetric neutron angular distribution about 90° in the c.m. system, resulting that an average neutron velocity in the beam direction is zero. It is, therefore, safe to assume that the mean forward recoil velocity of the recoiling nuclei is just the c.m. velocity.

The values of $F(\tau)$ as a function of mean nuclear lifetime were calculated using the

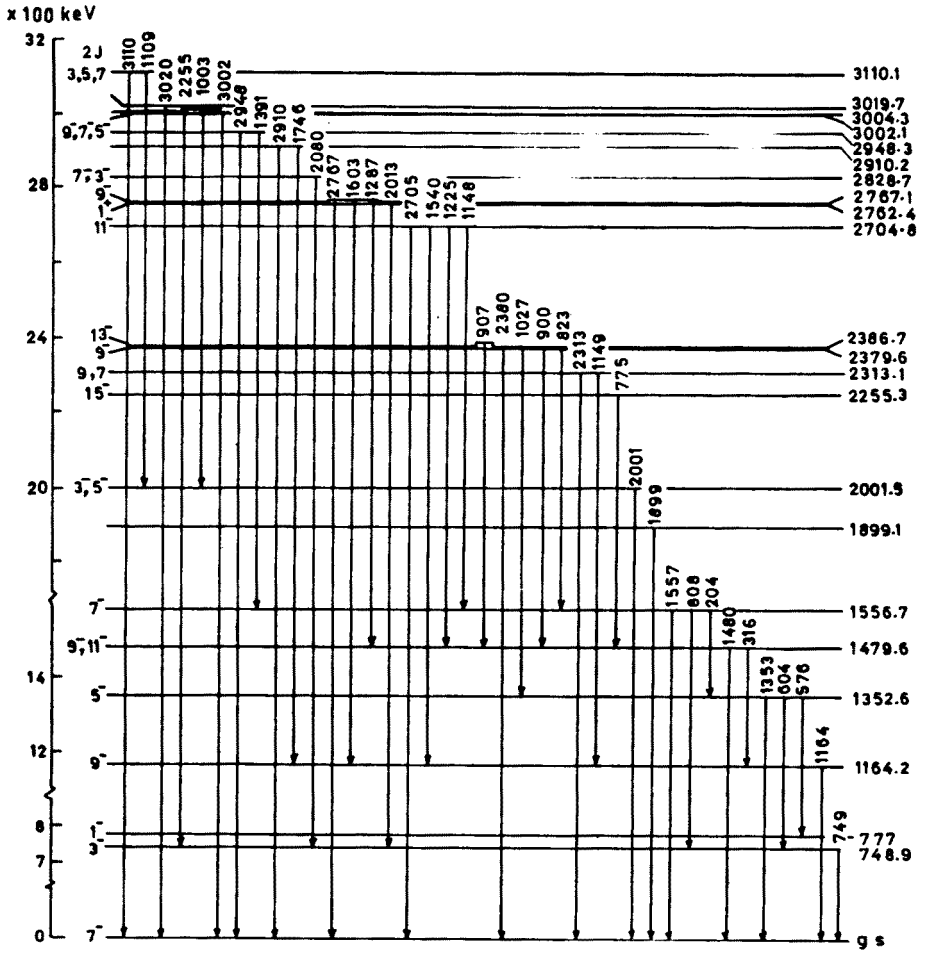


Fig. 6. Partial decay scheme of ^{51}Cr. Spin values are given as $2J$ and energies in keV. Note the discontinuity in energy scale

stopping power theory of Lindhard et al. [10] as modified by Blaugrund [11] to take into account the effect of nuclear scattering. The effect of cascade feeding was taken into account by the method of Hoffman et al. [12].

4. *Analysis of angular distribution data*

The yields of γ-rays were normalised to the yield of well known isotropic γ-ray at different angles in each nucleus. Theoretical angular distribution, for different spin sequences were calculated according to the Hauser-Feshbach [13] theory of compound nucleus using the computer code CINDY written by Sheldon and Rogers [14]. The value of mixing δ was varied from $-90°$ to $+90°$ in 38 steps for each spin sequence. The details are described in our earlier communication [15]. The χ^2 fits were made between the experimental and

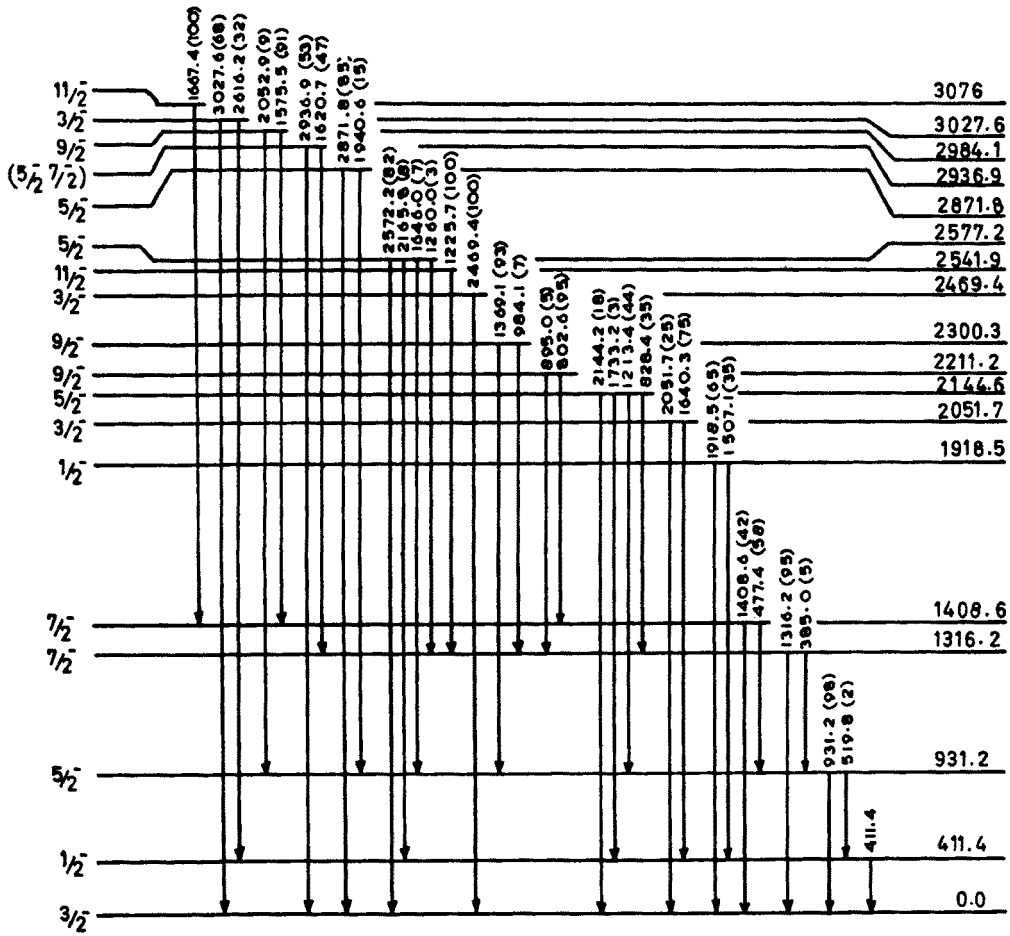


Fig. 7. Partial decay scheme of ^{55}Fe. Energies are given in keV

theoretical angular distribution as shown in Figs. 9 to 11. The 0.1 per cent confidence limit was used as a criterion to exclude unacceptable fits. The sign convention for the multipole mixing ratio is that of Rose and Brink [16]. The error in mixing ratio is corresponding to the values of mixing ratio at $\chi^2_{\min}+\chi_{\min}/n$, (where n is number of degrees of freedom) as suggested by Ezell and Scott [17].

5. *Results and discussions*

The reduced transition probabilities B(E2) have been calculated from the experimentally derived values of branching ratio, mixing ratio and lifetime. The branching ratios of γ-transitions in each nucleus have been determined from the respective γ-ray spectrum at an angle of 55° with respect to the beam direction. The errors in branching ratios were

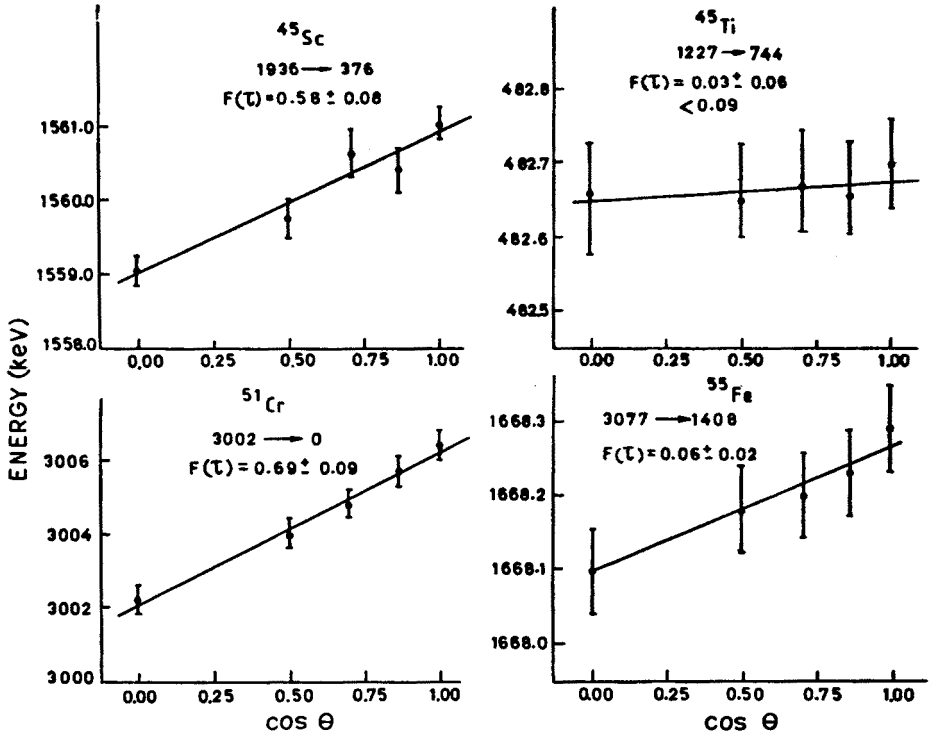


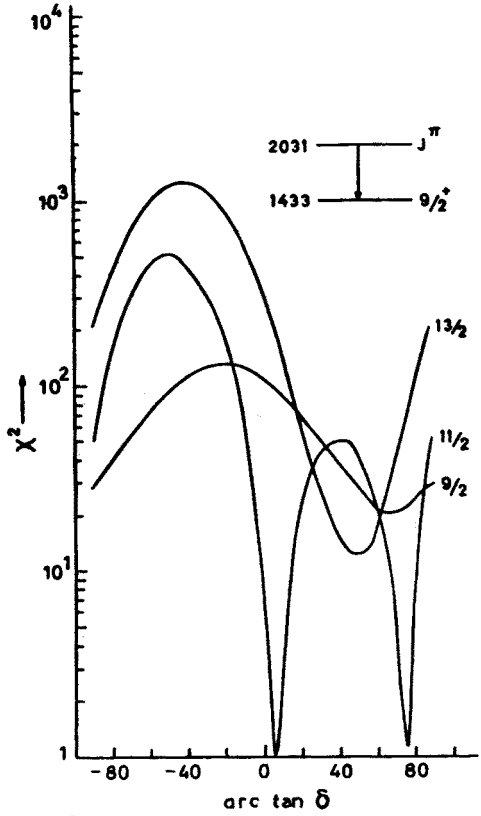
Fig. 8. Energy of photopeak vs cos θ for γ-transitions in ^{45}Sc, ^{45}Ti, ^{51}Cr and ^{55}Fe. The slope of the straight line gives the value of $F(\tau)$

estimated to be less than 5% for majority of the γ-lines. In some cases where the present experimental values are not available, the earlier reported values have been used. The result of each nucleus has been discussed separately.

5.1. ^{45}Sc

The experimental information extracted for this nucleus has been given in Table II. The values of $J(J+1)$ are plotted against the excitation energy of levels in Fig. 12 to show the band structure. Further the enhanced values of B(E2) in Table II support the band $K = 3/2^+$, $K = 1/2^+$ and $K = 3/2^-$. Previously, only one band $K = 3/2^+$ of states was reported by Toulemonde et al. [2]. The present study reveals the existence of two more bands $K = 1/2^+$ and $K = 3/2^-$ in addition to the prediction of Toulemonde et al. [2]. Styczen et al. [3] in the framework of deformed band mixing calculation and Ahalpara [18] using Hartree Fock calculations predicted two positive parity bands $K = 1/2^+$ and $K = 3/2^+$, which were observed in this work.

The lifetime of the levels at 1933 keV, 1936 keV, 2138 keV and 2321 keV are completely new measurements in this nucleus as shown in Table I. Out of the two possible spins (5/2, 7/2) for 1409 keV state, as quoted by Beene [19], a spin 7/2 seems to be the most probable spin for this level, being a member of $K = 3/2^-$ band.


2031
1433
J^π
9/2^+
13/2
11/2
9/2
χ²
arc tan δ

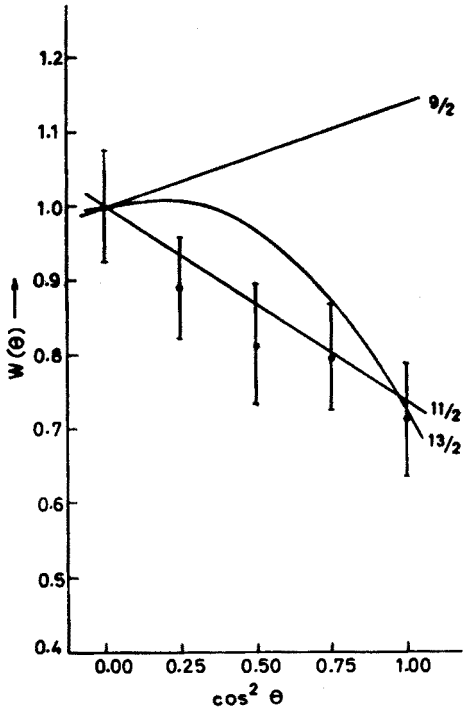
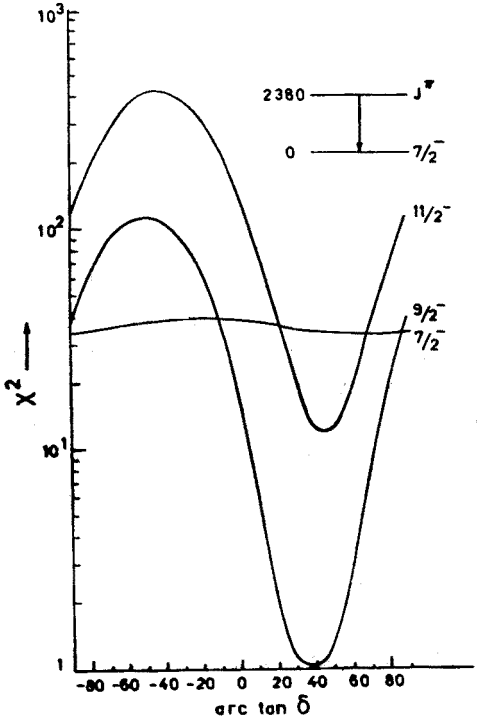

9/2
11/2
13/2
W(Θ)
cos² Θ

Fig. 9


2380
0
J^π
7/2^-
11/2^-
9/2^-
7/2^-
χ²
arc tan δ

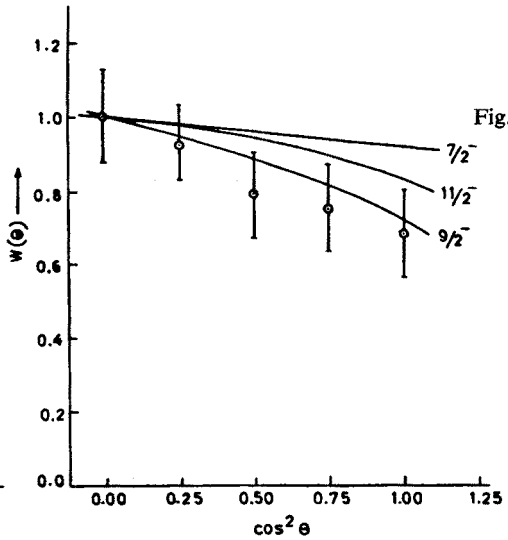

7/2^-
11/2^-
9/2^-
W(Θ)
cos² Θ

Fig. 10

5.2. ^{45}Ti

The variation of excitation energy of levels against the value of $J(J+1)$, as shown in Fig. 12, indicates the existence of a $K = 3/2^+$ band of states. The prediction of such a band in ^{45}Ti by Styczen et al. [3] and by Ahalpara [18] is therefore justified by our experimental results.

Apart from the justification of rotational band in ^{45}Ti, we have been able to assign mixing ratio of 1227 keV γ-ray for the first time as given in Table I. The 1520 keV γ-ray

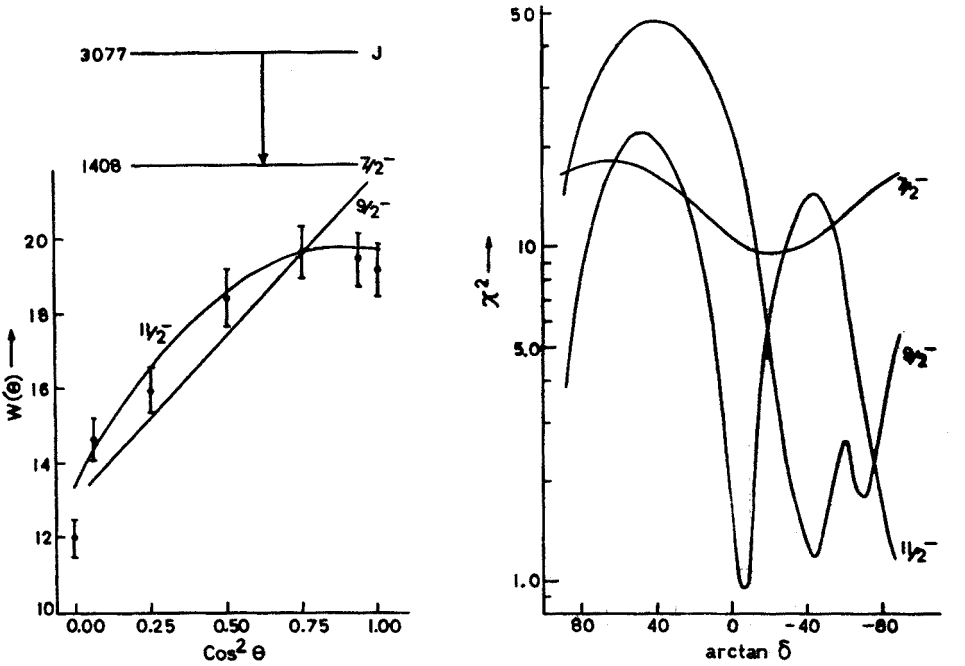


Fig. 11

Fig. 9, 10, 11. χ^2 curves along with the angular distributions for several γ-transitions in ^{45}Sc, ^{51}Cr and ^{55}Fe

was not reported by Zuk et al. [20] due to the interference of 1524 keV γ-ray arising from ^{45}Sc (p, α) ^{42}Ca reaction. In the present work, we have been able to resolve two photopeaks at 1520 keV and 1524 keV and hence the branching ratios of 68% and 32% respectively could be assigned to these transitions.

5.3. ^{51}Cr

Kasagi and Ohnuma [7] reported a deformed $K = 1/2^-$ band of states. Apart from the states of $K = 1/2^-$ band, two more band of states $K = 3/2^-$ (1899 keV, 2002 keV, 2313 keV and 2767 keV) and $K = 7/2^-$ (ground state, 1164 keV, 1480 keV, 2387 keV and 3180 keV) also follow the $J(J+1)$ rule, as shown in Fig. 12. The existence of these

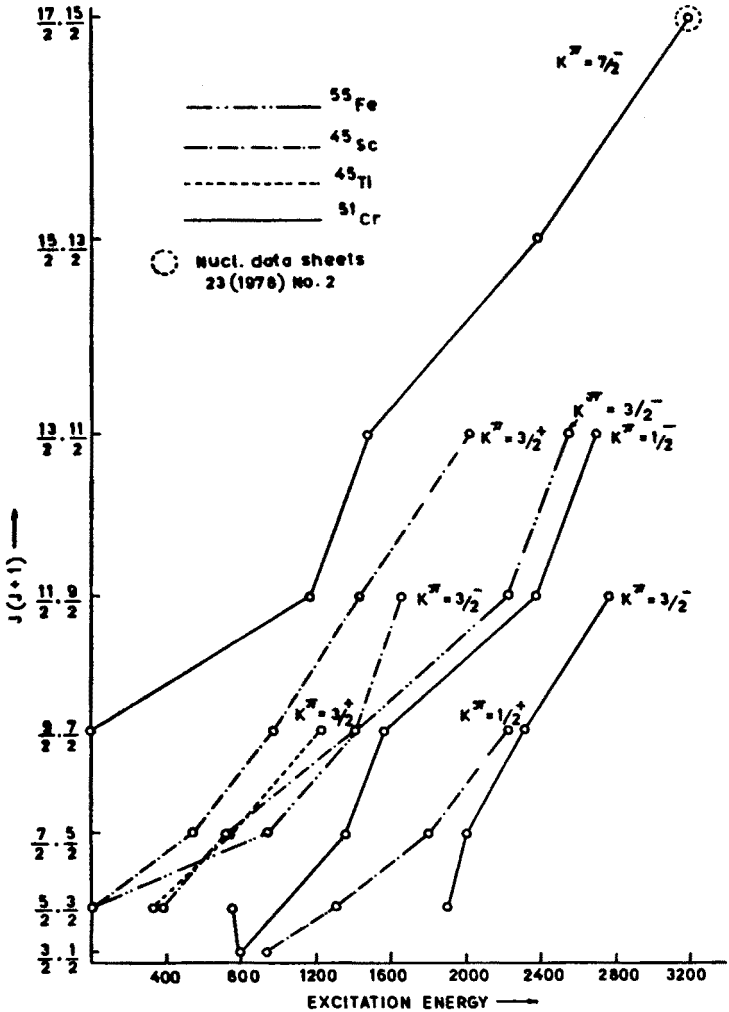


Fig. 12. Plot of excitation energy of levels (in ^{45}Sc, ^{45}Ti, ^{51}Cr and ^{55}Fe) against their $J(J+1)$ values

two bands is further justified by the enhanced B(E2) values of the various transitions in these bands as given in Table IV.

While working in the framework of deformed Hartree-Fock calculations Ahalpara and Bhatt [21] and also Szoghy et al. [6], working in the framework of Nilsson model, predicted the existence of $K = 1/2$ and $K = 7/2$ bands of states in ^{51}Cr. The present study reveals one more band $K = 3/2^-$ of states in addition to the predictions of Ahalpara and Bhatt [21] and Szoghy et al. [6]. It is interesting to note that almost all the states upto 2767 keV are members of $K = 1/2^-$ or $K = 3/2^-$ or $K = 7/2^-$ bands, which suggest that the ^{51}Cr nucleus is highly deformed.

The 2255 keV state with $J = 15/2^-$ was predicted to be a member of the $K = 7/2^-$ band by Ahalpara and Bhatt [21] and by Szoghy et al. [6]. This level energy, however,

does not fit under $J(J+1)$ rule. On the other hand the state at 3180 keV seems to be the member of this band, as shown in Fig. 12. Therefore, out of the two possible spins 15/2 and 17/2 for 3180 keV states as quoted by Auble [22], spin 15/2 seems to be more acceptable for this state.

The mixing ratios of two γ-transitions from the 2380 keV level have been measured for the first time and are given in Table I.

5.4. ^{55}Fe

On the basis of variation of level energy against $J(J+1)$, a band of states $K = 3/2^-$ is proposed for the first time, as shown in Fig. 12. The experimentally extracted values of B(E2) of several γ-transitions are given in Table V.

The lifetime of 3077 keV level as 630^{+300}_{-160} has been measured for the first time.

TABLE I

New values of branching ratio, lifetime and mixing ratio observed in ^{45}Sc, ^{45}Ti, ^{51}Cr and ^{55}Fe

Level (keV)	Transition $E\gamma$ (keV)	Branching ratio (%)	Lifetime (fs)	Mixing ratio
		^{45}Sc		
1932.6	1932.6	—	46^{+22}_{-16}	—
1935.5	1559	—	88^{+32}_{-22}	—
2138.4	2138.4	—	500^{+180}_{-120}	—
2321.2	2321.2	—	65^{+15}_{-10}	—
		^{45}Ti		
1226.9	1226.9	—	—	0.00 ± 0.03 or 1.60 ± 0.06
1519.9	1519.9	68	—	—
	1483.0	32	—	—
		^{51}Cr		
2379.6	2379.6	—	—	$0.78^{+0.33}_{-0.25}$
	823.0	—	—	$1.22^{+0.82}_{-0.53}$
		^{55}Fe		
3076.6	1668.0	—	630^{+300}_{-160}	—

TABLE II

The experimental values of B(E2) of several γ-transitions of $K = 1/2^+$, $K = 3/2^+$ and $K = 3/2^-$ bands in ^{45}Sc

$E_i(J^\pi)$ (keV)	$E_f(J^\pi)$ (keV)	Branching ratio (%)	Lifetime (fs)	$A_2 \pm \Delta A_2$ $\times 10^{-2}$	$A_4 \pm \Delta A_4$ $\times 10^{-2}$	Mixing ratio $\times 10^{-2}$	B (E2) W.U.
			$K = 3/2^+$ band				
12(3/2+)							
542.9(5/2+)	0(7/2−)	43	5.6 ± 1.6 ps[a]	—	—	—	—
	12(3/2+)	57		—	—	3.5^{+5}_{-6}[a]	<1.5
974.4(7/2+)	0(7/2−)	57	>1000	—	—	—	—
	12(3/2+)	34	1.97 ± 1.8 ps[a]	-12 ± 4	-2 ± 4	9 ± 4	18.0 ± 16.0
	542.9(5/2+)	9		14 ± 3	-12 ± 5	$236 > \delta > 36$	<224
1433.5(9/2+)	0(7/2−)	9	$5.4^{+3.0}_{-1.5}$ ps[a]	—	—	—	—
	542.9(5/2+)	70		25 ± 2	-4 ± 3	0.0	19.8 ± 10.9
	974.4(7/2+)	13		-13 ± 1	0 ± 3	78^{+26}_{-18}	38.4 ± 16.1
	1237(11/2−)	8		—	—	—	—
2030.5(11/2+)	947.4(7/2+)	—	>1000				
	1237.0(11/2−)	—	$1.1^{+0.6}_{-0.3}$ ps[a]	-17 ± 2	0 ± 3	8^{+4}_{-1} or 401^{+16}_{-28}	3.7 ± 2.0
	1433.5(9/2+)	—					
			$K = 3/2^-$ band				
376.3(3/2−)	0(7/2−)	8	42.1 ± 3.6 ps[a]	—	—	0.0[a]	21.6 ± 1.9
	12(3/2+)	92		30 ± 14	2 ± 3	0.0	—
720.6(5/2−)	0(7/2−)	100	325^{+105}_{-65}	-11 ± 1	0 ± 1	-10 ± 2	13.6 ± 6.9
1409.0(7/2−)	0(7/2−)	88	590^{+200}_{-140}	—	—	90 ± 40[a]	10.3 ± 6.2
	376.3(3/2−)	2		—	—	—	—
	720.2(5/2−)	10		—	—	—	—
1662.1(9/2−)	0(7/2−)	81	260^{+50}_{-40}	-25 ± 5	1 ± 6	154^{+26}_{-14}	14.8 ± 7.2
	720.2(5/2−)	2	—	—	—	—	—
	1237.0(11/2−)	14		—	—	3 ± 13[a]	3.0 ± 26.0
	1409(7/2−)	7		—	—	—	—
			$K = 1/2^+$ band				
938.8(11/2+)	12(3/2+)						
	376.3(3/2−)						
1303.3(3/2+)	12(3/2+)		>1000				
	376.3(3/2−)						
	542.9(5/2+)						

TABLE II (continued)

$E_i(J^\pi)$ (keV)	$E_f(J^\pi)$ (keV)	Branching ratio (%)	Lifetime (fs)	$A_2 \pm \Delta A_2$ $\times 10^{-2}$	$A_4 \pm \Delta A_4$ $\times 10^{-2}$	Mixing ratio $\times 10^{-2}$	B (E2) W.U.
1800.7(5/2+)	g.s.(7/2−)	14					
	12(3/2−)	34					
	376.3(3/2−)	8					
	542.9(5/2+)	34					
	720.2(5/2−)	6					
	1067.4(3/2−)	4					

[a] Lifetime values have been taken from Ref. [19] for B(E2) calculations.

TABLE III

The experimental values of B(E2) of several γ-transitions of $K = 3/2^+$ bands in ^{45}Ti

$E_i(J^\pi)$ (keV)	$E_f(J^\pi)$ (keV)	Branching ratio (%)	Lifetime (fs)	$A_2 \pm \Delta A_2$ $\times 10^{-2}$	$A_4 \pm \Delta A_4$ $\times 10^{-2}$	Mixing ratio $\times 10^{-2}$	B (E2) W.U.
			$K = 3/2^+$ band				
329.6(3/2+)	37(3/2−)	100	>1000	—	—	—	—
744.2(5/2+)	37(3/2−)	10	>1000	27 ± 6	-14 ± 12	-9 ± 3	—
	329.6(3/2+)	90		—	—	-40 ± 3[a]	<800
1226.9(7/2+)	g.s.(7/2−)	5	>1000	-4 ± 2	0 ± 5	0 ± 2 or 160 ± 6	
	329.6(3/2+)	34		-3 ± 2	0 ± 2	0 ± 7 or 710 ± 1430	<50
	744.2(5/2+)	51		-5 ± 3	-12 ± 5	-32^{+6}_{-3}	<155

[a] Mixing ratios have been taken from Ref. [19] for B(E2) calculations.

All the rotational bands with $\Delta J = 1$ observed in the present experiment are fitted with the expression

$$E = E_0 + AJ(J+1) + BJ^2(J+1)^2$$

to extract the band parameters E_0, A and B. The values of these parameters for different nuclei and bands are shown in Table VI.

The authors wish to thank Professors H. S. Hans and V. B. Bhanot for fruitful discussions and encouragement during the course of this work. We are also grateful to the accelerator crew for the smooth running of the machine.

TABLE IV

The experimental values of B (E2) of several γ-transitions of $K = 1/2^-$, $K = 3/2^-$ and $K = 7/2^-$ bands in ^{51}Cr

$E_i(J^\pi)$ (keV)	$E_f(J^\pi)$ (keV)	Branching ratio (%)	Lifetime (fs)	$A_2 \pm \Delta A_2$ $\times 10^{-2}$	$A_4 \pm \Delta A_4$ $\times 10^{-2}$	Mixing ratio $\times 10^{-2}$	B (E2) W.U.
			$K = 1/2^-$ band				
777(1/2$^-$)							
748.9(3/2$^-$)	g.s.(7/2$^-$)	100					
1352.6(5/2$^-$)	g.s.(7/2$^-$)	38		-26 ± 2	2 ± 2	-19 ± 3	<3
	748.9(3/2$^-$)	55	>700	-12 ± 1	0.3 ± 1	-7 ± 4	<4
	777(1/2$^-$)	7		—	—	0 ± 6[a]	<100
1556.7(7/2$^-$)	g.s.(7/2$^-$)	14					
	748.9(3/2$^-$)	80	>700	-13 ± 2	0 ± 3	75 ± 3	<0.6
	1352.6(5/2$^-$)	6		—	—	0 ± 3[a]	<93
2379.6(9/2$^-$)	g.s.(7/2$^-$)	33		-9 ± 3	0 ± 4	78^{+33}_{-25}	58.4 ± 33.1
	1352.6(5/2$^-$)	29	220^{+180}_{-170}	—	—	—	—
	1479.6(11/2$^-$)	27		—	—	—	—
	1556.7(7/2$^-$)	11		-24 ± 3	2 ± 4	-122^{+82}_{-53}	58 ± 34
2704.8(11/2$^-$)	g.s.(7/2$^-$)	—		—	—	—	—
	1164.2(9/2$^-$)	—	122^{+30}_{-40}	—	—	—	—
	1479.6(11/2$^-$)	—		-12 ± 1	3 ± 1	9 ± 2	—
	1556.7(7/2$^-$)	—		3 ± 5	-3 ± 5	-32^{+54}_{-75}	—
			$K = 3/2^-$ band				
1899.1(3/2$^-$)	g.s.(7/2$^-$)	100	450^{+250}_{-140}				
2001.5(5/2$^-$)	g.s.(7/2$^-$)	100	22 ± 6				
2313.5(7/2$^-$)	g.s.(7/2$^-$)	—	22 ± 6				
2767.1(9/2$^-$)	g.s.(7/2$^-$)	50	48^{+14}_{-12}	-4 ± 2	1 ± 2	36 ± 11	
	1164.2(9/2$^-$)	26					
	1479.6(11/2$^-$)	24		24 ± 5	-10 ± 10	-9 ± 2	
			$K = 7/2^-$ band				
g.s.(7/2$^-$)							
1164.2(9/2$^-$)	g.s.(7/2$^-$)	100	94^{+18}_{-22}	-50 ± 4	1 ± 4	84^{+35}_{-29}	147.4 ± 79.7
1479.6(11/2$^-$)	g.s.(7/2$^-$)	51	600^{+500}_{-200}	9 ± 2	2 ± 2	4 ± 3	8.7 ± 1.6
	1164.2(9/2$^-$)	49					
2386.7(13/2$^-$)	1479.6(11/2$^-$)	100	85^{+17}_{-15}	-13 ± 7	-10 ± 8	7 ± 2 or 433^{+81}_{-84}	5.7 ± 0.2

[a] Mixing ratios have been taken from Ref. [7] for B (E2) calculations.

TABLE V

The experimental values of B(E2) of several γ-transitions of $K = 3/2^-$ band in ^{55}Fe

$E_i(J^\pi)$ (keV)	$E_f(J^\pi)$ (keV)	Branching ratio (%)	Lifetime (fs)	$A_2 \pm \Delta A_2$ $\times 10^{-2}$	$A_4 \pm \Delta A_4$ $\times 10^{-2}$	Mixing ratio $\times 10^{-2}$	B(E2) W.U.
			$K = 3/2^-$ band				
g.s.($3/2^-$)							
931($5/2^-$)	g.s.($3/2^-$)	98	9.3 ± 2.8 ps[a]	-17 ± 2	-1 ± 2	0	9.9 ± 4.2
	411($11/2^-$)	2		—	—	—	—
1409($7/2^-$)	g.s.($3/2^-$)	43	40 ± 3 ps[a]	-16 ± 3	-1 ± 3	0	0.13 ± 0.06
	931($5/2^-$)	57		—	—	0.003 ± 0.015[a]	
2212($9/2^-$)	1316($7/2^-$)	5	470^{+230}_{-300}	—	—	—	—
	1409($7/2^-$)	95		-4 ± 5	2 ± 6	16 ± 9	9.9 ± 2.0
2541($11/2^-$)	1316($7/2^-$)	100	570^{+210}_{-420}	—	—	—	—

[a] Lifetimes and mixing ratios have been taken from Ref. [23] for B(E2) calculations.

TABLE VI

Band parameters E_0, A and B calculated for various bands in ^{45}Sc, ^{45}Ti, ^{51}Cr and ^{55}Fe nuclei

Nucleus	K^π-band	E_0	A	B
^{45}Sc	$3/2^+$	−250.30	87.41	−0.679
	$3/2^-$	−183.58	140.13	−2.65
	$1/2^+$	839.92	133.90	−2.75
^{45}Ti	$3/2^+$	−19.92	97.57	−1.17
^{51}Cr	$1/2^-$	616.03	77.34	−0.49
	$3/2^-$	1814.39	16.28	0.91
	$7/2^-$	−1670.40	127.11	−0.92
^{55}Fe	$3/2^-$	−520.83	167.48	−2.36

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