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Multipole mixing ratios of electromagnetic transitions in ^{152}Sm

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Abstract. Using $\gamma\gamma(\theta)$ and $e_K\gamma(\theta)$ directional correlation techniques, we have determined: (*a*) the multipole character of some transitions connecting the quadrupole and octupole vibrational bands to the ground state rotational band in ^{152}Sm following the decay of ^{152}Eu; and (*b*) the K-shell particle parameter of the 121·8 keV transition which de-excites the lowest energy level of the same nucleus.

The results show that transitions from the β and γ vibrational bands are predominantly E2, with a large E0 admixture in the former case, while such a contribution is almost absent in the transition from the γ band. These results are compared with Kumar's theoretical predictions and with previously reported experimental values.

The investigation on the 121·8 keV K-shell particle parameter yields a value which is smaller than theoretically predicted by $(8{\cdot}5 \pm 2{\cdot}1)\%$.

1. Introduction

The even–even nucleus ^{152}Sm is situated at the beginning of the region of deformed nuclei which extends from $A = 150$ to 190 and its level structure and the character of the transitions associated with it play an important role in understanding the nuclear excitation mechanism. In particular, accurate determinations of the magnitude and sign of the electric and magnetic multipole mixing ratios in $\Delta I = 0,1$ transitions from the β and γ vibrational bands to the ground state band provide sensitive tests of nuclear models.

The very long halflife of ^{152}Eu ($t_{1/2} = 12{\cdot}4$ yr) which decays by EC and β^+ emission to ^{152}Sm presents a great experimental advantage and in recent years a plethora of data concerning this decay has been produced. The decay scheme is shown in figure 1. The aim of the present work is: (*a*) to determine the multipole character of some transitions connecting the quadrupole and octupole vibrational bands with the ground state rotational band. Such measurements have been performed by several groups (see references in table 3). Nevertheless advances in theory, and in particular the work of Kumar and Baranger (1968), promote the need for accumulating experimental data of high precision. In addition to E2:M1 mixing ratios obtained from $\gamma\gamma$ directional correlations, the E0:E2 admixture determined from $e_K\gamma$ directional correlations serves as a further test of theory; (*b*) to measure the particle parameters of the 121·8 keV, E2 transition in ^{152}Sm. There is some controversy in the existing up-to-date data regarding the K-shell particle parameter of this transition from the first excited state of ^{152}Sm to its ground state. Most of the previous measurements have resulted in a b_2^K (E2:121·8 keV) value which is a few per cent lower than theoretically predicted.

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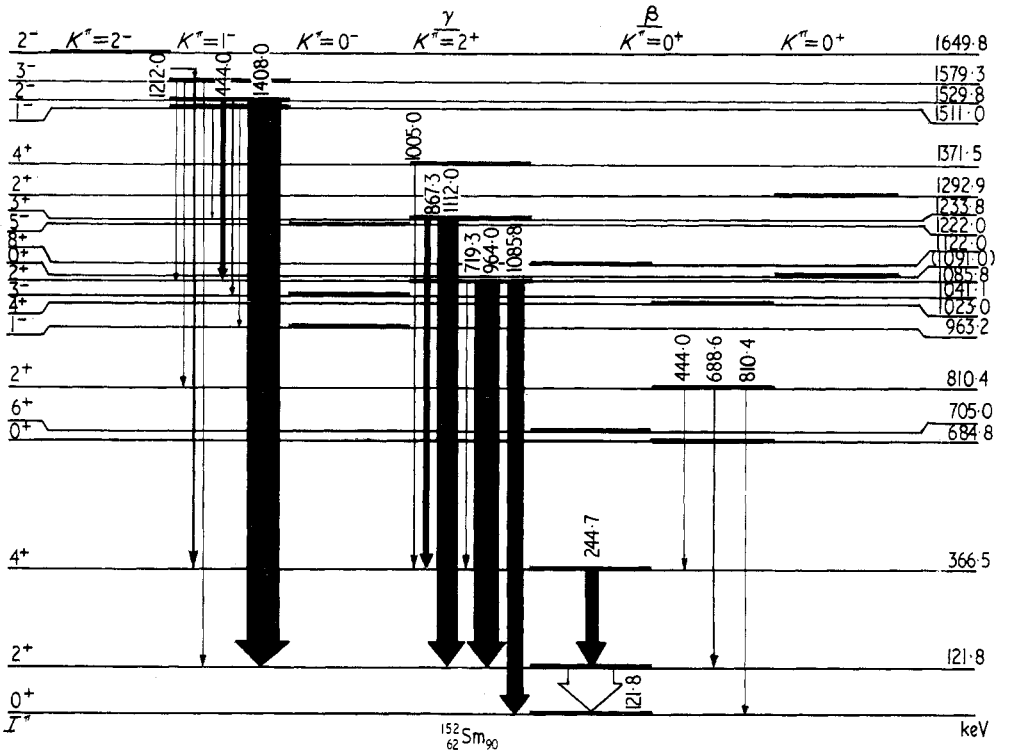

Figure 1. A simplified version of the level structure of ^{152}Sm populated following the β^+ and EC decay of ^{152}Eu (12·4 yr). It is based on the information from the work of Riedinger *et al* (1970).

2. Experimental procedure

2.1. Source preparation

Two types of sources were used throughout the experiment. In the $e_K\gamma$, γe_K, and some $\gamma\gamma$ directional correlation measurements the source was prepared by irradiating mass-separated ^{151}Eu in a flux of $1{\cdot}5 \times 10^{14}$ neutrons cm^{-2} for two weeks at UKAEA, Harwell. The mass-separated† ^{151}Eu had the form of a round spot approximately 3 mm in diameter on 680 μg cm^{-2} Al foil. The penetration depth of the ions in the foil had been kept to a minimum by decelerating them to a few keV and any correction for electron scattering is negligible. The strength of this source was 100 μCi.

The second type of source which was used for most of the $\gamma\gamma$ directional correlation measurements was liquid and was obtained from the Radiochemical Centre, Amersham, in the form of europium chloride in 0·1 N HCl. Several sources of various strength were prepared from this solution.

2.2. $\gamma\gamma$ directional correlations

All the measured correlations involved the 121·8 keV γ ray and as there is no other

† The mass-separated ^{151}Eu was kindly provided by Professor Z W Grabowski, Purdue University, Indiana, USA.

transition of significant intensity in this energy region, it is possible to use a NaI(T1) crystal to record it. Thus the experiment had the advantage of the high efficiency of a NaI(T1) detector, without being affected by its poor energy resolution. The only additional contribution in the region of the 121·8 keV photopeak comes from the Compton scattering of the higher energy transitions. In order to minimize this and to test its effect on the final results, a thin NaI(T1) crystal measuring 3·8 cm in diameter and 0·6 cm thick was used during the first group of measurements, and for the remaining measurements a 7·6 × 7·6 cm NaI(T1) crystal was used. In both cases the NaI(T1) crystal was used as the moving detector.

The γ ray transitions in the region between 0·2 and 1·5 MeV which precede the 121·8 keV transition were detected by a 30 cm^3 Ge(Li) detector which had a resolution of 2·3 keV at 1·33 MeV. The time resolution of the coincident system (2τ) was 50 ns. The source was placed at a distance between 8 to 14 cm from each detector according to its strength. It was centred with an accuracy of better than 0·8 %.

The correlation was measured at four angles and these were changed periodically in order to minimize the effect of a possible misplacement of the Ge(Li) crystal with respect to the axis of the system. The coincidence spectrum at each angle was recorded in a quadrant of a 2048 channel analyser. To minimize the effect of possible electronic drifting, particularly in the NaI(T1) gate, the counting time per position was chosen to be relatively short (10 min). As a check on possible fluctuations and also to allow a miscentring correction to be applied, the counts associated with the NaI(T1) detector were recorded at each position.

Accidental coincidences were recorded separately after the end of each run. Following this, the NaI(T1) gate was moved above the 121·8 keV photopeak and the correlation experiment repeated. The coincidence spectrum recorded in this way was used to simulate the coincidence spectrum between the Compton background under the 121·8 keV photopeak and the preceding higher energy γ rays. The accidental contribution to this spectrum was then evaluated and the corrected spectrum associated with these Compton events subtracted from the spectrum in coincidence with the 121·8 keV photopeak. After correcting for accidental coincidences the number of counts under each photopeak was determined. A computer program fitted the data to the angular correlation function and applied appropriate solid angle and source finite-size corrections. A χ^2 test was incorporated to check the reliability of the data.

2.3. Correlations involving internal conversion electrons

2.3.1. $e_K\gamma$ directional correlations. The internal conversion electrons were detected by a magnetic lens spectrometer which was operated at an energy resolution of 2·0 % in $B\rho$ units (FWHM) (see figure 2). This was chosen in such a way that the K- and L-conversion lines would be well resolved up to the region of 1 MeV and at the same time this would allow sufficient transmission in the spectrometer and therefore an adequate counting rate. Since the investigated transitions were in an energy region beyond 0·6 MeV, the intensity of the conversion electron lines was rather low.

The internal conversion electrons were recorded in coincidence with the 121·8 keV γ transition which was detected by a 10 cm^3 Ge(Li) crystal and used as a moving detector (see figure 3). An important contribution to the coincident spectrum is due to coincidences between the 344·2 keV transition in ^{152}Gd and the β decay electrons which feed it and are selected by the spectrometer. There is thus a true coincident contribution lying in the region of the 121·8 keV photopeak from the Compton distribution of the

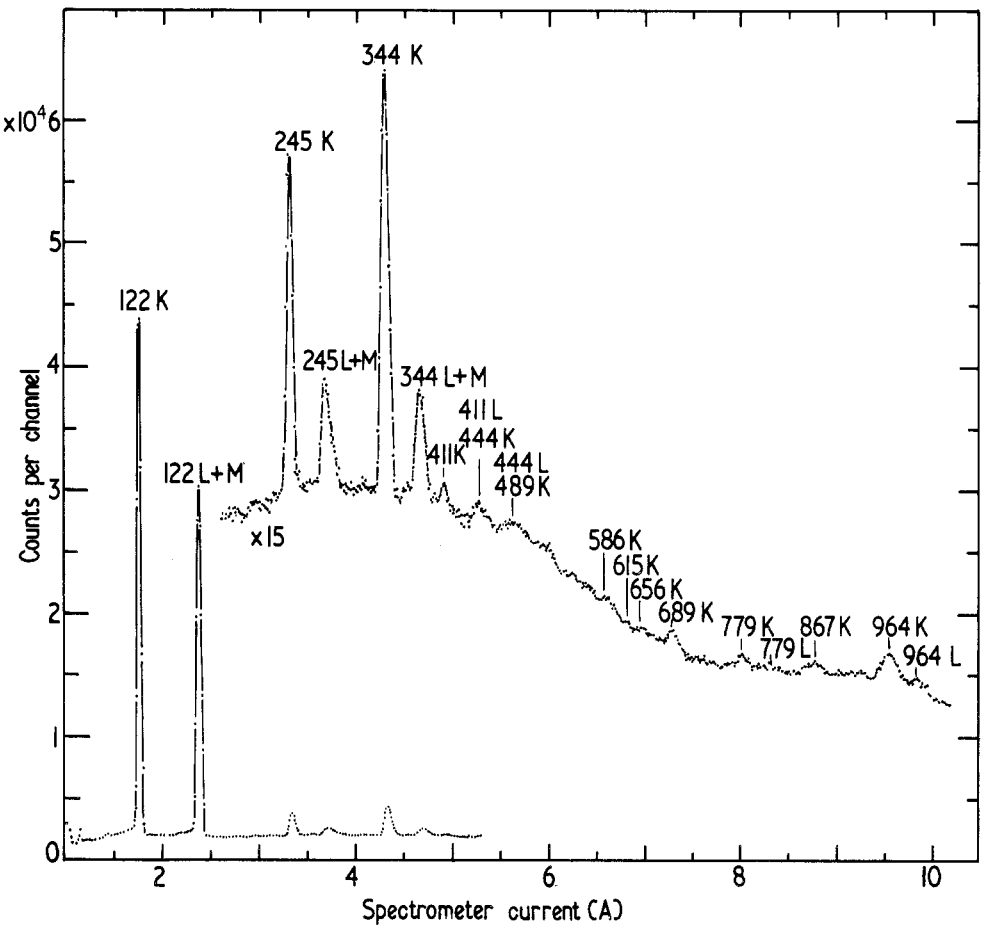

Figure 2. Internal conversion electron spectrum of ^{152}Sm. The electron lines are marked with the energy of the corresponding γ transition.

344·2 keV γ rays and in order to determine this as accurately as possible the good resolution of a Ge(Li) detector in the γ channel is necessary. The coincident spectrum obtained at four correlation angles was recorded in quadrants of a 400 channel analyser. Accidental coincidences were recorded simultaneously and, operating the multichannel analyser in the add–subtract mode, the accidental coincidences were subtracted automatically.

2.3.2. γe_K directional correlations. The 121·8 keV K-electrons were again selected by the magnetic spectrometer and the 30 cm^3 Ge(Li) detector was used to detect the coincident γ rays (see figure 4). The β^+ radiation feeds only the lowest energy levels in ^{152}Sm and has extremely low intensity so it does not contribute to the coincidence spectrum, which is determined entirely by the 121·8 keV conversion electrons. This presents one of the major experimental advantages in these γe_K directional correlation measurements.

The experimental system and data collection were similar to those used for the $\gamma\gamma$ correlation measurements.

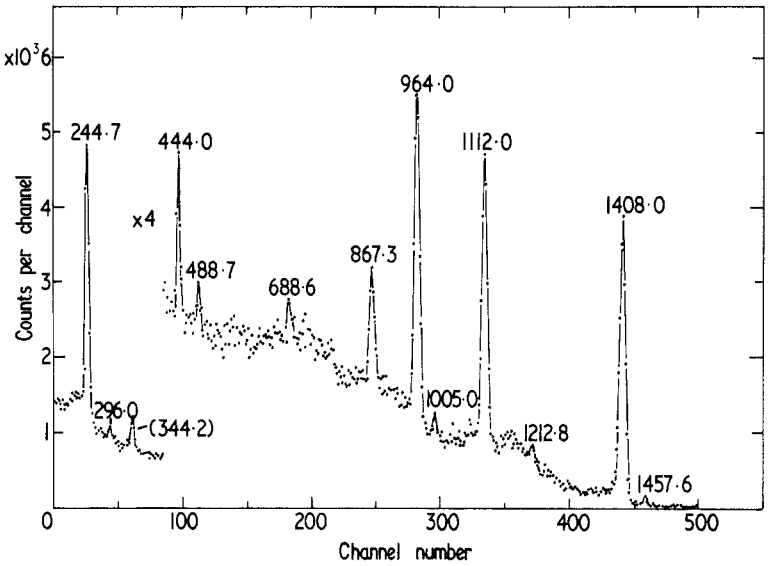

Figure 3. The ^{152}Sm γ ray low energy spectrum in coincidence with the 122 keV K-shell internal conversion electrons. Accidental coincidences have been subtracted. The presence of the 344 keV line of ^{152}Gd is due to its coincidence with the β^- background. Energies are given in keV.

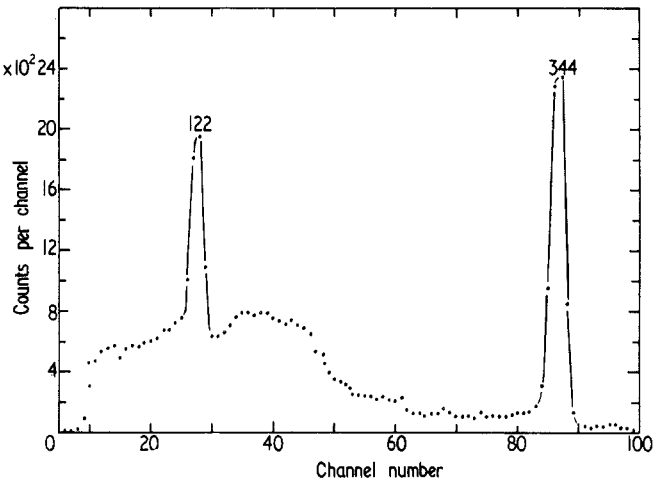

Figure 4. The γ ray spectrum of ^{152}Sm in the region of 122 keV in coincidence with the 689 keV K-conversion electrons. Energies are given in keV. Accidental coincidences have been subtracted. The appearance of the 344 keV line is due to its coincidence with the β^- background.

3. Experimental results

3.1. Data analysis

All the investigated correlations involved the 121·8 keV transition and nine $\gamma\gamma$ angular correlations were measured. The final result for each correlation was calculated by taking the weighted mean of all individual runs which used the same type of source.

Almost half of the investigated correlations involve intermediate unobserved transitions. The angular correlation function in this case has the form

$$W(\theta) = \sum_{k \text{ even}} G_k Q_k^{(1)} A_k^{(1)} U_k^{(2)} Q_k^{(3)} A_k^{(3)} \mathrm{P}_k(\cos\theta)$$

where the superscript refers to the order of the transition in the cascade. For simplicity the notation $A_{kk} = A_k^{(1)} A_k^{(3)}$ and $Q_{kk} = Q_k^{(1)} Q_k^{(3)}$ is used, where the A_k coefficients describe the components of the cascade and the Q_k factors are the solid angle corrections when a particular radiation is recorded by a detector. The deorientation parameters U_k correct for effects of the unobserved intermediate transition and if there is more than one such transition, U_k is the product of all individual deorientation parameters. The coefficients G_k account for attenuation effects due to interactions of the static electromagnetic moments of the nuclear states with extranuclear fields. In general, liquid sources are not expected to show any substantial attenuation but large attenuation effects may be observed when solid sources are used. It is assumed that the attenuation is predominantly associated with the 122 keV level.

The attenuation coefficients may be determined if one observes a correlation having known A_{kk} coefficients, providing the Q_{kk} coefficients are also known. In the present work both solid and liquid sources were used and since no attenuation is expected for the latter the ratio A_{kk}(solid)/A_{kk}(liquid) provides an additional means for evaluating G_k. The values of G_k determined from different cascades are presented in table 1 and the mean

Table 1. Solid source attenuation coefficients of the 121·8 keV level of ^{152}Sm, as determined from various transitions.

Transition energy	G_2A_{22}	G_4A_{44}	G_2	G_4
244·7	0·082(3)	−0·004(5)	0·81(3)[a]	—
688·6	−0·13(3)	0·28(5)	—	0·86(16)[b]
867·3	0·071(6)	−0·146(8)	0·82(16)	0·79(4)[b]
964·0	−0·008(4)	0·253(6)	—	0·78(2)[b]
1112·0	−0·187(5)	−0·077(8)	0·80(3)	0·79(17)
1408·0	0·176(5)	−0·017(12)	0·85(4)	—
	Weighted mean		0·81(2)	0·78(2)

a Calculated from the ratio G_2A_{22}/A_{22}(theory).
b Calculated from the ratio G_4A_{44}/A_{44}(calc), where A_{44}(calc) was deduced from the value of δ.

values are $G_2 = 0{\cdot}81(2)$ and $G_4 = 0{\cdot}78(2)$. The G_2 coefficient is consistent with a previous result using the same source, $G_2 = 0{\cdot}85 \pm 0{\cdot}05$ (Doubt and Hamilton 1971) and with the value obtained using a similarly prepared source (Nasir *et al* 1967). The assumption that $G_k \simeq 1$ for the liquid source is also consistent with previous work (Nielsen *et al* 1969 and Helppi and Hattula 1970). These G_k values were used when evaluating results obtained with the solid source in order to determine mixing ratios.

The six most intense transitions out of the nine investigated in the $\gamma\gamma$ correlation measurements were used in a series of γe_K directional correlation experiments to measure the particle parameters b_K of the 121·8 keV K-conversion electrons. In most cases these may be simply evaluated from the ratio $A_{kk}(\gamma e_K)/A_{kk}(\gamma\gamma)$. However, when the A_{44} coefficient is large, and the normalized fourth rank particle parameter b_4 may be

accurately measured, then b_2 may be deduced by use of the recurrence relation (Hager and Seltzer 1968b)

$$b_2 = 1{\cdot}4 - 0{\cdot}4b_4.$$

This latter method has the advantage of considerably reducing the experimental error on b_2.

The 964·0 and 688·6 keV $2^+ \rightarrow 2^+$ transitions from the lowest members of the β and γ vibrational bands to the first excited state of the ground state band were studied to determine the extent of E0 admixture by measuring $e_K\gamma$ directional correlations. The intensity of the E0:E2 mixing ratio q^2 may be defined in terms of the E0 and E2 absolute transition probabilities by the relation (Church and Weneser 1958)

$$q^2(\mathrm{E0:E2;i \rightarrow f}) = T_{if}(\mathrm{E0})/(\alpha_K(\mathrm{E2})T_{if}(\mathrm{E2})). \tag{1}$$

By expressing T_{if} in terms of reduced matrix elements, q may be evaluated from the expression

$$q(\mathrm{E0:E2;i \rightarrow f}) = 2{\cdot}86 \times 10^{-7}\left(\frac{\Omega_K}{\alpha_K(\mathrm{E2})E_\gamma^5}\right)^{1/2}\frac{\epsilon(\mathrm{E0:E2;i \rightarrow f})}{R_0^2} \tag{2}$$

where $\epsilon(\mathrm{E0:E2;i \rightarrow f}) = (2I_i+1)^{1/2}\rho_{if}(\mathrm{E0})eR_0^2/M_{if}(\mathrm{E2})$, and Ω_K (in s^{-1}) is the electronic factor defined and given graphically by Church and Weneser (1956a). In equation (2) E is in MeV and R_0 is in barns. In the present work values of Ω_K were calculated using a computer program written by Pauli (1969). By definition q has the same sign as the parameter ϵ. The latter is related to the dimensionless ratio X as defined by Rasmussen (1960)

$$X(\mathrm{E0:E2;i \rightarrow f}) = \epsilon^2(\mathrm{E0:E2;i \rightarrow f}). \tag{3}$$

The A_{kk} coefficients obtained from an $e_K\gamma$ experiment and the internal conversion coefficient α_K are quadratic functions of the mixing ratios, δ and q, and the penetration parameter λ which is defined by Church and Weneser (1956b) and takes account of nuclear penetration by the IC electrons for the M1 process. If δ has been determined from a $\gamma\gamma$ experiment and α_K is known, one can plot q against λ using the functions A_{kk} and α_K and their experimental values. The interception of the ellipses give the set(s) of solutions for q and λ. The α_K values used in the present work are taken from Riedinger *et al* (1970).

3.2. Results

The correlation measurements using the two sizes of NaI(Tl) detector were found to be consistent if care was taken when assessing the background below the photopeaks and it was thus possible to average the two sets of data. Previous experience (Doubt and Hamilton 1971 and references cited therein) suggest that failure to correctly take account of this background may be one of the main sources of error in many of the measurements of correlations in ^{152}Sm.

The convention for the sign of the multipole mixing ratio δ adopted in the present work is that of Krane and Steffen (1970). The results are summarized in tables 1–5, and particular aspects of certain measurements are now considered separately.

3.2.1. 244·7–121·8 keV correlation. In this 4^+–2^+–0^+ cascade the theoretical A_{kk} values can be calculated since only pure E2 transitions are involved and the correlation can

Table 2. $\gamma\gamma$ directional correlation coefficients and multipole mixing ratios for the various transitions in coincidence with the 121·8 keV ground state transition in ^{152}Sm. Energies are given in keV. The solid source results (S) have been corrected for attenuation, and those obtained with the liquid source (L) are assumed to be unattenuated.

Initial level Energy	I, K^{π}; band	Transition energy	A_{22}	A_{44}		Mixing ratio, δ
366·5	4,0$^+$; ground	244·7	0·102(4)	0·005(6)	S	
810·4	2,0$^+$; β	688·6	−0·16(4)	0·36(7)	S	8^{+9}_{-3}
1085·8	2,2$^+$; γ	964·0	−0·002(6)	0·299(24)	L	$-10{\cdot}2^{+0{\cdot}8}_{-1{\cdot}0}$
			−0·010(5)	0·323(8)	S	$-11{\cdot}3^{+0{\cdot}7}_{-0{\cdot}8}$
1233·8	3,2$^+$; γ	867·3	0·087(16)	−0·142(25)§	L	$-12{\cdot}4^{+2{\cdot}5}_{-4{\cdot}0}$
			0·088(8)	−0·186(12)	S	$-12{\cdot}2^{+1{\cdot}2}_{-1{\cdot}6}$
1233·8	3,2$^+$; γ	1112·0	−0·234(7)	−0·097(18)	L	-26^{+5}_{-7}
			−0·230(8)	−0·099(11)	S	-30^{+7}_{-12}
1371·5	4,2$^+$; γ	1005·0	0·01(6)	0·10(10)§	S	$-3{\cdot}0^{+1{\cdot}0}_{-2{\cdot}4}$†
1529·8	2,1$^-$; octup	444·0	−0·009(10)	0·004(21)§	L	0·03 ± 0·08
1529·8	2,1$^-$; octup	1408·0	0·207(8)	−0·009(10)	L	0·057 ± 0·010‡
			0·216(7)	−0·022(15)	S	0·046 ± 0·010‡
1579·3	3,1$^-$; octup	1212·0	−0·18(4)	−0·03(5)§	S	$0{\cdot}05^{+0{\cdot}03}_{-0{\cdot}05}$

† Only the negative solution of δ is given, see text.
‡ Assuming δ (E3 : E1) = 0.
§ The values listed correspond to $U_k A_{kk}$.

Table 3. Experimental and theoretical values of multipole mixing ratios in various electromagnetic transitions in ^{152}Sm.

Transition energy (keV)	Experimental multipole mixing ratio δ						Theory
	a	b	c	d	f	g	h
444·0			0·15 ± 0·12		0·03 ± 0·08		
688·7	13^{+28}_{-5}e	17^{+5}_{-3}	$^{+30}_{-30} \rightarrow \infty$	$^{+25}_{-25} \rightarrow \infty$		8^{+9}_{-3}	10·8
867·3	−5·0 ± 0·7	−6·1 ± 0·3	−5·6 ± 0·5	$-7{\cdot}1^{+1{\cdot}2}_{-0{\cdot}9}$	$-12{\cdot}4^{+2{\cdot}5}_{-4{\cdot}0}$	$-12{\cdot}2^{+1{\cdot}2}_{-1{\cdot}6}$	−16·5
964·0	−11·0 ± 1·0	−9·2 ± 0·2	−15·8 ± 2·2†	−8·2 ± 0·5	$-10{\cdot}2^{+0{\cdot}8}_{-1{\cdot}0}$	$-11{\cdot}3^{+0{\cdot}7}_{-0{\cdot}8}$	−24·3
1005·0	-6^{+3}_{-19}	$-2{\cdot}8^{+0{\cdot}2}_{-0{\cdot}3}$	$-4{\cdot}5^{+1{\cdot}2}_{-2{\cdot}5}$	$-3{\cdot}0^{+0{\cdot}9}_{-2{\cdot}0}$		$-3{\cdot}0^{+1{\cdot}0}_{-2{\cdot}4}$‡	−9·6
1112·0	−8·9 ± 1·0	$-16{\cdot}8^{+3{\cdot}6}_{-2{\cdot}5}$	-16^{+3}_{-4}	$-13{\cdot}7^{+2{\cdot}1}_{-3{\cdot}1}$	-26^{+5}_{-7}	-30^{+7}_{-12}	−26·6
1212·8			0·03 ± 0·03	0·03 ± 0·03		$0{\cdot}05^{+0{\cdot}03}_{-0{\cdot}05}$	
1408·0			0·047 ± 0·008	0·03 ± 0·01	0·057 ± 0·010§	0·046 ± 0·010§	

a Lange (1971); b Ramaya *et al* (1971); c Helppi and Hattula (1970); d Barrette *et al* (1970); e McGowan *et al* (1968); f present work, liquid source; g present work, solid source; h Kumar (1971).
† Recalculated from A_{22}.
‡ Only the negative solution is given. The same applies for Barrette *et al* (1970).
§ Assuming that δ(E3 : E1) = 0; see text.

be used for determining the attenuation coefficients. The experimental $G_k A_{kk}$ values obtained are

$$G_2 A_{22} = 0{\cdot}082(3) \qquad G_4 A_{44} = -0{\cdot}004(5).$$

The theoretically predicted A_{kk} values are $A_{22} = 0{\cdot}102$ and $A_{44} = 0{\cdot}009$ which yield $G_2 = 0{\cdot}807(31)$. Since A_{44} is very small and its experimentally measured value has a rather large error, no useful assessment of G_4 can be made.

Table 4. γ conversion electrons directional correlation coefficients for the various transitions in coincidence with the 121·8 keV K-shell electron in ^{152}Sm.

Transition energy (keV)	G_2A_{22}	G_4A_{44}	b_2^K(E2; 121·8 keV)
244·7	0·162(8)	−0·026(11)	1·97 ± 0·13
688·6	−0·29(6)	−0·10(10)	2·4 ± 0·7
			1·54 ± 0·15†
867·3	0·142(22)	0·03(6)	2·0 ± 0·4
964·0	−0·023(14)	−0·201(23)	1·72 ± 0·04†
1112·0	−0·339(13)	−0·013(18)	1·81 ± 0·08
1408·0	0·289(12)	−0·020(23)	1·64 ± 0·08
		weighted mean	1·73 ± 0·04

† Value deduced from b_4 using the recurrence relation.

Table 5. Conversion electron–gamma directional correlation coefficients and E0 : E2 mixing ratio for the 688·6 and 964·0 keV transitions in coincidence with the 121·8 keV ground state transition in ^{152}Sm.

Transition energy (keV)	G_2A_{22}	G_4A_{44}	Penetration parameter λ	q(E0 : E2) Experiment	q(E0 : E2) Theory†
688·6	0·081(25)	0·04(5)	$-365 \leqslant \lambda \leqslant 290$	$2·16 \leqslant q \leqslant 2·78$	3·43
964·0	0·00(4)	0·06(7)	$-134 \leqslant \lambda \leqslant 165$	$-0·215 \leqslant q \leqslant 0·317$	−0·037

† From Kumar (1971).

3.2.2. 444·0–964·0 etc–121·8 keV and 444·0–244·7–121·8 keV correlations. The spectroscopically observed 444·0 keV photopeak is a composite of two unresolved transitions. The first one de-excites the 2^-, 1529·8 keV level and the second originates from the 2^+, 810·4 keV β vibrational level. Since the latter involves a triple 2^+–4^+–2^+–0^+ cascade, its theoretical A_{kk} values can be calculated. In a case where two unresolved transitions of different cascades are involved, the measured angular correlation coefficients may be written

$$A'_{kk} = I_1/(I_1+I_2)A_{kk}^{(1)} + I_2/(I_1+I_2)A_{kk}^{(2)}$$

where I_1 and I_2 are the relative intensities of the two cascades.

The mean A'_{kk} values obtained for this correlation using a liquid source are

$$A'_{22} = -0·009(10) \quad \text{and} \quad A'_{44} = 0·004(21).$$

Using the transition intensities given by Riedinger *et al* (1970) the values of I_1 and I_2 were calculated and hence the values of A_{kk} (444·0–964·0 etc–121·8 keV) were derived. This last cascade has in fact two decay channels. The first is the 444·0–964·0–121·8 keV and the second one the much weaker 444·0–719·3–244·7–121·8 keV which is a 2^-–2^+–4^+–2^+–0 cascade and therefore involves only pure E2 intermediate transitions. For this reason the deorientation parameters U_k can be calculated.

Since the 964·0–121·8 keV correlation has been measured (see a later section) the U_k values can be calculated for this decay channel as well. After the appropriate calculations we obtain

$$A_2(444·0 \text{ keV}, 2^-–2^+) = -0·38(10)$$

which yields

$$\delta(\mathrm{M2:E1}) = 0{\cdot}03(8),$$

and suggests pure, or almost pure, E1 character for this transition.

3.2.3. 688·6–121·8 keV correlation. The 688·6 keV transition de-excites the 810·4 keV, 2^+ level which is the lowest member of the β vibrational band. Since the electric monopole process is an important mode of de-excitation for the members of the β vibrational band, accounting for almost 90% of the conversion electrons (Riedinger *et al* 1969), this transition presents the possibility of investigating both E2:M1 and E0:E2 mixing ratios.

The main experimental problem in the $\gamma\gamma$ directional correlation measurements was the very low peak-to-total ratio due to the large Compton background under the 688·6 keV photopeak, so that statistical variation of the Compton background can easily mask the correlation. Using a solid source, a total of eight $\gamma\gamma$ directional correlation experiments were performed and the mean values obtained are

$$G_2A_{22} = -0{\cdot}13(3) \qquad G_4A_{44} = 0{\cdot}28(5).$$

By inserting the values of the attenuation coefficient given previously we obtain

$$A_{22} = -0{\cdot}16(4) \qquad A_{44} = 0{\cdot}36(7)$$

which yield $\delta(\mathrm{E2:M1}) = 8^{+9}_{-3}$. A comparison of this value of δ with the results of previous investigations and Kumar's theoretical prediction is given in table 3.

The results obtained from a series of γe_K directional correlation experiments were

$$G_2A_{22} = -0{\cdot}29(6) \qquad G_4A_{44} = -0{\cdot}10(10)$$

which, when divided with the corresponding values of the $\gamma\gamma$ correlation measurements, yield the particle parameters of the 121·8 keV transition,

$$b_2(\mathrm{E2}) = 2{\cdot}3(7) \qquad b_4(\mathrm{E2}) = -0{\cdot}4(4).$$

Using the recurrence relation given in the previous section, $b_2(\mathrm{E2})$ may be recalculated from the $b_4(\mathrm{E2})$ value and this yields the more precise result

$$b_2(\mathrm{E2}) = 1{\cdot}54(15).$$

The results from the $e_K\gamma$ directional correlation measurements were used for the plot of λ against q, as described earlier. From the plot (figure 5) there are two independent sets of solutions,

(i) $2{\cdot}16 \leqslant q \leqslant 2{\cdot}78 \qquad -365 \leqslant \lambda \leqslant 290$

(ii) $-0{\cdot}55 \leqslant q \leqslant 2{\cdot}26 \qquad 865 \leqslant \lambda \leqslant 2600.$

Since the value of A_{44} restricts λ to the range $-387 \leqslant \lambda \leqslant 481$, only the first solution is acceptable. If no penetration effects are considered, that is if $\lambda = 0$, the corresponding E0:E2 mixing ratio becomes

$$q = 2{\cdot}62 \pm 0{\cdot}17.$$

In a recent similar investigation, Stefansson *et al* (1972) obtained $A_{22}(e_K\gamma) = 0{\cdot}10 \pm 0{\cdot}05$. In their analysis they used the value $\delta = 28^{+10}_{-6}$ but this does not greatly change their final result: $q = 2{\cdot}5 \pm 0{\cdot}3$ for $\lambda = (0 \pm 3) \times 10^3$. The greater accuracy in the present correlation coefficient, $A_{22}(e_K\gamma) = 0{\cdot}10 \pm 0{\cdot}03$, although not significantly reducing the error on q, which is mostly set by the accuracy of the α_K measurement, does greatly reduce the permitted range of λ values. In an earlier investigation Riedinger *et al* (1969)

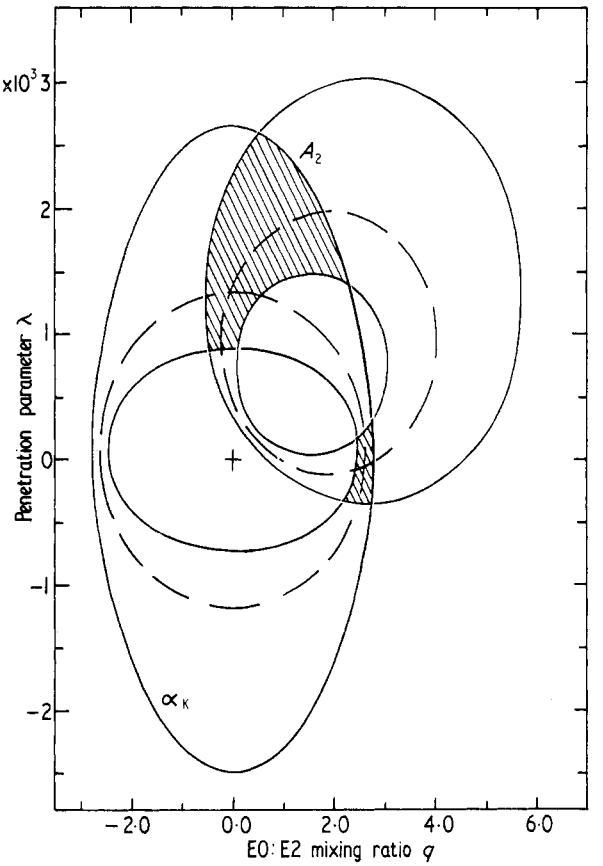

Figure 5. The E0:E2 mixing ratio q against penetration parameter λ plot obtained from the relations for the measured directional coefficient A_2 (689 K) ($= -0{\cdot}166 \pm 0{\cdot}052$) and the experimental internal conversion coefficient α_K ($= 0{\cdot}0373 \pm 0{\cdot}0041$) taken from Riedinger *et al* (1970). The solutions are given by cross hatching. Mixing ratio δ (E2:M1) $= 8^{+9}_{-3}$.

measured the gamma intensities and used the electron intensities of Malmsten *et al* (1966) to determine the E0:E2 admixture. For their calculations they assumed a pure E2 transition and neglected penetration effects. The result they obtained is given in terms of the dimensionless quantity X which has the value

$$X = 0{\cdot}45 \pm 0{\cdot}05.$$

From equations (2) and (3) this result corresponds to $|q| = 2{\cdot}60 \pm 0{\cdot}15$. Since we have used a value of α_K derived from the same gamma and electron intensities, this value of q is in fact identical to the one which can be derived from our plot of α_K in figure 5 under the assumptions that $\delta = \infty$ and $\lambda = 0$. From the theoretical predictions of Kumar (1971) for the E0 and E2 transition probabilities and equation (1), one obtaines $q = 3{\cdot}43$ which is in agreement with both the magnitude and sign of the value obtained in the present work.

3.2.4. 867·3–(244·7)–121·8 keV correlation. The first transition of this $3^+(4^+2^+)0^+$ cascade de-excites the second member of the γ vibrational band at 1233·8 keV. Since the

unobserved 244·7 keV transition is a pure E2, the parameters $U_k(244{\cdot}7)$ are known. The results obtained with the liquid source yield the mixing ratio

$$\delta = -12{\cdot}4^{+2{\cdot}5}_{-4{\cdot}0}.$$

The corresponding value obtained with the solid source is

$$\delta = -12{\cdot}2^{+1{\cdot}2}_{-1{\cdot}6}.$$

3.2.5. 964·0–121·8 keV correlation. The 1085·8 keV, 2^+ level, from which this cascade originates, is the lowest member of the γ vibrational band. The results obtained from the $\gamma\gamma$ directional correlation using liquid sources are

$$A_{22} = -0{\cdot}002(6) \qquad A_{44} = 0{\cdot}299(24)$$

while the solid source gives

$$G_2A_{22} = -0{\cdot}008(4) \qquad G_4A_{44} = 0{\cdot}253(6).$$

Since the A_{22} value specifies δ very precisely an accurate A_{44} value may be calculated and one obtains $A_{44} = 0{\cdot}323$ with an insignificant error. From a comparison of this value with the solid source result the G_4 attenuation coefficient may be obtained:

$$G_4 = 0{\cdot}782(18).$$

This method was also used in the case of the two preceding transitions, but the accuracy was not so great (see table 1). The A_{22} values give the E2:M1 mixing ratio:

$$\delta(\text{E2:M1; solid source}) = -11{\cdot}3^{+0{\cdot}7}_{-0{\cdot}8}$$

$$\delta(\text{E2:M1; liquid source}) = -10{\cdot}2^{+0{\cdot}8}_{-1{\cdot}0}$$

and indicate an almost pure E2 character of this transition. It may be noted that the sign of δ is opposite to that obtained for the E2:M1 mixing ratio of the 688·6 keV transition between the 2^+ β vibrational level and the 2^+ level of the ground band.

The $e_K\gamma$ measurement yields

$$G_2A_{22} = 0{\cdot}00(4) \qquad G_4A_{44} = 0{\cdot}06(7)$$

and these were used for the q against λ plot (figure 6). The set of solutions obtained are

$$-0{\cdot}215 \leqslant q \leqslant 0{\cdot}317 \qquad -134 \leqslant \lambda \leqslant 165.$$

If penetration effects are ignored, that is if $\gamma = 0$, the possible E0:E2 mixing has the limits

$$-0{\cdot}060 \leqslant q \leqslant 0{\cdot}297.$$

This result does not establish the existence of an E0 admixture, but merely reduces its possible limits. According to the collective model, the E0 process is forbidden between members of the γ and ground state bands but some deviations from this rule are expected due to band mixing effects. Kumar (1971) using a pairing-plus-quadrupole force model, predicts a nonzero electric monopole transition matrix element and his value for the E0:E2 mixing ratio is

$$q = -0{\cdot}037$$

which is within the limits of the present result.

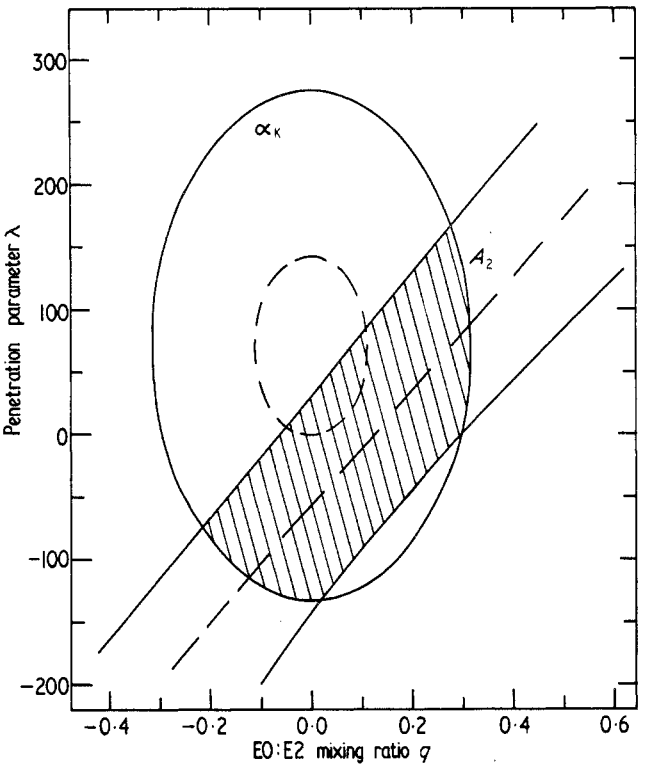

Figure 6. The same plot as figure 5, for the 964 keV transition. A_2 (964 K) = $-0{\cdot}002 \pm 0{\cdot}080$, $\alpha_K = 0{\cdot}0023 \pm 0{\cdot}0002$; δ (E2 : M1) = $-11{\cdot}3 \pm 0{\cdot}8$.

3.2.6. 1005·0–(244·7)–121·8 keV correlation. The A_{22} value obtained for this $4^+(4^+2^+)0^+$ cascade, which originates from the 1371·5 keV γ vibrational level gives the two independent solutions for the mixing ratio of the 1005 keV γ ray:

$$\delta_1 = 0{\cdot}52^{+0{\cdot}20}_{-0{\cdot}16} \quad \text{and} \quad \delta_2 = -3{\cdot}0^{+1{\cdot}0}_{-2{\cdot}4}.$$

The A_{44} indicates $|\delta| \geqslant 0{\cdot}3$ and therefore both solutions δ_1 and δ_2 are acceptable. Nevertheless, sign considerations of the E2 : M1 mixing ratio in transitions from the other members of the γ band favour the negative solution which corresponds to an M1 admixture of 90^{+7}_{-10} %.

3.2.7. 1112·0–121·8 keV correlation. The first transition of this 3^+–2^+–0^+ cascade de-excites the 1233·8 keV level of the γ vibrational band. The $\gamma\gamma$ correlation measurements give:

$$\delta\,(\text{E2}:\text{M1};\ \text{liquid source}) = -26^{+5}_{-7}$$

$$\delta\,(\text{E2}:\text{M1};\ \text{solid source}) = -30^{+7}_{-12}$$

which indicate an almost pure E2 character of the 1112·0 keV transition.

3.2.8. 1212·8–(244·7)–121·8 keV correlation. The 1579·3 keV, 3^- level, from which this cascade originates, has been assigned by Riedinger *et al* (1970) as a member of an octupole

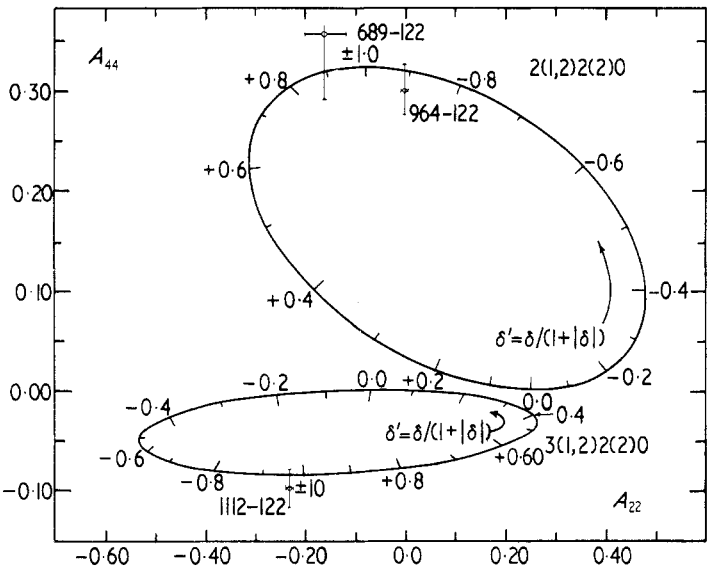

Figure 7. Theoretical A_{22} coefficients for 2(1,2)2(2)0 and 3(1,2)2(2)0 cascades, plotted against A_{44} coefficients by varying the multipole mixing ratio δ of the first transition. The experimental results are shown in the figure with their error limits representing one standard deviation.

$K^\pi = 1^-$ band. The A_{22} value gives two independent solutions

$$\delta_1 = 0{\cdot}05 \pm 0{\cdot}05 \qquad \delta_2 = 4{\cdot}1^{+1{\cdot}1}_{-0{\cdot}8}$$

while A_{44} gives $|\delta| \leqslant 0{\cdot}08$ and therefore the accepted solution is

$$0 \leqslant \delta \leqslant 0{\cdot}08$$

indicating a pure E1 character of the 1212·8 keV transition.

3.2.9. 1408·0–121·8 keV correlation. The 1408·0 keV transition de-excites 1529·8 keV, 2^- level which is another member of the $K^\pi = 1^-$ octupole band. As in the case of the 1212·8 keV transition, the dominant multipolarity is expected to be E1. The results suggest a small M2 admixture and indicate that the E1 transition may be substantially hindered, probably due to its K-forbidden nature ($\Delta K = 1, \Delta I = 0$). In order to examine the possibility of a triple E1 : M2 : E3 multipole mixing, δ_{31}(E3 : E1) against δ_{21}(M2 : E1) has been plotted using the A_{22} value and the K-shell conversion coefficient obtained by Dzhelepov *et al* (1966). The two sets of solutions given by cross hatching in figure 8 are:

(i) δ_{21}(M2 : E1) = 0·14(3) $\qquad$ δ_{31}(E3 : E1) = −0·09(4)
(ii) δ_{21}(M2 : E1) = −0·09(3) $\qquad$ δ_{31}(E3 : E1) = 0·16(4)

and there is no preference for either of them. However, more recent measurements of the ICC have resulted in smaller values. Riedinger *et al* (1970) used the conversion electron intensities determined by Malmsten *et al* (1966) and obtained $\alpha_K = 0{\cdot}46(4) \times 10^{-3}$. If this value is used in the δ_{31} against δ_{21} plot, it results in only one set of solutions with the absolute upper limits of δ_{31} and δ_{21} decreased by approximately 50%. However, if we use the γ ray intensities determined by Barrette *et al* (1971) together with the electron intensity of Malmsten *et al* (1966) the resulting upper limit of the ICC just approaches the

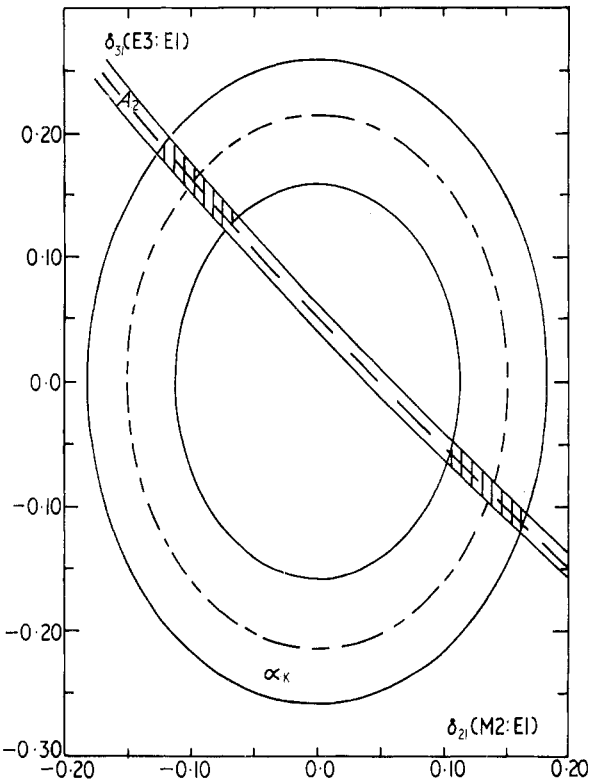

Figure 8. Solutions for the δ_{31} (E3:E1) against δ_{21} (M2:E1) mixing ratio based on the A_2(1408 keV) value (= −0·35(2)) obtained from the present work and the internal conversion coefficient α_K (= 0·00055(3)) as measured by Dzhelepov *et al* (1966). Full curves indicate one standard deviation.

theoretical ICC for an E1 transition (Hager and Seltzer 1968a). Consequently, the possibility of a triple E3:M2:E1 admixture is not conclusively supported by internal conversion coefficient measurements. Nevertheless, the results of $\gamma\gamma$ directional correlation measurements give approximately equal E3:E1 and M2:E1 admixtures. If it is assumed that δ_{31}(E3:E1) = 0, then:

$$\delta(\text{M2:E1; liquid source}) = 0{\cdot}057(10)$$

$$\delta(\text{M2:E1; solid source}) = 0{\cdot}046(10)$$

which indicates an M2 admixture of $(0{\cdot}33 \pm 0{\cdot}12)\%$ or $(0{\cdot}22 \pm 0{\cdot}09)\%$ respectively.

4. Discussion

The values of the multipole mixing ratios obtained from the $\gamma\gamma$ directional correlation measurements in general agree with the results of earlier investigations, though the δ(E2:M1) values for the 867·3 keV and 1112·0 keV transitions are significantly higher than those previously reported (see table 3) and show a closer agreement with the theoretical predictions of Kumar (1971).

All the transitions from the β and γ vibrational bands are predominantly E2 as predicted. In the particular case of the 1005·0 keV transition from the 1371·5 keV, 4^+ γ vibrational level, the M1 admixture was found to be relatively higher than the other transitions from the same band to the ground state rotational band.

The $\gamma\gamma$ correlation results show that transitions from negative to positive parity levels proceed by pure (or almost pure) E1 radiation, as expected. In the case of the 1408·0 keV transition which de-excites the 1529·8 keV, 2^- level, the investigation confirms the existence of a small M2 admixture which may be explained in terms of the K-forbiddenness of this transition ($\Delta K = 1, \Delta I = 0$). The possibility of a triple E3 : M2 : E1 admixture is not excluded, although the supporting evidence from internal conversion coefficient measurements is poor, and the correlation results indicate that both E3 : E1 and M2 : E1 mixing ratios lie in the same range of values.

The K-shell particle parameter of the 121·8 keV transition, obtained from the combined $\gamma\gamma$ and γe_K directional correlation measurements, deviates from the theoretical value by $(8{\cdot}5 \pm 2{\cdot}1)\%$. Previous investigations of particle parameters of E2 transitions in ^{152}Sm produced contradictory results. Table 6 reproduces some of these values.

Table 6. Measured and theoretical values of particle parameter of the 121·8 keV, E2 transition in ^{152}Sm.

	b_2^K(E2; 121·8 keV)
Theory[a]	1·89
Nasir *et al* (1967)	1·60 ± 0·05
Zganjar *et al* (1968)	1·65 ± 0·17
Nielsen *et al* (1969)	1·86 ± 0·13 1·82 ± 0·06[b]
Agarwal *et al* (1969)	1·82 ± 0·05[b]
Blumberg *et al* (1969)	1·77 ± 0·03
Holmberg *et al* (1971)	1·93 ± 0·04
Present work	1·73 ± 0·04

a From Hager and Seltzer (1968b); b Calculated from the b_4 value.

Holmberg *et al* (1967, 1971) are in agreement with the theoretical prediction. Nasir *et al* (1967), Zganjar *et al* (1968), and more recently Blumberg *et al* (1969) give values which differ considerably from theory. Blumberg *et al* used several types of sources prepared by evaporation and ion implantation in order to check the suggestion of Koopmann and Krugten (1969) that systematic errors might arise from the hygroscopy of the europium chloride sources if the $\gamma\gamma$ correlation is performed in air. Their results do not indicate any such effect. In the present measurements an ion-implanted source was used which is not expected to show any hygroscopic effects.

The value of b_2 (121·8 keV) can be obtained from the 964·0–121·8 keV correlation almost independently of the conditions under which the $\gamma\gamma$ correlation is performed since, by using the recurrence relation, b_2 can be obtained from b_4. The $A_{44}(\gamma\gamma)$ coefficient may be obtained by interpolation using the δ values determined by the $A_{22}(\gamma\gamma)$ coefficient. There is practically no experimental error on this A_{44} coefficient even if δ is allowed to change by up to 50%, and it should be noted that most experiments are in agreement on the δ value (cf table 3). This calculated value, $A_{44} = 0{\cdot}323$, is insensitive to any effects,

for example perturbations, which may arise from the conditions under which the correlation was measured. In order to obtain the theoretical b_2 value, the ratio $A_{44}(\gamma e_K)/A_{44}(\gamma\gamma)$ should be $-1{\cdot}23$. Thus, the γe_K correlation should yield $A_{44} = -0{\cdot}397$, while the result obtained is $G_4A_{44} = -0{\cdot}201(23)$ and this would require an attenuation factor G_4 of the order of 50%. This attenuation in turn implies that the $\gamma\gamma$ correlation with the solid source should yield $G_4A_{44}(\gamma\gamma) = 0{\cdot}163(19)$ which is very far from the value $G_4A_{44}(\gamma\gamma) = 0{\cdot}252(6)$ obtained. It is difficult to believe that the conditions under which the $\gamma\gamma$ experiment was run, would show such a discrepancy. In addition to this, a G_4 coefficient as small as 0·5 does not appear consistent with the G_2 value and with previous results obtained with the same type of source (Barrette *et al* 1970). Our conclusion therefore is that the observed discrepancy between the theoretical predictions and the experimentally determined particle parameters of the 121·8 keV transition cannot be accounted for solely by the proposed explanations of systematic errors due to different conditions under which the $\gamma\gamma$ and $e_K\gamma$ experiments were performed.

However, it should be noted that the average b_2 value is largely determined by the result of the 964·0–121·8 keV γe_K correlation and it may be that the 964·0 keV transition is more complex than indicated by spectroscopic studies. In particular, there is a marked discrepancy between the δ value obtained in the group of $\gamma\gamma$ correlation measurements ($\delta \simeq -10$) and that obtained by Coulomb excitation (McGowan *et al* 1968), ($\delta = -3{\cdot}8 \pm 1{\cdot}8$). In principle this should not affect the present analysis which is made by taking the ratio of two sets of measurements in which the 964·0 keV γ ray is common.

Finally, there is a good agreement between results obtained from the $e_K\gamma$ directional correlation measurements and Kumar's theoretical predictions for the 688·6 keV transition between the β vibrational and the ground state bands. However, the existence of penetration effects are not proved unambiguously for this transition since the range of values for the penetration parameter λ includes zero. There is a less striking agreement between theory and experiment in the case of the 964·0 keV transition between the γ vibrational and the ground state bands. The much smaller E0 admixture makes its unambiguous detection almost impossible with the technique used in the present work. Although the E0 : E2 mixing ratio obtained for this transition does overlap with Kumar's predicted value, the relatively large experimental error, as compared with the theoretical q(E0 : E2) value, makes any direct comparison between theory and experiment difficult, although the result does indicate that the E0 : E2 admixture may indeed be very small.

Summarizing, it may be said that the multipole ($L = 0, 1, 2$) admixtures in transitions from the β and γ vibrational bands to the ground state band in ^{152}Sm, justify the collective character of the energy levels involved and show a rather remarkable agreement with the theoretical predictions of Kumar and Baranger's pairing-plus-quadrupole force model which is the most successful in describing the low excited states of even–even nuclei in the deformed and transitional region. The small but nevertheless apparent disagreement between theory and experiment regarding the K-shell particle parameter of the 121·8 keV transition in ^{152}Sm cannot be satisfactorily explained.

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