pression proposed by MSB; the calculated values being too high by ~15%.

In conclusion we find that for nuclei which can be described by the VMI model, the relation (7) can be used for correlating and predicting $Q_{I,I+2}$ values for $I=0$, 2, 4, and 6.

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[1] M. A. J. Mariscotti, G. Scharff-Goldhaber, and B. Buck, Phys. Rev. 178, 1864 (1969).

[2] C. A. Mallmann, Phys. Rev. Letters 2, 507 (1959).

[3] A. Schwarzschild, Phys. Rev. 141, 1206 (1966).

[4] R. M. Diamond, F. S. Stephens, R. Nordhagen, and K. Nakai, in *Proceedings of the International Conference on Properties of Nuclear States, Montréal, Canada, 1969* edited by M. Harvey *et al.* (Presses de l' Université de Montréal, Montréal, Canada, 1969), p. 7.

[5] R. O. Sayer, P. H. Stelson, F. K. McGowan, W. T. Milner, and R. L. Robinson, Phys. Rev. C 1, 1525 (1970).

[6] R. M. Diamond, F. S. Stephens, W. H. Kelly, and D. Ward, Phys. Rev. Letters 22, 546 (1969).

[7] G. Scharff-Goldhaber and A. S. Goldhaber, Phys. Rev. Letters 24, 1349 (1970).

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Beta-Gamma Band Mixing in ^{152}Sm

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High-resolution singles and 4096×2048 Ge(Li)-Ge(Li) coincidence-spectrum measurements have been made to clarify the properties of the β and γ vibrational bands in ^{152}Sm. A $2_\gamma \to 2_\beta$ transition is placed from coincidence experiments and $B(E2;\, 2_\gamma \to 2_\beta)/B(E2;\, 2_\gamma \to 2_g) = 1.3 \pm 0.4$. The $B(E2;\, 3_\gamma \to 2_\beta)/B(E2;\, 3_\gamma \to 2_g) < 0.6$. Of the six transitions out of the 2_γ and 2_β levels, the intensities of four were revised from coincidence measurements and new branching ratios obtained. The $2_\gamma \to 4_g$ transition intensity is shown to be too low to allow a one-parameter fit to the γ-band branching ratios.

Recently, Varnell, Bowman, and Trischuk[1] reported, on the basis of energy fits, transitions from the 2^+ member of the γ vibrational band to the 0^+ and 2^+ members of the β vibrational band in ^{152}Sm. Such transitions are forbidden in the collective model;[2] and their existence would imply large mixing of the β and γ vibrational bands. The experimental branching ratios from the γ vibrational band in ^{152}Sm are in near agreement with a single band-mixing parameter z_2, but a small admixture of the β band seems required to give good agreement between theory and experiment, although the error limits are large.[1,3] However, such β-γ band mixing does nothing to improve the poor agreement between theory and experiment for the β-band branching ratios.[1,3] If this $2_\gamma^+ \to 2_\beta^+$ transition is correctly placed, then $B(E2,\, 2_\gamma \to 2_\beta) \geq B(E2,\, 2_\gamma \to 2_g)$ which is a most surprising result. Since the ^{152}Eu decay to ^{152}Sm and ^{152}Gd is complex with several known doublets[1,4] and other unplaced transitions,[4] it is possible that the 275.6-keV transition assigned as a $2_\gamma \to 2_\beta$ belongs elsewhere.

It is important to the understanding of the structure of the β and γ bands in ^{152}Sm to know if transitions do occur between these levels and with what strength. Thus we have carried out a γ-γ 4096 ×2048 coincidence experiment with two Ge(Li) detectors to determine definitively whether a 275.6-keV transition does occur between the 2_γ^+ and 2_β^+ levels and if all the singles intensity observed belongs to this transition.

In addition, a question has been raised[5] about the branching ratios from the 2^+ β-band member in ^{152}Sm. Mukherjee and SenGupta[5] reported that the 810-keV transition is a doublet, and the reported[1,3] 444-keV transition intensity is too large.[5] Such doublets could also raise questions about the report[6] that it is the $2_\beta - 4_g$ transition that is anomalous in ^{152}Sm. Our γ-γ coincidence results provide answers to these questions also.

An ND3300 system with buffer tape storage was

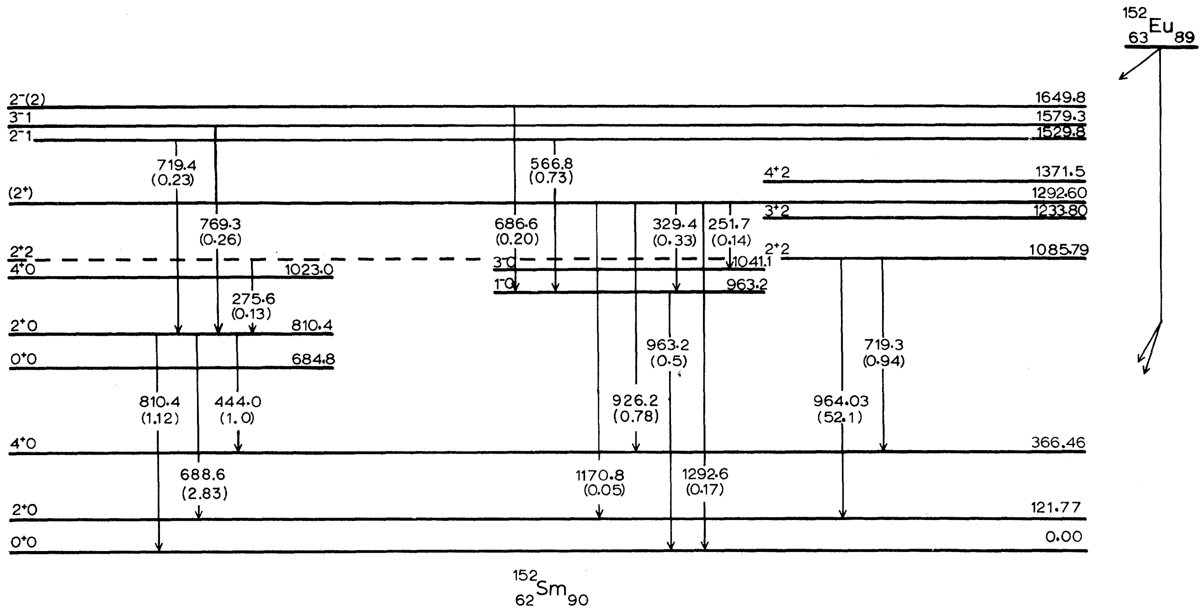

FIG. 1. A partial decay scheme of ^{152}Sm populated by ^{152}Eu. Only the levels and/or transitions where new information was obtained in this work are given.

used in the 4096×2048 mode with two Ge(Li) detectors with efficiencies of 4% that of a 7.6-cm ×7.6-cm NaI detector at 1.3 MeV. A lead absorber was placed over one detector to cut out scattering between the crystals. 41 coincidence spectra were analyzed. The full details of this analysis will be presented later.[7] Here we concentrate on the transitions that we observed into and out of the well-established β and γ vibrational levels.[1,3]

A partial level scheme that presents the β and γ vibrational levels in ^{152}Sm and the new features of this level scheme found in our work in comparison to the earlier studies[1,3] is shown in Fig. 1. The first important feature is that the 275.6-keV transition is definitely seen to be the $2_\gamma^+ \to 2_\beta^+$ transition. It is seen in coincidence with the 688- and 810-keV transitions which depopulate the 2_β^+ level and in coincidence with the strong 444-keV transition that feeds the 2_γ^+ level. There was no evidence for the 275.6-keV transition in any other gate. A quantitative analysis of the 688-keV gate confirmed that within errors of 25%, all of the singles intensity belonged as shown in Fig. 1. We looked for other γ-β interband transitions. Several possible transitions were obscured by nearby intense peaks. Very weak evidence was found for the $3_\gamma \to 2_\beta$ 423.4-keV transition. Since the results overlap zero intensity for the $3_\gamma \to 2_\beta$ transition within 2σ, only an upper limit is deemed safe to quote for this transition.

In Table I are presented the results of the relative strengths of the interband transitions observed. The $B(E2, 2_\gamma \to 2_\beta)$ is indeed larger than that of the $2_\gamma \to 2_g$ transition. On the other hand, the ratio $B(E2, 3_\gamma \to 2_\beta)/B(E2, 3_\gamma \to 2_g)$ is considerably less than this similar ratio for the 2_γ state. Since the 3_γ state does not involve any mixing of

TABLE I. γ-ray intensities and reduced $E2$ branching ratios for $\gamma \to \beta$ interband transitions in ^{152}Sm.

Transition	Energy (keV)	Intensity [$I_{344.2}$ (keV) = 100]	Reduced branching ratios
$2_\gamma^+ \to 2_\beta^+$	275.6	0.13 ± 0.04	$\frac{B(E2;\ 2_\gamma^+ \to 2_\beta^+)}{B(E2;\ 2_\gamma^+ \to 2_g^+)} = 1.3 \pm 0.4$
$3_\gamma^+ \to 2_\beta^+$	423.4	0.0073 ± 0.004 (coinc. work)	$\frac{B(E2;\ 3_\gamma^+ \to 2_\beta^+)}{B(E2;\ 3_\gamma^+ \to 2_g^+)} < 0.04$ [a]
		<0.021 (undetected in singles work)	<0.05

[a]The upper limit was obtained from a 2σ increase in the observed value.

the β band which has no odd-spin member, these data can be explained by β-band mixing into the γ band. Then the $3_\gamma - 2_\beta$ strength could be less than the $2_\gamma - 2_\beta$ strength because in the latter transition both states involve admixtures of each other. From γ-ray singles measurements with a Ge(Li) detector whose efficiency was 10% of a 7.6-cm ×7.6-cm NaI detector at 1.3 MeV, a search was made for the reported[1] 401-keV $2_\gamma \rightarrow 0_\beta$ transition ($I_\gamma = 0.009 \pm 0.009$, where I_γ at 344 keV is 100). From our singles data we can only put an upper limit of less than 0.01 units on this transition.

New doublets that involve transitions from the 2_β and 2_γ levels and new intensities for the doublet members of other transitions from the 2_β and 2_γ levels were determined from a quantitative analysis of coincidence spectra. The 688-keV transition from the 2_β level was shown for the first time to be a doublet by gating on the 841.4-keV transition from the 963.2-keV 1^- level. The new 686.6-keV transition depopulates an already known level.[1,3] The intensity of the 686.6-keV transition to be subtracted from the earlier[1,3] 688.6-keV intensity was obtained from a comparison in the coincidence spectrum with the 566.8-keV intensity. The latter's singles intensity was determined from our high-resolution singles spectrum to be 0.45 ± 0.10. The intensity of the 444.0-keV $2_\beta \rightarrow 4_g$ transition was obtained by comparing intensities in the 244-keV gate. After correcting for the 444-719-244 cascade, the $2_\beta \rightarrow 4_g$ transition intensity was found to be 1.0 ± 0.2. This compares favorably with the earlier results of 1.14 ± 0.12 and 0.9 ± 0.3 (Refs. 1, 3), respectively,

TABLE II. Experimental and theoretical values for reduced $E2$ branching ratios and resultant band-mixing parameters in ^{152}Sm.

Level band	$\frac{I_i \rightarrow I_1}{I_i \rightarrow I_2}$	$\frac{B(E2; I_i \rightarrow I_1)}{B(E2; I_i \rightarrow I_2)}$ Ref. 6	Present work	Theory [a]	First-order band mixing	Second-order band mixing
γ band					$Z_\gamma \times 10^2$	$Z_{\beta\gamma} \times 10^2$
2_γ^+ I_g	$\frac{2_\gamma \rightarrow 2_g}{2_\gamma \rightarrow 4_g}$	10.0 ± 1.3 (12.6 ± 1.6) [b]	11.9 ± 1.3	20.0	4.7 ± 0.9	$-(1.3 \pm 0.7)$ [c]
	$\frac{2_\gamma \rightarrow 2_g}{2_\gamma \rightarrow 0_g}$	2.55 ± 0.30	2.44 ± 0.13	1.43	9.3 ± 1.1	$-(1.1 \pm 0.8)$ [c]
	$\frac{2_\gamma \rightarrow 0_g}{2_\gamma \rightarrow 4_g}$	3.92 ± 0.37 (4.96 ± 0.47) [b]	4.98 ± 0.56	14.0	6.3 ± 0.6	$-(1.7 \pm 1.0)$ [c]
β band					$Z_\beta \times 10^2$ without β-γ mixing	$Z_\beta \times 10^2$ with $\delta_{\beta\gamma} = -(0.45 \pm 0.17) \times 10^{-2}$ [d]
$2_\beta^+ \rightarrow I_g$	$\frac{2_\beta \rightarrow 4_g}{2_\beta \rightarrow 2_g}$	3.52 ± 0.55	3.18 ± 0.68	1.8	2.4 ± 1.0	1.8 ± 1.0
	$\frac{2_\beta \rightarrow 0_g}{2_\beta \rightarrow 2_g}$	0.177 ± 0.022	0.176 ± 0.016	0.7	8.3 ± 0.4	7.9 ± 0.3
	$\frac{2_\beta \rightarrow 4_g}{2_\beta \rightarrow 0_g}$	19.9 ± 2.8	17.9 ± 4.0	2.57	5.5 ± 1.0	6.0 ± 1.0

[a] Bohr-Mottelson model with no band mixing.

[b] $Z_{\beta\gamma}$ was calculated for a Z_γ of $+(7.6 \pm 0.5) \times 10^{-2}$ as calculated (see Refs. 1, 3) from

$$\frac{B(E2;\ 3_\gamma^+ \rightarrow 4_g^+)}{B(E2;\ 3_\gamma^+ \rightarrow 2_g^+)}\ .$$

[c] The 2_γ-4_g transition of Ref. 6 was obtained from Ref. 1. The results in parentheses are that of Ref. 6 corrected for the doublet character of the 719-keV transition.

[d] $\delta_{\beta\gamma} = -(0.45 \pm 0.17) \times 10^{-2}$ was calculated by using the error-weighted average value of $Z_{\beta\gamma} = -(1.36 \pm 0.50) \times 10^{-2}$ and the relation

$$\delta_{\beta\gamma} = \frac{1B_0(E2;\ 0_g^+ \rightarrow 2_\beta^+)}{6B_0(E2;\ 0_g^+ \rightarrow 2_\gamma^+)} Z_{\beta\gamma}\ .$$

and does not confirm the interpretation from an analysis[5] of conversion-coefficient data. Within two standard deviations, the conversion-coefficient data are consistent with the present intensity.

In the 810-keV coincidence spectra, only the known 769.3-keV transition is seen along with a new transition of 719.4 keV and the 275-keV γ ray discussed above. In the singles spectra with the 10% efficiency detector with 2.38-keV full width at half maximum at 810 keV, the 810-keV transition did not show any line broadening as earlier reported at 2.6-keV resolution.[5] Thus we conclude that this transition is not a doublet as proposed.[5]

The $2_\gamma \rightarrow 4_g$ transition is seen now to be a doublet as discussed above and shown in Fig. 1. The revised intensity (0.94 ± 0.10) for the $2_\gamma \rightarrow 4_g$ transition was obtained from the 244-keV gate. The new 719.4-keV transition intensity (0.23 ± 0.08) was obtained from the 688- and 810-keV gates. The sum of these agrees well with the earlier total intensity of 1.11 (Ref. 3) and 1.19 (Ref. 1). The 329-keV gate was used to get the 963.2-keV intensity (0.5 ± 0.2) to strip from the $2_\gamma \rightarrow 2_g$ transition.

The revised branching ratios from the β and γ bands in ^{152}Sm, as based on our new intensities and averages of earlier work,[1,3] are given in Table II. These results are also compared with recent results from Coulomb excitation studies.[6] The new $2_\gamma \rightarrow 2_g$ intensity has altered the γ-band branching ratios so that there is now a more clear disagreement between experiment and theory for a single band-mixing parameter z_γ (notation of Ref. 3). The results of the Yale group[6] also must be corrected for the doublet character of the 719-keV transition, since they obtained the intensity of the $2_\gamma - 4_g$ transition from the singles intensity reported[1] in the decay of ^{152}Eu. This correction is a 26% decrease in the $2_\gamma - 4_g$ transition intensity used.[6] With this correction, there is better agreement between the present results and that of the Yale group. Also one sees that it is the reduction in this $2_\gamma - 4_g$ transition that yields the more clear disagreement between experiment and theory which includes only a single band-mixing parameter Z_γ. As in the β band where the $2_\beta - 4_g$ transition is too small for theory and experiment to agree,[6] it is the $2_\gamma - 4_g$ transition that is too small in intensity also. For the γ band, however, if one includes mixing of the β band into the γ band, then a value of $Z_{\beta\gamma} = -(1.36 \pm 0.5) \times 10^{-2}$ gives reasonable agreement between theory and experiment to the γ-band data. The β-band branching ratios are also altered by our new data as given in Table II, but there is no improvement in the poor agreement between theory and experiment.

A new level at 1292.6 keV (Fig. 1) is placed from the observed 329–963-keV and 244–926-keV coincidences. The interpretation of this level is considered in other work.[4]

In conclusion, these data indicate more clearly that the collective model with a perturbation treatment of corrections for the coupling of intrinsic and rotational motions,[8] which works well for strongly deformed nuclei, is not adequate to describe nuclei in the transitional region. Mixing of the β and γ bands is indicated by the interband transitions and the branching ratios from the γ band. The structure of the β-type vibration, however, is evidently more complex, since the branching ratios there are still unexplained by theory. The present results provide significant information for further theoretical treatment which include more than two-band mixing for the vibrational levels. Also, these data are important in the analysis of Coulomb-excitation measurements of the vibrational bands in ^{152}Sm. One cannot treat any one band alone, but must consider these bands together.

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[1]L. Varnell, J. D. Bowman, and J. Trischuk, Nucl. Phys. A127, 270 (1969).

[2]A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 27, No. 16 (1953).

[3]L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. 179, 1214 (1969).

[4]L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. C 2, 2358 (1970).

[5]P. Mukherjee and A. K. SenGupta, Phys. Rev. 182, 1265 (1969).

[6]I. A. Fraser, J. S. Greenberg, S. H. Sie, R. G. Stokstad, G. A. Burginyon, and D. A. Bromley, Phys. Rev. Letters 23, 1047 (1969).

[7]K. R. Baker, J. H. Hamilton, A. V. Ramayya, and F. E. Coffman, to be published.

[8]B. R. Mottelson, J. Phys. Soc. Japan Suppl. 24, 87 (1968).