Transitional Nuclei. I. Decay of ^{154}Eu to Levels of ^{154}Sm and ^{154}Gd†

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The γ-ray spectra accompanying the decay of ^{154}Eu(16 yr) has been studied by using an isotopically separated ^{154}Eu source as well as a Ge(Li) Compton suppression spectrometer. Over 150 γ rays have been detected and can be ascribed to 32 different levels. It is suggested that the positive-parity levels can be accounted for by assignment to one- and two-phonon vibrational bands, and that the negative-parity levels form the bands of the fragmented octupole state. The level structure of the $K=0$ and 1 members can be accounted for by assuming a strong Coriolis coupling between them. The relative $E2$ transition probabilities from the one- and two-phonon bands cannot be reconciled with simple two-band mixing theory. Properties associated with z_K indicate that z_K is not a good quantity in this nucleus, because of the strong mixing of the β- and γ-vibrational bands, and that its use in the past may have given false results for properties associated with it. The level energies in keV are:

ground-state band: 123.14(2^+), 371.18(4^+), and 717.96(6^+);
β band: 680.71(0^+), 815.55(2^+), and 1047.65(4^+);
γ band: 996.32(2^+), 1127.90(3^+), and 1263.94(4^+);
2β or M band: (1292.7(0^+)), 1418.36(2^+), and (1698.2(4^+));
$\beta\gamma$ band: 1531.39(2^+), 1660.94(3^+), and 1790.4(4^+);
$K=0$ octupole state: 1241.34(1^-), 1251.48(3^-), and 1364.2(5^-);
$K=1$ octupole state: 1509.1(1^-), 1397.53(2^-), and 1616.72(3^-), and 1559.68(4^-);
$K=2$ octupole state: 1719.62(2^-), 1796.78(3^-), and (1861.4(4^-)).

Other levels are at 1277.6, (1415.6), 1645.93, 1770.3, 1838, and 1894.69. The $K=2$ octupole state is consistent with Solov'ev and co-workers' assignment of a nearly pure two-quasiparticle configuration of [411] $[523]_p$, while the $K=1$ state is more consistent with its being of nearly pure [411] $[532]_p$ two-quasiparticle configuration. Consideration is given to a rotation-vibration Coriolis-type interaction between the $K=0$ and 1 bands and a proposed pseudo-rotor-particle-coupling Coriolis-type interaction between the $K=1$ and 2 bands of the octuple state. It is suggested that the levels at 1531.39, 1660.94, and 1790.4 keV form a $\beta\gamma$-coupled second vibrational band.

INTRODUCTION

ALTHOUGH extensive work has been done on the decay of ^{154}Eu,[1] the possible contamination of γ rays from the decay of impurities, particularly ^{152}Eu and ^{155}Eu, has hindered the detection and identification of weaker γ rays. In this work an isotopically separated source of ^{154}Eu and a high-resolution Ge(Li) Compton suppression spectrometer have been used. The latter allowed the detection and measurement of many low-intensity γ rays which are not detectable with ordinary Ge(Li) spectrometers.

The nucleus ^{154}Gd with 64 protons and 90 neutrons exists at the edge of the so-called region of strong deformation. Hence this nucleus may be expected to exhibit some of the properties characteristic of more spherical (transitional) nuclei. To test this, one possibility is to investigate how well the predictions of the collective model can account for the properties of this nucleus. Among these properties, of course, are the energy sequence of the rotational members of a given band, their logft values, and the inter- and intraband transition probabilities. Since the Compton spectrometer is one of the first instruments which allows measurement of low-intensity, low-energy transitions, it is worthwhile to investigate these in relation to the Alaga rules[2] and their extension.[3] In particular, the band-mixing parameter z_K and properties related to it can be tested.

If a nucleus is strongly deformed, one expects that the octupole state found in spherical nuclei will be split into several components, with $K^\pi=0^-$, 1^-, 2^-, and 3^-.[4] Recently, Solov'ev *et al.*[5] have predicted that the $K=0$ state will be the most collective of these states, while the others will be more nearly pure two-quasiparticle in their configuration. In the transitional region as the deformation increases, the $K=0$ and 1 bands may undergo a rotation-vibration-type Coriolis coupling, thereby altering the energy sequency of the rotational levels to the point of inversion for the $K=1$ band (i.e., $I=2$, 1, 4, 3 instead of $I=1$, 2, 3, 4) and concomitant compression of the $K=0$ band. This and other possibilities are investigated for the negative-parity levels and their assignments found here.

One of the more recent serious criticisms of the deformed nucleus model has been that the second vibrational (two-phonon) states of the β, γ, and coupled

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] See references in C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

[2] G. Alaga, K. Alder, A. Bohr, and B. R. Mattelson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 9 (1955).

[3] P. G. Hansen, O. Nathan, and R. K. Sheline, Nucl. Phys. **12**, 389 (1959).

[4] O. Nathan and S. G. Nilsson, in *α-, β-, and γ-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), Chap. X.

[5] V. G. Solov'ev, P. Fogel', and A. A. Korneichuk, Dokl. Akad. Nauk SSSR **154**, 72 (1964) [English transl.: Soviet Phys.—Doklady **9**, 45 (1964)].

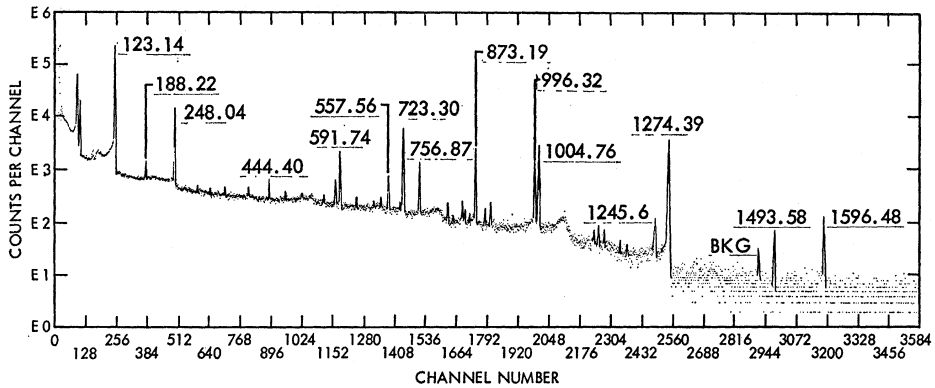


FIG. 1. γ-ray Compton-suppressed singles spectra of isotopically separated source (total count time: 12 days).

($\beta\gamma$) vibrations have not been observed in the deformed or transitional nuclei. If such collective bands were to occur, one might expect the transition probabilities to the first vibrational (one-phonon) states would be large in comparison to those to the ground-state band, and that the relative logft values would be approximately the same as those to the corresponding first vibrational (one-phonon) band. The even-spin members should act somewhat like "spherical two-phonon" levels do in inelastic scattering experiments. For a coupled ($\beta\gamma$) second vibrational state, it might be expected that the energy of the bandhead would be lowered from the value E(β bandhead)$+E$(γ bandhead), the spin sequence would be $I^\pi=2^+, 3^+, 4^+, \cdots$ with $K=2$. These and other properties have been found to agree well with three levels found in this nucleus. This band is considered in more detail in a second paper.[6,7]

TABLE I. Energies of γ rays from ^{154}Eu[a] less than 1150 keV.

E_γ	E_γ
123.14±0.04	664.68
131.58	676.59
146.05	692.41
188.22	715.76
232.01	723.30±0.04
248.04±0.04	756.87
322.01	815.55
346.72	845.39
382.00	850.64
401.30	873.19
403.55	880.61
444.40	892.73
476.92	904.05
478.26	924.49
518.00	996.32±0.04
557.56	1004.76±0.04
582.00	1012.8 ±0.2
591.74	1047.4 ±0.1
602.81	1049.4 ±0.1
613.26	1118.5 ±0.1
625.22	1128.4 ±0.1
649.44	1140.9 ±0.1

[a] Error is ±0.050 keV except where indicated. All peaks with $E_\gamma<1000$ keV had an internal consistency of ±0.020 keV [i.e., when E_γ was determined using various standards and analyzers (see text) values agree to within ±0.020 keV]. The 0.060 keV reflects this error, that of the standards used, and any unknown error.

[6] R. A. Meyer (unpublished).

[7] R. A. Meyer, Bull. Am. Phys. Soc. (to be published).

EXPERIMENTAL

A. Sources

Two sources were used for a majority of the measurements. One was an isotopically separated ^{154}Eu source on loan from the University of California's Los Alamos Scientific Laboratory and had a separation factor of 10^4; this was confirmed by a search for known γ rays of the most likely contaminants ^{152}Eu and ^{155}Eu.[8] By using the photopeak positions of the most intense noninterfering γ rays, an upper limit could be set which corresponded closely to the 10^{-4} value quoted by the LASL group. The other source was the product of a neutron irradiation on the separated isotope ^{153}Eu. This source was found to have 0.79% ^{152}Eu and 14% ^{155}Eu, based on known γ-ray intensities of ^{152}Eu and ^{155}Eu.[8] A cooling time of two months was used to allow for decay of any ^{156}Eu which might have been present.

B. Detector-Electronic Equipment

Several Ge(Li) detectors were used, all with cooled field-effect-transistor preamplifiers. A 6-cc Ge(Li) detector was employed for measurement of the singles spectra, while a 7-cc Ge(Li) detector was used with especially close geometry to facilitate initial level

TABLE II. Energies of γ rays from ^{154}Eu[a] greater than 1150 keV.

E_γ	E_γ
1232.1 ±0.5	1489.6
1241.6	1494.6
1246.6	1509.3±0.5
1274.45±0.09	1531.7
1290.0	1537.8
1292.0	1509.1±0.8
1295.5	1555.5±0.5
1408.5	1597.3
1418.5	1667.3
1419.2	1674.0±0.5
1425.9±0.5	(1844.8±0.5)

[a] Error is ±0.2 keV except where noted.

[8] Source made available through the kind permission of Donald W. Barr of Los Alamos Scientific Laboratory, Los Alamos, N. M.

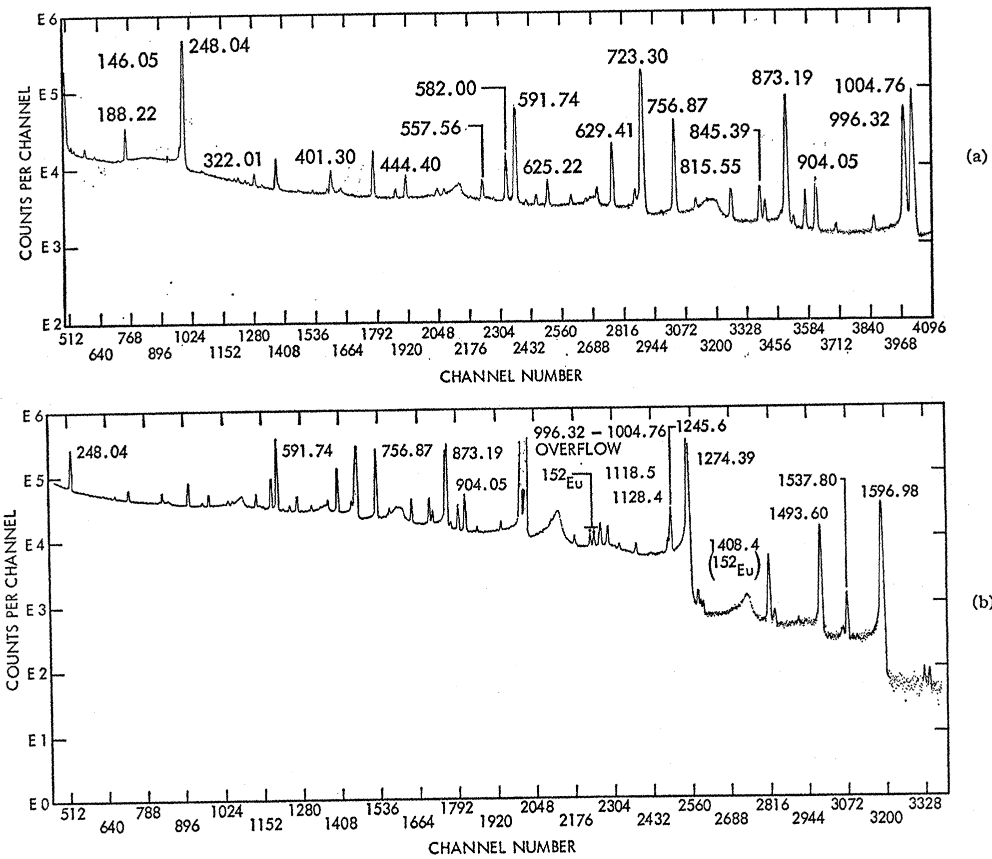


FIG. 2. Compton-suppressed γ-ray spectra, (a) with 250 eV per channel, (b) with 500 eV per channel.

identification by enhancing the sumpeaks. The LRL Compton suppression spectrometer described elsewhere[9] was used for detection of low-intensity γ rays, while a Ge(Li) slice detector with resolution of 580 eV at 59.5 keV was used for measurement of the low-energy γ rays ($E_\gamma < 410$ keV). The LRL Biomedical 180° coincidence spectrometer with a 19-cc Ge(Li) detector was used in singles mode for the identification of weak high-energy γ rays. Each Ge(Li) detector was used with a separate stabilized 4096-channel Nuclear Data pulse-height analyzer.

The 180° spectrometer mentioned above was used for the coincidence experiments, as was a variable-angle coincidence spectrometer with built-in, automatic random even subtraction mode. The latter device was used in coincidence experiments that involved higher count rates and is described elsewhere.[10]

C. Experimental Procedure and Results

1. *Energy Determination*

The energies of the γ rays were determined by internal calibration. The isotopically separated source[6] and known energy standards were used; these were ^{207}Bi, ^{203}Hg, ^{137}Cs, ^{54}Mn, ^{22}Na, ^{88}Y, and ^{226}Ra. All the energies were taken from Gunnink *et al.*,[11] except the ^{226}Ra, which was taken from Meyer *et al.*[12] The energy analysis was done by the use of the Gunnink-Niday computer code on the Livermore CDC computers; details of the analysis are published elsewhere.[13] Two separate groups of experiments were performed, one for energies less than 1100 keV and one for energies above 1100 keV. This allowed for an internal accuracy of 20 eV and an overall accuracy of 50 eV in the measurement of the more intense γ rays (with energy less than 1000 keV). The results are given in Tables I and II.

2. *Intensity Determination*

The γ-ray intensities were determined for spectra from all detectors. Efficiency calibration of the detectors is reported in detail elsewhere.[11,12] However, it should be pointed out that the relative intensity of γ rays with energy differences of 200–300 keV could be obtained to 1% [as was done for a number of γ rays which were used in the $B(E\lambda)$-value calculations]. For photopeak analysis, use was made of the Gunnink-

[9] D. C. Camp, University of California Radiation Laboratory Report No. UCRL-50156, 1967 (unpublished).

[10] L. G. Mann, K. G. Tirsell, and S. D. Bloom, Nucl. Phys. **A97**, 425 (1967).

[11] R. Gunnink, J. B. Niday, and R. A. Meyer (to be published).

[12] R. A. Meyer, R. Gunnink, J. B. Niday, and R. Anderson (to be published).

[13] R. Gunnink, H. B. Levy, and J. B. Niday, University of California Lawrence Radiation Laboratory Report No. 15140 (unpublished).

TABLE III. γ-ray intensities.[a]

E_γ (keV)	Transition from	Transition to	I_γ (per 10^6 decays)
58.4	1719.62	1660.62	40±4
80.4	1127.90	1047.65	30±15
82.0	82	ground-Sm	32±22
123.14	123.14	ground	405 000
125.39	1418.36	1292	70±20
128.4			≤100
129.5	1660.94	1531.39	140±20
131.58	1127.90	996.32	110
134.84	815.55	680.71	72
135.8	1796.78	1660.94	≤11
138.39	1698	1559.68	≤10
143.0	1418.36	1275	<7
146.05	1397.53	1251.48	260
154.94	1418.36	1263.94	<5
156.19	1397.53	1241.34	100
159.9	1719.62	1559.68	<10
162.09	1559.68	1397.53	10±5
165.91			23±5
180.73	996.32	815.55	45±10
182.2			
184.72	266.7	82.0(Sm)	40±10
188.22	1719.62	1531.39	2280
195.5±0.5	1559.68	1364.2	20±10
209.4±0.4	1719.62	1509.5	24±8
219.4	1616.74	1397.55	23±9
229.0±0.5			20±8
232.01	1047.65	815.55	240
237.0	1531.39	1292	60±40
248.04	371.18	123.14	65 900
260.9	1397.53	1136.15	20±9
265.4	1796.78	1531.39	≤16
267.44	1531.39 1263.94	1263.94 996.32	140
269.80	1397.53	1127.90	70±10
274.0±0.5			40
275.4	1531.39	1263.94	≤0.5
279.9	1531.39	1251.48	30
290.0	1531.39	1241.34	34
295.7	1559.68	1263.94	24
296±1			14±9
301.25	1719.63	1418.36	100
305.12	1719.63	1414.50	176
308.2	1559.68	1251.48	≤16
312.28	1127.90	815.55	147
315.42	996.32	680.71	46
320±1			10±7
322.01	1719.62	1397.53	670
328.48	1047.65	717.96	92
346.72	717.96	371.18	300
352.0	1770.3 1616.72	1418.36 1263.98	≤9
368.21[b]	1645.93	1277.72	30
370.71	1418.36	1047.65	54±14
375.2±0.5	1617.75	1241.34	18±10
382.00	1645.93	1263.94	101
397.14	1660.94	1263.94	300[d]
401.30	1397.53	996.32	2100
403.55	1531.39	1127.90	270
414.30			50
419.4	1660.91	1241.34	40±20
422.08	1418.36	996.32	≤12
431.78	1559.68	1263.94	≤28
435.9	1251.48	815.55	≤26
444.40[b]	815.55	371.10	5030[b]
460.20	1275	815.55	≤28
467.92	1719.62	1251.48	570
463.9	(1880.2)	1397.53	43
478.26	1719.67	1241.34	2150
480.61	1616.72	(1136.15)	49
483.74	1531.39	1047.65	50[c]
484.64			40[c]
(486.36)	(1719.62)	(1233.26)	≤22
488.26	1616.72	1127.90	70±30[b]
506.4	1770.3	1263.94	60±20
509.88			365[c]
512.03	1559.68	1047.65	≤417[c]
518.00	1645.93	1127.90	467
532.84	1796.78	1263.91	109±20
545.60	1263.94	717.96	166±23
557.56	680.71	123.14	2540
563.4	1559.68	996.32	
569.23	1616.72	1047.65	100
582.00	1397.53	1815.55	8400
591.74	1719.62	1127.90	48 400
597.5	1861.4	1263.94	56[c]
598.31	1645.93	1047.65	61[c]
600.00	1415.60	815.55	60±40
602.81	1418.36	815.55	340
612.0	1292.75	680.71	≤60
613.26	1660.94	1047.90	930
620.52	1616.72	996.32	93
625.22	996.32	371.18	3100
624.4	1770.3	1127.90	40±20
649.44	1645.93	996.32	760[c]
650.6	1698.26	1047.65	100[c]
660.7	1796.78	1136.15	≤29
664.68	1660.94	996.32	290
668.9	1796.78	1127.90	120±30
676.59	1047.65	371.18	1400
692.41	815.55	123.14	16 950
701.7			≤46
715.76	1531.39	815.55	1750
722.30	1719.62	996.32	197 000
727.3			≤760
737.65	1418.36	680.71	<84
756.87	1127.90	371.18	43 400
774.4	1770.3	996.32	100±50
790.12	1838.7	1047.65	110±30
800.2	1796.78	996.32	327±50
801.2	1616.72	815.55	
815.55	815.55	ground	4650
830 38	1645.93	815.55	≤50
845.39	1660.94	815.55	5500
850.64	1531.39	680.71	2300
873.19	996.32	123.14	115 000
880.61	1251.48	371.18	820
892.73	1263.94	371.18	4600
898.37	1894.69	996.32	20±5
904.05	1719.62	815.55	8240
906.1	(1277)	(371.18)	120
919.24			125
924.49	1047.90	123.14	590
928.4	1509.1	680.71	≤50
981.3	1796.78	815.55	80±20
984.5			64±40
996.32	996.32	ground	103 000
1004.76	1127.90	123.14	173 500
1012.8	1136.07	123.14	29±12
1023±1	1838.7	815.55	71±30
1033.4			120
1047.4	1418.36	371.18	500[c]
1049.4			175[c]
1072.2	1790.4	717.96	≤40
1110	(1233)	123.14	30±20
1118.5	1241.34	123.14	1030
1124.2			70±10
1128.4	1251.48	123.14	2670
1136.1	(1136.1)	ground	75±10
1140.9	1263.94	123.14	2160
1153.1±0.5			140±40
1160.6	1531.39	371.18	440
1170.0±0.5	(1292)	(123.14)	44±20
1188.6	1559.68	371.18	820
1216.8			≤37

TABLE III. (*continued*).

E_γ (keV)	Transition from	to	I_γ (per 10^6 decays)	E_γ (keV)	Transition from	to	I_γ (per 10^6 decays)
1232			93±60	1468±1	1838.0	371.18	≤25
1241.6	1241.34	ground	1300	1490.2	1861.4	371.18	30±5
1246.6	1616.73	371.18	6960	1493.6	1616.72	123.14	6500
1274.39	1397.53	123.14	355 000	1510.0±0.5	1509.1	ground	50±10
1290.0	1660.94	371.18	115[c]	1522±1	1894	371.18	6±3
1292.0	1414.5	123.14	131[c]	1531.4	1531.39	ground	61±4[c]
1295.5	1418.36	123.14	90±10	1537.80	1660.94	123.14	500±20
1327	1698.26	371.18	≤20	1554			≤15
1387.0±0.5	1509.1	123.1	200±20	1596.48	1719.62	123.14	16 700
1400	1770.3	371.18	30±10	1667.3	1790.4	123.14	20±3
1408.4	1531.39	123.14	210±30[b]	1673.6	1796.78	123.14	14±4
1415.0±0.5	1414.5	ground	40	1716.9	1838	123.14	6±4
1418.6	1418.36	ground	74[c]	1773±1	(1814)	(123.14)	3±2
1419.0	1790.4	371.18	20[c]	1838.0±0.5	1837.8	ground	8±2
1425.6	1796.78	371.18	13±8	1895±1	(1895±1)	ground	6±2

[a] The error concomitant with a given γ ray, unless state is: 2% for $I_i \geq 10\,000$; 3% for $10\,000 > I_i > 1000$; etc.
[b] Intensity derived from isotopically separated source only.
[c] Resolved by peak shape fit.
[d] This peak may be a doublet.

Niday code, as well as hand calculation and spectral shape fitting of weaker peaks, doublets, and areas of spectral uncertainty (with respect to background). The values determined are given in Table III. Typical spectra are shown in Figs. 1 and 2.

3. *Coincidence Spectra*

Separate coincidence spectra were taken at 180° with both sources used, while for those taken at 90° the reactor source was used. Gates with a width of approximately 10% were set at 123, 248, 188, and 700 keV. Typical spectra from the 123-keV gate as well as the 248-keV gate are shown in Figs. 3 and 4. The photopeaks seen in coincidence with the 123- and 248-gated spectra are given in Table IV. Details of the coincidence spectrometers are given elsewhere.[10]

The 188.23-keV γ ray has been observed before and was suspected to be from the decay to ^{154}Sm. However, such an assignment was negated by having found the 185.6-keV 4+0 to 2+0 transition in ^{154}Sm.[14] It was suspected that the 188.23-keV γ ray was an $E1$ transition between the 1719.62- and the 1531.39-keV level. To verify this a coincidence experiment was performed by setting a gate on the 188-keV area of the spectra as well as the adjacent higher-energy area (in order to determine backgrounds, Compton, etc. gates); photopeaks in coincidence with the 188-keV area are given in Table V. Also, to verify this, a spectrum was taken with a 720-keV gate (note that the 692 was also gating this spectrum). The major coincidences obtained in this experiment were: 67, (115), 123, 129.1, 170±1, 188.4, 248.0, 374, 510, 582.3, 591.7, 730, 872.4, 904.9, and 996.3.

D. Level Scheme for ^{154}Gd

The level scheme for ^{154}Gd deduced from known decay schemes[1] and the γ-ray spectra of ^{154}Eu decay measured in this work are shown in Fig. 5.

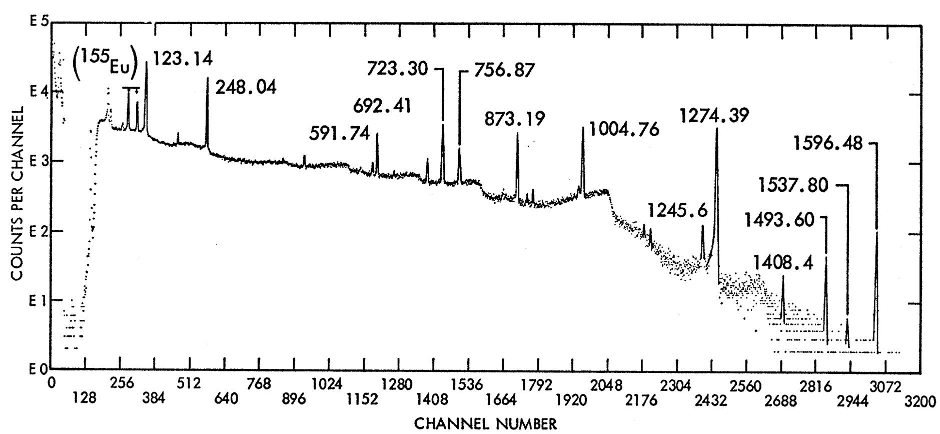


FIG. 3. 123-keV gated spectra taken at 90°.

[14] D. G. Alkhazov, V. D. Vasil'ev, Yu P. Gangrskii, and I. Kh. Lemberg, Izv. Akad. Nauk SSSR Ser. Fiz. 28, 229 (1964).

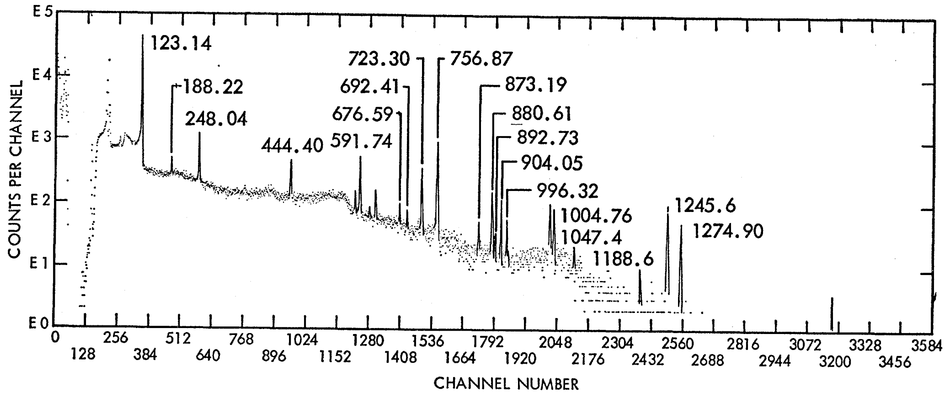


FIG. 4. 248-keV gated spectra taken at 90°.

1. *Ground-State Rotational Band*

A large amount of information has been accumulated on the ground-state rotational band from both ^{154}Eu decay and ^{154}Tb decay as well as from Coulomb excitation[14,15] and reaction spectroscopy.[16] Making use of the $\alpha_T(123.14)$ measurement of Dingus *et al.*,[17] we obtain from an intensity balance a logft value of 12.4 and 13.7 for the population of the 2^+ and 4^+ states, respectively (see Table VI). The 6^+ member at 717.96 keV is predominantly fed by the 4^+0 member of the β-vibrational band.

2. *β-Vibrational Band*

The 0^+, 2^+, and 4^+ members of the β-vibrational band have energies of 680.71±0.05, 815.55±0.05, and 1047.65±0.07 keV, respectively. The suppression of the energy of the levels from the simple $I(I+1)$ sequence can possibly be explained by the strong coupling of other bands into this band or by a transitional-type potential (see, for example, the following discussion of the 1292.75-keV band and Ref. 6). Here, as in most cases, in this nucleus a strong $M1$ component to the $\Delta I=0$ transitions had to be assumed in order to explain the relative $B(E2)$ values to the ground-state rotational band. The need to assume such a strong $M1$ component has been postulated by others.[18] For comparison, the conversion electron data of Hamilton *et al.* and Dzelepov are given in Table VII along with the calculated conversion coefficients.

3. $K^\pi=2^+$ *γ-Vibrational Band*

This band has been well studied. The energy of the bandhead can be set at 996.32±0.07 keV while that of the 3^+ member can be set at 1127.90±0.07 keV. It was possible to make a precise determination of the mixing of this band into the ground-state rotational band. This

TABLE IV. γ rays coincident with 123- and 248-keV gated spectra.[a]

E_γ	123.14	248.04	E_γ	123.14	248.04
58.7	w	w	1004.80	s	···
123.14		s	1047.4	m	s
188	m	m	1110	w	···
248.04	s		1118.5	s	···
347.1	w	w	1128.4	s	···
444.4	m	s	1140.9	s	···
557.5	s	···	1152.3	m	···
582	s	m	1160.6	w	m
613	···	m	1188.6	w	u
625.2	m	s	1241.6	w	m
676.5	m	s	1274.8	s	?
692.5	s	m	1291.0	w	w
756.7	m	s	1295.5	w	w
845	m	s	1386	v.v.w.	···
873.2	s	···	1408.5	s	···
880.4	m	s	1419.2	w	···
892.8	m	s	1425.9	···	v.v.w.
904.1			1494.6	s	···
907.9	v.v.w.	m	1538.2	s	···
924.9	s	···	1597.0	s	···
			1667.3	v.v.w.	···

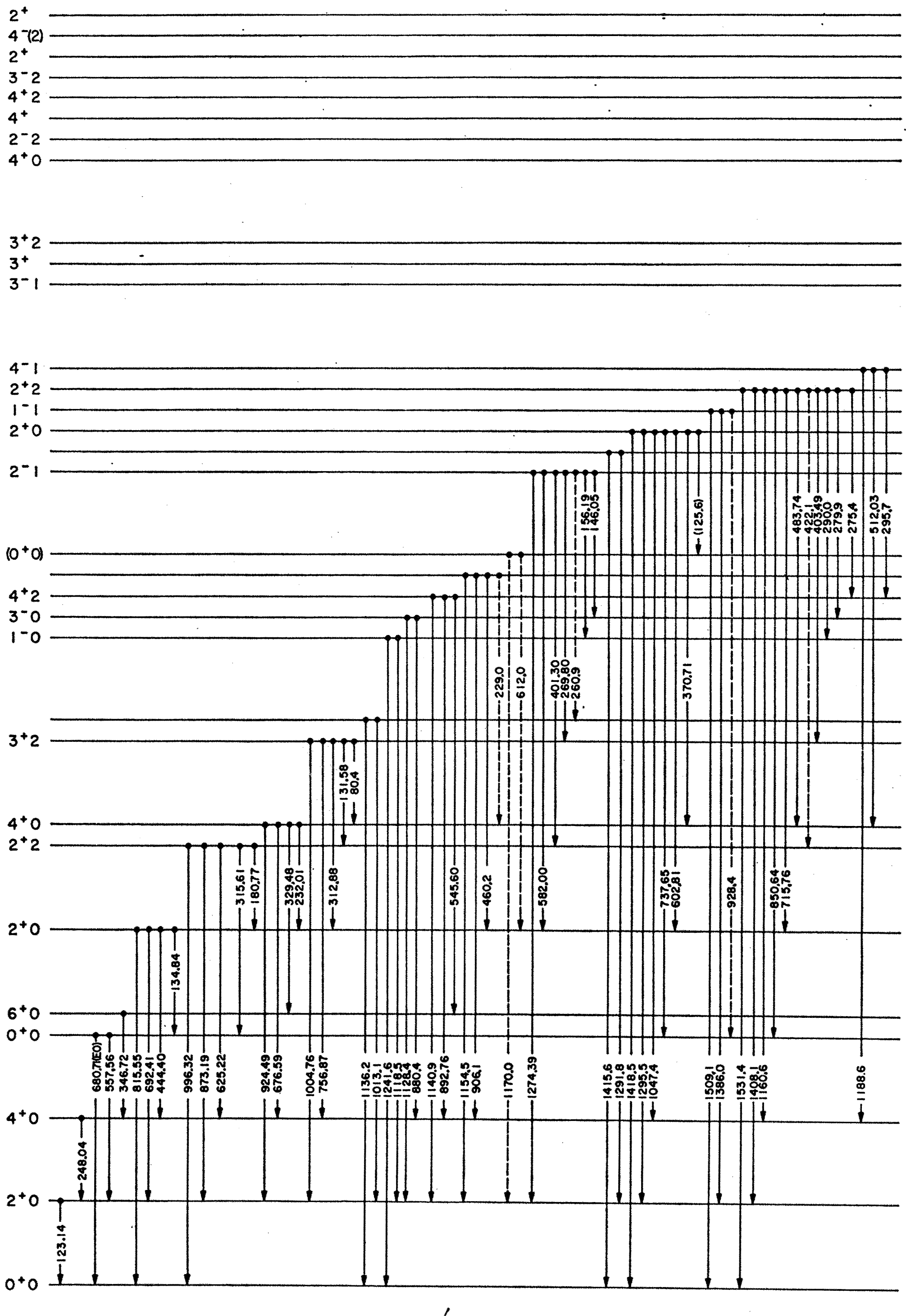
[a] s denotes strong; m denotes medium; w denotes weak; v.v.w. denotes very, very weak.

TABLE V. γ rays coincident with 188-keV gate.[a]

E_γ	Relative intensity (after subtraction of randoms)
39.8	v.w.
42.6	v.s.
49.9	v.s.
123.1	v.s.
141.3	m
188.4	m
248.0	m
444.4	m
483.7	m to w
557.8	s
692.5	m
715.6	v.s.
850.6	v.s.
996.3	m
1160.5	m
1128	m
1408.1	m
1531.7	m

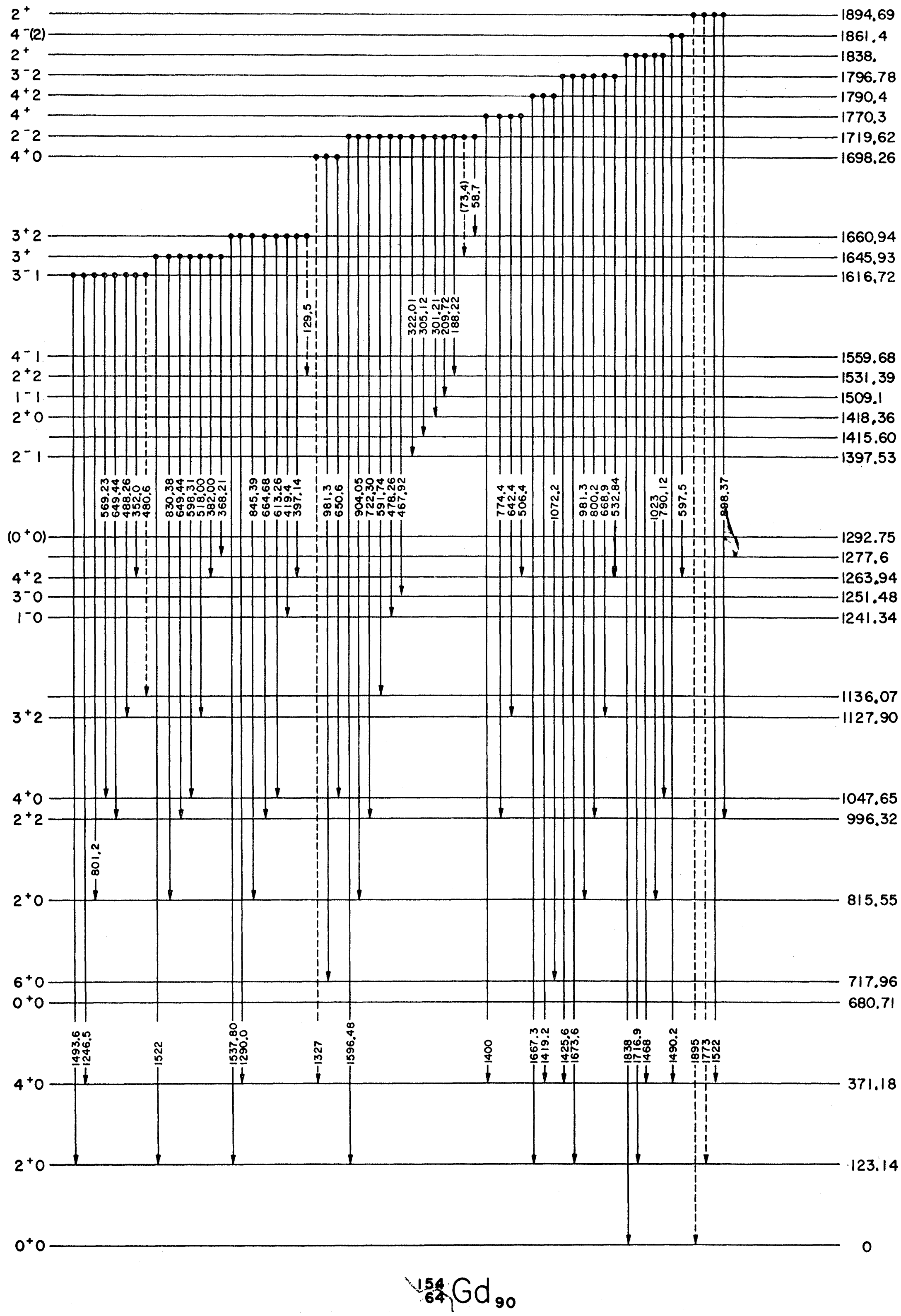
[a] s denotes strong; m denotes medium; w denotes weak; v.w. denotes very weak; v.s. denotes very strong.

[15] K. S. Toth and J. O. Rasmussen, Phys. Rev. **115**, 150 (1959).
[16] O. Lönsjö and G. B. Hagemann, Nucl. Phys. **88**, 624 (1966).
[17] R. S. Dingus, W. Talbert, and M. G. Stewart, Nucl. Phys. **83**, 545 (1966).
[18] N. R. Johnson (private communication); L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. Letters **19**, 1243 (1967).



(a)

FIG. 5. (a) Decay scheme deduced from γ rays and coincidence spectra. Spacing of close-lying levels is not to scale. (b) Decay scheme deduced from γ rays and coincidence spectra. Spacing of close-lying levels is not to scale. (c) Band diagram of levels in ^{154}Gd.



(b)

FIG. 5. (*continued*).

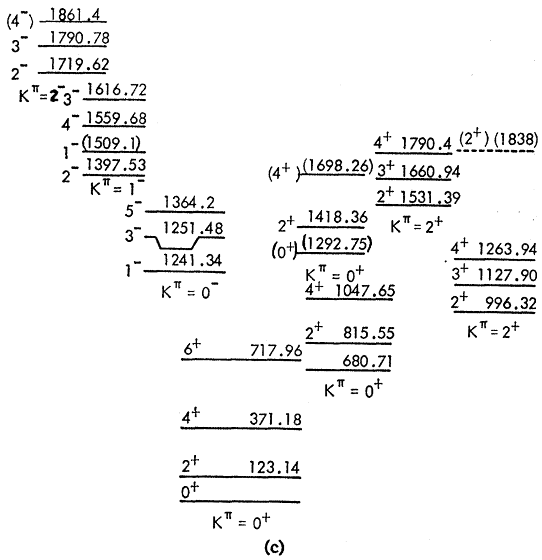


FIG. 5. (*continued*).

is given in a later section, as is also the determination of the relative intrinsic quadrupole moment.

4. $K^{\pi}=0^{-}$ Octupole Band at 1241.6

The work of Block *et al.*[19] confirms the assignment of the 1241.34-, 1251.48-, and 1364.2-keV levels as the

TABLE VI. *ft* values for the β decay of ^{154}Eu.

Level	$I^{\pi}K$	E_{β}	%	Log*ft*
ground	$0^{+}0$	...		
123.14	$2^{+}0$	1855	14.3	12.4
371.18	$4^{+}0$	1607	0.56	13.7±0.2
717.96	$6^{+}0$	...		
680.71	$0^{+}0$	...	...	...
815.55	$2^{+}0$	1162	0.46	13.1
1047.65	$4^{+}0$	930	0.129	13.2
996.32	$2^{+}2$	982	2.53	12.1
1127.90	$3^{+}2$	850	16.7	11.0
1293.94	$4^{+}2$	714	0.68	12.1
1241.34	$1^{-}0$	736	<0.0007	>14.2
1251.48	$3^{-}0$	726	0.247	12.6
1364.8	$5^{-}0$	...	...	...
(1292.75)	$(0^{+}0)$	...	...	...
1418.36	$2^{+}0$	559	0.104	12.6
(1698.26)	$(4^{+}0)$	280	(0.01)	(12.4)
1509.1	$1^{-}1$	...	...	...
1397.53	$2^{-}1$	580	34.4	10.10
1616.72	$3^{-}1$	360	1.35	10.8
1559.68	$4^{-}1$	418	0.146	12.2
1414.5	...	563	0.03	13.3
1531.39	$2^{+}2$	447	0.255	11.8
1660.94	$3^{+}2$	317	0.700	10.90
1790.4	$4^{+}2$	179	0.072	12.0
1645.93	3^{+}(?)	331	0.14	11.6
1770.4	4^{+}(?)	208	0.04	12.0
1719.62	$2^{-}2$	258	26.8	9.05
1796.78	$3^{-}2$	188	>0.013	<11.1
1861.4	$4^{-}2$	117	0.01	11.0±0.4
1838	(2^{+})	...	0.0014	12.0±0.3
1880	$(4^{-}?)$	98	0.04	10.6
1894.69	(2^{+})	...	0.019	11.0

[19] R. Block, B. Elbeck, and P. O. Tjøm, Nucl. Phys. **A91**, 576 (1967); B. Elbeck (private communication).

TABLE VII. *K*-conversion coefficients.

E_{γ}	I_{γ}	I_{eK}[a]	α_K(expt)	α_K(theor)[b]
444.4	5.03	0.11	0.024	0.0155
625.2	2.94	0.03	0.011	0.0066
676.5	1.19	0.12	0.109	0.0055
692.5	17.13	0.62	0.039	0.0053
756.7	42.20	0.12	0.003	0.0044
815.6	4.88	0.024	0.005	0.00375
873.2	114.1	0.31	0.0029	0.00315
924.9	0.55	<0.02	<0.04	0.0028
996.30	103.0	≡0.23	≡0.0024	0.0024
1004.8	173.49	0.39	0.0025	0.00235

[a] Electron intensities taken from Ref. 28 and normalized to the 996.30 transition being pure *E*2 as shown by B. S. Dzhelepov, L. K. Pelser, and V. O. Sergejev, *Decay Schemes of Radioactive Nuclei* (Pergamon Press, Inc., New York, 1960).
[b] α_K from L. A. Sliv and I. M. Band, *α, β, and γ-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965); and R. Dingus (private communication).

1^{-}, 3^{-}, and 5^{-} members, respectively, of the first $K=0$ octupole band. This is further supported by the coincidence of the 1128.4- and 1118.4-keV photons in a 123.14-keV gated spectrum and the coincidence of the 880.4-keV photon in a 248.04-keV gated spectrum. From the energy calibration experiments we can assign the energies as 1241.34±0.07 and 1251.48±0.07 keV for the 1^{-} and 3^{-} members of this band, respectively. The log*ft* values of 13.7 and 12.6 for the 1^{-} and 3^{-} bands are consistent with a K^{π} assignment of 0^{-}.

Using the assumption that the γ rays from these levels are *E*1 in nature, the relative $B(E1)$ values to the ground-state rotational band are given in Table VIII. The branching ratio from the 1^{-} level is compared with those from the first 1^{-} level in several Gd isotopes. The increasing trend toward the theoretical value as deformation increases should be noted. Also of interest is the very fast relative *E*1 transition from the $3^{-}0$ state to $2^{+}0$ where it is enhanced by a factor of 6 over the theoretical value. This may be indicative of its strong coupling into other bands (see discussion of negative-parity bands).

5. Level at 1277.6 keV

A level with spin of 3±1 is tentatively postulated at 1277.6 keV. A 1153.3-keV γ ray was identified in coincidence with the 123.14-keV gated spectrum, and a 906.5-keV γ ray was found in coincidence with the 248.04-keV gated spectrum. This level may be associated with the 1645.93-keV level.

TABLE VIII. Branching ratios $B(E1', 1^{-}\rightarrow 2^{-})/B(E1, 1^{-}\rightarrow 0^{+})$ for $_{64}$Gd.

	Energy 1^{-} level	Branching ratio[a]	$(3^{-}\rightarrow 4^{+})/(3^{-}\rightarrow 2^{+})$
^{152}Gd	1317	1.24	...
^{154}Gd	1241.34	1.07 ±0.06	0.21 ±0.02
^{156}Gd	1242	1.25	...
^{158}Gd	978	2.04	...
Theoretical		2.000	1.333

[a] Branching ratios for ^{152,156,158}Gd taken from C. F. Perdrisat, Rev. Mod. Phys. 38, 41 (1966).

TABLE IX. Relative transition probabilities from the $K^\pi=2^-$ band.

			From 1719.62-keV level		
$E1$ transitions				$B(E1)$ theor.	
E_γ	to E_{level}	$I^\pi K$	$B(E1)$ rel.[a]	$KF=2$	$KF=1$
1596.48	123.14	2^+0	0.00815 ± 0.00025		
904.05	815.55	$2^+0(\beta)$	0.021 ± 0.001		
723.30	996.32	$2^+2(\gamma)$	1.000	1.00	
591.74	1127.90	$3^+2(\gamma)$	0.448 ± 0.021	0.500	
301.21	1418.36	2^+0	0.0070 ± 0.0007		
188.22	1531.39	2^+2	0.670 ± 0.017	0.670	0.670
58.4	1660.94	3^+2	0.42 ± 0.08	0.335	0.20
$E2$ transitions				$B(E2)$ theor.	
			$B(E2)$ expt.[b]	$KI=2$	$KI=1$
467.92		3^-0	0.25 ± 0.03	0.250	4.000
478.26		1^-0	1.00	1.000	1.000
322.01		2^-1	2.08 ± 0.13	...	...
322.01		2^-1	1.00	...	...
159.9		(1^-1)?	≤0.4	0.756	0.168
			From 1796.78-keV level		
			$B(E1)$ rel.[a]	$KI=2$	$KI=3$
800.2		$2^+2(\gamma)$	0.71 ± 0.20	0.56	19.86
668.9		$3^+2(\gamma)$	0.49 ± 0.14	0.78	6.94
532.84		$4^+2(\gamma)$	1.00	1.00	1.00

[a] Based on the assumption that these are pure $E1$.
[b] Assuming $M1/E2\ll1$.

6. Band at 1292.75

A new $K^\pi=0^+$ band is proposed with a bandhead at 1292.7 keV with 2^+ and (4^+) members at 1418.36 and (1698.26) keV, respectively. This band has properties which indicate it is strongly coupled to the β-vibrational band and appears to be collective in nature. The former is supported by the fact that the $B(E2$, relative) values from the band favor the β-vibrational band. A level at 1698 keV was observed in inelastic scattering and may be the 4^+ member of this band tentatively proposed at 1698.26. Excitation of the 1418.36-keV state has not been reported. This, however, would be expected if another $K^\pi=0^+$ band at even higher energy coupled with the β-vibrational band to deplete the $B(E2)$ strength to the 2^+ member,[20] or if it were an m-type band as postulated by Kumar.[21]

The 1292.75-keV level was detected only by its population from the 1418.36-keV level and subsequent decay to the ground state. The γ rays from the 1418.36-keV level were seen in both the 123.14- and the 248.04-keV gated coincidence spectra. Although the γ-ray intensities are small, the relative $B(E2)$ values indicate strong mixing with both the ground state and β-vibrational band. Here again a large $M1$ component had to be assumed for the $\Delta I=0$ transitions to bring the relative transition probabilities into agreement with simple two-band mixing theory. It should be pointed out that the transition from the 1418.36- to the 371.18-keV level has an anomalously large $B(E2)$ value. Further support for the assignment of $K^\pi=0^+$ for the 1418.36-keV member comes from the relative $B(E1)$ values of transitions from the 1719.62-keV state (see Table IX). If the γ rays are correctly assigned as originating from the 4^+ member tentatively proposed at 1698.2 keV, then they have equally strong relative $B(E2)$ values for transitions to the β-vibrational band, in contrast to transitions to other bands. These values, in addition to the detection of an intraband transition to the 2^+ member, are in agreement with this, being the 4^+ member of the 1292.75-keV, $K^\pi=0^+$ band. However, its assignment can only be considered tentative. This band is discussed in detail elsewhere.[6,7]

7. $K=1$ Octupole Band

The 2^- level at 1397.53 keV has been well studied in the past[1]; however, no K assignment has been made. For this nucleus the $\log ft$ value of 10.1 agrees well with an assignment of K of 1 or 2. Using the assumption that the γ rays are $E1$ in nature, a comparison of the $B(E1)$ values for this state with those of the 1719.62 state shows that the level is definitely not $K=2$ (see Table X) which leads to the best choice being $K=1$. The nearly equal $E1$ strength to the lower $K=2(\beta)$ and $K=0(\gamma)$ vibrational states supports this assignment in addition to the expected enhancement of an $E1$ to the ground-state band because of the Coriolis effects on $E1$ transition involving $K=1$. Contrary to the proposal by Gallagher and Solov'ev,[22] it is proposed that this band has a strong two-quasiparticle contribution of $[532]\uparrow[411]\uparrow_p$ to its configuration. The energy of the 2^- member agrees well with that predicted by Pyatov and Solov'ev[23] as well as Gallagher and Solov'ev[22] for a $[532]\uparrow[411]\uparrow_p$ two-quasiparticle configuration.

The level at 1616.72 keV has been observed in (d,d') scattering by Block *et al.*[19] Their data for the ratio of $d\sigma/d\Omega$ at 90° and 125° are not inconsistent with an assignment of 2^+ or 3^-. In the γ-ray spectra of this work the lack of any γ ray corresponding to a ground-state transition, the strong coincidence of the 1494.6-keV γ ray with a 123.14 gate, and the coincidence of the 1246.5-keV γ ray with a 248.0-keV gate best support an assignment of 3^- for this level.

The fact that no γ ray representing the transition to the $K=2\gamma$ vibrational band was observed along with the large $B(E1)$ values to the ground-state band leads

TABLE X. Relative $B(E1)$ values from $I^\pi=2^-$ levels.

Transition to:	$B(E1)$ relative 1397.96(2^-1)	1719.62(2^-2)	Theory $K=1$	$K=2$
2^+0(ground)	5.50 ± 0.07	0.00815 ± 0.00025	...	...
$2^+0(\beta)$	1.32 ± 0.05	0.021 ± 0.001	...	...
$2^+2(\gamma)$	1.000	1.000	1.000	1.000
$3^+2(\gamma)$	0.111	0.448 ± 0.021	0.200	0.500

[20] D. Bes (private communication).
[21] K. Kumar, Nucl. Phys. **A92**, 653 (1967); and (private communication).
[22] C. J. Gallagher, Jr., and V. G. Solov'ev, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter **2**, No. 2 (1962).
[23] N. I. Pyatov and V. G. Solov'ev, Bull. Acad. Sci. USSR, Phys. Ser. **12**, 1512 (1964).

to the assumption $K \leq 1$. The $\log ft$ value of 10.8 for the β^- intensity of the 1616.72-keV level is in agreement with its being the 3^- member of a $K=1$ band. Such an assignment is further supported by comparing the $E1$ transition probability to the ground-state rotational band with the $B(E1)$ values from the other 3^- levels (see Table XI).

It should be pointed out that the $B(E1)$ value for the transition from this level to the 4^+ member of the ground-state rotational band relative to the $B(E1)$ value for the transition to the 2^+ member is 2.44 times the theoretically expected value. The 1^- member of this band is assigned to a level at 1509.1 keV. The 1387.0-keV γ ray from this level was detected only by using the isotopically separated isotope. The level itself is fed entirely from higher-lying levels.

The inversion of normal energy sequence and enhanced $B(E1$, relative) values indicate this band is strongly Coriolis (rotation-vibration) coupled to the $K^\pi=0^-$ band. This is considered further in the section on negative-parity levels.

8. 1414.5-keV Level

A level at 1414.5±0.5 keV is only tentatively proposed. From the γ-ray intensity balance the β-decay feed to this level, if it exists, would have a $\log ft$ of 13.2. Further information must await final analysis of the ground-state decay of ^{154}Tb which appears to favor this level.[24]

9. 1559.68-keV Level

The 1559.68-keV level has not been observed before in inelastic scattering, Coulomb excitation, or decay of ^{154}Tb. A 1188.6-keV γ ray was found to be in coincidence with the 248.04-keV gated spectra. No 1436.6-keV γ ray could be found in singles and coincidence spectra. An assignment of 4^- for the spin and parity of this level is consistent with these results. The relative $B(E1)$ values and $\log ft$ value are consistent with this level being the 4^- member of the $K^\pi=1^-$ octupole band (see discussion of negative-parity levels).

10. K=2 Band at 1531.39 keV

A $K^\pi=2^+$ band is proposed with levels at 1531.39 ±0.07, 1660.94±0.07, and 1790.4±0.4 keV with spin of 2^+, 3^+, and 4^+, respectively. The $\log ft$ values as well as the energy-level spacings of the members of this band correspond well with those of the γ-vibrational band. Also, the excitation in inelastic scattering tends to support this as a collective band. Each member of this band is discussed separately.

1. 1531.39-keV level. The 1408.1-keV γ ray was observed to be in coincidence with the 123.14-keV gate. It should be pointed out that only the isotopically separated ^{154}Eu source could be used for the measurement of this γ ray to avoid interference from the

[24] R. A. Meyer, R. Griffioen, and R. Gunnink, Bull. Am. Phys. Soc. (to be published).

TABLE XI. Relative $E1$ transition moments from 3^-K levels.

Level $I^\pi K$	E_γ	to	$B(E1)$expt	$B(E1)$ theor. $K=0$	$K=1$
1796.78(3^-2)	1667.3	ground			
	1419.0[a]				
1616.72(3^-1)	1493.6	ground	1.00		
	1241.6		0.61±0.03	1.333	0.751
	488.26	γ band	1.5±0.8		8.75
	620.52		1.000		
1251.48(3^-0)	1128.4		1.00		
	880.61		0.213±0.013		

[a] 1419.2 is an unresolvable doublet.

1408-keV γ ray found in the decay of ^{152}Eu. Also, when a coincidence spectrum was taken by setting a gate at 692 keV [$2^+0(\beta)$ vibrational state to the 2^+0 ground state], the 715.6-keV γ ray was found to be in coincidence. Furthermore, the coincidence spectra obtained by setting a gate at the 188.22-keV γ ray (the γ ray represents a transition from the 1719.62-keV level to the 1531.39-keV level) has the 1531.7-, 1408.1-, 1160.0-, 850.6-, 715.6-, and 483.7-keV γ rays in coincidence. Hence a spin of $I^\pi=2^+$ is assigned to this level. Further support for this and its collective nature comes from the observation of Block *et al.*[19] of this level in their (d,d') data.

If the relative $B(E1)$ values given in Table IX for transitions from the 1719.62-keV 2^-2 level are compared, an assignment of $K=2$ is indicated. This is further supported by the large relative $B(E2)$ values of transitions to the γ-vibrational band in contrast to the relative $B(E2)$ values of transitions to other bands. It should be pointed out that the relative transition probabilities calculated from transitions to the ground-state rotational band, although weak, are inconsistent with any K assignment.

2. 1660.94-keV level. The coincidence experiments show the 1537.8-keV γ ray is in strong coincidence with the 123.14-keV γ ray, and the 1290.0-keV γ ray is in coincidence with the 248.04-keV γ ray. The 1290.0-keV γ ray was present with a small intensity in the coincidence spectrum. Also, γ rays were detected which represent transitions between the 1660.94-keV level and the 2^+ and 4^+ members of the $k=0$ β-vibrational band, as well as between the 2^+ and 4^+ members of the γ-vibrational band. No evidence could be found for a γ ray equivalent to the transition to the 6^+ member of the ground-state band. This fact, coupled with the absence of population of the 1660.94-keV level in (d,d') scattering, indicates an I^π assignment of 3^+. If we can assume the 58.4-keV γ ray to be predominately $E1$, the $B(E1)$ value of this transition from the 2^-2 state at 1719.62 keV, coupled with the relative $B(E2)$ transition probabilities (see section on mixing parameters), are most consistent with an assignment of $K=2$. The relative $B(E1)$ values from the 1719.62-keV level (given in Table IX) to the 1660.94- versus the 1531.39-keV level are in good agreement with an assignment of $K=2$.

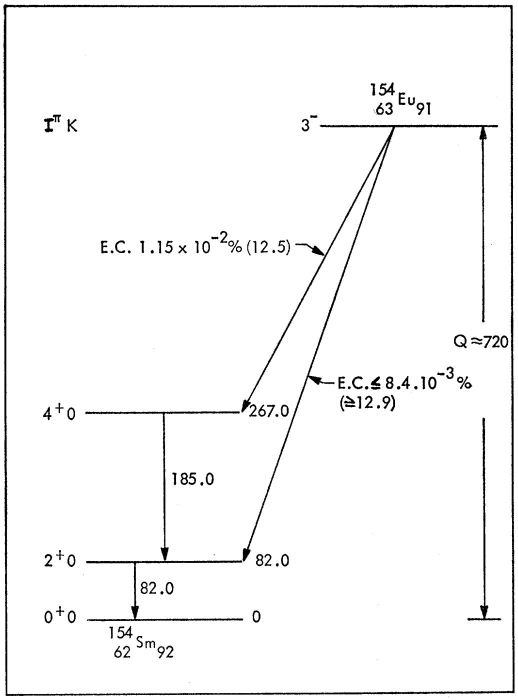


FIG. 6. Partial decay scheme showing electron-capture branches of ^{154}Eu decay.

3. 4^+ level at 1790.4 keV. It is proposed that this level is the 4^+ member of the $K=2$ band. Although the low γ-ray intensities preclude any definite K assignment, the limits on the logft and energy spacing with respect to the 1531.39- and 1660.94-keV levels are consistent with its being a member of this band.

This level appears to form an undetected doublet in the (d,d') data of Block *et al.*[19] They assign a spin and parity of 3^- to a level at 1794 keV. However, the 3^- level has been found to be at 1796.78 keV. The agreement between the level energies presented here and those of Block *et al.* are all within 1.2 keV, except the 1794-keV level. (In the published data of Block *et al.*,[19] the full width at half-maximum of the peak at 1794 keV appears to be 1.5 to 2 times that of other peaks.) Hence, it is proposed that the (d,d') experiment was exciting both a 3^- and a 4^+ level at 1790.4 and 1796.78 keV, respectively, which, in view of the resolution, appears as an unresolved doublet. Furthermore, their ratio of $d\sigma/d\Omega$ at 90° and 125° is consistent with a mean between a 3^- and a 4^+ excitation.

It has been proposed that this band is the two-phonon $(\beta\gamma)$ vibrational band. This is discussed in detail elsewhere.[6,7]

11. Levels at 1645.93 and 1770.3 keV

These two levels have been seen by Harmatz *et al.*,[25] who observed them being populated in the decay of ^{154}Tb. Their assignment was a spin of 2 or 3 for the 1770.3-keV level. Only an upper limit for a transition to the ground-state rotational band could be made. The resultant $B(E2)$ value with respect to the $B(E2)$ value of the transition to the γ-vibrational band tends to indicate these levels may form a two-phonon band. This is further supported by the $B(E2$, relative) values to the β-vibrational band, which are at least 100 times faster than those to the ground-state band. More accurate analysis, however, must await completion of the ^{154}Tb decay which strongly populates these levels.[24]

12. K^{π} 2^- Band at 1719.62 keV

The relatively low logft value for β decay to the bandhead in this nucleus can be explained by an allowed $(\Delta\Lambda=2)$ β transition from the $[411]_p[521]_n$ parent configuration in ^{154}Eu to the strong $[411]_p[523]_p$ two-quasiparticle component which makes up the predominant character of this level.[22] The assignment of $K=2$ to this bandhead is further supported by the relative $B(E1)$ and $B(E2)$ values of transitions from this level.

The 3^- member of this band is assigned as the level at 1796.78 keV. The assignment is supported by the relative $B(E1)$ values of transitions to the various members of the γ-vibrational band as well as the magnitude of the $B(E1)$ values to the γ band in relation to the $B(E1)$ values to the ground-state and β-vibrational band. As mentioned earlier, Block *et al.* assign a level at 1794 keV with $I^{\pi}=3^-$. Although no intraband γ ray could be measured because of interference from Pb x rays, a γ ray equivalent to the interband transition to the bandhead of the $K^{\pi}=1^-$ band was detected.

13. Levels above 1800 keV

Several levels with energies greater than 1800 keV have been observed to be weakly populated. These are at 1838, 1861, 1880, and 1894.69 keV. Only the levels at 1838, 1861.4, and 1894.69 keV had sufficient γ-ray intensity emanating from them to be characterized in any way. The level at 1838 keV can be tentatively assigned to spin of 2^+ and appears to be of two-phonon character. This is based on the large $B(E2$, relative) values for transitions to the β-vibrational band in contrast to transitions to other bands. The 1861.4-keV level can only be tentatively proposed to have spin and parity of 4^-. If the assignment of 4^- is correct, then the relative $B(E1)$ values are consistent with an assignment of 4^-2.

A 2^+ level at 1894.69 keV is proposed on the basis of the logft value of 11 and the relative intensities of the γ rays. If a pure $E2$ nature is assumed, the values $B(E2)$ relative to the ground state and the 2^+ member of the γ-vibrational band are in agreement with this assignment. This level has not been identified in inelastic scattering and may be constructed mainly of the $[413]\downarrow[411]\downarrow_p$ two-quasiparticle configuration origi-

[25] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 123, 1758 (1961).

TABLE XII. Band-mixing parameters to ground-state rotational band.

Initial level	E_γ	J_iJ_f	$B(E2)$ rel. expt.	RV[a]	DC[b]	$10^3 z_K$[c]	$10^3 z_K$[d] (av)
$K=0$ β-vibrational band							
815.55(2^+0)	444.40	24	2.72±0.08	3.0	1.0	14	
	692.41	22	1.000	1.00	1.00		56
	815.55	20	0.121±0.004	0.33	0.19	98	
1047.65(4^+0)	346.72	46	5.91±0.18	9.0	1.75	38	
	676.59	44	1.000				64
	924.59	42	0.0855±0.0025	0.17	1.10	91	
$K=2\gamma$-vibrational band							
996.32(2^+2)	625.22	24	0.145±0.005	1.17	1.00	126	
	873.19	22	1.000	1.00	1.00		98
	996.32	20	0.464±0.011	0.49	0.44	71	
1127.90(3^+2)	1004.76	32	1.032±0.031	1.00	0.94	80	
	756.87	34	1.000	1.00	1.00		80
1263.94(4^+2)	545.60	46	0.43±0.07	0.98	0.22	146	
	892.73	44	1.000	1.00	1.00		102
	1140.9	42	0.138±0.007	0.38	0.01	58	
$K=2$ band at 1531.39							
1531.39(2^+2)	1531.7	20	0.17±0.04			80	
	1408.5	22	1.000				63±10
	1160.0	24	4.86±0.73			46±5	
1660.94(3^+2)	1537.8	32	1.000				85
	1290.0	34	0.55±0.12			85	
1790.4(4^+)	1072.2	46	~0.08			80±40	
	1419	44	1.00				80±30
	1667.3	42	0.29±0.05			80±10	
1418.36(2^+0)	1418.5	20	0.54±0.13				
	1295.5	22	1.00				
	1047.4	24	16.6±3.8				

[a] Reference 54.
[b] Reference 55.
[c] These values were calculated with the aid of the tables given by R. Graetzer, G. B. Hagemann, K. A. Hagemann, and B. Elbeck, Nucl. Phys. **76**, 1 (1966).
[d] I.e., assuming a virtual $M1$ component (see text).

nally ascribed to the γ vibration by Gallagher and Solov'ev.[22] They predict an energy ratio of 1.2 for the bandhead energy of the $[411]\uparrow[523]\uparrow_p$ two-quasiparticle bandhead to the $[413]\downarrow[411]\downarrow_p$ two-quasiparticle bandhead energy, as contrasted to the 1.1018±0.0004 measured here. The level may be associated with the two-phonon structure of ^{154}Gd.

E. Decay of ^{154}Eu to ^{154}Sm

The ^{154}Eu–^{154}Sm disintegration energy has been calculated to be 720 keV by using the mass-link relationships.[26] To determine if there is any electron-capture branching in the ^{154}Eu decay, a search was made for the known 185- or 82-keV γ rays from the 4^+0 to 2^+0 level transition or 2^+0 to 0^+0 (ground) level transition, respectively.[14] A measure of the relative abundance of electron-capture decay to the 4^+0 state in ^{154}Sm was made possible by use of the Compton suppression spectrometer. In this decay the 185.0±0.5-keV γ ray arising from the 4^+0 to 2^+0 transition in ^{154}Sm has been found.[14] In addition the Ge(Li) spectra that were gated by the 188-keV area of the NaI(Tl) crystal yielded a very weak coincidence with an 82.0-keV photon. The latter γ ray was also detected by use of a thin Ge(Li) detector with resolution of 580 eV.

If a pure $E2$ transition is assumed, the measured intensity of the 185.0±0.5-keV γ ray requires a $\log ft$ of 12.2 for the electron capture populating the 4^+0 state (see Fig. 6). For population of the 2^+ ground-state rotational level the $\log ft$ value must be set at $\log ft$ $(3^- \rightarrow 2^+0) \geq 12.9$.

[26] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1965).

BAND MIXING IN THE GROUND AND EXCITED STATES

A. Band-Mixing Parameter

The degree of mixing in the wave function for the ground state of the vibrational bands has a very strong effect on the $E2$ transition probabilities between these bands. Such an effect has been calculated by Bohr and Mottelson[27] and by Hansen *et al.*,[3] who give a correction factor $f(z_K,I_f,I_i)$ to the transition probability $B(E2)$ derived by Alaga *et al.*[2] The z_K values from various bands of ^{154}Gd were first estimated by Hamilton *et al.*[28] from conversion electron data. With the high degree of precision obtained in the measurement of the energies and intensities of the ^{154}Gd transitions in this work, it is well worthwhile to calculate the mixing parameters from the various bands in order to test the validity, in this nucleus, of the Alaga rules and their extension by Hansen *et al.*[3] The z_K values calculated for this nucleus are given in Table XII. Recently Bosch and co-

[27] Aa. Bohr and B. Mottelson (unpublished).
[28] J. H. Hamilton, T. Katoh, W. H. Brantely, and E. F. Zganjar, Phys. Letters **13**, 43 (1964).

TABLE XIII. Interbanding mixing.

	E_γ (keV)	$I^\pi K$	$B(E2)$	$10^3 z_K$
1531.39 Int. $\beta(2^+2)$	850.64	20	0.388±0.017	103
	715.76	22	1.000	
	483.74	24	0.20±0.05	200
1660.94 Int. $\beta(3^+2)$	845.39	32	1.00	
	613.26	34	0.84±0.05	60
1418.36 Int. $\beta(2^+0,m)$	737.6	20	<0.09	
	602.81	22	1.00	
	370.7	24	1.8±0.6	
γ Int. β Band				
996.32	180.73	22	1.00	
	315.6	20	0.06±0.03	
1127.90	(80.25)	34		
	312.28	32	(180±90)	

workers[29,30] have calculated ratios of the $E2$ transition probabilities of deformed even-even nuclei within the framework of the rotation-vibration model[31,32] as well as the Davydov model.[33,34] Their results are compared in the fifth and sixth columns of Table XII. Strictly, a multiband mixing calculation should be used to determine a band-to-band effective z_K'. However, if the mixing is small, a two-band calculation is sufficient for the estimation of z_K'.[35] If such an assumption is made, the values given in Table XIII are obtained.

The very poor agreement between these values can be somewhat reconciled by assuming a large $M1$ mixture into the $\Delta I=0$ transitions. Values calculated using this assumption are given under the last column in Table XII. However, the recent angular-correlation work of Hamilton *et al.*[18] has been interpreted as evidence that the $M1$ component in these transitions is small, even though such a large $M1$ component for a $\Delta I=0$ transition could be accounted for by theory. Although the error is large, the z_K' values from the interband transitions indicate a large amount of mixing and poorer agreement with the simple rules than the ground-state transitions.[34] An indication that these bands might be mixed by quantal fluctuations[21] is the trend of z_K values in the $K=2$ bands where the odd-spin and even-spin members give different values when a large (virtual) $M1$ component is assumed for the $B(E2)$ moments from the even-spin members. It would indeed be useful to have similar values from other transitional-type nuclides. The alternation of $B(E2)$ values has been seen in other nuclei with stronger deformation such as ^{162}Dy,[31] but appears to be very minimal if nonexistent in strongly deformed nuclei such as ^{166}Er.[36,37]

[29] S. M. Abecasis and H. E. Bosch, Aeronautica Argentina, Serie Communicaciones LR17, 1967 (unpublished).

[30] S. M. Abecasis, H. E. Bosch, and A. Plastino, Aeronautica Argentina, Serie Communicaciones LR19, 1967 (unpublished).

[31] A. Fassler and W. Griener, Z. Physik **197**, 440 (1966).

[32] A. Fassler and W. Greiner, Z. Physik **170**, 105 (1962).

[33] A. S. Davydov and V. S. Rostovsky, Nucl. Phys. **60**, 529 (1964).

[34] A. Faessler, W. Greiner, and R. K. Sheline, Nucl. Phys. **70**, 33 (1965).

[35] C. M. Lederer (private communication).

[36] A. Backlin, A. Suarez, O. W. B. Schult, B. P. K. Maier, U. Gruber, E. B. Skera, D. W. Hafemeister, W. N. Skelton, and R. K. Sheline, Phys. Rev. **160**, 1011 (1967).

[37] S. B. Burson, P. F. A. Goudsmit, and J. Konijin, Phys. Rev. **158**, 1161 (1967).

[38] E. R. Marshalek, Phys. Rev. **158**, 993 (1967).

[39] E. R. Marshalek, Phys. Rev. **139**, B770 (1965).

TABLE XIV. z_K parameters.

	Large $M1$ value	Odd-spin level value	Phenomenological[a]	Microspin[a]
z_K^{nb}				
z_0^1	0.06	···	0.063	0.063
z_2^1	0.10	0.08	0.099	0.053
z_2^2	0.063	0.085	···	···

[a] Taken from Marshalek (see Refs. 32 and 33).
[b] The $z_K^n=z$ parameter for the nth phonon band with K characteristics.

In a recent work Marshalek[38,39] calculates β- and γ-band properties in the framework of the Hartree-Fock-Bogoliubov (HFB) theory. The "average value" or $\bar{z}_K$ from a strong (virtual) $M1$ component agrees with the HFB calculated value for the β band. However, the z_2 parameter for the odd-spin level of the γ band lies between the HFB and phenomenological results (see Table XIV), whereas the (virtual $M1$) $\bar{z}_2$ agrees well with the phenomenological calculation. The z_K parameters from this work are tested for their usefulness by calculating several related quantities. These calculations are presented in the following sections.

B. Second-Order Energy Term

The energy levels of a rotational band can be expanded in powers of $I(I+1)$, as was done by Bohr and Mottelson[27,40]:

$$E=A(I)(I+1)+B(I)^2(I+1)^2+C(I)^3(I+1)^3+\cdots.$$

The displacement of the levels from the simple $I(I+1)$ rule has been partly ascribed to band mixing, where the second-order term B has contributions from band mixing.[41] Here we investigate what contribution such mixing from known bands might make if the z_K parameters were correct. However, we must make the qualification that there may be anharmonic terms in the nuclear potential that intermix more than two bands; hence these formulas can only be considered as limiting cases.[35] The contribution to the second-order term B for a given band can be calculated, provided the mixing parameter, intrinsic quadrupole moment, and the $B(E2)$ moments are known from [4,42]

$$z_2=\surd(15/2\pi)\epsilon_2 Q_0\langle 2'|M(E2,2)|0\rangle^{-1},$$
$$=\surd(15/2\pi)\epsilon_2 Q_0[B(E2,0\rightarrow 2)\uparrow]^{-1/2},$$

and the knowledge that

$$\delta E_2=2\epsilon_2^2(E_{2'}-E_0)\{I^2(I+1)^2-2I(I+1)\}.$$

[40] Aa. Bohr and B. Mottelson, At. Energ. (USSR) **14**, 14 (1963).

[41] O. B. Nielsen, in *Proceedings of the Rutherford Jubilee Conference on Nuclear Physics*, edited by J. B. Birks (Heywood and Company, Ltd., London, 1962).

[42] Y. Yoshizawa, B. Elbeck, B. Herskind, and M. C. Oesen, Nucl. Phys. **73**, 273 (1965).

TABLE XV. Second-order energy terms.

	Even spin	Odd spin	Theoretical[a]
	10^3K		
β	11.2 ±0.70	...	...
γ	2.42±0.24	1.93+0.19	1 ±8
$(\beta\gamma)^b$	0.32	0.47	
	$-B_K$(eV)		
β	71.6 ±4.8	...	66.0
γ	8.37±0.84	6.67±0.67	1.18
$(\beta\gamma)^b$	0.31	0.67	...
Total	193.48[c]		160

[a] Taken from Ref. 32.
[b] Calculated assuming $B(E2)\uparrow \propto \sigma(d,d')$.
[c] Calculated using the form $AI(I+1)+B(I)^2(I+1)^2+C(I)^3(I+1)^3$.

Similarly, we have

$$z_0=\sqrt{(5/16\pi)}\epsilon_0 Q_0\langle 0''|M(E2), \quad 0|0\rangle^{-1},$$
$$=\sqrt{(5/16\pi)}\epsilon_0 Q_0[B(E2, 0\rightarrow 0'')\uparrow]^{1/2},$$

and

$$\delta E_0=\epsilon_0^2(E_{0''}-E_0)I^2(I+1).$$

Here the values of Q_0 are taken from Elbeck[43] while the values of $B(E2)\uparrow$ were taken from Block *et al.*[19] and Yoshizawa *et al.*[42]

If a strong $M1$ component is assumed in order to obtain a consistent z_K from the even-spin levels, then the values of ϵ_K and B_K can be calculated. These are given in Table XV. For comparison the z_K obtained from the odd-spin members of the $K>0$ bands are included as well as the values calculated in the HFB framework by Marshalek.[38] The agreement of B_K is striking, but may well be fortuitous. The contribution calculated for the two-phonon level was made assuming the cross section obtained by Block *et al.*[19] could be set proportional to $B(E2)\uparrow$, and consequently must be treated as approximate. However, the magnitude suggests that even such terms could not account for the discrepancy between ϵ_K and B_K. The suggestion of Gunther and Parsignault[44] that a $K=1$ band could be giving strong coupling to account for the suppression does not appear to have support here, although there may be a $K=1$ band present at an energy just above the pairing gap.[24]

C. Quadrupole Moment of the γ-Vibrational State

The variations in the intrinsic quadrupole moment of the ground state of deformed and near-deformed nuclei are well known; however, little, if anything, is known of the variation of highly excited states in this region. Consequently, a determination of the quadrupole moment of an excited state in ^{154}Gd is worthwhile, as well as a comparison of the trend of Q_{22} as the ground state becomes more stable toward deformation.

The $B(E2)$ transition probabilities measured in experiments such as Coulomb excitation, etc., are direct

[43] B. Elbeck, thesis, Munksgaard, Copenhagen, 1963 (unpublished).
[44] C. Gunther and D. R. Parsignault, Phys. Rev. 153, 1297 (1967).

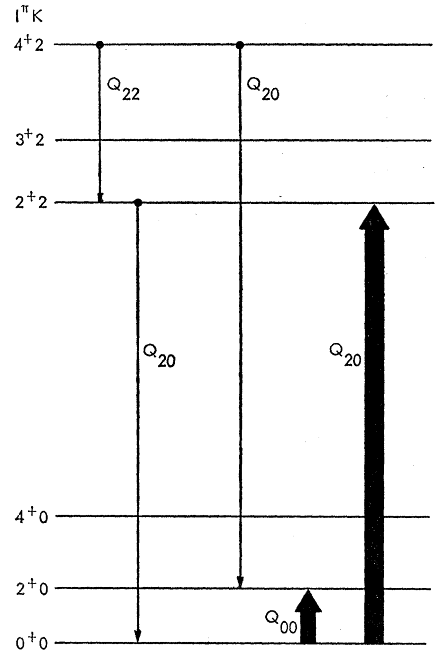


FIG. 7. Relation of various intrinsic quadrupole moments in the calculation of Q_{22}.

functions of quadrupole strength. In particular, the $B(E2)$ values to the 2^+0 and 2^+2 states of the ground-state rotational band and the γ-vibrational band, respectively, are proportional to Q_{00} and Q_{20}, respectively (see Fig. 7). The interband transition probability $B(E2, 22\rightarrow 00)$ and $B(E2, 42\rightarrow 20)$ are also determined by Q_{20}, while the intraband value is determined by Q_{22}. Since the internal state of the nucleus is the same in the 4^+2 and 2^+2 levels, the transition probability between the 4^+2 level and the 2^+0 level can be calculated. From this and a measurement of the intensity ratio between the 4^+2 level to the 2^+2 level and the 2^+ member of the ground-state rotational band, the ratio of Q_{22} to Q_{00} can be calculated. However, the fact that the γ-vibrational band is mixed into the ground-state rotational band strongly affects the relative transition probabilities. This must be taken into account before a meaningful result is obtained. If this is done, the following relationship results[45]:

$$\left(\frac{Q_{22}}{Q_{00}}\right)^2=\left[\frac{B(E2, 0^+0\rightarrow 2^+2)\uparrow}{B(E2, 0^+0\rightarrow 2^+0)\uparrow}\right]\left[\frac{B(E2, 4^+2\rightarrow 2^+2)\downarrow}{B(E2, 4^+2\rightarrow 2^+0)\downarrow}\right]\times\left[f(z)\frac{\langle 422-2\ 4220\rangle^2}{\langle 4220\ 4222\rangle^2}\right],$$

where $f(z)$ is the band-mixing parameter function and is given by Hansen *et al.*[3] From the γ-ray intensities determined here, the Coulomb excitation data of Yoshizawa *et al.*,[42] the deuteron inelastic scattering

[45] B. S. Dzhelepov, Bull. Acad. Sci. USSR, Phys. Ser. 28, 3 (1964).

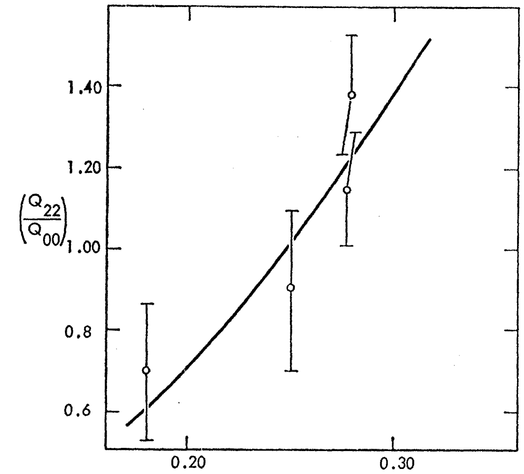


FIG. 8. Calculated ratio of Q_{22}/Q_{00} for nuclei with various deformations.

data of Block *et al.*,[19] and a weighted average value for z_K the value of Q_{22}/Q_{00} can be calculated to be $(Q_{22}/Q_{00})\approx 0.9\pm 0.2$. There are relatively few values determined for Q_{22}/Q_{00}; however, if the ones available are plotted as a function of deformation, Fig. 8 results. The apparent trend to increased ratio of Q_{22}/Q_{00} as the deformation increases is in contrast to that arrived at by Dzhelepov.[44] The trend for Q_{22}/Q_{00} to be less than 1 at weak deformation has been found for several cases[36,44]; however, this may be because the z_K is not a good quantity for weak deformation rather than a deformation effect, since the calculation of Q_{22}/Q_{00} or related quantities is strongly dependent on the value of z_K. Since the assumption that $Q_{22}=Q_{00}$ is made in a number of models,[46,47] further determinations of this effect are clearly called for.

D. *K*-Forbidden β Decay

When the multipolarity λ is less than ΔK for a given transition, it becomes totally forbidden by the intensity rules obtained from *I*-independent operators, and one must resort to a power-series expansion. *K*-forbidden β decay in even nuclei has been of some interest recently[48,49]; consequently, it is instructive to ascertain the effects the mixing of higher-lying bands into the ground-state band may have upon β decay to the ground state in this nucleus.

Since, in general, the population of levels by β decay and the resultant log*ft* values can be most accurately determined by the intensity balance technique (see, for example, Hansen *et al.*[49]), the log*ft* values given in Table VI are used here. The general rule predicting a retardation of 10^2 for each degree of *K* forbiddenness holds for this nucleus. For the β-vibrational band, the *ft* ratio of 1.3 ± 0.2 for β decay to the 4^+ and 2^+ members is in agreement with the theoretical value of 1.33 for a β transition of $L=1$.[40] However, the decay to the 2^+ member of the ground-state rotational band cannot be reconciled with such a simple picture. If the wave function of the ground-state band is expressed as[50]

$$\Psi_I=\Psi_{I,K=0}^{(0)}+\sum \epsilon_2[2I(I-1)(I+1)(I+2)]^{1/2}\Psi_{I,K=2}^{(0)},$$

we can attempt to ascertain what effect the higher-lying bands have on the log*ft* value. Unfortunately, to obtain values of ϵ_2, a knowledge of the $B(E2)\uparrow$ values is necessary (see previous section). However, with the data available for the mixing of the γ-vibrational band into the ground-state band, it can be estimated that there is less than 1% contribution to the decrease in the log*ft* value to the 2^+ member of the ground-state band. This is in general agreement with that found by Hansen *et al.* by using β-ray spectroscopy techniques. Furthermore, if the data obtained in (d,d') experiments can be taken as proportional to $B(E2)\uparrow$, then the $K=2$ (βγ) two-phonon band can be estimated to account for

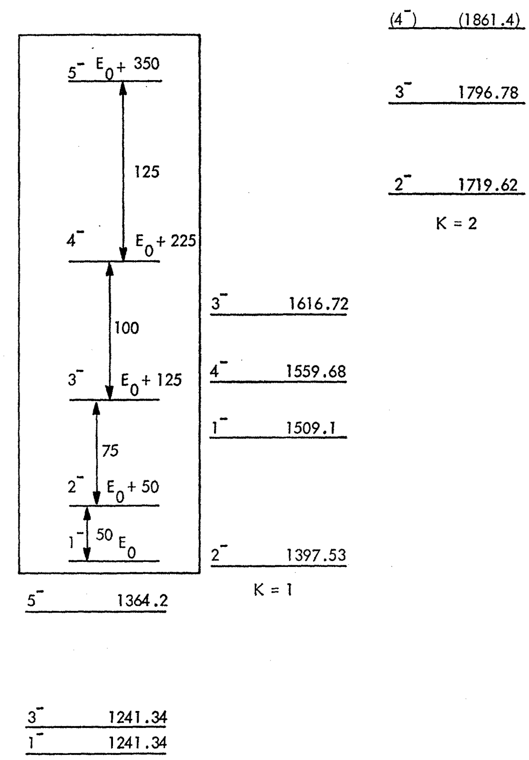


FIG. 9. Partial level scheme of ^{154}Gd showing the suggested octupole band and their rotational members found in the decay of ^{154}Eu. (Insert is an unperturbed level sequence for a deformed nucleus in the Gd region.)

[46] A. Davydov and G. Filippov, Zh. Eksperim. i Teor. Fiz. **35**, 440 (1958) [English transl.: Soviet Phys.—JETP **8**, 303 (1959)].
[47] A. Davydov and Y. Rostovski, Zh. Eksperim. i Teor. Fiz. **36**, 1788 (1959) [English transl.: Soviet Phys—JETP **9**, 1275 (1959)].
[48] P. G. Hansen, N. R. Johnson, and H. L. Nielsen, Nucl. Phys. **55**, 171 (1964).
[49] P. G. Hansen, H. L. Nielsen, and K. Wilsky, Nucl. Phys. **54**, 657 (1964); **89**, 571 (1966).
[50] See Ref. 42 and B. Elbeck, thesis, Munksgaard, Copenhagen, 1963 (unpublished), and references cited therein.

less than 0.5% of the decrease in the $\log ft$ to the 2^+ level. It should be pointed out that since the significance of the z_2 values in this nucleus is questionable these calculations which are z_2-dependent (recall that ϵ_2 is proportional to z_2) must be regarded as dubious.

NEGATIVE-PARITY LEVELS

The octupole state of a purely spherical nucleus is expected to be fragmented into components when the nucleus becomes deformed. Consequently, bands with K^π of 0^-, 1^-, 2^-, and 3^- should be expected in the gadolinium isotopes.[4] The negative-parity levels suggested in this work indicate the band structure shown in Fig. 9. For comparison, the calculated rotational sequence of an uncoupled band, assuming a moment of inertia typical for the odd-parity bands in the Gd isotopes, is given in the insert. Recently, calculations have been done for the nucleus ^{156}Gd using the model of Donner, Faessler and Greiner.[31,51,52] Unfortunately, they neglect the mixing of bands in their calculations. However, even with the inclusion of Coriolis coupling, which does give the $K=1$ level sequence inversion, their model cannot account for the level sequence in all three bands.[51]

The fact that suppression, even inversion, of the normal rotational sequence is occurring through some sort of interaction not only in ^{154}Gd but in ^{152}Gd through ^{158}Gd is seen in the data of Block *et al.*[19] Since this inversion and suppression decreases as the nuclear deformation increases, it may be due in part to the transitional nature of the light Gd nuclides. These properties as well as the behavior of the two-phonon levels in this nucleus[6,7] may be due to a potential of the type given in Fig. 10 which recently has been calculated for ^{154}Sm by Kumar.[21,53] It indeed would be useful to have calculations for the properties of the octupole states from a potential of this type. However, the strong suppression of the energy of the levels in the $K^\pi=0^-$ band and the apparent inverted sequence of the $K=1$ band suggests further interactions may be necessary to account for these trends. It is suggested here that one, and possibly two, types of Coriolis forces are acting on these bands: (1) a rotation-vibration coupling (RVC) Coriolis-type interaction acting on the more collective $K=0$ and $K=1$ bands, and (2) a pseudo-rotor-particle coupling (p-RPC) Coriolis-type force acting on the $K=1$ and $K=2$ bands.

It is expected that the $K=0$ and $K=1$ bands of the octupole state will undergo an RVC Coriolis-type interaction. Furthermore, because the r-symmetry rule does not allow even-spin states in the $K=0$ band, only the odd members of the $K=1$ band will be affected. This, of course, results in a net energy shift upward for the $K=1$ band and a concomitant downward shift in the energy sequence (suppression) of the $K=0$ band.[4,27] The 10.04-keV separation of the $I=1$ and $I=3$ members of the $K=0$ band is indicative of the occurrence of a strong interaction. This is further supported by the $B(E1$, relative) values from these levels (see Table VIII) as well as in the neighboring nuclei (note the very poor agreement with simple theory in the case of the 3^-1 levels). Further investigation of the $K=0$ level trend would be useful to ascertain whether this inversion-suppression is due to the RVC Coriolis-type interaction as deformation sets in and the octupole state is fragmented.

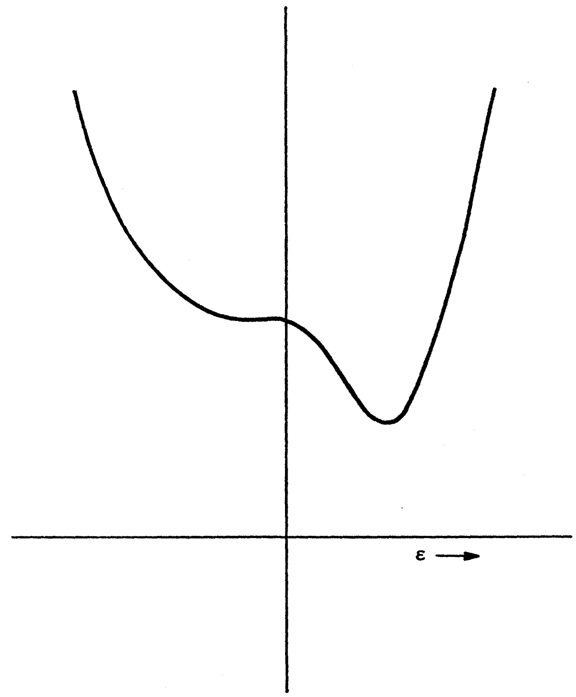


FIG. 10. Suggested potential well for the nucleus ^{154}Gd (after Kumar, Ref. 20).

Solov'ev and co-workers[5,54] have performed calculations on the basis of the superconducting model by second-quantization methods for strongly deformed nuclei. They also have extended their multipole expansion of the nucleon interaction to include the octupole-octupole interaction.[55] Even though their calculations are less accurate in the transitional region, it is worthwhile to compare their results to this nucleus. In general, when the secular equation is solved they find that if a root of a state occurs near its pole, the state will be more pure two-quasiparticle than collective in nature, the general trend being that the higher K states are less collective to the extent that the $K=3$ state is almost pure (99%) two-quasiparticle. Also, it is found that the $K=1$ and $K=2$ states can be made up of a

[51] W. Donner (private communication).
[52] W. Donner and W. Greiner, Z. Physik 197, 440 (1966).
[53] K. Kumar and M. Baranger, Nucl. Phys. A92, 608 (1967).
[54] V. G. Solov'ev, JINR-P-1973, Dubna, 1964 (unpublished).
[55] V. G. Solov'ev, P. Fogel', and A. A. Korneichuk, Bull. Acad. Sci. USSR, Phys. Ser. 28, 1495 (1964).

TABLE XVI. Octupole states.

K	Solov'ev *et al.* root	(pole)	Expt	Expt minus theor.
0	1.33	(2.15)	1.24134	−0.09
1	1.64	(1.82)	(1.398−0.050)[a]	(−0.18)
2	1.81	(2.02)	1.71967	−0.09
3	2.25	(2.30)	2.2262[b]	(−0.02)[b]

[a] The 2^- level less calculated $E_{2-1}-E_{1-1}$ (unperturbed).
[b] From $^{154}Tb^m$ decay, Ref. 24.

large contribution from a single two-quasiparticle configuration. When this occurs it is found necessary to take into account blocking, which then reduces the energy of the octupole state by the same amount as it reduces the corresponding two-quasiparticle state.[5] In Table XVI the values predicted by Solov'ev and co-workers are compared with those found in this work. All the states are found at a lower energy than calculated. This, however, should be expected for several reasons. First, the $K=0$ state is expected to be the most collective and to undergo RVC-type Coriolis interaction with the $K=1$ state. Second, the $K=1$ and $K=2$ states are nearly pure two-quasiparticle in makeup; hence, they may have their energy lowered because of the blocking effect. The drastic lowering of the $K=1$ state may be due to blocking since Solov'ev and co-workers predict the $K=1$ state, in general, to be even less collective in nature than the $K=2$ octupole states. However, it may be worthwhile to consider yet another interaction once the two-quasiparticle configuration of the $K=1$ and $K=2$ octupole states are considered.

Gallagher and Solov'ev[22] have assigned the major configuration of the $K^\pi=2^-$ state to the $[411]\uparrow_p[523]\uparrow_p$ two-quasiparticle state. For one-quasiparticle states the selection rule governing unhindered RPC-type Coriolis coupling is either

$$\Delta\sum=0 \quad \text{with} \quad \pm\Delta\Lambda=\mp n_z=1$$

or

$$\Delta\sum=\pm1 \quad \text{with} \quad \Delta\Lambda=0$$

in the formalism of asymptotic quantum numbers $[Nn_z\Lambda]\Omega^\pi$, where $\Omega=\Lambda+\sum$. If there exists a pair of two-quasiparticle bands made up of the configuration $[Nn_z\Lambda]\uparrow[N'n_z'\Lambda']\uparrow$ and $[Nn_z\Lambda]\uparrow[N''n_z''\Lambda'']\uparrow$, where N', n_z', Λ' and N'', nz'', Λ'' are related by the conditions above, then it is possible within the framework of the rotor-particle coupling theory that these two orbitals will configuration-interact. (Although obvious, it should be pointed out that a necessary requirement is that the spins of the mating members be aligned.) This is defined here as p-RPC. As has been pointed out in this work, the $K^\pi=1^-$ band may have a strong contribution from the $[411]\uparrow[532]\uparrow$ orbital. The $K^\pi=2^-$ band has been given as $[411]\uparrow[523]\uparrow$ by others. This matches the requirements of p-RPC as given above. Furthermore, recently Żylićz *et al.*[56] have measured the sign and magnitude of the Coriolis coupling between the $[523](7^-/2)$ and $[532](5^-/2)$ orbitals and find it to be large albeit suppressed because of the $(uu'+vv')$ constriction. If the assumption that the two-quasiparticle states can configuration-interact is correct, this suggests that perhaps the $K=1$ and $K=2$ octupole states in this nucleus (and perhaps others of this series) are undergoing a p-RPC Coriolis-type coupling which is affecting the $I\geq2$ levels in the $K=1$ band. At first approximation this could, in conjunction with RVC, account for the abnormal sequence of levels in the $K=1$ band as well as its apparently low bandhead position. The 3^-2 level energy would be increased by p-RPC while the 3^-0 level energy would be decreased by RVC and second-order p-RPC. The 3^-1 level energy would be subject to opposing RVC and p-RPC. This would explain why the 3^-1 level energy is not greater than it is.[57] The 2^-1 level would be decreased in energy since no 2^-0 level exists to give a counteracting RVC. This, then, would account for the large 2^-0 to 3^-1 energy separation as well as the large disagreement with that predicted by the second quantization method used by Solov'ev. The two 1^- levels would be expected to repel each other (note that this would tend to further compress the relative 1^-0 to 3^-0 energy separation since the 3^-0 level would have second-order suppression). That such double coupling may be occurring is further supported by the relative transition moments from all three bands as they do not agree with simple Alaga rules. However, it should be pointed out that the latter is somewhat dubious if the $K=2$ band is assumed to be uncoupled, as the level spacings may indicate. The identification of more levels of the $K=1$ and $K=2$ bands would be very useful in resolving this.

In general, it appears that the $K=1$ level-order inversion and the $K=0$ level suppression can be explained by assuming an RVC-type Coriolis interaction. The relative $B(E1)$ and $B(E2)$ values for the even-spin members of the $K=1$ band indicate they too may be undergoing an interaction. However, this may be due to the transitional nature of this nucleus and not a p-RPC-type Coriolis interaction between the $\{[411]\uparrow3^+/2[523]\uparrow7^-/2\}2^-$ and $\{[411]\uparrow3^+/2[523]\uparrow5^-/2\}1^-$ two-quasiparticle states which contribute largely to the wave function of the $K=2$ and $K=1$ octupole states, respectively.

CONCLUSION

In general, an attempt has been made to apply the parameters of nuclei with strong deformation to the properties of ^{154}Gd. It is found that simple band mixing cannot account for the relative $B(E2)$ transition probabilities from even-spin members of collective bands, even when a large $M1$ component is assumed. The z_K values for a given band are inconsistent. The amount of (virtual) $M1$ necessary is even larger for

[56] J. Żylićz, P. G. Hansen, H. L. Nielsen, and K. Wilskey, Nucl. Phys. 84, 13 (1966).

[57] Recall $E(\text{RVC})\propto I(I+1)$.

two-phonon levels than for one-phonon levels. The modified Alaga rules appear to break down for the higher-phonon bands, but this may be due to the bands being mixed by quantal fluctuations as described by Kumar. There are indications that even the one-phonon bands may have a large mixture, since (1) the $\bar{z}_K$ parameters (z_K determined by assuming a large $M1$ component) for the even-spin levels are not the same as z_K for the odd-spin members, and (2) there are indications of large mixing of the γ-vibrational state into the β-vibrational state. If the z_K parameters for the more strongly deformed nuclei are compared to increasing deformation, there is a trend to more consistent values; however, even in the strongly deformed nuclei such as ^{166}Er, there appears to be a residual effect. It is interesting to note that when $\bar{z}_K$ is used to calculate the second-order energy coefficient B_k, agreement is found with the results of the HFB calculations of Marshalek and that $\sum_k B_k$ from the two-phonon contributions still are much less than B (experimental).

If the results of Bosch and co-workers[29,30] (which are based on the R-V model[31,32,34]) are compared to the experimental results, fair agreement is found for the level of lowest even spin but agreement becomes worse as the spin value of a level becomes larger. Also, it should be pointed out that the relative $B(E2)$ values for the odd-spin members agree remarkably well no matter what theory is used. If we assume the β band and γ band were being strongly mixed such that z_K was a poor parameter and, of course, was giving results that indicated a much smaller amount of mixing than is present, then a number of properties which have appeared questionable in the past may be resolved. It would reconcile the contradictory evidence of Hamilton *et al.*, who by angular-correlation experiments find a small or zero $M1$ component for the γ rays which represent $\Delta I=0$ transitions and the large $M1$ component required for agreement of the z_K values. The deviation from the normal $I(I+1)$ sequence of a rotational band may be due more to band mixing than originally suggested,[41] since the contribution to the $I^2(I+1)^2$ term from band mixing can only be calculated from the values of z_K. A poor z_K and strong mixing might also explain the K-forbidden β-decay results. Further indication that z_K may be giving results too low is the calculation of Q_{22}, which tends to show $Q_{22}<Q_{00}$. Perhaps a quantity such as $y_K=z_K+f(z_K{}^n)$ with $n>1$ should be used in place of the simple z_K if such a quantity is going to be of continued usage. It is interesting to note that of the suspected bandheads of the β and γ bands in this region the β bandhead is rapidly increasing in energy while the γ bandhead is relatively constant in energy. The effect that appears to be that of increasing deformation (i.e., z_K values becoming consistent for a given band as deformation increases) may be no more than the fact that the difference in energies of the β and γ bands ($\Delta E=|E_\beta-E_\gamma|$) is increasing, there by decreasing the effective coupling interaction. It indeed would be worthwhile locating the $\beta\beta$, $\gamma\gamma$, and $\beta\gamma$ second-vibrational states in nuclei where the energy of the β band was greatly different from the energy of the γ band. Such might shed more light on the arguments put forth by Sheline *et al.*[58] and more recently documented by Sakai.[59]

The negative parity levels and their properties are consistent with a strong RVC-type Coriolis coupling between the $K=0$ and $K=1$ fragments of the octupole state and a tentative p-RPC coupling between the $K=1$ and $K=2$ fragments. The octupole-band properties agree with those calculated by Solov'ev, who assigns nearly two-quasiparticle configurations to the octupole states with $K\geq 1$ and more collective properties of the $K=0$ state.

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[58] R. K. Sheline, Rev. Mod. Phys. **32**, 1 (1960).
[59] M. Sakai, Nucl. Phys. **A104**, 301 (1967).