communication.
[16]S. C. Burnett, H. C. Britt, B. H. Erkkila, and W. E. Stein, Phys. Letters 31B, 523 (1970).
[17]M. Zielinska-Pfabe, Phys. Letters 29B, 280 (1969).
[18]S. P. Kapitza, N. S. Rabotnov, G. N. Smirenkin, A. S. Soldatov, L. N. Usachev, and Yu. M. Tsipenyuk, Zh. Eksperim. i Teor. Fiz. – Pis'ma Redakt 9, 128 (1969). [transl.: JETP Letters 9, 73 (1969)].
[19]J. R. Nix, Ann. Phys. (N.Y.) 41, 52 (1967).

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Studies of the Radioactive Decays of ^{152}Eu and ^{154}Eu

L. L. Riedinger* and Noah R. Johnson
Oak Ridge National Laboratory,† Oak Ridge, Tennessee 37830
and
J. H. Hamilton
Physics Department, Vanderbilt University,‡ Nashville, Tennessee 37203
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γ rays emitted in the radioactive decays of ^{152}Eu and ^{154}Eu have been studied with Ge(Li) and NaI detectors. Energies and relative intensities were derived from singles experiments with large volume Ge(Li) detectors and assignments of γ rays to transitions in the level schemes were made with the help cf Ge(Li)-NaI coincidence measurements. In all, 71 γ rays were observed in the ^{152}Eu decay and 51 in the ^{154}Eu case. Three members of each of the β- and γ-vibrational bands were observed. In addition the results of the coincidence experiments are used to assign a level at 1649.8 keV as the probable 2^- member of the $K=2$ band in ^{152}Sm. The properties of this state and of the $K^\pi=0^-$ and 1^- bands are compared with the properties of the corresponding states in ^{154}Gd. It is found that there is evidently less Coriolis coupling between the negative-parity states in ^{152}Sm than in ^{154}Gd. The members of the $K^\pi=1^-$ band in the former are not inverted as in the latter, and the $B(E1)$ ratios from the $K^\pi=0^-$ states in the former are in better agreement with the predictions of the rotational model. The low-energy levels in ^{152}Gd are considered in light of two possible interpretations. We find that it is preferable to consider these states as resulting from quasirotations and quasivibrations than to treat them as members of one-, two-, and three-phonon vibrational excitations about spherical equilibrium shapes. Finally, a new 2^+ level at 1293 keV in ^{152}Sm is discussed in light of recent experiments involving two-neutron-transfer reactions to levels in this nucleus.

I. INTRODUCTION

The onset of nuclear deformation is rather abrupt at the beginning of the rare-earth region of deformed nuclei. The ^{152}Gd nucleus with 88 neutrons has been characterized as nearly spherical in shape, partially on the basis of a vibrational-like spectrum. The $N=90$ nuclei, for example ^{152}Sm and ^{154}Gd, display the low-lying excited states characteristic of rotational spectra and are considered to be deformed. However, these three nuclei are better referred to as transitional, since their properties preclude classification as well-formed spherical or deformed nuclei. For example, the first excited state of ^{152}Gd occurs at 344 keV, lower than expected for a quadrupole vibration about a spherical shape. The levels of the rotational spectra of ^{152}Sm and ^{154}Gd deviate more widely from the $I(I+1)$ energy spacings expected for rigid rotators than do the levels in heavier rare-earth nuclei. Also, the quadrupole-vibrational states of the two latter nuclei are found at lower energies than the corresponding levels in the heavier nuclei. Comparative studies of these three nuclei can lead to a wealth of information concerning collective effects in transitional nuclei, and thus several years ago we initiated experiments on the γ rays emitted in the radioactive decays of ^{152}Eu and ^{154}Eu.

Some preliminary results of this work have been published.[1] Many additional investigations of these level schemes have been performed, as reported earlier.[2] In recent years, particularly during the course of our work, other studies have been reported by Dzhelepov and his coworkers,[3-6] Liu *et al.*,[7] and Varnell, Bowman, and Trischuk (VBT),[8] who have investigated the ^{152}Sm, ^{152}Gd, and ^{154}Gd excitation spectra through radioactive decay techniques. Bisgaard, Nielsen, and Sodemann (BNS),[9] Katoh and Spejewski,[10] Malmsten, Nilsson, and

Andersson (MNA),[11] Larsen, Skilbreid, and Visiten (LSV),[12] Aquili, Cesareo, and Giannini,[13] and Mukherjee and Sen Gupta[14] have studied only the ^{152}Eu decay properties, while Ng, Mann, and Walton,[15] Brantley *et al.*,[16] Hamilton and Manthuruthil,[17] Meyer,[18] and Andersson and Ewan[19] have reported recent work on the decay of ^{154}Eu.

The conclusions from our work concerning the β- and γ-vibrational bands of ^{152}Sm and ^{154}Gd have already been published.[20,21] It is found that, under the assumption of axially-symmetric nuclei in zeroth order, the branching ratios from the members of the γ band in each nucleus can be explained through the inclusion of nonadiabatic mixing between the β, γ, and ground-state levels. However, there seems to be no way to explain in a similar manner the branching ratios from the β-vibrational levels. The present paper discusses the general features of the excitation spectra of the three nuclei, with special emphasis on the negative-parity levels of ^{152}Sm and ^{154}Gd, and on the low-lying positive-parity states of ^{152}Gd. Although the over-all results of our experiments are similar to the results of other Ge(Li) measurements reported recently,[8,13,18] significant additions and differences will become apparent in the presentation of our work. In the case of ^{152}Eu, many γ rays not reported in Refs. 8 or 13 are observed in our spectra; some of these are assigned to transitions in the level schemes of ^{152}Gd and ^{152}Sm. More important, γ-γ coincidence measurements performed in our work enable placement of new transitions and provide definite evidence for the placement of other transitions assigned previously only by energy fits. In work on ^{154}Eu, Meyer[18] was able to observe more γ rays with a Compton-suppression spectrometer than are reported here. However, our extensive γ-γ coincidence measurements provide positive evidence for the placement of many γ rays whose locations in the ^{154}Gd level scheme were based previously only on energy fits.

II. EXPERIMENTAL PROCEDURE

For a detailed discussion of the experimental techniques, the reader is referred to Ref. 21. Sources of 12.4-yr ^{152}Eu and 16-yr ^{154}Eu were prepared by neutron irradiation of the europium oxides enriched to 99% in masses 151 and 153, respectively, and counted by γ-ray spectrometers in the singles and coincidence modes. The best singles spectra were obtained with a 40-cm^3 Ge(Li) detector coupled to a 4096-channel pulse-height analyzer. The γ-γ coincidence experiments were performed with 6-cm^3 Ge(Li) and 7.5-cm × 7.5-cm NaI detectors and a Victoreen multiparameter analyzer operated in the 100 × 200-channel mode. The biased amplifier output from the Ge(Li) detector was coupled to the 100-channel input of the multiparameter analyzer and the amplifier output from the NaI detector was fed to the 200-channel input. The analyzer was provided with an external gate signal from a fast-coincidence unit having a resolving time [full width at half maximum (FWHM)] of $2\tau = 69$ nsec. A lead baffle, 1 cm thick and covered with a 0.2-mm layer of cadmium and 0.07 mm of copper, was used in these measurements to minimize crystal-to-crystal scattering. The coincident efficiency of this system was found to be approximately 87% when measured with γ rays from ^{207}Bi and ^{60}Co sources. This enabled us to extract quantitative results from our coincidence measurements. Windows were set above the gating peaks and computer programs were used for the subtraction of the coincident contributions due to Compton backgrounds under the gating peaks as well as for correcting the matrix of data for random-coincident effects.

III. EXPERIMENTAL RESULTS

A. Decay of ^{152}Eu

The γ-ray singles spectrum of ^{152}Eu measured with a 40-cm^3 Ge(Li) detector is shown in Figs. 1 and 2. The resolution of this particular experiment was 2.3 keV FWHM for 1332 keV. The energies and intensities of the γ rays emitted in the ^{152}Eu decay are given in Table I. Energies of the strong lines were determined from energies of standard γ rays (given by Marion[22]) by counting the ^{152}Eu source and the standard sources simultaneously with a somewhat smaller, 35-cm^3 Ge(Li) detector. The ^{152}Eu lines assigned with uncertainties of 0.12 keV or less were measured in this way. The energies of the other γ rays were then found by using the well-determined integral linearity of the system in conjunction with the strong ^{152}Eu transitions as internal standards.

Relative γ-ray intensities were determined by summing the counts over the nearly Gaussian peaks after background had been subtracted. The errors on the intensities reflect a 5% uncertainty in the efficiency calibration and uncertainty in the background levels under the peaks. The energies and intensities for the transitions from the β- and γ-vibrational bands have already been quoted in Ref. 21. Those intensities were derived from experiments with the 35-, 20-, and 6-cm^3 Ge(Li) detectors and thus differ slightly (but within errors) from the values obtained through the use of the 40-cm^3 detector, which are listed in Table I. The peaks resulting from the contaminant ^{154}Eu are labeled in Figs. 1 and 2. The intensity of the 1005.0-keV γ ray has been reduced by 25% to correct for

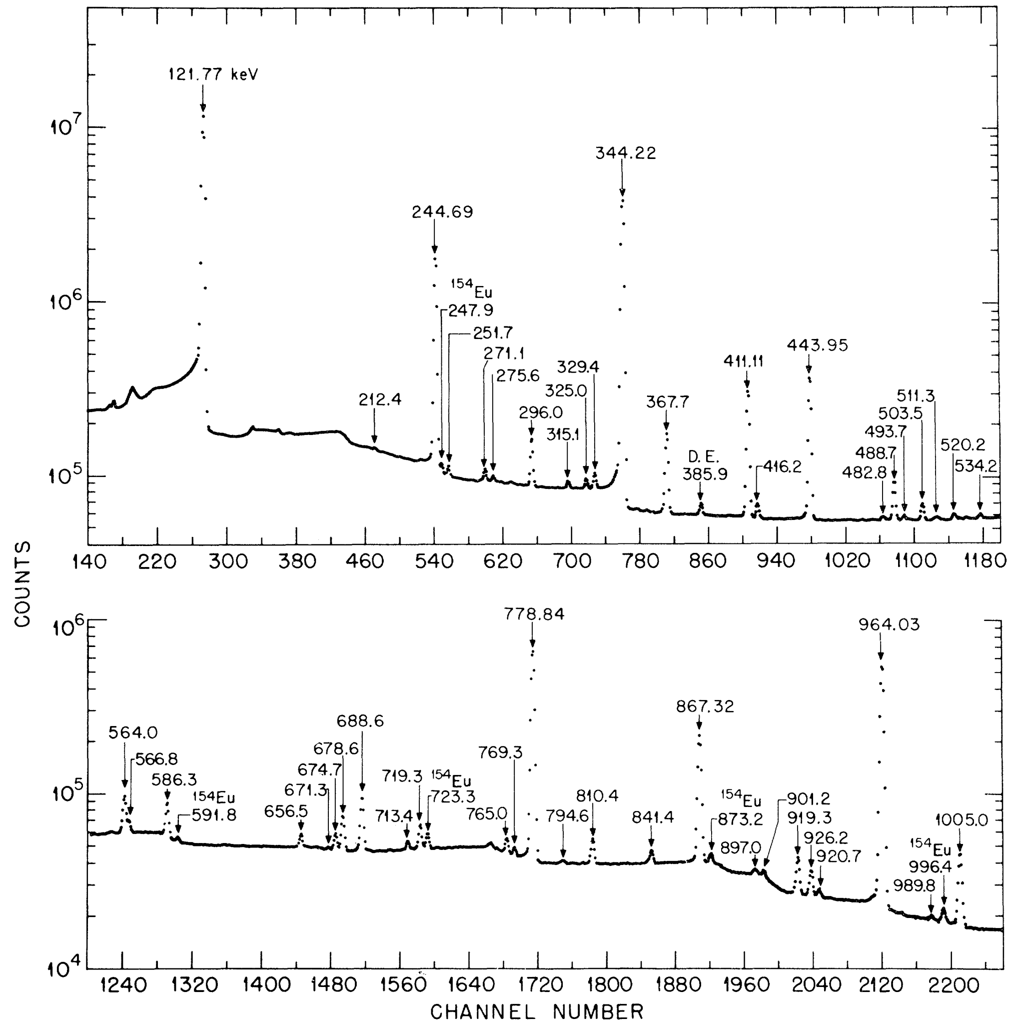

FIG. 1. Low-energy portion of the ^{152}Eu γ-ray spectrum taken with a 40-cm^3 Ge(Li) detector.

the contribution of the intense 1004.75-keV γ ray of ^{154}Eu.

Table I also lists the results of VBT,[8] which are in good agreement with the present work. The errors on our intensity values are larger in most cases than those assigned by VBT.[8] This results primarily from the fact that we have assigned more conservative errors to the efficiency calibrations of our Ge(Li) detectors. The major difference in the two sets of data lies in the fact that the present work revealed 29 more γ rays than were observed by VBT.[8] Of these, four γ rays at 1262 ± 3, 1608 ± 2, 1649 ± 3, and 1769 ± 3 keV were reported previously by LSV[12] in a study of the high-energy transitions in ^{152}Sm and ^{152}Gd.

MNA[11] have detected the electrons emitted in ^{152}Eu decay and measured their relative intensities. Using these values in conjunction with our γ-ray intensities, we are able to determine the K-shell internal-conversion coefficients, which are listed in Table II. The γ-ray and electron intensities have been normalized to yield the predicted α_K value[23] for the 344.22-keV transition (several groups have experimentally verified this value, as summarized in Ref. 2). Because of the approximately 3-keV difference in the K-shell binding energies for Sm and Gd, comparisons of the energies of MNA[11] to those listed in Table I indicate the nucleus from which the γ ray or conversion electron results. The assignment to samarium or gadolinium is thus listed in column 2 of Table II for each case. The experimental conversion coefficients are compared with the theoretical values calculated by Hager and Seltzer.[23] Multipolarity assignments resulting from comparisons of the observed and calculated coefficients are given in the last

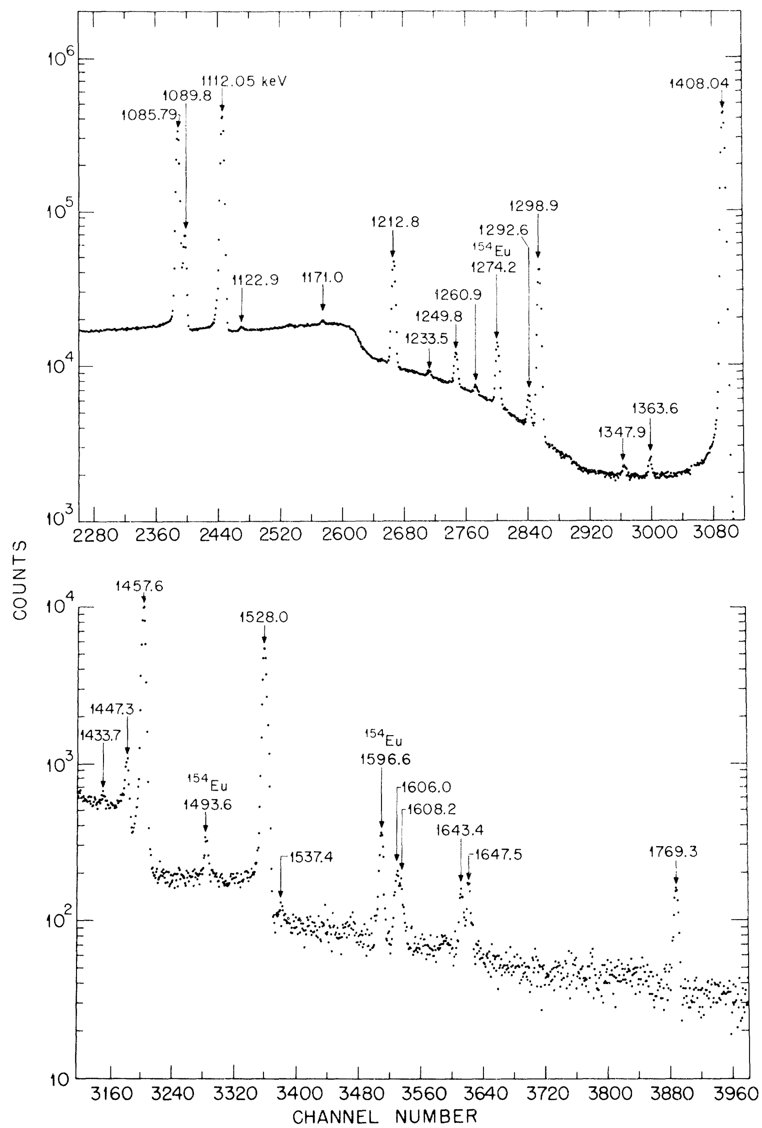

FIG. 2. High-energy portion of the ^{152}Eu γ-ray spectrum taken with a 40-cm^3 Ge(Li) detector.

column. In many cases, $E2$ assignments are made in spite of the fact that the conversion coefficients clearly allow for small $M1$ components. The levels from which these transitions originate are interpreted as the results of collective quadrupole vibrations and thus the deexcitations are expected to be quadrupole in character. The conversion coefficients of some of the stronger transitions have been measured by Dzhelepov, Zhukovskii, and Maloyan (DZM)[5]; these values are also listed in Table II. There is good agreement between their values and those resulting from our experiments.

Six γ-γ coincidence experiments were performed on the ^{152}Eu decay. In these experiments, the 6-cm^3 Ge(Li) detector was set to gate on γ rays in small energy ranges of the spectrum, while the NaI crystal usually detected γ rays over the entire energy range. Most of the results from these measurements are shown in Table III. In column 2 are listed energies of γ rays in coincidence with the gating transition given in the first column. The detector used to observe the coincidence γ rays of column 2 is listed in column 6. In most cases, the areas of the coincident peaks could be analyzed to yield coincident quotients, i.e., the number of γ rays from a particular transition, per gating event of interest in the window. The details of this method of analysis have been described[24,25] previously. From these coincidence quotients and known branching ratios, we are able to assign in column 3 the γ-ray intensities corresponding to particular transitions in the decay scheme (the levels

TABLE I. Energies and relative intensities of the γ rays emitted in the decay of ^{152}Eu.

E_γ (keV) Present work	Varnell *et al.*[a]	I_γ Present work	Varnell *et al.*[a]
121.77 ±0.08	121.8	108 ±5	116 ±4
212.4 ±0.6		0.067 ±0.029	
244.69 ±0.08	244.7	28.2 ±1.4	29.0 ±0.9
251.7 ±0.6		0.26 ±0.04	
271.1 ±0.6	271.0	0.28 ±0.04	0.27 ±0.02
275.6 ±0.6	275.4	0.11 ±0.03	0.12 ±0.01
296.0 ±0.3	295.9	1.51 ±0.09	1.60 ±0.04
315.1 ±0.3		0.17 ±0.03	
325.0 ±0.3		0.26 ±0.03	
329.4 ±0.3		0.44 ±0.04	
344.22 ±0.08	344.2	100	100
367.7 ±0.2	367.6	3.15 ±0.18	3.16 ±0.09
	400.5		0.009 ±0.009
411.11 ±0.08	410.9	8.05 ±0.40	8.25 ±0.16
416.2 ±0.3		0.38 ±0.04	
443.95 ±0.08	443.8	10.3 ±0.6	10.4 ±0.6
444.0	444.1	0.9 ±0.3	1.14 ±0.12
482.8 ±0.2		0.11 ±0.02	
488.7 ±0.2	488.4	1.48 ±0.09	1.49 ±0.04
493.7 ±0.4	493.6	0.09 ±0.04	0.11 ±0.03
503.5 ±0.2	503.3	0.55 ±0.03	0.55 ±0.02
511.3 ±0.2		0.29 ±0.14	
520.2 ±0.2		0.18 ±0.04	
534.2 ±0.2		0.16 ±0.04	
564.0 ±0.2 [b]	563.8	1.87 ±0.15	1.79 ±0.05
566.8 ±0.4	566.3	0.41 ±0.10	0.45 ±0.03
586.3 ±0.2	586.0	1.62 ±0.21	1.72 ±0.05
656.5 ±0.2	656.5	0.46 ±0.05	0.55 ±0.03
671.3 ±0.7		0.046 ±0.021	
674.7 ±0.2	674.7	0.30 ±0.08 [c]	0.65 ±0.06
674.7		0.36 ±0.09	
678.6 ±0.2	678.6	1.61 ±0.12	1.71 ±0.11
688.6 ±0.2	688.7	3.03 ±0.17	3.03 ±0.06
713.4 ±0.2	712.9	0.27 ±0.07	0.33 ±0.03
719.3 ±0.2	719.4	1.11 ±0.10	1.19 ±0.04
765.0 ±0.3		0.64 ±0.11	
769.3 ±0.3	769.2	0.29 ±0.08	0.26 ±0.02
778.84 ±0.09	779.1	46.6 ±2.3	46.5 ±0.4
794.6 ±0.6		0.15 ±0.04	
810.4 ±0.2	810.7	1.08 ±0.09	1.17 ±0.04
841.4 ±0.2	841.8	0.59 ±0.08	0.58 ±0.03
867.32 ±0.09	867.7	15.0 ±0.7	14.9 ±0.2
901.2 ±0.3	901.0	0.23 ±0.07	0.32 ±0.16
919.3 ±0.2	919.7	1.47 ±0.11	1.49 ±0.04
926.2 ±0.2		0.91 ±0.08	
930.7 ±0.3	930.8	0.24 ±0.06	0.28 ±0.03
964.03 ±0.10	964.4	52.6 ±2.6	52.6 ±1.1
989.8 ±0.3		0.13 ±0.04	
1005.0 ±0.3	1005.0	2.37 ±0.24	2.31 ±0.12
1085.79 ±0.10	1086.0	37.2 ±2.2	36.7 ±0.5
1089.8 ±0.2	1090.0	6.24 ±0.50	6.09 ±0.21
1112.05 ±0.10	1112.2	49.6 ±2.5	49.1 ±0.5
1122.9 ±0.4		0.074 ±0.028	
1171.0 ±0.4		0.13 ±0.03	
1212.8 ±0.3	1212.8	5.11 ±0.27	5.14 ±0.18
1233.5 ±0.4		0.095 ±0.020	
1249.8 ±0.3	1249.7	0.62 ±0.07	0.65 ±0.04
1260.9 ±0.5		0.12 ±0.03	
1292.6 ±0.4		0.38 ±0.07	

TABLE I (*Continued*)

E_γ (keV) Present work	Varnell *et al.*[a]	I_γ Present work	Varnell *et al.*[a]
1298.9 ±0.3	1299.2	6.01 ±0.31	5.90 ±0.45
1347.9 ±0.5		0.045 ±0.018	
1363.6 ±0.4		0.084 ±0.024	
1408.04 ±0.12	1408.1	77.6 ±3.9	75.9 ±1.8
1433.7 ±0.5		0.015 ±0.007	
1447.3 ±0.4		0.15 ±0.02	
1457.6 ±0.3	1458.3	1.91 ±0.10	1.81 ±0.09
1528.0 ±0.3	1529.8	1.30 ±0.07	1.2 ±0.1
1537.4 ±0.6		0.0054 ±0.0022	
1606.0 ±0.7		0.027 ±0.006	
1608.2 ±0.7		0.023 ±0.005	
1643.4 ±0.7		0.019 ±0.004	
1647.5 ±0.7		0.026 ±0.005	
1769.3 ±0.7		0.033 ±0.003	

[a]See Ref. 8. Note that the errors here are smaller than the present work as we have assigned a more conservative error to the relative efficiency calibration of the Ge detector.
[b]Possible doublet from coincidence data.
[c]From our coincidence data.

involved are shown in columns 4 and 5). The uncertainties in these intensities are estimated to be less than 30% in most cases. Agreement between a singles intensity from Table I and the coincident intensity shown in column 3 of Table III indicates that the γ ray proceeds entirely from the transition listed in Table III. It was assumed at all times that $W(\theta)$, the angular-distribution function, is equal to unity. There will, of course, be errors, usually small, which result from this assumption. The results of all the experiments are incorporated into the decay schemes of Figs. 3 and 4. If transitions into and out of a given level are definitely shown to be in coincidence, they are drawn with dots at the connecting level.

The relative intensities of the β-ray and electron-capture decays from the 3^- ground state of ^{152}Eu to levels in ^{152}Gd and ^{152}Sm, respectively, can be determined from a consideration of the γ-ray and conversion-electron intensity balances for each level. The β-decay branching percentages and logft values to each level are calculated from our γ-ray intensities and the electron intensities of MNA[11] and these are listed in Table IV. Our logft values for the 121.77- and 366.46-keV states agree well with the adopted values[2] of 11.9 and 11.5, respectively, which were determined from β^+ measurements (the various experiments which led to these adopted values are listed in Ref. 2).

When the logft values presented in Table IV are considered in detail, one observes the following. It is generally the case that for each degree of ΔK forbiddenness the logft increases by about 2 units. For example, one observes that the logft values of the $\Delta K = 3$, once-forbidden nonunique (1FNU) transitions to the ground-state and β-vibrational bands are larger by 4 units over those for normal transitions of this class, as expected by the rule (see Ref. 26 for systematics of logft values). For the $\Delta K = 1$, 1FNU transition to the γ band, the logft values are increased by about 2 units for reasons not presently understood. The logft values for transitions to the 0^+, 4^+, and 1^- members of the excited $K = 0$ bands are sufficiently uncertain because of possible unobserved γ-ray feeding of these levels that one can only say that the observed logft values are consistent with the above generalization for K-forbidden β decay. The γ population of the $I^\pi K = 3^-0$ level can be increased or decreased by statistical variations in the observed γ-ray intensities to and from this level and by inclusion of unobserved transitions. Thus, this logft also may be consistent with the spin assignments and the expected K-forbiddenness retardation factor. The $\Delta K = 2$ and 3 allowed transitions to the 2^-1, 3^-1, and 3^-0 levels also have normal allowed logft values when reduced by the amounts predicted by the K-forbiddenness rule. The logft of the allowed transitions to the 1649.8-keV level is more in line with a $\Delta K = 2$ than a $\Delta K = 1$ transition even when one allows for possible uncertainties in the γ depopulation of this level, which would reduce the logft. The logft of the 1FNU β decay to the 1769.2-keV level can be consistent with a $\Delta K = 1$ or $\Delta K = 3$ transition because of possible unobserved γ rays from this level. The decays to the state assigned a spin

TABLE II. Experimental and theoretical K-shell internal-conversion coefficients for transitions following the decay of ^{152}Eu.

E_γ (keV)	Nucleus	$10^4\times\alpha_K$ experimental: Present work[a]	Dzhelepov *et al.*[b]	$10^4\times\alpha_K$ theory[c]: $E1$	$E2$	$M1$	Multipolarity
121.77	Sm	6300 ±400	6990 ±570	1350	6600	8200	$E2$
244.69	Sm	800 ± 50	880 ± 90	210	798	1200	$E2$
271.1	Gd	320 ±130		176	618	1070	($E1$)
296.0	Sm	99 ± 21		130	455	730	$E1$
315.1	Gd	260 ±180		120	400	720	$E1$ or $E2$
344.22	Gd	300	308	96	310	565	$E2$
367.7	Gd	61 ± 9		82	260	480	$E1$
411.11	Gd	175 ± 18	210 ± 30	63	178	358	$E2$
443.95	Sm	45 ± 4	55 ± 4	49	142	250	$E1$
488.7	Sm	125 ± 26		39	111	194	$E2$
503.5	Gd	123 ± 51		39	111	213	$E2$
564.0	Sm	33 ± 16		28	78	135	$E1$
566.8	Sm	122 ± 60		28	77	133	$M1$ or $E2$
586.3	Gd	283 ± 67		28	76	149	$E0+E2$
656.5	Sm	539 ±116		20	54	94	$E0+E2$
678.6	Gd	56 ± 10	65	21	54	102	$E2$
688.6[d]	Sm	373 ± 41	700 ±130	18	48	84	$E0+E2$
719.3	Sm	45 ± 20		17	44	76	$E2$
765.0	Gd	58 ± 20		16	41	76	$E2$
778.84	Gd	17 ± 2	19 ± 1	16	40	73	$E1$
810.4	Sm	38 ± 17		13	33	57	$E2$
867.32	Sm	30 ± 3	29 ± 5	12	29	48	$E2$
964.03	Sm	23 ± 2	26 ± 1	9.4	23	37	$E2$
1005.0	Sm	26 ± 9		8.7	21	34	$E2$
1085.79	Sm	20 ± 3	18 ± 3	7.6	18	28	$E2$
1112.05	Sm	17 ± 2	19 ± 1	7.2	17	27	$E2$
1212.8	Sm	7.2 ± 2.0	8 ± 1	6.2	14	22	$E1$
1298.9	Gd	8.3 ± 2.2	8 ± 1	6.0	14	22	$E1$
1408.04	Sm	4.6 ± 0.4	5.5 ± 0.3	5.2	12	15	$E1$

[a]Electron intensities were measured by MNA (Ref. 11). γ-ray intensities from Table I are used. These values are normalized to give the observed (see Ref. 2) conversion coefficient the 344.22-keV transition.
[b]See Ref. 5.
[c]Conversion coefficients from tables of Hager and Seltzer (see Ref. 23).
[d]The electron intensity of this transition could contain a small contribution from an $E0$ transition of 684.8 keV.

parity of 5^- are second forbidden. The observed logft of 11.4 for decays to this level is in line with such second forbidden decays[26] so that no K forbiddenness, $\Delta K \leq 2$, is implied. Thus $K=1$ is suggested for this level.

1. *Levels in* ^{152}*Sm*

A. β-vibrational band. These three levels were discussed in detail in a previous manuscript[21] and are considered only briefly below, partially in review. The 0^+ member at 684.8 keV has been found in the decay of ^{152m}Eu,[27,28] but in our work deexcitation of this level is only tentatively observed. Of the total singles intensity of the 564.0-keV γ ray, 1.4 ± 0.4 units are assigned to a transition feeding the 1085.79-keV level. This leaves 0.5 ± 0.4 units of intensity which could result from the $0^+\beta\to2^+$ transition. The 810.4-keV state is designated the 2^+ member of this band mainly on the basis of the large α_K value for the 688.6-keV transition, which is observed to be in coincidence with the 121.77-keV γ ray. The magnitude of the $E0$ component in this transition has been extracted and discussed previously.[21] Further, the γ ray has been found to be $E2$ in character by McGowan *et al.*[29] The intensity of the $2^+\beta\to4^+$ transition must be derived from our coincidence measurements, since there is another transition in the decay scheme with very nearly the same energy. As indicated in Table III and shown in Fig. 5 of Ref. 21, a spectrum of coincidences with the 244.69-keV transition displays a 444.0-keV peak with intensity of 0.8 units. Furthermore, from the relative heights of the 244.69-, 964.03-, and 1085.79-keV peaks in coincidence with the 443.95-keV γ ray, one finds that 1.1 units of the relative intensity arise from the $2^+\beta\to4^+$ transition. The spectrum in the former case is of

TABLE III. Results of ^{152}Eu coincidence measurements with a NaI-Ge(Li) system. Column 2 gives energies of γ rays in coincidence with those listed in column 1. The coincident intensity assigned to the transition described in columns 4 and 5 is given in column 3 for each case in which a quantitative result could be extracted. The errors in the intensities are estimated to be less than 30% in most cases.

E_{γ_1} (keV)	E_{γ_2} (keV)	I_{γ_2} belonging to $(I^\pi K)_i \rightarrow (I^\pi K)_f$	$(I^\pi K)_i$ [a]	$(I^\pi K)_f$ [a]	Detector for γ_2
121.77	244.69	28.7	4^+0	2^+0	NaI
	443.95	6.1			NaI
	564.0	0.8			NaI
	688.6	2.8	$2^+0(\beta)$	2^+0	NaI
	867.32	13.5	3^+2	4^+0	NaI
	964.03	53.9	2^+2	2^+0	NaI
	1112.05	46.1	3^+2	2^+0	NaI
	1408.04	77.9	2^-1	2^+0	NaI
	(1528.0) [b]	1.3			NaI
	964.03	50	2^+2	2^+0	Ge(Li)
	1112.05	53	3^+2	2^+0	Ge(Li)
244.69	121.77				NaI
	444.0	0.8	$2^+0(\beta)$	4^+0	NaI
	867.32	14	3^+2	4^+0	NaI
	1005.0	2.3	4^+2	4^+0	NaI
	1212.8	5.0	3^-1	4^+0	NaI
	(1363.6) [b]	0.08			NaI
	488.7	1.9	2^-1	3^-0	Ge(Li)
	674.7	0.3	3^-0	4^+0	Ge(Li)
	719.3	0.9	2^+2	4^+0	Ge(Li)
	1005.0	1.4	4^+2	4^+0	Ge(Li)
344.22	367.7	1.9	3^-	4^+	NaI
	411.11	8.0	4^+	2^+	NaI
	504.0				NaI
	520.2				NaI
	586.3	0.9	$2^{+\prime}$	2^+	NaI
	678.6				NaI
	778.84	47	3^-	2^+	NaI
	1089.8	6.9	3^+	2^+	NaI
	1298.9	5.2	2^-	2^+	NaI
	678.6	1.6	3^+	4^+	Ge(Li)
	713.4	0.3			Ge(Li)
367.7	344.22	2.5 [c]	3^-	4^+	NaI
	411.11				NaI
411.11	344.22	7.5 [c]	4^+	2^+	NaI
	678.6	1.5	3^+	4^+	NaI
443.95	244.69	1.1 [c]	$2^+0(\beta)$	4^+0	NaI
	964.03				NaI
	1085.79				NaI
488.7	674.7				NaI
	919.3				NaI
520.2	778.84				Ge(Li)
719.3	443.95				NaI
	564.0				NaI
964.03	564.0	1.4	$2^-(2)$	2^+2	Ge(Li)
	121.77				NaI
	443.95	11	2^-1	2^+2	NaI
	564.0	1.9	$2^-(2)$	2^+2	NaI
1085.79	443.95	11	2^-1	2^+2	NaI
	564.0	1.7	$2^-(2)$	2^+2	NaI
1112.05	121.77				NaI
	296.0				NaI

[a] Those entries without K quantum numbers refer to levels in ^{152}Gd. A prime denotes a second level of that spin and parity.

[b] The parentheses indicate that the evidence for a coincidence relationship was not conclusive.

[c] In this case all the intensity of the gating γ ray of column 1 feeds (either directly or by total cascade) the level from which the transition in column 2 proceeds and thus the value in column 3 is the intensity of γ_1. Then also columns 4 and 5 describe the transition to which γ_1 is assigned.

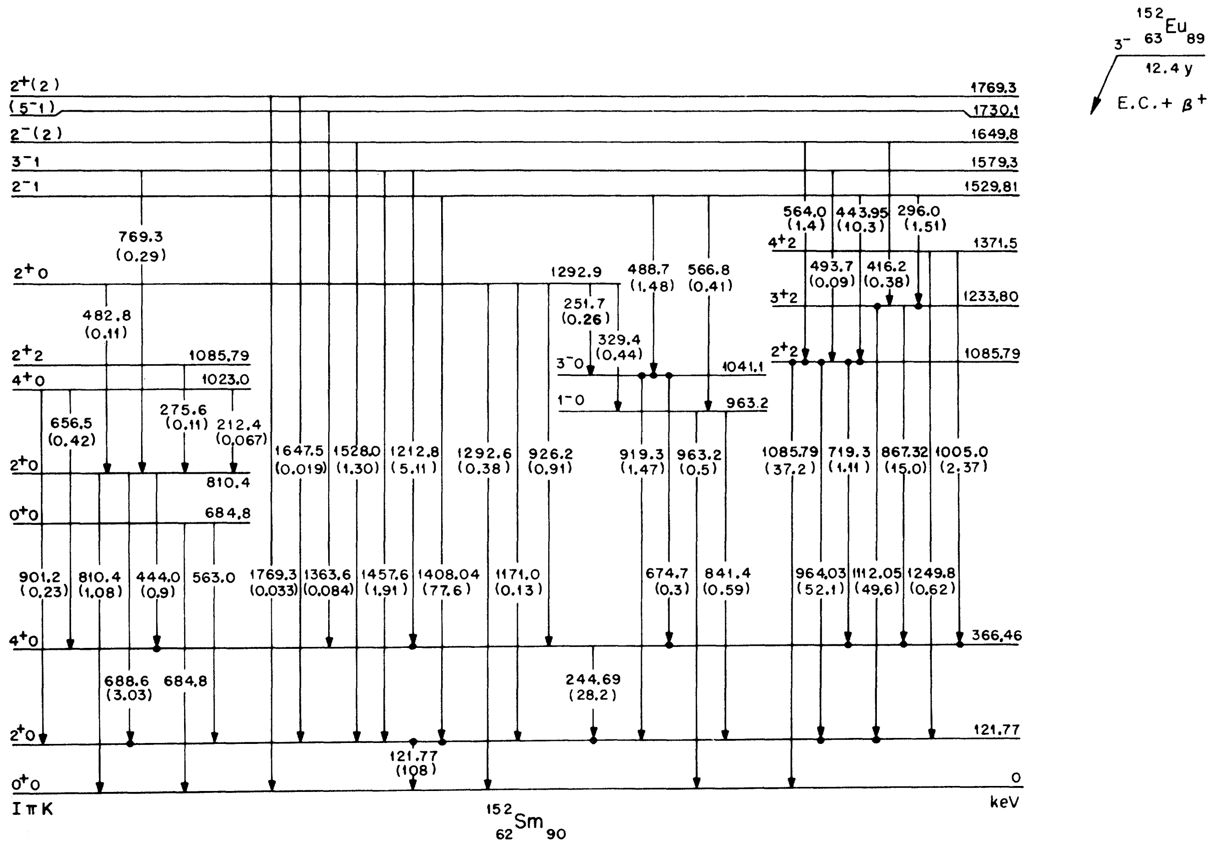

FIG. 3. Levels of ^{152}Sm populated in the decay of ^{152} Eu. Dots denote cases for which the data establish a definite coincidence relationship between the transition entering and one leaving the level.

higher quality and thus that value is given a larger weight in deriving an intensity of 0.9 for the $2^+\beta \to 4^+$ transition.

Recently Mukherjee and Sen Gupta[14] have argued on the basis of internal-conversion-electron measurements of the 444-keV doublet that the $2^+\beta \to 4^+$ member cannot account for more than 5% of the total intensity. This is in disagreement with our previously reported value[20] of $(7.5 \pm 2.5)\%$, (not 10% as reported in Ref. 14) for the fraction of the doublet due to the transition from the β band (the other member of the doublet feeds the $2^+\gamma$ level and should be an $E1$ transition). As in our work, their α_K values were based on the electron data of MNA.[11] The resultant α_K is lower than the theoretical $E1$ value (see Table II and Ref. 14). Thus, within two standard deviations on their α_K value, $(4.3 \pm 0.5) \times 10^{-3}$, they arrive at an upper limit of 5% $E2$ in the doublet. This conversion coefficient has also been measured independently, however, by DZM[5] and was found to be higher than the $E1$ value given in Table II. This latter value allows for a 10% $E2$ admixture (within one standard deviation). In addition, VBT[8] report the $2^+\beta \to 4^+$ transition as 9.9% of the total intensity of this doublet. Very recent coincidence measurements by Baker *et al.*[30] yield, however, an intensity of 0.50 ± 0.15 for the $2^+\beta \to 4^+$ transition, which comprises $(4.5 \pm 1.3)\%$ of the doublet intensity. It is thus possible that our intensity for this transition should be lowered slightly in view of the measurements of Mukherjee and Sen Gupta[14] and Baker *et al.*[30] Such a decrease would not eliminate the discrepancy[20,21] in the Z_β values derived for the $2^+\beta$ level, but would in fact yield greater disagreement.

The 4^+ member of the β band is assigned as a result of the large conversion coefficient of the 656.5-keV transition. A region of the spectrum in Fig. 1 was expanded and shown in Fig. 6 of Ref. 21 to point out the previously unobserved 901.2-keV γ ray, which was assigned to the $4^+\beta \to 2^+$ transition.

B. $K^\pi = 0^-$ band. The 963.2-keV level is strongly populated in the decay of ^{152m}Eu and is assigned spin and parity of 1^- on the basis of the $E1$ character of the 963-keV transition.[27] The 841.4-keV γ ray observed in Fig. 1 is assumed to be the $1^- \to 2^+$ transition. The portion of the 964.03-keV γ-

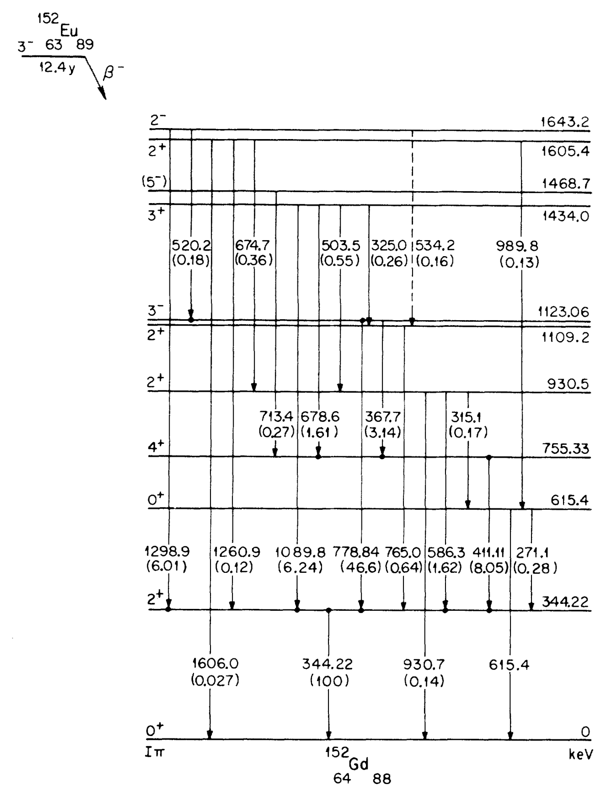

FIG. 4. Levels of ^{142}Gd populated in the decay of ^{152}Eu. Dots denote cases for which the data establish a definite coincidence relationship between the transition entering and one leaving the level. The dashed transition is placed with less certainty than are the remaining ones.

ray intensity which belongs to the $1^- \rightarrow 0^+$ transition is deduced from the $I_\gamma(963.2)/I_\gamma(841.4)$ measurement of Dzhelepov, Zhukovskii, and Maloyan[3] on the ^{152m}Eu decay. The 3^- state at 1041.4 keV has been observed through inelastic proton scattering by Kenefick and Sheline[31] and through Coulomb excitation by several groups.[32-35] Sayer[35] quotes a $B(E3)$ value of 16.6 ± 2.0 single-particle units, which indicates a very collective level. In our NaI-Ge(Li) experiments, we found 0.3 units of the 674.7-keV γ ray to be in coincidence with the 244.69-keV transition. The remainder of the 674.7-keV intensity is assigned to a transition in ^{152}Gd. As listed in Table III, the 674.7- and 919.3-keV γ rays are observed in coincidence with the 488.7-keV γ ray, which is also detected as a coincidence with the 244.69-keV transition in another experiment. These measurements lead to the placements of the 488.7-, 674.7-, and 919.3-keV transitions shown in Fig. 3.

C. γ-vibrational band. All but two of the transitions from these levels have been verified by our coincidence measurements. Since the 2^- level at 1529.81 keV decays to the 2^+ members of the γ- and ground-state bands, one would expect a 719.4-keV transition to the $2^+\beta$ level. However, 0.9 ± 0.3 units of the 719.3-keV singles intensity is observed to be in coincidence with the 244.69-keV transition, while no 719.3-688.6-keV relationship is found experimentally. Within experimental error, this observed coincident intensity agrees with the singles intensity and, thus, the 719.3-keV γ ray is assigned exclusively to the $2^+\gamma \rightarrow 4^+$ transition. Another coincidence experiment implies that only

FIG. 5. Ge(Li) γ-ray spectrum of ^{152}Eu in coincidence with the 964.03-keV transition.

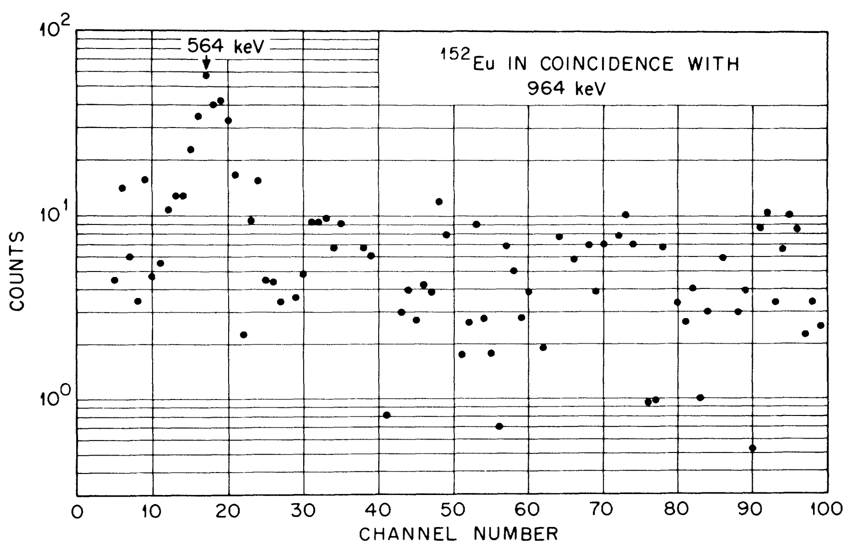

TABLE IV. Logft values for the β^-, β^+, and electron-capture decays of ^{152}Eu($I^\pi K = 3^-3$).

Level energy (keV)	$I^\pi K$ [a]	Total decay energy (keV)	Branching percentage	Logft
		^{152}Sm		
121.77	2^+0	1745	1.3	11.8
366.46	4^+0	1501	1.7	11.6
684.8	0^+0	1182	0.11 [b]	$\gtrsim$12.5
810.4	2^+0	1057	1.3	11.3
963.2	1^-0	904	0.12 [b]	$\gtrsim$12.2 [b]
1023.0	4^+0	844	0.16 [b]	$\gtrsim$12.1 [b]
1041.1	3^-0	826	0.017 [c]	13.0 [c]
1085.79	2^+2	781	21.2	9.9
1233.80	3^+2	633	16.7	9.8
1371.5	4^+2	495	0.85	10.9
1529.81	2^-1	337	24.7	9.1
1579.3	3^-1	288	2.1	10.0
1649.8	$2^-(2)$	217	0.78 [d]	10.2 [d]
1730.1	(5^-1)	137	0.020	11.4
1769.2	$2^+(2)$	99	0.009 [e]	11.6 [e]
		^{152}Gd		
344.2	2^+	1484	10.2	11.9
615.4	0^+	1213	0.033 [b]	14.2 [b]
755.33	4^+	1073	0.96	12.5
930.5	2^+	897	0.25	12.8
1109.2	2^+	719	0.097	12.9
1123.06	3^-	705	13.5	10.8
1434.0	3^+	394	2.1	10.7
1468.7	(5^-)	259	0.075	11.5
1605.4	2^+	223	0.089	11.3
1643.2	2^-	185	1.6	9.7

[a]The levels without K quantum numbers belong to the ^{152}Gd nucleus which is considered spherical.

[b]Part or all of this feeding could arise from γ population so that the logft could be significantly increased.

[c]The intensity of this electron-capture branch could be increased by a factor of 7 and still be within the error limits on the γ-ray intensities populating and depopulating this level; and so the logft could easily be reduced by as much as 0.9 units. On the other hand, part or all of the intensity assignment could be from γ population, so the logft could be significantly increased.

[d]This branching could be increased by a masked transition of 120 keV, so that the logft could decrease by as much as 0.5 units.

[e]Several transitions that could depopulate this level are masked and thus this logft could possibly be reduced by 1 to 2 units.

(60 ± 20)% of the 1005.0-keV singles intensity results from the $4^+\gamma \to 4^+$ decay. However, since none of our data shows any indication of another transition at this energy, the total singles intensity is assigned to the $4^+\gamma \to 4^+$ transition. In contrast to the $2^+ \to 2^+$ and $4^+ \to 4^+$ decays from the β band, the conversion coefficients of the corresponding transitions from the γ band agree with the $E2$ values, which fact indicates little or no $E0$ or $M1$ radiation in these latter transitions. The 275.6-keV γ ray is placed between the 2^+ members of the β and γ bands purely from energy considerations, since it was too weak to be observed in the coincidence mode. Such a transition is forbidden in the simple adiabatic model, which attributes these levels to distinct types of vibrations about the deformed core. The placement of this transition offers support to the interaction between the β and γ bands that was needed to explain the $E2$ branching ratios from the γ-vibrational levels.[21]

D. $K^\pi = 1^-$ band. The 1529.81-keV level is reported to have spin-parity of 2^-, on the basis of the $E1$ conversion coefficient of the 1408.04-keV transition[36] and the correlation between the 1408.04- and 121.77-keV γ rays.[37] The existence of 296.0-, 443.95-, and 488.7-keV deexcitations has been verified here by coincidence measurements for the first time. The 566.8-keV transition was placed previously[8, 13] from energy consideration alone. Each of these transitions has a conversion coefficient which is compatible with the particular assignment. Assignment of spin and parity of 3^- to the 1579.3-keV state was first made by BNS[9] on the basis of conversion-coefficient and directional-correlation measurements. The 493.7- and 769.3-keV transitions which we assigned as decays of this state were also proposed by VBT.[8] The 5^- member of this band was first assigned at 1726 keV by Veje *et al.*[38] through inelastic deuteron scattering experiments. In very recent (α, 2n) measurements, Hagemann *et al.*[39] place this state at 1729.3 keV. One of our coincidence experiments gives some indication that a γ ray at approximately 1364 keV feeds the 366.46-keV state. Thus, the weak 1363.6-keV γ ray observed in the singles spectrum is tentatively assigned as decaying from a level at 1730.1 keV. Although the energy of this state agrees with that of the 5^- member, there are insufficient data to make a definite conclusion that this level has spin and parity of 5^-. However, there is one argument which favors such assignment. If we assume, as is most likely, that this state is not populated by higher-lying levels in ^{152}Sm, we find a logft value of 11.4 for it. This logft is reasonable[26] for second-forbidden nonunique electron capture to a 5^- state from a 3^- parent, since there would be no K forbiddenness to retard the decay as occurs in the allowed and once-forbidden decays. There is another possible interpretation for this level, however, due to the presence of a 1608.2-keV γ ray in the singles spectrum of Fig. 2. If this γ ray can be assigned as the decay of the 1730.1-keV state to the 2^+ member of the ground band, the tentative 5^- assignment would have to be changed, probably to 3^-. It is impossi-

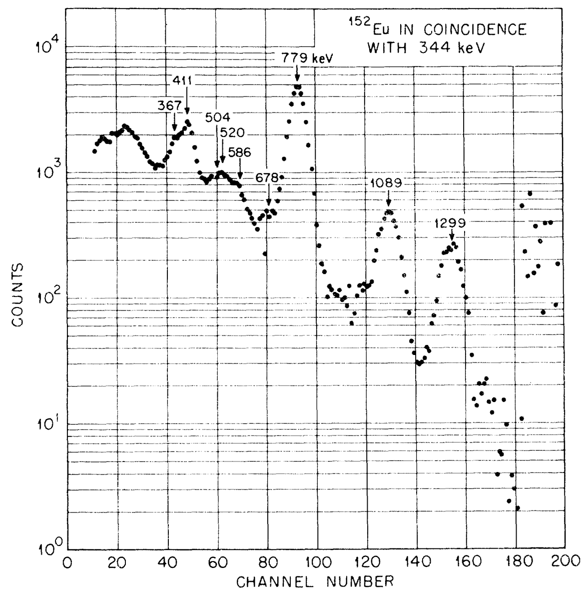

FIG. 6. NaI γ-ray spectrum of ^{152}Eu in coincidence with the 344.22-keV transition.

ble to decide upon the spin of this level from our data. A tentative 5^- assignment is somewhat preferred because of the work of Veje *et al.*[38]

E. 1292.9-keV level. Very recently, Schick[40] has suggested a new level in ^{152}Sm at 1292.8 keV. Following his suggestion, we have also placed such a level in our decay scheme (see Fig. 3). Six γ rays from Table I conveniently fit as decays to the 0^+, 2^+, and 4^+ members of the ground-state band, to the 2^+ member of the β band, and to the two states in the $K^\pi = 0^-$ band. It must be emphasized that the six transitions from the 1292.9-keV level are placed on the basis of energy fits alone. We have no coincidence data pertaining to these transitions. One of these γ rays, that at 482.8 keV, could also be placed in the ^{152}Gd scheme as a decay of the 1605.4-keV state. Zolnowski, Funk, and Mihelich (ZFM)[41] observe such a γ ray in the decay of ^{152}Tb, but the intensity of this relative to that of the 1606.0-keV γ ray from their work indicates that only approximately 4% of the 482.8-keV intensity seen in the ^{152}Eu decay can be so placed in ^{152}Gd.

MNA[11] did observe the K-conversion-electron line of the 482.8-keV transition in the ^{152}Eu decay. However, it was not resolved from the L-electron peak of the strong 443.95-keV transition and thus a conversion coefficient was not listed in Table II for this transition. In order to get an estimate of this α_K, we have used the calculated[23] K/L ratio for the $E1$ 443.95-keV transition to extract the K-electron intensity for the 482.8-keV decay. The resulting conversion coefficient is $(6.0 \pm 2.2) \times 10^{-2}$, which is large compared with the calculated value[23] of 1.16×10^{-2} for an $E2$ transition. By analogy to the $I_\beta \to I$ transitions in ^{152}Sm and ^{154}Gd, the large α_K suggests the presence of $E0$ radiation. This, plus the fact that transitions from the 1292.9-keV state are seen to 0^+, 2^+, and 4^+ members of the ground-state band, suggest an assignment of $I^\pi K = 2^+0$ for this new level, in agreement with that of Schick.[40] Assuming that the 482.8-keV γ ray is pure $E2$ radiation, we find that X, the dimensionless ratio of the $E0$ to $E2$ reduced matrix elements (see Ref. 21), is 0.15 ± 0.07 for the $2^+ \to 2^+$ transition to the β band. This value is $\frac{1}{3}$ of X measured for the $2^+\beta \to 2^+$ transitions in ^{152}Sm and ^{154}Gd.[21]

Although our coincidence experiments are not able to check the placement of the transitions from the 1292.9-keV state, the recent work of Baker *et al.*[30] involving two large-volume Ge(Li) detectors does verify the assignments of the 329.4-, 482.8-, and 926.2-keV γ rays. Furthermore, by gating on the 926.2-keV γ ray, they are able to assign no transitions feeding the 1292.9-keV level, which indicates that this state is populated mainly by electron capture. The logft value for this decay is 10.9 under the assumption of no γ feeding of the 1292.9-keV state. This logft is quite low when compared with the value of 11.8 for population of the $I^\pi K = 2^+0$ state at 121.77 keV. There would have to be cascading transitions with a total intensity of approximately 1.9 units in order to increase the logft to the 1292.9-keV state to a "reasonable" value of 11.8. Unless these are very low-energy transitions, they should have been easily observed.

F. Other levels. The coincidence experiments reported here furnish the first direct evidence that a 564.0-keV transition feeds the 1085.79-keV level. Proof of this is displayed in Fig. 5, which gives the Ge(Li) spectrum in coincidence with the 964.03-keV γ ray in the NaI gate. A window was not set above the 964.03-keV γ ray in the normal way for subtraction of coincidences resulting from Compton events, because of the inherently poor resolution of the NaI detector. The experiment was, however, performed in the multiparameter mode, which enabled us to examine spectra in coincidence with events above and below the 964.03-keV peak. The absence of the 564.0-keV peak in these latter spectra led us to conclude that this γ ray is in coincidence with the 964.03-keV transition. The intensity of the 564.0-keV peak in Fig. 5 is 1.4 ± 0.4, whereas the total singles intensity is 1.87 ± 0.15. This coincident relationship establishes for the first time the existence of a level at 1649.8 keV.

As indicated in Table III, there is some evidence for a 1528-keV γ ray in coincidence with the 121.77-keV transition. Since the energy of the 1528.0-keV γ ray observed in Fig. 2 is exactly correct for a transition to the 2^+ level, it is assigned as a decay of the 1649.8-keV level. On the basis of an energy fit, the 416.2-keV γ ray is also assigned as a transition from this state.

As seen in Table II, the conversion coefficient of the 564.0-keV transition agrees with the predicted $E1$ value. This fact indicates that the 1649.8-keV level must be assigned a spin and parity of 1^-, 2^-, or 3^-. The absence of transitions to the 0^+ and 4^+ members of the ground-state band favors the assignment as a probable 2^- state. This assignment is given further credence by the fact that in (d, d') experiments of Veje *et al.*[38] neither the 2^- level at 1529.81 keV nor this level at 1649.8 keV were seen (this scattering process does not populate 2^- states).

The Q values for the decays of ^{152}Eu to ^{152}Sm and ^{152}Gd (1.867 and 1.828 MeV, respectively) are such that the 1769.3-keV γ ray in Fig. 2 must be a ground-state decay in either nucleus. The existence of a 1647.5-keV γ ray in the singles spectrum leads us to place these two γ rays in ^{152}Sm as transitions to the ground and first excited states. A similar conclusion was reached by LSV[12] in studies of the ^{152}Eu decay. Their conversion-coefficient measurements indicate that both of these transitions are $E2$ in character, which leads to an assignment of 2^+ to the 1769.3-keV state. This level is also populated in the (t, p) experiments of Hinds *et al.*[42] and is thought to have a spin of 2 from the angular distribution of the emitted protons. The K quantum number of this level could be either 0 or 2. The logft value for electron capture to the level appears to agree well with the values for decay to the β-vibrational members, while it disagrees with the values for the γ-band states. Thus, a $K=0$ assignment might be suggested. However, the logft could be lowered easily at least to agree with the values for decays to the γ band, since other possible transitions from this 1769.3-keV level to the 4^+ 366.46-keV, the 2^+ 810.4-keV, and the 2^+ 1085.79-keV levels would have been masked by much stronger nearby lines. The intensities of these possible transitions could easily be 10 to 100 times that of the 1647.5- and 1769.3-keV γ rays observed from this level. Moreover, a large $E0$ component is characteristic of $\Delta I=0$, $\Delta K=0$ transitions from β-vibrational[16, 17, 19] bands and also from $K=0$ bands which cannot be so described (see, for example, the discussion by Dzhelepov and Shestopalova[43]). The absence of such an $E0$ component in this transition leads to a tentative $K=2$ assignment.

In their (d, d') experiments, Veje *et al.*[38] observe a rather strong multiple line at 1765 keV. It is possible that the 1643.4-keV γ ray seen in Fig. 2 feeds the first 2^+ state and thus establishes a level at 1765.2 keV. This state, along with that at 1769.3 keV, could explain the multiple line seen in (d, d') exposures. Veje *et al.*[38] contend that the angular distribution of this line indicates a 3^- or 4^+ state. If the 1765.2-keV level were 3^- or 4^+, one would expect also to see a 1398.7-keV γ ray to the first 4^+ state. The absence of such a peak in Fig. 2 prevents us from definitely attributing the 1643.4-keV γ ray to such a level.

2. Levels in ^{152}Gd

The NaI spectrum in Fig. 6 is composed of coincidences with a Ge(Li) gate set on the 344.22-keV γ ray. The coincident intensities of the peaks at 411, 586, 779, 1089, and 1299 keV are in agreement with the singles intensities of the corresponding γ rays. Since none of these γ rays are also found to be in coincidence with each other, they are assigned as directly feeding the 344.22-keV state. The 0^+ level at 615.4 keV has been observed previously in the ^{152m}Eu and ^{152}Tb decays.[27, 44, 45] The 271.1-keV γ ray in Fig. 1 is placed as the transition to the first excited state without verification from the coincidence measurements, although the conversion coefficient of this transition (see Table II) is smaller than the expected $E2$ value. However, the value of $N_K(E0; 0' \rightarrow 0)/N(E2; 0' \rightarrow 2)$ is 0.12 ± 0.03 from the ^{152}Eu decay (as determined from our γ-ray intensity and the electron intensity of MNA[11]) compared with approximately 0.10 from ^{152}Tb decay, as measured by Gromov *et al.*[45] This supports the assignment of the 271.1-keV γ ray to the $0' \rightarrow 2$ transition. It is interesting to note that Reiner[46] has predicted $N_K(E0; 0' \rightarrow 0)/N(E2; 0' \rightarrow 2)$ to be 0.21 for ^{152}Gd. This overestimate of the $E0/E2$ ratio for ^{152}Gd is similar to that found for the 0^+ excited state in the deformed nuclei ^{152}Sm and ^{154}Gd. The values for the two latter nuclei were derived and discussed in Ref. 21.

The coincidence observed between the 344.22- and 586.3-keV γ rays verifies the existence of the level at 930.5 keV. The very large K conversion coefficient for this transition indicates the presence of $E0$ radiation and the assignment of 2^+ for the 930.5-keV state. The conversion coefficient of the 315.1-keV transition is consistent with the $E2$ character that is expected. Gromov *et al.*[45] have reported the population of this state in the ^{152}Tb decay. The ratios of the γ-ray intensities for the 930.7-, 586.3-, and 315.1-keV transitions are $1.0 : (6.8 \pm 1.9) : (0.71 \pm 0.22)$ in this work and $1.0 : (9.0 \pm 2.1) : (1.2 \pm 0.3)$ in Ref. 45. The $E0$ mode in the $2^{+\prime} \rightarrow 2^+$ transition accounts for 72% of the observed electrons in this case, whereas the $E0$ electrons in the $2^+\beta \rightarrow 2^+$ transition of ^{152}Sm comprise 87% of the total.[21] We find $\mu_K(2') = N_K(E0;$

$2' \to 2)/N(E2; 2' \to 2)$ to be 0.020 ± 0.006 for ^{152}Gd, but Reiner[46] has not explicitly calculated μ_K for the $2'$ state in ^{152}Gd. It would be interesting to see if the agreement between experiment and theory is better here than for the 0^+ level.

Gromov *et al.*[45] have placed a 2^+ state at 1109.8 keV from the ^{152}Tb decay. The 765.0-keV γ ray observed in the singles spectrum of Fig. 1 is tentatively placed as a transition from this level to the 2^+ state at 344.22 keV. They[45] also report the intensity of the 1109.8-keV transition to the ground state as approximately 60% of the 765.0-keV intensity. One would not expect to find this γ-ray peak in Fig. 2, because it would be masked by the tail of the strong 1112.05-keV peak. As seen in Table II, the conversion coefficient of the 765.0-keV transition might be slightly large. This could represent the effect of $E0$ radiation.

The 367.7-keV γ ray is found to be in coincidence with the 344.22- and 411.11-keV transitions and hence, it is placed as a transition from the 1123.06-keV state. As listed in Table III, two coincidence experiments with gates set on the 344.22- and 367.7-keV γ rays indicate that only about 70% of the singles intensity for the 367.7-keV γ ray should be assigned to the $3^- \to 4^+$ transition. However, since no other transitions are observed in coincidence with this γ ray, one might conclude that the results quoted above are questionable because of the difficulty in accurately resolving the 344.22-, 367.7-, and 411.11-keV γ rays in the coincidence spectra observed with the NaI detector. It is also possible that angular-correlation effects could account for some of this discrepancy. We therefore choose to assign the entire 367.7-keV singles intensity to the transition from the 1123.06-keV state.

The 678.6-keV γ ray is placed as a transition from the 1434.0-keV level on the basis of the coincidence measurements. There had been some confusion previously concerning the energy and intensity of this transition, as DZM[5] have, for example, attributed part of the 688.6-keV γ-ray intensity to this transition. The spin of 3 for the 1434.0-keV state is indicated by the directional-correlation measurements of Schick and Grodzins[47] on the 1089-344-keV cascade, while the $E2$ conversion coefficient of the 678.6-keV transition (see Table II) dictates positive parity for this state. This level is not observed in the ^{152}Tb work of Gromov *et al.*[45]

There is evidence for a 713-keV γ ray in coincidence with the strong 344.22-keV transition. In their inelastic deuteron scattering experiments, Bloch, Elbek, and Tjøm (BET)[48] excited a level at 1467 keV, which they explained as a possible 5^- state. Such a level would be expected to decay to the 4^+ state at 755.33 keV, and thus the 713.4-keV γ ray is tentatively placed as a transition from a 1468.7-keV level. The fact that this weak peak is not observed in the spectrum of coincidences with the 411.11-keV transition does not necessarily contradict this assignment, since this spectrum was not statistically of sufficient quality to demonstrate such a weak coincidence relationship. It is also possible that the 713-keV γ ray could be placed as a transition between the 930.5- and 1643.2-keV levels. However, the energy agreement is poorer for the latter case.

A 1260.9-keV γ ray is observed in the Ge(Li) singles spectrum of Fig. 2. Also, it was stated above that only 0.3 ± 0.1 units of the 674.7-keV γ-ray singles intensity is accounted for by the $3^- \to 4^+$ transition in ^{152}Sm. Gromov *et al.*[45] place in ^{152}Gd a 2^+ level at 1606.1 keV, which is partially deexcited by 1261.7- and 675.6-keV γ rays. Here we place the 1260.9- and the remainder of the 674.7-keV γ rays as transitions from a level at 1605.4 keV. Their value for $I_\alpha(1261.7)/I_\alpha(675.6)$ is 0.89 ± 0.22, while this intensity ratio from our measurements is 0.33 ± 0.13. This discrepancy is not understood, but it may indicate that more of our 674.7-keV γ ray should be placed in the Sm decay scheme. If this level is 2^+ in character as Gromov *et al.*[45] maintain, the decay to the ground and excited 0^+ states should probably be seen. The assignment of the 1606.0-keV γ ray to this transition is reasonable in view of the $E1$ or $E2$ conversion coefficient found by LSV.[12] Since these higher γ-ray energies could not be measured very accurately, the difference in the energies of the cascading and crossover transitions is judged to be acceptable in this case. The 989.8-keV γ ray fits well as the transition to the 615.4-keV state. The 1643.2-keV state has been assigned spin and parity of 2^- on the basis of directional-correlation[47,49] and conversion-coefficient[9,12,50] measurements. The previously unobserved 520.2-keV γ ray is also attributed to a decay of this state, based on our coincidence results, while the 534.2-keV γ ray is only suggested as a transition from this level. It should be pointed out that the decay of the 1643.2-keV state to that at 930.5 keV may also be present. The 713.4-keV γ ray was tentatively assigned, as discussed above, to a transition from a state at 1468.7 keV. However, there certainly could exist a weak 712.7-keV component which might result from the deexcitation of the 2^- 1643.2-keV level. Such a decay to the 2^+ 930.5-keV state would be very reasonable on the basis of spin considerations.

Of the eleven γ rays from Table I which cannot be placed in the decay scheme, the three with energies of 794.6, 1347.9, and 1447.3 keV are seen in the ^{152}Tb decay by ZFM.[41] It is thus probable that these should be assigned to ^{152}Gd.

TABLE V. Energies and relative intensities of γ rays emitted in the ^{154}Eu decay.

E_γ (keV) Present work	Meyer [a]	I_γ Present work	Meyer [b]
123.07 ± 0.09	123.14 ± 0.04	116 ± 6	121
146.3 ± 0.8	146.05	0.085 ± 0.027	0.078
188.0 ± 0.4	188.22	0.61 ± 0.12	0.68
232.1 ± 0.4	232.01	0.079 ± 0.043	0.072
247.90 ± 0.09	248.04 ± 0.04	20.1 ± 1.0	19.7
321.8 ± 0.5	322.01	0.16 ± 0.04	0.20
329.9 ± 0.7	328.48	0.036 ± 0.026	0.027
397.2 ± 0.4	397.14	0.12 ± 0.05	0.090
401.2 ± 0.2	401.30	0.58 ± 0.10	0.63
404.2 ± 0.4	403.55	0.054 ± 0.032	0.081
444.5 ± 0.2	444.40	1.69 ± 0.15	1.50
467.9 ± 0.2	467.92	0.20 ± 0.09	0.17
478.3 ± 0.2	478.26	0.69 ± 0.15	0.64
511.2 ± 0.2	509.85	0.17 ± 0.08	0.11
	512.03		0.12
518.2 ± 0.2	518.00	0.16 ± 0.09	0.14
557.6 ± 0.2	557.56	0.74 ± 0.10	0.76
582.03 ± 0.11	582.00	2.53 ± 0.23	2.51
591.79 ± 0.10	591.74	14.8 ± 0.8	14.5
613.3 ± 0.2	613.26	0.22 ± 0.08	0.28
625.2 ± 0.2	625.22	0.89 ± 0.12	0.93
649.8 ± 0.2	649.44	0.28 ± 0.11	0.23
676.5 ± 0.2	676.59	0.43 ± 0.11	0.43
692.43 ± 0.11	692.41	4.97 ± 0.30	5.06
715.7 ± 0.3	715.76	0.32 ± 0.13	0.52
723.26 ± 0.11	723.30 ± 0.04	60.1 ± 3.1	58.8
756.81 ± 0.11	756.87	12.9 ± 0.6	13.0
815.5 ± 0.2	815.55	1.38 ± 0.18	1.39
845.4 ± 0.2	845.39	1.60 ± 0.22	1.64
850.7 ± 0.2	850.64	0.60 ± 0.13	0.69
873.16 ± 0.12	873.19	34.8 ± 1.7	34.3
880.6 ± 0.2	880.61	0.20 ± 0.08	0.25
892.8 ± 0.2	892.73	1.31 ± 0.10	1.37
904.1 ± 0.2	904.05	2.42 ± 0.17	2.46
924.7 ± 0.2	924.49	0.19 ± 0.10	0.18
996.29 ± 0.12	996.32 ± 0.04	29.4 ± 1.5	30.8
1004.75 ± 0.12	1004.76 ± 0.04	50.6 ± 2.5	51.8
1118.2 ± 0.3	1118.5 ± 0.1	0.30 ± 0.08	0.31
1128.5 ± 0.3	1128.4 ± 0.1	0.79 ± 0.09	0.80
1140.7 ± 0.3	1140.9 ± 0.1	0.69 ± 0.10	0.65
1160.3 ± 0.3	1160.6	0.10 ± 0.03	0.13
1188.3 ± 0.3	1188.6	0.23 ± 0.05	0.24
1241.4 ± 0.3	1241.6 ± 0.2	0.30 ± 0.07	0.39
1246.2 ± 0.3	1246.6 ± 0.2	2.40 ± 0.22	2.08
1274.49 ± 0.14	1274.45 ± 0.09	100	100
1290.4 ± 0.3	1290.0 ± 0.2	0.068 ± 0.026	0.073
1316.4 ± 0.3		0.074 ± 0.029	
1418.2 ± 0.5	1418.5 ± 0.2	0.027 ± 0.016	0.022
1494.2 ± 0.3	1494.6 ± 0.2	1.88 ± 0.09	1.94
1530.7 ± 0.5	1531.7 ± 0.2	0.009 ± 0.005	0.018
1538.0 ± 0.3	1537.8 ± 0.2	0.15 ± 0.02	0.15
1596.7 ± 0.3	1597.3 ± 0.2	5.15 ± 0.26	4.98

[a] See Ref. 18. The uncertainties in the energies are 0.05 keV except where otherwise indicated. It is unclear what the errors are on the energies of the 328.48-, 397.14-, 467.92-, 1160.6-, and 1188.6-keV γ rays. Meyer (Ref. 18) also observes other transitions not seen in the present measurements.

[b] See Ref. 18. The uncertainties in the intensities are reported as 2% for $I_\gamma > 3.0$, 3% for $3.0 > I > 0.30$, 4% for $0.30 > I > 0.003$. The error in the 1531.7-keV intensity is 7%. These uncertainties are, in general, much smaller than those assigned in the "present work" in column 3. Much of this difference results from interpretations as to the reliability of efficiency calibrations of Ge(Li) systems.

B. Decay of ^{154}Eu

The energies and relative intensities of γ rays observed in our experiments on the ^{154}Eu decay are listed in Table V. Also given in this table are the values of Meyer,[18] who was able to observe an additional 120 γ rays with a Compton-suppression spectrometer. Seven coincidence experiments with the Ge(Li) detector gating on various parts of the γ-ray spectrum were performed. These measurements helped in the construction of the decay scheme of Fig. 7, where 27 of the 47 transitions are assigned on the basis of the coincidence studies. Of the 15 energy levels placed in the scheme, the existence of 13 are verified by coincidence measurements.

One of the most important coincidence measurements performed on this nucleus concerned the 692.43-keV transition from the β band. As discussed in detail in Refs. 20 and 21, the experimental branching ratios from the 2^+ member of this band can be brought into agreement with the predictions of a single-parameter band-mixing theory only if the intensity of the $2^+\beta \rightarrow 2^+$ transition is approximately half the singles intensity of the 692.43-keV γ ray. Our coincidence measurements indicate, however, that this γ ray arises solely from the $2^+\beta \rightarrow 2^+$ transition. The intensities of the observed 123-, 582-, 845-, and 904-keV peaks and the absence of other peaks in a spectrum of coincidences with a 692-keV gate (Ge) rule out the possibility of a second transition of 692 keV in the level scheme.

The results of our measurements on the ^{154}Eu decay are quite similar to those of Meyer.[18] Our coincidence measurements verify in many cases the assignments made by Meyer on the basis of singles experiments only. Since no discrepancies with the previous assignments are found, the remaining results of our coincidence studies are given only in Fig. 7, and the reader is referred to Ref. 18 for a detailed discussion of the ^{154}Gd level scheme.

IV. DISCUSSION

A. β- and γ-Vibrational Bands in ^{152}Sm and ^{154}Gd

The properties of the quadrupole-vibrational bands in ^{152}Sm and ^{154}Gd have been discussed in detail in Refs. 20 and 21. Only a few remarks are appropriate here. The measured γ-ray intensities were used to calculate $E2$ branching ratios from the members of the β and γ bands. These ratios from the γ band agree with the predictions of the rotational model when γ-ground-state and γ-β band mixings are included. However, in each nucleus, no unique amount of β-ground-state mixing could be found to explain the experimental $B(E2)$ ratios. In addition the $E0$ reduced matrix element ρ was determined to be 0.28 ± 0.02 for the 2^+ member of the β band of ^{152}Sm and estimated to be 0.44 for the 2β level of ^{154}Gd. Very recent data from Coulomb-excitation experiments[51] require further discussion of these quantities. The experiments indicate that $B(E2; 0 \rightarrow 2\beta)$ in ^{154}Gd is $(0.024 \pm 0.004)e^2 \times 10^{-48}$ cm^4, very nearly equal to that in ^{152}Sm, while in Ref. 21 we used a value twice that of ^{152}Sm. This latter value, merely an estimate from (d, d') studies,[48] resulted in the large ρ for ^{154}Gd. Using the newly measured[51] $B(E2: 0 \rightarrow 2\beta)$ produces a decreased $\rho(2\beta)$ of 0.35 ± 0.04 for ^{154}Gd, somewhat greater than that for ^{152}Sm. Such a trend is opposite the slight decrease in ρ predicted by Bes[52] for ^{154}Gd compared with ^{152}Sm.

As discussed in Ref. 21, we have also measured the $E0/E2$ intensity ratio from the 0^+ member of the β band in each nucleus. Recent Coulomb-excitation experiments yield for the first time $B(E2: 0\beta \rightarrow 2) = (0.16 \pm 0.02)e^2 \times 10^{-48}$ cm^4 for ^{152}Sm,[39] and $(0.23 \pm 0.02)e^2 \times 10^{-48}$ cm^4 for ^{154}Gd.[51] These numbers, in conjunction with our $E0/E2$ ratios,[21] enable us to now calculate $\rho(0) = 0.26 \pm 0.02$ for ^{152}Sm and 0.38 ± 0.06 for ^{154}Gd. The near equality of $\rho(0)$ and $\rho(2)$ for each nucleus demonstrates conclusively that the monopole matrix element is constant, at least for the low-spin members of the band.

The change in mean-square radius between the ground and first excited states was estimated from the monopole matrix element according to Eq. (23) of Ref. 21. Since our new value of ρ for ^{154}Gd differs from the previous estimate, the calculation of $\Delta\langle R^2\rangle/\langle R^2\rangle$ is affected. However, the change in radius is also dependent on ϵ_β, the spin-independent amplitude of admixture between the β and ground-state bands. Previously we estimated ϵ_β from an average value of Z_β, the band-mixing parameter. For ^{154}Gd, the $0^+\beta \rightarrow 2^+$ and $0 \rightarrow 2^+\beta$ $E2$ matrix elements from Ref. 51 yield an increased value of ϵ_β, 1.3×10^{-2}. The new value of 14.0×10^{-4} for $\Delta\langle R^2\rangle/\langle R^2\rangle$ thus agrees with our previous value of 13.5×10^{-4} for ^{154}Gd, while an actual measurement of this quantity yields $(5.9 \pm 0.8) \times 10^{-4}$ according to Bernow *et al.*[53] and $(7.5 \pm 2.3) \times 10^{-4}$ according to Rehm, Henning, and Kienle.[54] The large discrepancy between the band-mixing estimate of $\Delta\langle R^2\rangle/\langle R^2\rangle$ and the supposedly direct measurements is difficult to understand. One possible explanation is that this simple centrifugal-stretching method of calculating the change in radius within the ground-state band is not accurate or legitimate. Another possibility is that microscopic interactions lead to large changes in radius of opposite sign compared with centrifugal stretching. Marshalek,[55] however, predicts such effects to be very small for the $N = 90$ nuclei.

B. Negative-Parity Levels in ^{152}Sm and ^{154}Gd

The energies and decay properties of these states are summarized in Table VI, where the $B(E1)$ ratios are compared with the predictions of the adiabatic symmetric-rotor model.[56] In ^{152}Sm, the 1^- state at 963.2 keV and the 3^- state at 1041.1 keV are assigned $K = 0$, while the 2^- state at 1649.8 keV is assigned $K = 2$. This was done mainly on the basis of the agreement between the experimental and theoretical $B(E1)$ ratios. The former assignments are also consistent with the large $\log ft$ values in Table IV, and with the predictions of Soloviev, Fogel, and Korneichuk,[57] who find that the $K = 0$ component of the octupole vibration should be the most collective and thus lowest in energy. The other negative-parity levels in ^{152}Sm are assigned $K = 1$, in agreement with BNS,[9] chiefly because of the observed $1^-, 2^-, 3^-$ sequence (the latter two states were seen in this work while the 1^- state was placed through studies of the ^{152m}Eu decay[3,8]). These assignments are made, however, in spite of the general disagreement between observed and predicted branching ratios. Although the 3^- state at 1579.3 keV decays with roughly equal strengths to the 2^+ members of the β and γ bands, which indicates a possible assignment of $K = 1$, the 1529.81-keV 2^- state has a much stronger decay to the γ band than to the β band. Furthermore, the larger $\log ft$ value for the second 2^- state than for the first one would indicate a lower K quantum number for the second 2^- state, contrary to the above conclusion. Such an argument based on $\log ft$ values may be deceiving, since these numbers are calculated through intensity balances. Unobserved decay of the 1649.8-keV level to the 2^- level at 1529.81 keV via a masked 120-keV transition could lower the $\log ft$ value by 0.5–0.6 units. This decrease alone, however, would not be enough to explain the discrepancy.

In ^{154}Gd the pattern is somewhat similar. The $B(E1)$ ratios from the first 1^- and second 2^- states agree with the predicted values for $K = 0$ and $K = 2$, respectively. Although the decay properties of the other negative-parity levels are more difficult to explain, some justification can be given for the K

TABLE VI. Experimental and theoretical $B(EL)$ ratios from negative-parity levels of ^{152}Sm and ^{154}Gd.

Energy of initial level (keV)				Relative $B(EL)$ experiment[a]		Relative $B(EL)$ theory[b]		
^{152}Sm	^{154}Gd	$(I^\pi)_i$	$(I^\pi K)_f$	^{152}Sm	^{154}Gd	$K_i = 0$	$K_i = 1$	$K_i = 2$
963.2	1241.4	1^-	0^+0	0.55 ± 0.02 [c]	0.7 ± 0.3	0.50	2.00	
			2^+0	1.00	1.00	1.00	1.00	
1041.1	1251.6	3^-	4^+0	1.6 ± 0.5	0.4 ± 0.2	1.33	0.75	
			2^+0	1.00	1.00	1.00	1.00	
1511.1	1509.1	1^-	0^+0	0.01 [c]	0.19 [d]	0.50	2.00	
			2^+0	1.00	1.00	1.00	1.00	
1529.81	1397.6	2^-	2^+0	0.24 ± 0.02	5.4 ± 0.9			
			$2^+0(\beta)$	<0.005	1.4 ± 0.3			
			$3^+2(\gamma)$	0.50 ± 0.04			2.00	0.50
			$2^+2(\gamma)$	1.00	1.00		1.00	1.00
			3^-0	7.6 ± 1.9			4.00	0.25
			1^-0	1.00			1.00	1.00
1579.3	1617.3	3^-	$2^+0(\beta)$	1.0 ± 0.3				
			$2^+2(\gamma)$	1.2 ± 0.5				
			4^+0	4.6 ± 0.4	2.2 ± 0.2	1.33	0.75	
			2^+0	1.00	1.00	1.00	1.00	
	1559.1	4^-	$4^+2(\gamma)$		9.3 ± 4.8			
			4^+0		1.00			
1649.8	1719.6	2^-	2^+0	0.047 ± 0.014	0.0080 ± 0.0004			
			$3^+2(\gamma)$	0.68 ± 0.22	0.45 ± 0.02		2.00	0.50
			$2^+2(\gamma)$	1.00	1.00		1.00	1.00
			$2^+0(\beta)$		0.0206 ± 0.0014			
			$2^+2(\beta\gamma)$		0.58 ± 0.15			

[a] All transitions are assumed to be $E1$ except in the case of the $E2$ decays of the 1529.81-keV state in ^{152}Sm to the $K^\pi = 0^-$ levels.

[b] Predictions of adiabatic symmetric-rotor model. See Ref. 56.

[c] Values measured by Dzhelepov *et al.* (Ref. 6) in ^{152}Eu decay.

[d] Measurement by Meyer, Ref. 18.

assignments shown in Fig. 7 with the help of logft values and the inelastic deuteron scattering work of BET.[48] As pointed out in Ref. 18, there is evidently a large amount of Coriolis coupling between the $K^\pi = 0^-$ and 1^- bands. The two members of the $K = 0$ band are separated by only 10.2 keV, and 1^- and 3^- members of the $K = 1$ band are pushed above the 2^- and 4^- levels, respectively. Although the quadrupole-vibrational bands in ^{152}Sm and ^{154}Gd are quite similar, the octupole levels in these two nuclei show striking differences. In ^{152}Sm the $K^\pi = 0^-$ band lies much lower than in ^{154}Gd (the bandheads are 963.2 and 1241.4 keV, respectively) and its members are less compressed. Furthermore, the members of the $K = 1$ band in ^{152}Sm appear to fall in the normal $1^-, 2^-, 3^-$ order. These differences clearly indicate less Coriolis coupling in the case of ^{152}Sm, with the result that the $B(E1)$ ratios from the $K^\pi = 0^-$ levels are better described by the symmetric-rotor model than in the ^{154}Gd case. The fact that the agreement between the observed and predicted $B(E1)$ ratios from the $K^\pi = 1^-$ states is not improved in ^{152}Sm suggests that couplings of this band with other excitations besides the $K^\pi = 0^-$ band are important.

C. 1292.9-keV Level

It is very interesting and important to speculate about the nature of this 1292.9-keV state. If the 482.8- and 1171.0-keV γ rays can, indeed, be placed solely as decays of this level, then $B(E2; 482.8)/B(E2; 1171.0) = 7.1 \pm 2.1$, which indicates enhanced decay to the 2^+ member of the β band relative to that to the 2^+ member of the ground-state band. Schick,[40] thus suggests that this state may be the 2^+ member of the two-phonon β-vibrational band. However, evidence from two-nucleon-transfer reactions leads us to prefer another interpretation. In the (t,p) reaction on ^{150}Sm leading to levels in ^{152}Sm, Hinds *et al.*[42] observed three 0^+ states; the ground state, the β-vibrational bandhead, and a previously unseen one at approximately 1091 keV. They refrain from attributing the third 0^+ state to a two-phonon β vibration, since

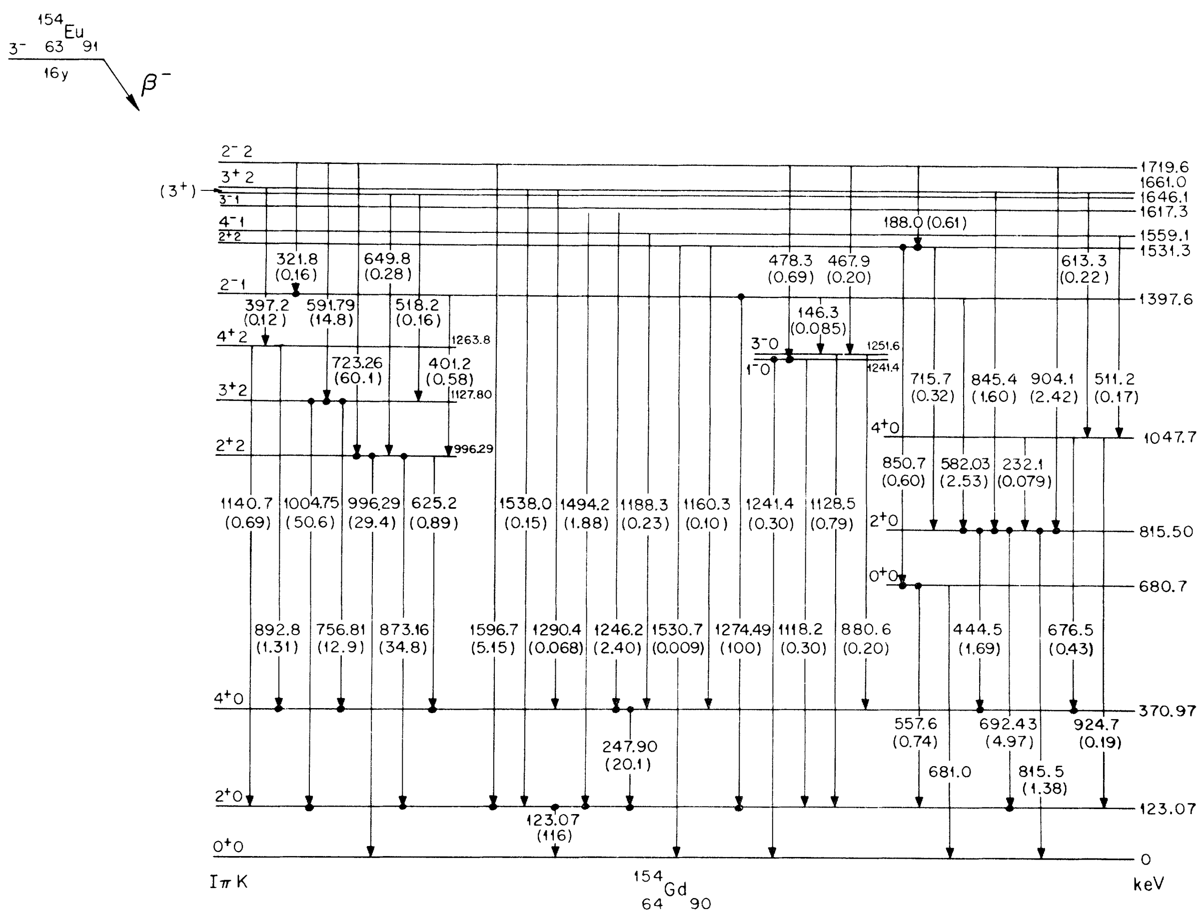

FIG. 7. Levels of ^{154}Gd populated in the decay of ^{154}Eu. Dots denote cases for which the data establish a definite coincidence relationship between the transition entering and one leaving the level.

such a state would be composed mainly of four-particle configurations, which should not be strongly populated in a two-particle transfer reaction. They prefer to call the 1091-keV state a spherical one or at least one with very small equilibrium deformation. If the ^{150}Sm nucleus is spherical, one would expect to strongly populate a spherical state in the (t,p) reaction. Furthermore, they tentatively associate a 1293-keV 2^+ state with the third 0^+ level. The smaller moment of inertia for this band then for the other $K=0$ bands in ^{152}Sm fits with their interpretation of the 1091-keV state. We believe that the new level seen here and by Schick[40] after radioactive decay is the same level populated in the ^{150}Sm(t,p) reaction, and that the interpretation of this 1293-keV state by Hinds *et al.*[42] is reasonable.

If this explanation is correct, it is then interesting to ask how much this "spherical" excitation interacts with the deformed ground and β-vibrational states. Information on this question comes from the recent experiments of McLatchie, Kitching, and Darcey (MKD).[58] They place an upper limit of 3% on the population of the 1091-keV state in the ^{154}Sm$(p,t)^{152}$Sm reaction. Since the target nucleus is thought to be well-deformed, this limit on the direct population can be interpreted as a limit on the mixing of this third 0^+ state with the deformed states in ^{152}Sm. Such a small interaction between the "spherical" and deformed states is rather surprising because of their proximity in energy.[58] More information on the size of this interaction might be obtained from our branching ratios for the 1292.9-keV state. Assuming purely $E2$ γ rays, we find $B(E2;2'\to0)/B(E2;2'\to2)=1.78\pm0.52$, whereas the Alaga[56] ratio for $K_i=K_f=0$ is 0.70 (the prime here denotes the 2^+ 1293-keV state, while no primes indicate members of the ground-state band). Our data also yield $B(E2;2'\to4)/B(E2;2'\to2)=22.7\pm5.8$, while the Alaga ratio is 1.8 for $K_i=0$ and 0.05 for $K_i=2$. Mixing these two bands to account for the disagreement between the experimental and predicted $B(E2)$ ratios does not help much. The $2'\to0/2'\to2$ ratio yields a mixing parameter Z of -0.10, while the $2'\to4/2'\to2$ ratio gives $Z=+0.18$. The great discrepancy between these two values indicates that no simple mixing of the two bands can explain the interband transitions. Postulating an $M1$ admixture in the $2'\to2$ transition leads to greater disagreement between the two Z values.

The level scheme of Fig. 3 contains only one decay of the 1292.9-keV state to the β band. Our γ-ray spectrum can yield only a rough upper limit of 0.025 units of intensity for the 608-keV $2'\to0\beta$ transition. This means that $B(E2;2'\to0\beta)/B(E2;2'\to2\beta)$ must be less than 0.073, while the Alaga ratio is 0.70 for $K_i=0$ or 2. This discrepancy indicates mixing between the "spherical" and β bands, although it could be within the 3% limit of MKD,[58] depending on the actual intensity of the 608-keV transition.

D. Positive-Parity Levels in ^{152}Gd

The first 2^+ state at 344.22 keV is usually attributed to a one-phonon vibration of a spherical ^{152}Gd nucleus. The 0^+ and 4^+ levels at 615.4 and 755.33 keV are then described as members of the two-phonon triplet. Toth, Faler, and Rasmussen[44] classified the second 2^+ at 930.5 keV and another 0^+ state at 1048 keV as members of a three-phonon vibrational band. Gromov *et al.*[45] treated the third 2^+ state at 1109.2 keV, the second 0^+ state, and a possible 4^+ level as members of a three-phonon band. It is difficult to associate the 930.5-keV state with the two-phonon triplet because of the resulting spread in energies of the members. However, classification of this level as a member of a three-phonon band should render it impossible to detect the transition to the ground state. The $B(E2)$ ratios for the 315.1-, 586.3-, and 930.7-keV transitions, respectively, are 3.2 : 1.0 : 0.016; the transition to the second 0^+ is thus enhanced significantly over the transition to the first 2^+ level and tremendously over that to the ground state. The fact that the 930.7-keV transition is observed indicates the difficulty in treating these levels in the usual manner. We must point out, however, that since this transition is assigned solely from energy considerations, it is possible for the 930.7-keV γ ray to correspond to some other placement in the decay scheme.

A different description of these levels is evidently required by the work of Gono, Ishihara, and Sakai (GIS).[59] The conversion electrons emitted in the ^{150}Sm$(\alpha,2n)^{152}$Gd and ^{153}Eu$(p,2n)^{152}$Gd reactions were detected in these experiments. The results indicate the presence of a rotational band up through spin of 10, with the 344.22- and 755.33-keV states assigned as the first and second members of this band. Furthermore, another band of levels built on the 615.4-keV state was observed. The 930.5-keV level is interpreted as the 2^+ member of this band, with 4^+ and 6^+ members at 1280 and 1668 keV. Each level in this excited band decays by $E0$ and $E2$ radiation to the equal-spin member of the rotational band, just as in $\Delta I=0$ transitions between the β and the ground-state bands[16,17] in ^{154}Gd, for example. This structure of levels is thus very similar to the β-vibrational band in a deformed nucleus. As indicated in Table II, the strong $E0$ component in the $2^+\to2^+$ transition from the 930.5-keV state is also observed in decay measurements.

A level at approximately 1280 keV was not observed in the present work. If the 930.5- and 1280-keV states are the 2^+ and 4^+ members of a band of energy levels, one would expect similar population of these states by β decay of the 3^- parent. As seen in Table IV, the logft value for β decay to the 930.5-keV level is 12.8. Assuming an equal logft value for decay to the 1280-keV state, we find that the β feed should account for approximately 0.09 units of relative intensity. By analogy to the β-vibrational levels in ^{152}Sm and ^{154}Gd, the most intense deexcitation of the 1280-keV state should be that to the 4^+ level at 755.33 keV. If there is no population of the 1280-keV state from higher-energy ^{152}Gd levels, then the maximum intensity of this 525-keV transition would be 0.09 units. The γ ray of such a weak transition very possibly would not be seen in our Ge(Li) spectra. Therefore, our data do not contradict the assignment made by GIS[59] of a 1280-keV state as a 4^+ member of a band containing also the 930.5-keV state. It should be pointed out that we do observe a 534.2-keV γ ray with a relative intensity of 0.16 ± 0.04. If the energy of the 4^+ state were actually 1290 keV, this γ ray possibly could be assigned to the transition to the 755.33-keV state. However, there are already two other possible placements for the 534.2-keV transition (from the 1643.2- and 1769.3-keV levels in ^{152}Gd and ^{152}Sm, respectively).

These $(\alpha, 2n)$ and $(p, 2n)$ experiments point out the importance of the ideas discussed by Sakai,[60] who asserts that the 0^+, 2^+, and 4^+ triplet of states in spherical nuclei can be described in approximately the same manner as are levels in deformed nuclei. The first excited 0^+ and second excited 2^+ states in spherical nuclei are treated as the first members of quasi-β and quasi-γ bands, respectively. The 4^+ member of the triplet is described as a level in the rotational band, as suggested by the experiments of GIS[59] on ^{152}Gd. This treatment should be especially effective for a transitional nucleus where the members of the two-phonon triplet are far removed from degeneracy. In the case of ^{152}Gd, the second observed 2^+ state appears to be the second member of the quasi-β band. However, this does not really violate the suggestion of Sakai.[60] As discussed above, in the conventional treatment of these levels, this 930.5-keV state probably cannot be interpreted as a member of the two-phonon triplet; and it is the 2^+ member of this triplet that Sakai would consider as the bandhead of the quasi-γ band. The failure to observe such a 2^+ level around 700 keV is not understood. However, there is a candidate above the 930.5-keV state at 1109.2 keV, where the energy difference between these two states nearly equals that between the 2^+ members of the β and γ bands in ^{154}Gd (see Fig. 7). This interpretation would explain why one sees transitions from this level to the ground-state band but not to the quasi-β band, or in the phonon model, why there are no observed transitions to the 0^+ and 4^+ states, as they are members of the two-phonon triplet. The 3^+ state at 1434.0 keV might then be designated the 3^+ member of this quasi-γ band, although the logft to this level is much smaller than that to the 1109.2-keV state.

Describing some of the low-lying positive-parity states of ^{152}Gd as members of a quasi-β band is given further impetus by the experiments of BET.[48] They found that the inelastic deuteron scattering cross sections for the 615.4-, 930.5-, and 1280-keV levels are similar to those for the $0^+, 2^+, 4^+$ members of the β bands in deformed nuclei.

V. CONCLUSIONS

The experiments described above have provided considerable new information on the ^{152}Sm and ^{152}Gd level schemes, and interesting comparisons of the properties of the quadrupole-vibrational levels[20,21] and of the negative-parity levels in ^{152}Sm and ^{154}Gd. The general disagreement between the observed and predicted branching ratios from the members of the $K^\pi = 1^-$ band in each nucleus probably indicates the existence of strong Coriolis coupling between this band and other negative-parity bands. The inverted ordering of the states in the 1^- band in ^{154}Gd is in contrast to the normal level ordering in ^{152}Sm. This suggests a greater coupling between the 0^- and 1^- bands in ^{154}Gd than in ^{152}Sm. A quantitative treatment of the Coriolis interactions in these two nuclei, similar to that described by Günther, Ryde, and Krien[61] for ^{160}Dy, is needed. At the present, such a detailed analysis of the negative-parity states would be hindered by the knowledge of only one member of the 2^- band in ^{152}Sm (Meyer[18] has reported a $K^\pi I = 2^-3$ level in ^{154}Gd). As further refinements in β- and γ-ray spectrometers enable the observation of additional high-energy states, quantitative treatment of the mixing between these states should become possible.

Before the nature of this 1293-keV state can be definitely concluded, intensities for the presently unobserved decays to the β and γ bands are needed. Also, the seemingly small logft for electron capture to this state must be explained or proven to be larger. If this level has small equilibrium deformation, one might not expect much direct population from the deformed parent. Furthermore, it is important to observe the 1091-keV 0^+ state in the radioactive decay of either the ^{152}Eu ground or isomeric state, so that the decay characteristics of this state might be studied.

In ^{152}Gd, the difficulty in assigning the members of a two-phonon triplet from our measurements and the band structures observed by GIS[59] give credence to the ideas of quasirotational and vibrational excitations as advanced by Sakai.[60]

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*Present address: University of Notre Dame, Notre Dame, Indiana.

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[1] L. L. Riedinger, J. H. Hamilton, and N. R. Johnson, Bull. Am. Phys. Soc. 11, 529 (1966); J. H. Hamilton, L. L. Riedinger, and N. R. Johnson, Bull. Am. Phys. Soc. 11, 407 (1966); L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Bull. Am. Phys. Soc. 13, 670 (1968).

[2] *Nuclear Data Sheets,* compiled by K. Way *et al.* (U. S. Government Printing and Publishing Office, National Academy of Sciences – National Research Council, Washington, D. C., 1964).

[3] B. S. Dzhelepov, N. N. Zhukovskii, and A. G. Maloyan, Yadern. Fiz. 1, 941 (1965) [transl.: Soviet J. Nucl. Phys. 1, 671 (1965)].

[4] N. A. Voinova, B. S. Dzhelepov, N. N. Zhukovskii, Yu. V. Kalinichev, A. G. Maloyan, and A. G. Sergeev, Yadern. Fiz. 3, 3 (1966) [transl.: Soviet J. Nucl. Phys. 3, 1 (1966)].

[5] B. S. Dzhelepov, N. N. Zhukovskii, and A. G. Maloyan, Yadern. Fiz. 3, 785 (1966) [transl.: Soviet J. Nucl. Phys. 3, 577 (1966)].

[6] B. S. Dzhelepov, A. G. Dmitriev, N. N. Zhukovskii, and A. G. Maloyan, Izv. Akad. Nauk SSSR Ser. Fiz. 30, 1265 (1966) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 30, 1322 (1966)].

[7] Y-t Liu, O. B. Nielsen, P. Salling, and O. Skilbreid, Izv. Akad. Nauk SSSR Ser. Fiz. 31, 63 (1967)[transl.: Bull. Acad. Sci. USSR, Phys. Ser. 31, 69 (1967)].

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

[9] K. M. Bisgaard, K. B. Nielsen, and J. Sodemann, Phys. Letters 7, 57 (1963).

[10] T. Katoh and E. H. Spejewski, Nucl. Phys. 69, 477 (1965).

[11] G. Malmsten, O. Nilsson, and I. Andersson, Arkiv Fysik 33, 361 (1966).

[12] J. S. Larsen, O. Skilbreid, and L. Visiten, Nucl. Phys. A100, 248 (1967).

[13] A. Aquili, R. Cesareo, and M. Giannini, private communication.

[14] P. Mukherjee and A. K. Sen Gupta, Phys. Rev. 182, 1265 (1969).

[15] L. K. Ng, K. C. Mann, and T. G. Walton, Nucl. Phys. A116, 433 (1968).

[16] W. H. Brantley, J. H. Hamilton, T. Katoh, and E. F. Zganjar, Nucl. Phys. A118, 677 (1968).

[17] J. H. Hamilton and J. C. Manthuruthil, Nucl. Phys. A118, 686 (1968).

[18] R. A. Meyer, Phys. Rev. 170, 1089 (1968).

[19] I. Andersson and G. T. Ewan, Nucl. Phys. A123, 608 (1969).

[20] L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. Letters 19, 1243 (1967).

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

[22] J. B. Marion, Nucl. Data A4, 301 (1968).

[23] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[24] N. R. Johnson, E. Eichler, G. D. O'Kelley, J. W. Chase, and J. T. Wasson, Phys. Rev. 122, 1546 (1961).

[25] E. Eichler, G. D. O'Kelley, R. L. Robinson, J. A. Marinsky, and N. R. Johnson, Nucl. Phys. 35, 625 (1962).

[26] N. B. Gove, in *Proceedings of the Conference on Nuclear Spin-Parity Assignments, Gatlinburg, Tennessee, 1965,* edited by N. B. Gove and R. L. Robinson (Academic Press Inc., New York, 1966), p. 83.

[27] I. Marklund, O. Nathan, and O. B. Nielsen, Nucl. Phys. 15, 199 (1960).

[28] I. Andersson and G. T. Ewan, private communication from G. T. Ewan; Atomic Energy of Canada Limited Progress Report No. PR-P-73, 1967 (unpublished).

[29] F. K. McGowan, R. O. Sayer, P. H. Stelson, R. L. Robinson, and W. T. Milner, Bull. Am. Phys. Soc. 13, 895 (1968).

[30] K. Baker, J. H. Hamilton, F. C. Coffman, and A. V. Ramayya, to be published.

[31] R. A. Kenefick and R. K. Sheline, Phys. Rev. 135, 939 (1964).

[32] Y. Yoshizawa, B. Elbek, B. Herskind, and M. C. Olesen, Nucl. Phys. 73, 273 (1965).

[33] G. G. Seaman, J. S. Greenberg, D. A. Bromley, and F. K. McGowan, Phys. Rev. 149, 925 (1966).

[34] B. Zeidman, B. Elbek, B. Herskind, and M. C. Olesen, Nucl. Phys. 86, 471 (1966).

[35] R. O. Sayer, thesis, Oak Ridge National Laboratory Report No. ORNL-TM-2211, 1968 (unpublished).

[36] O. Nathan and M. A. Waggoner, Nucl. Phys. 2, 548 (1957).

[37] P. Debrunner and W. Kundig, Helv. Phys. Acta 33, 395 (1960).

[38] E. Veje, B. Elbek, B. Herskind, and M. C. Olesen,

Nucl. Phys. A109, 489 (1968).
[39]G. B. Hagemann, B. Herskind, M. C. Olesen, and B. Elbek, to be published. Some of the results from this work are contained in a contribution to *Proceedings of the International Conference on Properties of Nuclear States, Montreal, Canada, 1969* (Presses de l' Université de Montréal, Montréal, Canada, 1969).
[40]W. C. Schick, Bull. Am. Phys. Soc. 15, 75 (1970).
[41]D. R. Zolonowski, E. G. Funk, and J. W. Mihelich, to be published; D. R. Zolonowski, private communication.
[42]S. Hinds, J. H. Bjerregaard, O. Hansen, and O. Nathan, Phys. Letters 14, 48 (1965).
[43]B. S. Dzhelepov and S. A. Shestopalova, in *Proceedings of the International Symposium on Nuclear Structure, Dubna, 1968* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 39.
[44]K. S. Toth, K. T. Faler, and J. O. Rasmussen, Phys. Rev. 115, 158 (1959).
[45]K. Ya. Gromov, V. V. Kuznetsov, M. Ya. Kuznetsova, M. Finger, J. Urbanec, O. B. Nielsen, K. Wilsky, O. Skilbreid, and M. Jørgensen, Nucl. Phys. A99, 585 (1967).
[46]A. S. Reiner, Nucl. Phys. 27, 115 (1961).
[47]W. Schick and L. Grodzins, Nucl. Phys. 62, 254 (1965).
[48]R. Bloch, B. Elbek, and P. O. Tjøm, Nucl. Phys. A91, 576 (1967).
[49]Z. Grabowski, Arkiv Fysik 20, 177 (1961).
[50]W. Schneider, Nucl. Phys. 21, 55 (1960).
[51]L. L. Riedinger, E. Eichler, J. Fuglsang, G. B. Hagemann, and B. Herskind, in *Proceedings of the Fifth International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, Germany, 1969,* edited by R. Bock and W. R. Hering (North-Holland Publishing Company, Amsterdam, The Netherlands, 1970).
[52]D. R. Bes, Nucl. Phys. 49, 544 (1963).
[53]S. Bernow, S. Devons, I. Duerdoth, D. Hitlin, J. W. Kast, W. Y. Lee, E. R. Macagno, J. Rainwater, and C. L. Wu, Phys. Rev. Letters 21, 457 (1968).
[54]K. E. Rehm, W. Henning, and P. Kienle, Phys. Rev. Letters 22, 790 (1969).
[55]E. R. Marshalek, Phys. Rev. Letters 20, 214 (1968).
[56]G. Alaga, K. Adler, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 29, No. 9 (1955).
[57]V. G. Soloviev, P. Fogel, and A. A. Korneichuk, Izv. Akad. Nauk SSSR Ser. Fiz. 28, 1599 (1964) [transl.: Bull. Am. Acad. Sci. USSR, Phys. Ser. 28, 1495 (1964)].
[58]W. McLatchie, J. E. Kitching, and W. Darcey, Phys. Letters 30B, 529 (1969).
[59]Y. Gono, M. Ishihara, and M. Sakai, in *Proceedings of the International Symposium on Nuclear Structure Contributions, Dubna, 1968* (International Atomic Energy Agency, Vienna, Austria, 1969).
[60]M. Sakai, Nucl. Phys. A104, 301 (1967).
[61]C. Günther, H. Ryde, and K. Krien, Nucl. Phys. A122, 401 (1968).

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Nuclear Orientation of ^{253}Es in Neodymium Ethylsulfate*

A. J. Soinski, R. B. Frankel,† Q. O. Navarro,‡ and D. A. Shirley
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720
(Received 29 June 1970)

Einsteinium-253 nuclei were oriented at low temperatures in a neodymium ethylsulfate lattice. From the temperature-dependent α-particle angular distribution a nuclear magnetic moment $|\mu| = (2.7 \pm 1.3)\mu_N$ was deduced. From the values for the angular distribution function at the lowest temperatures it was possible to test the predictions of the Mang shell-model theory for the relative phases and amplitudes of the α-partial waves. As predicted, the waves of angular momentum $L=0$ and 2 are in phase, and the $L=0$ and 4 waves are out of phase. The predicted wave amplitudes are in error, especially that of the $L=4$ wave. The predicted relative intensities (which are proportional to the amplitudes squared) for the S, D, and G waves are 1.000:0.179:0.0052, whereas the relative intensities that best fit the experimental angular distribution are 1.000:0.216:0.0078.

INTRODUCTION

An α particle emitted by the ground state of an even-even nucleus has a unique angular momentum L. The parent nucleus has spin $I_i = 0$, and angular momentum conservation requires that the daughter energy level populated by the α particle should have $I_f = L$. For odd-odd or odd-mass nuclei, $I_i \neq 0$, and various values of L are generally permitted. On the basis of angular momentum conservation, Spiers[1] predicted that anisotropic α-particle emission would take place from oriented nuclei. Subsequent nuclear-orientation experiments confirmed this prediction and also yielded information about the relative amplitudes and phases of the observed α partial waves.

Hill and Wheeler[2] made the first quantative estimate of enhanced α-particle emission from the poles of prolately deformed spheroidal nuclei. Their reasoning can be understood with the aid of