Low-Energy Coexisting Band in ^{154}Gd

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A low-energy coexisting band J^π (E_x keV) 0^+ (1182), 2^+ (1418), 4^+ (1701) is identified in the deformed nucleus, ^{154}Gd. Detailed γ-ray spectroscopy following the β decays of ^{154}Eu ($J = 3$), ^{154g,m_1,m_2}Tb ($J = 0, 3, 7$) is used to establish this structure. The structure is explained in terms of the pairing and deformation degrees of freedom, a "pairing isomer," which results from the $\nu[505]\uparrow$ Nilsson intruder orbital.

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Shape coexistence in nuclei, i.e., the existence of deformed states in spherical nuclei [1,2] and superdeformed states in nuclei with weak to moderate deformation [3], is a widespread and well-established phenomenon. These deformed coexisting structures, distinguished by closely spaced bands of rotational states with strongly enhanced intraband $E2$ transitions, have been identified widely as excited states in nuclei near closed shells (in the Pt isotopes a deformed intruder structure even becomes the ground state [2]). However, the converse possibility, the widespread occurrence of weakly deformed excited states in strongly deformed nuclei, has never been addressed. The reason for this is that this second possibility for shape coexistence is much harder to realize experimentally because weakly deformed states lack the distinctive collective characteristics of strongly deformed states.

The excited states of ^{154}Gd have been classified [4] into rotational bands characteristic of an axially symmetric rotor. This classification supports a picture of a variety of intrinsic excitations with essentially uniform rotational energy constants, and, thus, essentially uniform deformations. In contrast, Shahabuddin *et al.* [5] argue that strong (t, p) population of a 0^+ level at 1182.1 keV and a 2^+ level at 1418.1 keV indicates that these are associated "spherical" states in a "deformed" nucleus. However, the 1418.1 keV level was previously associated [6] with a 0^+ level at 1295.5 keV (suggested members of the 2β band), and there is a lack of spectroscopic evidence which directly links the level at 1182.1 keV (unobserved in β decay studies) to the 1418.1 keV level.

In a γ-ray spectroscopy program that we have initiated to make a systematic study of the collective excitations in the $N = 90$ nuclei, we have not only observed population of the 0^+ 1182.1 keV state through β decay, but also we have identified a weakly deformed band (cf. Fig. 1) built upon that state. We present details which identify this band to establish a new type of collective structure in nuclei and to illustrate the detailed spectroscopy that is necessary to identify weakly deformed states in a strongly deformed nucleus.

Excited states in the nucleus ^{154}Gd are accessible through the β decay of four long-lived isotopes: ^{154}Eu (8.6 yr, $J^\pi = 3^-$), ^{154}Tb (21.5 h, $J = 0$), ^{154}Tb (9.4 h, $J^\pi = 3^-$), and ^{154}Tb (22.7 h, $J^\pi = 7^-$). These decays provide the means to study low-spin states below 2 MeV in ^{154}Gd in great detail [$Q_{\beta^-}(^{154}\mathrm{Eu}) = 1968.5 \pm 1.1$ keV, $Q_{\mathrm{EC}}(^{154}\mathrm{Tb}) = 3560 \pm 50$ keV [7]]. For our studies, the Tb sources were produced by the ^{153}Eu(^{4}He, $3n$) and ^{154}Gd(p, n) reactions using 38 MeV ^{4}He and 9.75 MeV p beams from the LBNL 88" cyclotron; the Eu sources used were both commercially obtained and produced by the ^{153}Eu(n, γ) reaction in the Oregon State University reactor. Coincidence measurements were carried out using the "8π spectrometer," an array of 20 Compton-suppressed Ge detectors which provided good long term stability, excellent peak : total ratio (~ 0.5 at 660 keV), and low

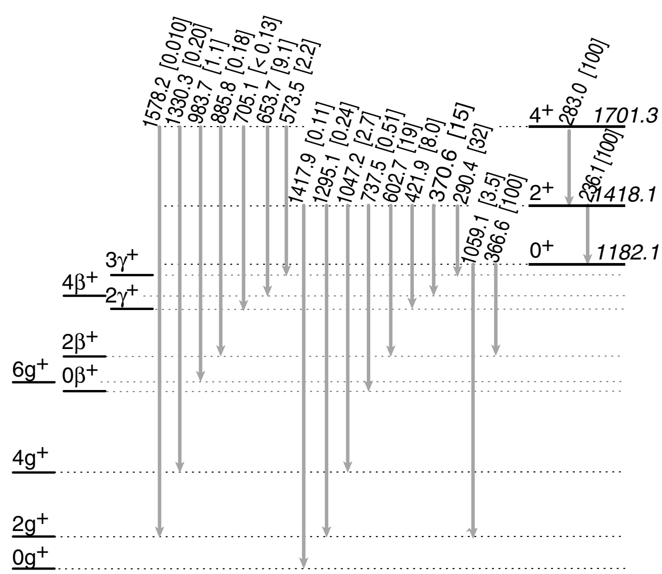

FIG. 1. Levels and transitions associated with the weakly deformed intruder structure in ^{154}Gd. Relative $B(E2)$ values (in brackets) show that the strongest collective transitions are the in-band 236 and 283 keV γ rays.

incidence of summing (source-to-detector distance 22 cm). Source strengths were typically $\sim 10\ \mu$Ci.

Three levels are associated with the new band presented in Fig. 1: the 0^+ 1182.1, 2^+ 1418.0, and 4^+ 1701.3 keV levels. Of these, only the 2^+ 1418 level is already well established through β decay. The 0^+ 1182 level, although previously reported in transfer reaction [5] and (n,γ) [8] studies, is observed through the β decays of ^{154}Eu and ^{154g,m_1}Tb for the first time. In contrast with the accepted level scheme [4] for ^{154}Gd, our coincidence data from the decay of ^{154m_1}Tb indicate that only one state, the 4^+ level at 1701.3 keV, exists in the energy range 1698–1704 keV with $J^\pi = 2$–4. Transitions from the previously reported levels at 1698.5 and 1702.0 keV are inconsistent with the γ-ray energies and intensities found in coincidence (cf. Fig. 2) with a new 484.6 keV γ ray depopulating the known [4] 4^- level at 2185.9 keV. While the γ-ray coincidence data strongly support this band structure, evaluated data [4] associate the 0^+ 1182 with a 2^+ level reported at 1294.2 keV and the 2^+ 1418 with a 0^+ level at 1295.5 keV, which suggests a very different picture of the low-lying structure of ^{154}Gd.

The band formed by the 0^+ 1182, 2^+ 1418, 4^+ 1701 states has the characteristics of a structure which is considerably less deformed (much larger energy spacings) than the lower-lying states in ^{154}Gd. Moreover, the nearby higher-lying states in ^{154}Gd are consistent with band structures which have deformation similar to the ground state, indicating that the wide spacing in the new band is not due to mixing distortions. This raises the question of whether or not the present studies have failed to populate any low-spin (positive-parity) states in ^{154}Gd below $\sim$1500 keV. To address this question, we have adopted two strategies. The first has been to look in our data for the various reported γ rays which have led, in other studies, to proposing the 1294.2 and 1295.5 keV levels.

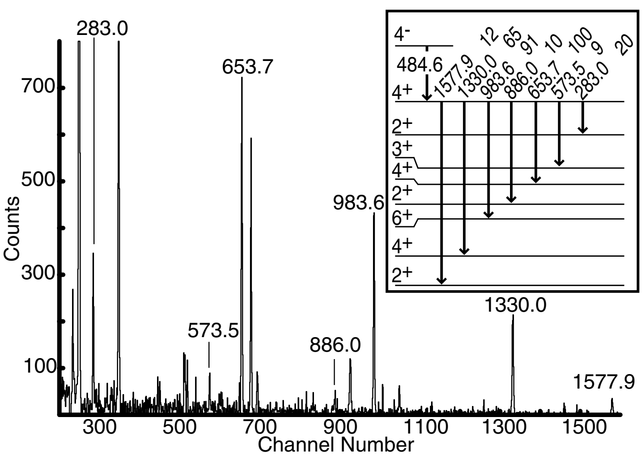

FIG. 2. The 485 keV γ-gated γ-ray spectrum from the ^{154}Tb decay showing transitions from the 4^+ level at 1701.3 keV identified in Fig. 1. The intensity of the 485 keV γ ray in the ^{154}Tb ($J = 3$) decay is 0.5% relative to the 123 keV γ ray.

The second has been to assess the "completeness" of the ^{154}Gd level scheme deduced in this work.

Studies which have reported γ rays to and from the 1294.2 and 1295.5 keV levels have been limited to ^{154}Eu$(\beta^-)^{154}$Gd [6], ^{154g,m_1,m_2}Tb$(\beta^+/\mathrm{EC})^{154}$Gd [9,10], and ^{153}Gd$(n,\gamma)^{154}$Gd [8]. There are serious inconsistencies [4] among these studies. A striking image of these inconsistencies is presented in Fig. 3, where we show a portion of the spectrum of γ rays deexciting the 1531.3 keV 2^+ state, populated in the decay of ^{154}Eu. The 349 keV γ ray is a new transition which feeds the 1182 keV 0^+ state. The 267 keV γ ray is part of a previously unresolved doublet, one part of which feeds the 1264 keV 4^+ state. The location for $\sim$237 keV γ rays, which would feed levels at 1294–1295 keV, is marked. We set an upper limit (per 100 β decays) for a 237.7 keV γ ray of 0.0003; cf. 0.0063 [4]. A similar method may be used to set upper limits for all γ rays which have been associated with the 1294.2 and 1295.5 keV levels (cf. Table I). The reported 615.1 keV $E0$ transition which Sousa *et al.* [9] assign as $1295.8 \rightarrow 680.7$ keV cannot be directly addressed by this study; however, Spits and Van Assche [8] refute the assignment.

Assessing completeness in a decay scheme study is extremely difficult. One may use rotational band patterns and population systematics and argue that if higher-lying levels with the same spin parity as the levels in question are populated then the levels in question should be seen. To quantify this, we have used the method described by Currie [11] to set upper limits on the intensity of γ-ray

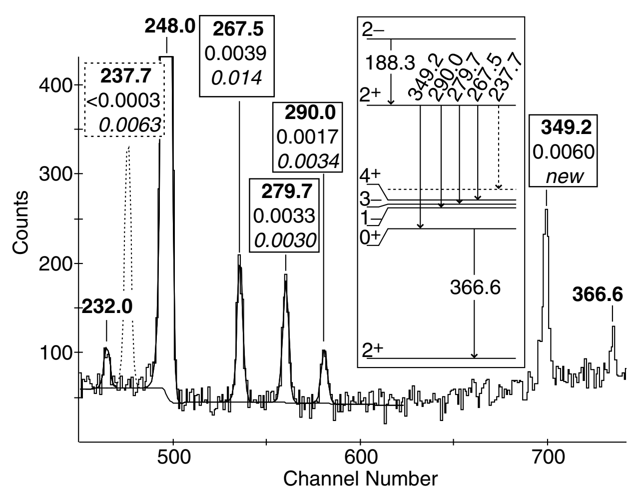

FIG. 3. The ^{154}Eu decay 188 keV γ-gated γ-ray spectrum. Boxes indicate the energy and measured I_γ (per 100 β decays) for coincident transitions out of the level at 1531.3 keV (cf. reported [4] intensity in italics). The 238 keV transition feeding the reported $(2)^+$ level at 1293.6 keV is missing (dotted line shape indicates the expected intensity). Doublets at 267.7 ($1264 \rightarrow 996$, $I_\gamma = 0.012$) and 290.0 keV ($1418 \rightarrow 1128$, $I_\gamma = 0.0016$) were previously unresolved. A new transition observed at 349 keV feeds the 0^+ level at 1182.0 keV.

TABLE I. Total transition intensity out of excited states in ^{154}Gd populated through the β decay of ^{154}Eu per 100 β decays. Data from the adopted [4] ^{154}Eu decay scheme and from reported neutron capture studies of Spits *et al.* [8] are included for reference. The notations "1°" and "2°" indicate observed primary and secondary γ-ray intensities following neutron capture (per 1000 neutrons captured).

J^{π}	E_x	/100 β D_{Eu}[a]	/100 β D_{Eu} [4]	/1000 n $(n,\gamma)2°$ [8]	/1000 n $(n,\gamma)1°$ [8]
2^+	123.1	89.5	89.1	59.7	0.08
4^+	371.0	7.98	7.68	14.1	···
0^+	680.7	0.277	0.271	3.41	0.7
2^+	815.5	2.98	2.98	9.26	2.33
2^+	996.3	23.1	23.1	8.14	0.08
4^+	1047.6	0.280	0.264	2.04	···
$1, 2^+$	1136.0	<0.004	0.010	···	···
0^+	1182.1	0.016	···	1.45	2.4
	1233.1	<0.002	0.003	···	···
4^+	1263.8	0.797	0.768	1.40	···
	1277.0	<0.004	0.014	0.16	···
$(2)^+$	1293.6	<0.002	0.006	···	···
$(2)^+$	1294.2	<0.004	0.016	0.49	···
0^+	1295.5	<0.004	···	0.23	···
2^+	1418.1	0.134	0.114	2.53	0.08
$(1, 2^+)$	1510.1	<0.001	0.024	···	···
2^+	1531.3	0.63	0.56	1.95	0.75
4^+	1645.8	0.17	0.16	0.56	···

[a]This work (decay of ^{154}Eu).

transitions unobserved in this study which are associated with previously reported levels.

In Table I we present the population intensities of all reported excited states in ^{154}Gd up to ~1.5 MeV, which (may) have $J^{\pi} = 0^+, 2^+, 4^+$, as seen in previous γ-ray spectroscopic studies and compare the reported intensities with that determined in the present work. We limit population intensities from our studies to the decay of ^{154}Eu due to the difficulties in separating the decays of ^{154g,m_1,m_2}Tb and the resulting ambiguity in setting reasonable upper limits on the population intensity. For comparison, we include two investigations [6,12] and an evaluation [12] of ^{154}Eu$(\beta^-)^{154}$Gd which report the intensities of very weak γ-ray lines and an investigation [8] of ^{153}Gd$(n,\gamma)^{154}$Gd. These results suggest that any 2^+ state below 1418 keV would be observable in the present work. While it could be argued that the lower Q value of the ^{154}Eu decay precludes population of a 0^+ level at 1295.5, the next reported [4] excited 0^+ state above the 1295.5 keV state is at 1574.0 keV. We observe population of this state in the decay of ^{154g}Tb with an intensity of 1.6% which can be compared with our observed population of the 1182.1 keV 0^+ state of 3.9%. If a 0^+ state exists in ^{154}Gd at 1295.5 keV, we deduce that it is populated a factor ~30 lower than the systematic trend observed in this study.

The low-energy band structure of ^{154}Gd has been addressed theoretically using the dynamic deformation model [13–15], the interacting boson model [16–19], and the "projection model" [19]. All of these investigations discuss ground, "β," and "γ" bands. Thus, based on the $B(E2)$ ratios out of the band, it might be tempting to call this new band a "2-phonon $\beta\beta$ vibration." However, the strong population in (t,p) transfer reactions (the 1182 0^+ state has 56% of the strength of the ground-state population [5]) precludes a two-phonon interpretation. Additionally, only Kumar *et al.* [14] discuss higher-lying bands; these calculations predict a 0_3^+ band 700 keV higher than the 1182 keV level found experimentally and predict $B(E2)$ ratios of transitions out of this band which are significantly greater than the experimental ratios; cf. Table II. Thus, a new microscopic description is required for this band.

Two-nucleon transfer reactions [i.e., (t,p) and (p,t) reactions] specifically probe pairing correlations, thus the strong (t,p) population of the 0^+ (1182) and 2^+ (1418) levels observed by Shahabuddin *et al.* [5] are the key data for an interpretation of the band identified in Fig. 1. We suggest that this structure may be a pairing isomer. Ragnarsson and Broglia [20] introduced the concept of "pairing isomers" (states which have a smaller pairing gap than the ground-state configuration) to successfully describe the strong (p,t) population of excited 0^+ states in the even-even actinides. Peterson and Garrett [21] pointed out that the $\frac{11}{2}^-$ [505] configuration neutron orbital is an example of a pairing isomer in the rare-earth region and is predominantly a hole state ($V^2 > U^2$) even when this state is low in excitation energy. In the odd-N Gd isotopes, bands built upon the $\frac{11}{2}^-$ [505] orbital are known to have greater deformation [22] than the ground

TABLE II. Comparison of theoretical and experimental $B(E2)$ ratios from γ rays out of the band built on the 0_3^+ state in ^{154}Gd. Theoretical values are predicted by the dynamic pairing plus quadrupole model (DPPQ) [14] for the "$\beta\beta$" band, 0^+ (1842), 2^+ (2156), 4^+ (2490). Experimental ratios from the decays of ^{154}Eu and ^{154}Tb are results of this work for the band presented in Fig. 1, 0^+ (1182), 2^+ (1418), 4^+ (1701).

Initial level I_i	Transition ratio I_f/I_f'	$B(E2)$ ratio DPPQ	$B(E2)$ ratio Expt.
$2_{\beta\beta}$	$0_g/2_g$	29.5	0.46
	$4_g/2_g$	54	11.3
	$0_\beta/2_\beta$	0.01	0.027
	$4_\beta/2_\beta$	2.7	0.79
	$0_\beta/0_g$	0.6	4.6
	$2_\beta/2_g$	2210	79.2
	$2_\beta/2_\gamma$	4.4	2.4
	$2_\gamma/2_g$	505	33.3
	$4_\beta/4_g$	110	5.6
$4_{\beta\beta}$	$4_\beta/4_g$	1.3×10^5	45.5

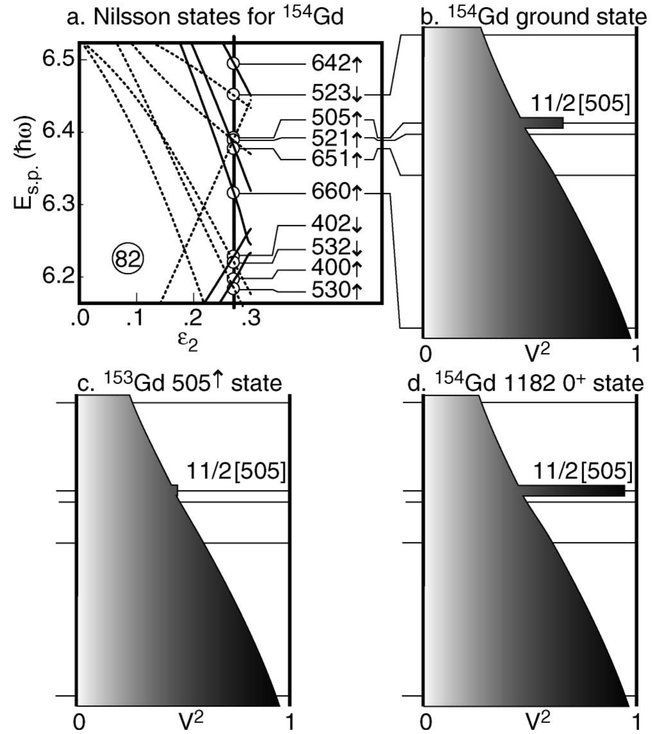

FIG. 4. A schematic depiction of the role of the $\frac{11}{2}^-$ [505] orbital in the proposed structure. (a) The $\nu[505]\uparrow$ orbital is an isolated up-sloping orbital in this region. (b) In the ground state of ^{154}Gd, the reduced pairing gap of the pairing isomer results in an increased occupation, V^2, of the $\nu[505]\uparrow$ orbital. (c) When the $\nu[505]\uparrow$ orbital is occupied ($V^2 = 0.5$) by the unpaired neutron in odd-N Gd isotopes (and occupancy is increased in the down-sloping orbitals) deformation is increased. (d) As population of this up-sloping orbital is further increased (at the expense of the neighboring down-sloping orbitals), deformation decreases.

state; this is illustrated in Fig. 4(c) where the $\frac{11}{2}^-$ [505] orbital is occupied ($V^2 = 0.5$) by the unpaired neutron (a decreased occupancy of this orbital which consequently increases the occupancy of neighboring down-sloping orbitals) resulting in a more-deformed structure. In the even-N Gd isotopes, *increased* occupancy of the up-sloping $\frac{11}{2}^-$ [505] orbital (and, accordingly, the decreased occupancy of the neighboring down-sloping orbitals) results in a configuration which favors a less-deformed shape [see Fig. 4(d)]. The increased energy separation in the band built on the 1182 0^+ state is indicative of a smaller deformation. The enhanced population of the 1182 0^+ state in (t, p) transfer reactions [5] indicates a smaller pairing gap than the ground-state configuration. This evidence suggests that the band structure built on the 1182 0^+ state is a realization of a pairing isomer.

We have measured γ-ray transitions from excited states in ^{154}Gd populated in the β decay of the isotopes ^{154}Eu and ^{154g,m_1,m_2}Tb. A low-energy coexisting band structure in the deformed nucleus ^{154}Gd has been identified using γ-ray coincidence spectroscopy. This structure is interpreted as a pairing isomer based upon the steeply up-sloping $\frac{11}{2}^-$ [505] Nilsson configuration.

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