Lifetime measurements in ^{156}Gd

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Background: The nature of low-lying oscillations or excitations around the equilibrium deformed nuclear shape remains an open question in a nuclear structure. The question revolves around the possible degrees of freedom in deformed nuclei. Rotational motion is an expected feature of deformed nuclei; the open challenge is whether the "granularity" of the nuclei allows single or multiple quanta of vibrational oscillations or excitations superimposed on the equilibrium deformed shape of the nucleus. Special emphasis is placed on the $K^\pi = 0^+$, β vibration whose existence is open to debate some 40 years after Bohr-Mottelson-Rainwater's Nobel prize for connecting nucleon motion to the emergence of collectivity.
Purpose: The ^{156}Gd nucleus is an excellent test case for the search of the predicted oscillations since it has one of the most developed level schemes up to 2.35 MeV and it lies in the well-deformed rare-earth region of the chart of nuclides. This nucleus has previously been studied by (n,γ), (n,e^-), (e,e'), (p,p'), (d,p), and (d,t) reactions with six known excited $K^\pi = 0^+$ bands. We measured level lifetimes of ^{156}Gd in order to determine the nature of the low-lying excited bands.
Method: The lifetimes of the excited states in the ^{156}Gd nucleus were measured following neutron capture using the GRID technique at the Institut Laue-Langevin in Grenoble, France.
Results: Twelve level lifetimes were measured from four excitation bands in the ^{156}Gd nucleus including the lifetimes of three of the $K^\pi = 0^+$ bands.
Conclusions: There are two $K^\pi = 0^+$ bands in this nucleus connected to the ground-state band. Transitions from the $K^\pi = 0^+_2$ band at 1049.5 keV to the ground-state band are more collective than the ones from the $K^\pi = 0^+_3$ band at 1168.2 keV. The moments of inertia of the various $K^\pi = 0^+$, the $K^\pi = 2^+$, and the $K^\pi = 4^+$ bands show that all the bands except the $K^\pi = 0^+_3$ band at 1168.2 keV have nearly identical moments of inertia with the ground-state band pointing to the fact that all of the bands discussed here with the exception of this indicating $K^\pi = 0^+_3$ band seem to be collective excitations built on the ground state. This result is consistent with various theoretical predictions. $B(E2)$ calculations for transitions from the $K^\pi = 2^+$ band to the ground-state band supports the assignment of this band as the γ band. Also, the $K^\pi = 0^+_4$ and the $K^\pi = 4^+_1$ bands at 1715.2 and 1510.6 keV, respectively, are shown to be strongly connected to the $K^\pi = 2^+$ γ band presenting evidence for the observation of a second set of two-phonon $\gamma\gamma$ vibrational excitations albeit with greatly varying degrees of anharmonicity in comparison to the case of ^{166}Er.

I. INTRODUCTION

The 1975 Nobel prize in Physics was awarded to Bohr, Mottelson, and Rainwater for the discovery of the connection between nucleon motion and the emergent collective behavior. Bohr-Mottelson-Rainwater described nuclei geometrically as a shape and the oscillations of the nucleus around that shape. The lowest-lying shape effecting oscillations or vibrations would be quadrupole ($\lambda = 2$) in nature, resulting in two types of vibrations in deformed nuclei: β with oscillations along the symmetry axis ($K^\pi = 0^+$) and γ-breaking axial symmetry with a projection of $K^\pi = 2^+$ on the symmetry axis. The γ vibration seems to be well characterized as the first $K^\pi = 2^+_1$ (or 2^+_γ) band and exhibits a systematic behavior across the region of deformed nuclei with typical $B(E2{:}\,2^+_\gamma \rightarrow 0^+_{\text{g.s.}})$ values of a few Weisskopf units (W.u.) and where "g.s." represents the "ground state" [1].

Today, over 40 years later, the existence and characterization of the low-lying β vibration remains an open question in nuclear structures [1–35]. This is due to the lack of sufficient experimental data on the identification and characterization of 0^+ excitations in deformed nuclei and to the interpretation of what is expected of a β vibration. The absence of a β-vibrational excitation in deformed nuclei will call into question why nuclei, unlike all other quantum systems, do not exhibit this mode of oscillatory motion.

In well-deformed regions of nuclei, excitations built on a deformed ground state have traditionally been described in terms of quadrupole excitations leading to the classifications of the first excited 0^+ bands as single-phonon β-vibrational excitations. However, discussions in recent years have focused on a debate about the absence, or lack of, a ($K^\pi = 0^+$) β vibration with a multitude of possible interpretations including the possibility for phase changes at the onset of deformation (for example, at $N = 90$ and $Z = 64$) and the application of new symmetries to describe these nuclei [4,36–41] or the change in the expectation of a β vibration. The discussions on the existence or absence of the $K^\pi = 0^+$ β-vibrational excitations in nuclei have spanned a wide spectrum of possibilities from shape coexistence where a competing shape is not the lowest favored shape but occurs low in the excitation spectrum of a given nucleus [2] to a redefinition of what can, in fact, be interpreted as a β vibration [42]. In the interacting boson model [43–45], the first excited 0^+ and 2^+ bands are members of the same representation and in a pure SU(3) limit would not decay to the g.s. Most deformed nuclei however are not pure SU(3) and the breaking of that symmetry gives rise to interband transitions from both of the low-lying $K^\pi = 2^+$ and $K^\pi = 0^+$ (γ and β) bands of significant strengths. Another recent development describes nuclei at the point of phase change from spherical to deformed in terms of β- and γ-shape parameters, the SU(3) symmetry [17,18,20] or the pseudo-SU(3) [35]. There is also the possibility for partial dynamical symmetries where the SU(3) symmetry is obeyed by some of the states and broken in others [46]. A systematic theoretical study of even-even deformed nuclei in the Hartree-Fock-Bogoliubov approach extended by the generator coordinate method and mapped into a five-dimensional collective Hamiltonian for even-even nuclei from $Z = 10$ to 110 provides guidelines for distinguishing between coexistence and β-vibrational oscillations. These studies and others [30,32] on the nature of the $K^\pi = 0^+$ bands in deformed nuclei predict widely varying levels of collectivity depopulating the first excited 0^+ states [1].

The Gd isotopes lie in a well-deformed region of the chart of nuclides with the ratio of the first two excited states $4^+/2^+$ ($R_{4/2}$) varying from 3.0 to 3.3 for ^{154}Gd to ^{160}Gd allowing a fertile testing ground for previous theories. The focus of this paper is ^{156}Gd with a $R_{4^+/2^+}$ ratio of 3.24, a well-known level scheme up to an excitation energy of 2.35 MeV and six excited $K^\pi = 0^+$ bands, four of them below the pairing gap at approximately 2 MeV. The ^{156}Gd nucleus has been studied extensively and with high precision using bent crystals GAMS 2/3 for (n,γ), the BILL electron spectrometer for (n,e^-) measurements [47], the early tests of the GRID (Gamma-ray-induced Doppler broadening) technique [48–50] using the GAMS 4 spectrometer at the Institut Laue Langevin (ILL) in Grenoble, and by (d,t) and (d,p) reactions at the Munich Tandem Accelerator [47]. Numerous other studies included electron, proton, and photon scatterings [51,52]. The ^{156}Gd nucleus was used for comparisons with early tests of the interacting boson model numerical studies for the SU(3) limit [53] as well as the later tests of partial dynamical symmetry tests [46]. The focus of this paper is the excited $K^\pi = 0^+$ bands. We have measured 12 level lifetimes in these bands in an attempt to characterize the nature of these states in search of the β and other low-lying vibrational excitations.

II. EXPERIMENT

The experiment was performed at the ILL neutron High Flux Reactor in Grenoble, France. The ^{156}Gd nucleus was populated by neutron capture on a 5.349-g Gd_2O_3 (gadolinium oxide) target. The GRID technique [49,54] of lifetime measurements is based on measuring the broadening of decay γ-ray lines using perfect crystals to measure the associated γ-ray wavelength. The broadening is due to the initial recoil velocity of the nucleus where the width of a given γ-ray transition emitted in flight results from the competition between the slowing-down process and the level lifetime. Knowing the slowing-down process from simulations, the nuclear level lifetime is extracted. The recoil velocities are typically 10^{-4} to 10^{-6} c, resulting in a broadening of only a few eV. The γ-ray wavelengths rely on crystal diffraction from nearly perfect flat crystals made of silicon or germanium. GAMS4 is a double-flat-crystal spectrometer with remarkable energy resolution and high precision of a few eV [50,55–57]. The broadened γ-ray peaks were fitted using the code GRIDDLE [58]. Figure 1 shows the broadening of the widths of γ-ray transitions depopulating from two different levels at 1129.44 and 1248.01 keV in the ^{156}Gd nucleus.

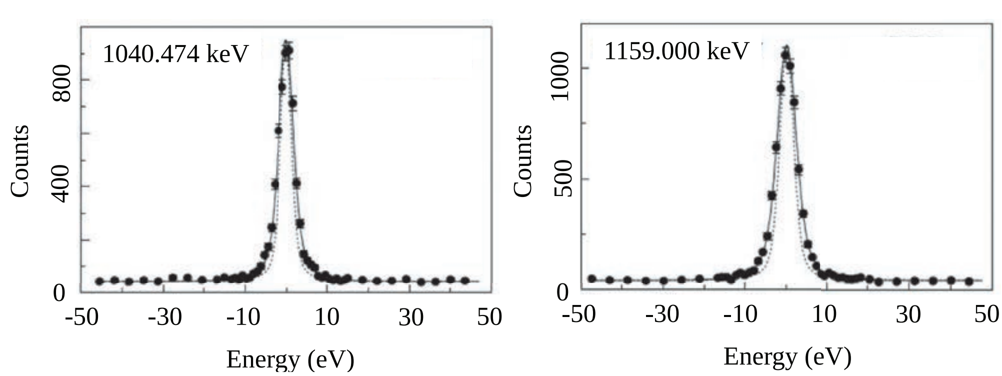

FIG. 1. Broadening curves for two γ-ray transitions 1040.474- and 1159.000-keV depopulating levels at 1129.440 and 1248.008 keV, respectively. The dotted line is the instrumental response expected without broadening, and the solid black line is the fit of the data points. The lifetime for a given transition is extracted from the observed broadening.

TABLE I. The energy levels and depopulating transitions measured in ^{156}Gd, the missing feeding of each level, and the upper and lower lifetime limits, resulting in the conservative overall range for the lifetimes.

E_x (keV)	J^π	E_γ (keV)	Feeding[a]	τ_{upper} (ps)	τ_{lower} (ps)	τ_{range} (ps)
$K^\pi = 0_2^+$ band at 1049.479 keV						
1049.479	0^+	960.510	44.3%	$2.86^{+1.88}_{-0.82}$	$2.52^{+1.59}_{-0.71}$	$1.81 < \tau < 4.75$
1129.440	2^+	1040.474	20.4%	$2.08^{+0.50}_{-0.34}$	$1.48^{+0.30}_{-0.22}$	$1.26 < \tau < 2.58$
1297.825	4^+	1009.622	40.5%	$2.52^{+0.84}_{-0.51}$	$1.84^{+0.54}_{-0.34}$	$1.49 < \tau < 3.36$
$K^\pi = 2^+$ band at 1154.151 keV						
1154.151	2^+	1065.182	43.7%	$1.20^{+0.14}_{-0.12}$	$0.96^{+0.11}_{-0.09}$	$0.87 < \tau < 1.35$
1248.008	3^+	1159.000	52.3%	$0.92^{+0.09}_{-0.08}$	$0.74^{+0.08}_{-0.06}$	$0.68 < \tau < 1.01$
1355.425	4^+	1067.236	34.8%	$0.91^{+0.10}_{-0.09}$	$0.64^{+0.07}_{-0.06}$	$0.58 < \tau < 1.02$
1506.868	5^+	1218.710	21.8%	$1.21^{+0.61}_{-0.31}$	$0.34^{+0.18}_{-0.10}$	$0.25 < \tau < 1.82$
$K^\pi = 0_3^+$ band at 1168.190 keV						
1168.190	0^+	1079.230	19.1%	$6.34^{+8.35}_{-2.31}$	$4.61^{+5.04}_{-1.60}$	$3.00 < \tau < 14.7$
1258.075	2^+	1169.092	14.4%	$3.46^{+1.60}_{-0.84}$	$3.17^{+1.84}_{-0.86}$	$2.31 < \tau < 5.06$
$K^\pi = 0_4^+$ band at 1715.181 keV						
1715.181	0^+	472.700	11.4%	$3.69^{+3.39}_{-1.21}$	1.88 ± 1.86	$0.02 < \tau < 7.08$
1771.089	2^+	1682.184	25.7%	$0.60^{+0.13}_{-0.10}$	$0.17^{+0.06}_{-0.04}$	$0.13 < \tau < 0.73$
1893.395	4^+	1605.217	1.3%	$0.37^{+0.08}_{-0.06}$	$0.0002^{+0.0001}_{-0.00005}$	$0.00015 < \tau < 0.45$

[a]Percentage of known level feeding [47,59].

The largest uncertainties in these measurements arise from the unknown feeding of the level of interest. Therefore, in cases where the feeding of a particular nuclear level is not completely understood, rather extreme and conservative assumptions have been made in order to extract conservative *upper* and *lower* limits. The upper limit of the extracted lifetime is determined assuming that the level is totally fed by cascades of γ-ray transitions from the compound capture state at 8.536 MeV. The cascades are typically several MeV unobserved transitions via two-step cascades connecting the level of interest to the compound state. This would yield the maximum broadening for the γ rays depopulating a given level or the longest slowing-down times resulting in the longest possible lifetime for the level of interest. Lifetimes shorter than the upper limit would yield more collective $B(E2)$ values. The lower limit of the lifetime is extracted by assuming that the missing feeding comes from the unplaced low-energy transitions measured in this nucleus. These are extreme and conservative limits for the measured lifetimes. The more realistic scenario would probably lie somewhere in the middle of the lifetimes resulting from these intentionally extreme feeding assumptions. Table I lists the percentage of known feeding for the levels of interest as well the results of the calculations for the extraction of upper and lower limits on the lifetimes. The extracted lifetime ranges are listed in Table II along with a listing for comparison of six previously measured lifetimes [47,59,60] for the states of interest, four were measured using the GAMS4 spectrometer in its early incarnation [47] and two were measured by Coulomb excitation [59,60]. In all the cases where previous measurements existed, there is agreement. A $0.6 \times \tau_{\text{max}}$ was used as a calibration factor for figures which correspond to the approximate middle of the range of the GRID measurement to match the lifetime of the 1154.2-keV level. A more detailed explanation on the calibration is found in Ref. [61].

Figure 2 presents a partial level scheme of ^{156}Gd showing in red the levels whose lifetimes were measured in this paper. A value of $0.6 \times \tau_{\text{max}}$ was used to calculate the $B(E2)$ values of the transitions for all the levels of interest that were measured with GRID. The $B(E2)$ values from the $K^\pi = 4^+$, $J^\pi = 4^+$ level was previously measured by Coulomb excitation.

III. RESULTS

The results of the lifetime measurements are shown in Table II with the uncertainties that have led to the broad

TABLE II. Level energies and lifetime ranges for all 12 states measured in this paper in comparison with previous measurements. Four of the previous values were measured by the GRID technique using the GAMS4 spectrometer [47]; another three were measured by Coulomb excitation [59,60].

E_x (keV)	τ_{grid} (ps)	Previous measurement (ps)
1049.479	$1.81 < \tau < 4.75$	$1.39 < \tau < 12.97$ [47]
1129.440	$1.26 < \tau < 2.58$	2.27 ± 0.17 [60]
1154.151	$0.87 < \tau < 1.35$	$0.87 < \tau < 1.44$ [47]
		0.82 ± 0.03 [59]
1168.190	$3.00 < \tau < 14.69$	
1248.008	$0.68 < \tau < 1.01$	
1258.075	$2.31 < \tau < 5.06$	2.22 ± 0.22 [59]
1297.825	$1.49 < \tau < 3.36$	
1355.425	$0.58 < \tau < 1.02$	$1.15 < \tau < 7.71$ [47]
1506.868	$0.24 < \tau < 1.82$	
1715.181	$0.02 < \tau < 7.08$	
1771.089	$0.13 < \tau < 0.73$	$0.14 < \tau < 1.44$ [47]
1893.395	$0.00015 < \tau < 0.45$	

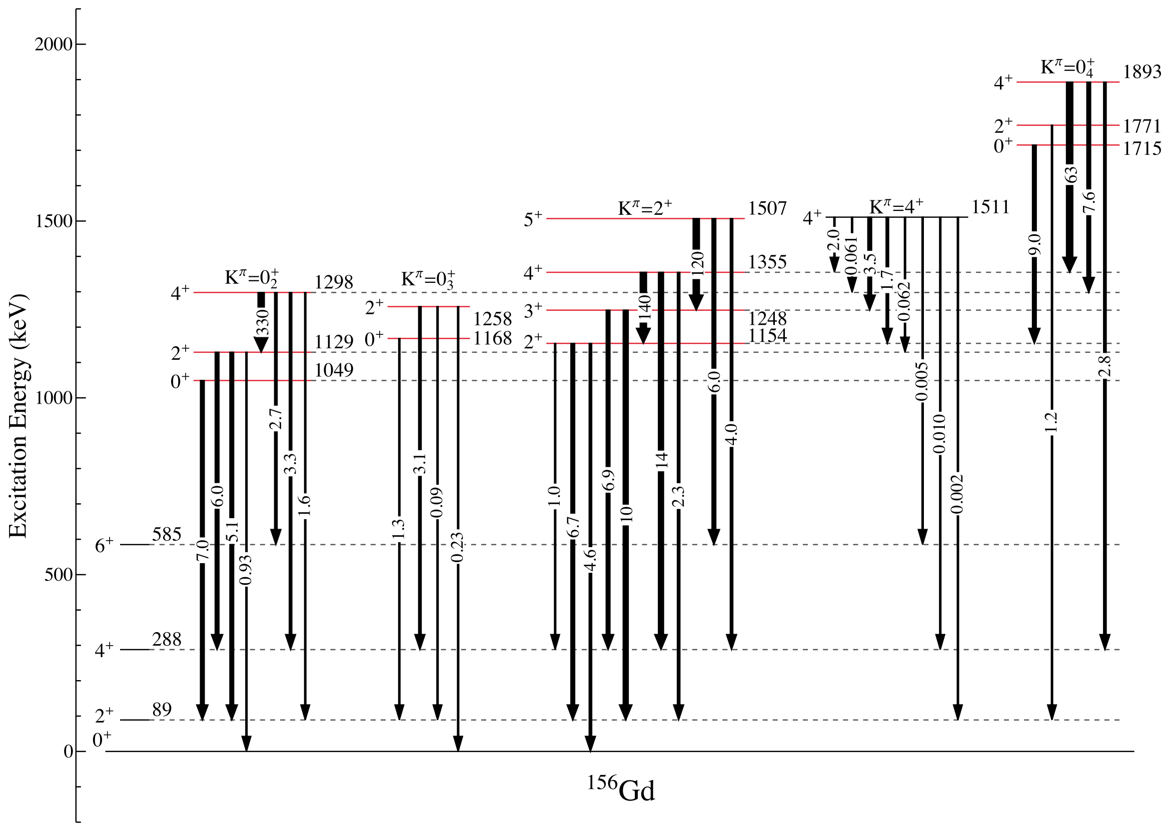

FIG. 2. A partial level scheme for ^{156}Gd showing levels for which lifetimes were measured using $0.6 \times \tau_{\mathrm{max}}$ of the GRID range as described in the text. The $K^\pi = 4^+$, $J^\pi = 4^+$ level was previously measured by Coulomb excitation. The width of the transition lines depopulating the levels of interest are in proportion to the transition probability in W.u. Absolute $B(E2)$ values are presented in Table III.

ranges of lifetimes as described in the experimental section. Table III shows the levels of interest including lifetimes and their depopulating transitions for the first three excited $K^\pi = 0^+$ bands and from the $K^\pi = 2^+$ γ band. This paper presents the lifetime measurements of all four excited states of the first $K^\pi = 0^+$ band, the $K^\pi = 2^+$ band, the $K^\pi = 0_2^+$ band, as well as two additional $K^\pi = 0^+$ bands. In each case, the measurements of the $K^\pi = 0^+$ bands include the lifetimes of the $J^\pi = 0^+$ bandheads. In the deformed rare-earth region of the chart of nuclides, there are very few lifetimes for the $J^\pi = 0^+$ levels, whereas there are numerous lifetime measurements for the $J^\pi = 2^+$ and $J^\pi = 4^+$ levels of $K^\pi = 0^+$ bands. This presents a unique opportunity to test predictions regarding the characters of these excited $K^\pi = 0^+$ bands. In addition, we have included lifetimes and depopulating transition probabilities to and from the $K^\pi = 4^+$ banded state at 1510.6 keV to allow for comparison with the $K^\pi = 2^+$ γ band. These $K^\pi = 4^+$ lifetimes had previously been measured by Coulomb excitation.

$K^\pi = 0_2^+$ *band at 1049.479 keV*. The lowest-energy excited band in ^{156}Gd is the $K^\pi = 0^+$ band at 1049.5 keV. Lifetimes were extracted for the bandhead and first two excited states. The $J^\pi = 0^+$ level was previously measured using GRID with a lifetime range of $1.39 < \tau < 12.97$ [47]. In the current measurement, using the same technique, the new lifetime range of $1.81 \rightarrow 4.75$ ps is in excellent agreement but with a smaller range of values yielding $B(E2\colon 0^+_{K^\pi=0_2^+} \rightarrow 2^+_{\mathrm{g.s.}}) = 4.20 \rightarrow 11.0$ W.u. The $J^\pi = 2^+$ level at the 1129.4-keV lifetime range was measured at $1.26 \rightarrow 2.58$ ps and compares well with the previously reported value of 2.27 ± 0.17 ps from Coulomb excitation [60]. The dominant transition probability from this level is $E_\gamma = 841.2$ keV to the $J^\pi = 4^+_{\mathrm{g.s.}}$ level with a $B(E2\colon 2^+_{K^\pi=0_2^+} \rightarrow 4^+_{\mathrm{g.s.}})$ range of $3.61 \rightarrow 7.42$ W.u. The $J^+ = 4^+$ level at 1297.8 keV has a measured lifetime range of $1.49 \rightarrow 3.36$ ps yielding a $B(E2\colon 4^+_{K^\pi=0_2^+} \rightarrow 6^+_{\mathrm{g.s.}})$ range of $1.60 \rightarrow 3.60$ W.u. Also calculated is an intraband transition from the $J^+ = 4^+$ level to the $J^\pi = 2^+$ level of the same band yielding a $B(E2\colon 4^+_{K^\pi=0_2^+} \rightarrow 2^+_{K^\pi=0_2^+})$ range of $200 \rightarrow 440$ W.u. typical of intraband rotational transition strengths.

Reduced matrix elements are also listed in Table III and are defined as the square roots of the $B(E2)$ values divided by the Clebsch-Gordon coefficient. The reduced matrix elements for those transitions depopulating the first excited $K^\pi = 0^+$ band average between 0.163 and 0.241 eb. These numbers are deduced from the averages of the lower(upper) limits for all the transitions depopulating this band. The measured $B(E2\colon 0^+_{K^\pi=0_2^+} \rightarrow 2^+_{\mathrm{g.s.}})$ value is in the range of $0.021 \rightarrow 0.055$ $e^2\mathrm{b}^2$. This value is divided by $2J_i + 1$ to yield a $B(E2\colon 2^+_{\mathrm{g.s.}} \rightarrow 0^+_{K^\pi=0_2^+})$ range of 0.0042–0.011 $e^2\mathrm{b}^2$. The intraband reduced matrix element is between 1.87 and 2.77 eb in agreement with values from Coulomb excitation [59].

$K^\pi = 2_1^+$ *band at 1154.151 keV.* Our results confirm previous reports of the $K^\pi = 2^+$ band as the γ band. The

TABLE III. Measured level lifetimes in the ^{156}Gd nucleus and the extracted $B(E2)$ values. All of the level lifetimes are measured in this paper with the exception of the $K^{\pi} = 4^{+}$ bandhead at 1510.595 keV [67]. Transition intensities and conversion coefficients are from Klora *et al.* [47]. The last column is the square root of $B(E)\lambda$ divided by the Clebsch-Gordan (CG) CG^2 ($\sqrt{\frac{B(E)\lambda}{\mathrm{CG}^2}}$). The CG^2 coefficients are the standard Alaga rules $(J_i K_i 2\,\Delta K | J_f K_f)^2$ values. If the exact multipole admixture is unknown, 100% $E2$ is calculated. The level lifetime for the $K^{\pi} = 4^{+}$ bandhead state at 1510.6 keV was not measured in this paper, but it is included to allow discussion and comparison.

K_i^{π}, J_i^{π}	E_x (keV)	τ (ps)	E_{γ} (keV)	K_f^{π}, J_f^{π}	I_{γ}	α	Multipolarity	$B(E1)$ or $B(E2)$ mW.u. or W.u.	$B(E\lambda)$ (e^nb^n)[a]	CG^2	Reduced matrix element (eb)
$0_2^+, 0^+$	1049.479	$1.81 < \tau < 4.75$	960.510	$0^+_{\mathrm{g.s.}}, 2^+$	138	0.00259	$E2$	$4.20 \rightarrow 11.0$	$0.021 \rightarrow 0.055$	1.000	$0.145 \rightarrow 0.234$
$0_2^+, 2^+$	1129.440	$1.26 < \tau < 2.58$	1129.423	$0^+_{\mathrm{g.s.}}, 0^+$	80	0.00197	$E2$	$0.56 \rightarrow 1.14$	$0.0028 \rightarrow 0.0057$	0.200	$0.118 \rightarrow 0.169$
			1040.474	$0^+_{\mathrm{g.s.}}, 2^+$	294	0.011	$E2+M1+E0$	$3.10 \rightarrow 6.28$	$0.016 \rightarrow 0.031$	0.286	$0.233 \rightarrow 0.331$
			841.243	$0^+_{\mathrm{g.s.}}, 4^+$	119	0.0032	$E2$	$3.61 \rightarrow 7.42$	$0.018 \rightarrow 0.037$	0.515	$0.187 \rightarrow 0.268$
$0_2^+, 4^+$	1297.825	$1.49 < \tau < 3.36$	1208.875	$0^+_{\mathrm{g.s.}}, 2^+$	97	0.00159	$E2$	$0.95 \rightarrow 2.14$	$0.0047 \rightarrow 0.011$	0.286	$0.129 \rightarrow 0.196$
			1009.622	$0^+_{\mathrm{g.s.}}, 4^+$	83	0.0168	$fE2+M1+E0$	$1.96 \rightarrow 4.43$	$0.0098 \rightarrow 0.022$	0.260	$0.194 \rightarrow 0.291$
			713.104	$0^+_{\mathrm{g.s.}}, 6^+$	11.7	0.0044	$E2$	$1.60 \rightarrow 3.60$	$0.0080 \rightarrow 0.018$	0.455	$0.132 \rightarrow 0.199$
			168.382	$0_2^+, 2^+$	1.08	0.0234	$E2$	$200 \rightarrow 440$	$1.00 \rightarrow 2.19$	0.286	$1.87 \rightarrow 2.77$
$2_1^+, 2^+$	1154.151	$0.87 < \tau < 1.35$	1154.151	$0^+_{\mathrm{g.s.}}, 0^+$	498	0.00192	$E2$	$2.74 \rightarrow 4.25$	$0.014 \rightarrow 0.021$	0.200	$0.265 \rightarrow 0.324$
			1065.182	$0^+_{\mathrm{g.s.}}, 2^+$	549	0.00219	89% $E2$	$4.01 \rightarrow 6.23$	$0.020 \rightarrow 0.031$	0.286	$0.264 \rightarrow 0.329$
			865.971	$0^+_{\mathrm{g.s.}}, 4^+$	26.9	0.00272	$E2$	$0.62 \rightarrow 0.96$	$0.0031 \rightarrow 0.0048$	0.015	$0.454 \rightarrow 0.565$
$2_1^+, 3^+$	1248.008	$0.68 < \tau < 1.01$	1159.000	$0^+_{\mathrm{g.s.}}, 2^+$	659	0.00178	$E2$	$6.12 \rightarrow 9.10$	$0.031 \rightarrow 0.046$	0.358	$0.294 \rightarrow 0.355$
			959.823	$0^+_{\mathrm{g.s.}}, 4^+$	173	0.00265	$E2$	$4.12 \rightarrow 6.12$	$0.021 \rightarrow 0.030$	0.143	$0.383 \rightarrow 0.458$
$2_1^+, 4^+$	1355.425	$0.58 < \tau < 1.02$	1266.451	$0^+_{\mathrm{g.s.}}, 2^+$	94	0.0014	$E2$	$1.40 \rightarrow 2.46$	$0.007 \rightarrow 0.012$	0.120	$0.241 \rightarrow 0.316$
			1067.236	$0^+_{\mathrm{g.s.}}, 4^+$	235	0.00206	$E2$	$8.24 \rightarrow 14.5$	$0.041 \rightarrow 0.072$	0.351	$0.342 \rightarrow 0.453$
			201.269	$2_1^+, 2_1^+$	0.63	0.078	$E2$	$86.1 \rightarrow 150$	$0.429 \rightarrow 0.748$	0.120	$1.89 \rightarrow 2.60$
$2_1^+, 5^+$	1506.868	$0.25 < \tau < 1.82$	1218.710	$0^+_{\mathrm{g.s.}}, 4^+$	81	0.00168	$E2$	$2.41 \rightarrow 17.6$	$0.012 \rightarrow 0.088$	0.319	$0.194 \rightarrow 0.525$
			922.186	$0^+_{\mathrm{g.s.}}, 6^+$	30	0.00268	$E2$	$3.60 \rightarrow 26.2$	$0.018 \rightarrow 0.131$	0.182	$0.314 \rightarrow 0.848$
			258.860	$2_1^+, 3^+$	1.15	0.073	$E2$	$74 \rightarrow 538$	$0.370 \rightarrow 2.69$	0.191	$1.39 \rightarrow 3.75$
$0_3^+, 0^+$	1168.190	$3.00 < \tau < 14.7$	1079.230	$0^+_{\mathrm{g.s.}}, 2^+$	111	0.00215	$E2$	$0.76 \rightarrow 3.72$	$0.0038 \rightarrow 0.019$	1.000	$0.062 \rightarrow 0.138$
$0_3^+, 2^+$	1258.075	$2.31 < \tau < 5.06$	1258.092	$0^+_{\mathrm{g.s.}}, 0^+$	68	0.00145	$E2$	$0.14 \rightarrow 0.31$	$0.00070 \rightarrow 0.0015$	0.200	$0.059 \rightarrow 0.088$
			1169.092	$0^+_{\mathrm{g.s.}}, 2^+$	180	0.00272	10% $E2$	$0.053 \rightarrow 0.12$	$0.00026 \rightarrow 0.00060$	0.286	$0.030 \rightarrow 0.046$
			969.868	$0^+_{\mathrm{g.s.}}, 4^+$	250	0.0024	$E2$	$1.90 \rightarrow 4.13$	$0.0095 \rightarrow 0.021$	0.515	$0.136 \rightarrow 0.202$

K_i^{π}, J_i^{π}	E_x (keV)	τ (ps)	E_{γ} (keV)	K_f^{π}, J_f^{π}	I_{γ}	α	Multipolarity	$B(E1)$ or $B(E2)$ mW.u. or W.u.	$B(E\lambda)$ (e^nb^n)[b]	CG^2	Reduced matrix element (eb)
$4_1^+, 4^+$	1510.595	274 ± 7	1421.601	$0^+_{\mathrm{g.s.}}, 2^+$	79	0.00117	$E2$	0.0020	10×10^{-6}		
			1222.432	$0^+_{\mathrm{g.s.}}, 4^+$	189	0.00191	$E2$	0.0102	50×10^{-6}		
			925.920	$0^+_{\mathrm{g.s.}}, 6^+$	22.6	0.00284	$E2$	0.0049	24×10^{-6}		
			381.155	$0_2^+, 2^+$	3.47	0.0241	$E2$	0.062	0.00031		
			356.466	$2_1^+, 2^+$	68	0.0252	$E2$	1.71	0.0085	0.556	0.124
			262.589	$2_1^+, 3^+$	31.9	0.069	$E2$	3.54	0.018	0.312	0.240
			212.771	$0_2^+, 4^+$	0.21	0.166	$E2+M1$	0.061	0.00030		
			155.168	$2_1^+, 4^+$	9.0	0.505	20% $E2$	1.97	0.0098	0.110	0.298
$0_4^+, 0^+$	1715.181	$0.02 < \tau < 7.08$	561.024	$2_1^+, 2^+$	4.81	0.0082	$E2$	$5.4 \rightarrow 1890$	$0.027 \rightarrow 9.48$	1.000	$0.164 \rightarrow 3.07$
			472.700	$1^-, 1^-$	28.6	0.0058	$E1$	$0.35 \rightarrow 120$	$(1.75 \rightarrow 600) \times 10^{-6}$	1.000	$0.0013 \rightarrow 0.025$
			348.726	$0^-, 1^-$	3.1	0.006	$E1$	$0.095 \rightarrow 33$	$(0.48 \rightarrow 165) \times 10^{-6}$	1.000	$0.0007 \rightarrow 0.013$

excited $K^\pi = 0^+$ band is much lower than the $K^\pi = 2^+$ band with strong $B(E2)$ values connecting it to the ground state. There are numerous 0^+ states identified in this nucleus, but they lack lifetime measurements. The ^{156}Gd presented in this paper shows a low-lying first excited $K^\pi = 0^+$ band near the $K^\pi = 2^+$ band with equivalent collectivity in $B(E2)$ values connecting it to the g.s. band. In ^{158}Gd, the collective 0^+ state was shown to be higher than the pairing gap, and, in ^{160}Gd, there are only limits for the lifetimes of the known 0^+ states. The indications point to the first excited $K^\pi = 0^+$ band in ^{156}Gd to be a β vibration of the deformed ground state.

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