Bulg. J. Phys. **44** (2017) 372–379

First Excited 0+ States in Deformed Nuclei

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Received *23 November 2017*

Abstract. The nature of vibrations or excitations built on a deformed nuclear shape remains an open question in nuclear structure. The ^{156}Gd nucleus is one of the most extensively studied nuclei with the (n, γ), (n, e^{-}), $(\alpha, 2n)$ reactions yielding a spectrum of six excited 0^{+} states. This work reports on the measurements of level lifetimes in the ^{156}Gd nucleus following neutron capture using the GRID (Gamma Ray Induced Doppler broadening) technique at the Institut Laue-Langevin (ILL) in Grenoble, France. In total, twelve level lifetimes have been measured, including the three $K^{\pi} = 0^{+}$ states at 1049, 1154, and 1715 keV. The $K^{\pi} = 0^{+}$ state at 1049 is more strongly connected to the ground state levels than the $K^{\pi} = 0^{+}$ state at 1154 keV by factors of 5 and the $K^{\pi} = 0^{+}$ state at 1715 keV is connected to the $K^{\pi} = 2^{+}$ band by an order of magnitude stronger B(E2) values than to the ground state levels.

PACS codes: 21.10.-k, 21.10.Tg, 21.10.Re, 27.70.+q

1 Introduction

The nature of first excited $K^{\pi} = 0^{+}_{2}$ states of deformed nuclei has remained an open question in nuclear structure physics for several decades. The question revolves around the lowest lying shape effecting oscillations or vibrations of a given deformed nucleus. This would be quadrupole in nature ($\lambda = 2$), 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 $K^{\pi} = 2^{+}$ (2^{+}_{γ}) band and exhibits a systematic behavior across the region of deformed nuclei with typical $B(E2 : 2^{+}_{\gamma} \rightarrow 0^{+}_{g.s.})$ values of a few Weisskopf units (W.u.) as shown in Figure 1 [1].

Today, over forty years later, the existence and characterization of the low-lying β vibration still remains an open question in nuclear structure. The question has been examined, challenged, defined, and redefined in time in numerous publications and reviews [1–35]. The absence of a cohesive agreement on the nature of the expected β vibration is in part due to the lack of sufficient experimental data

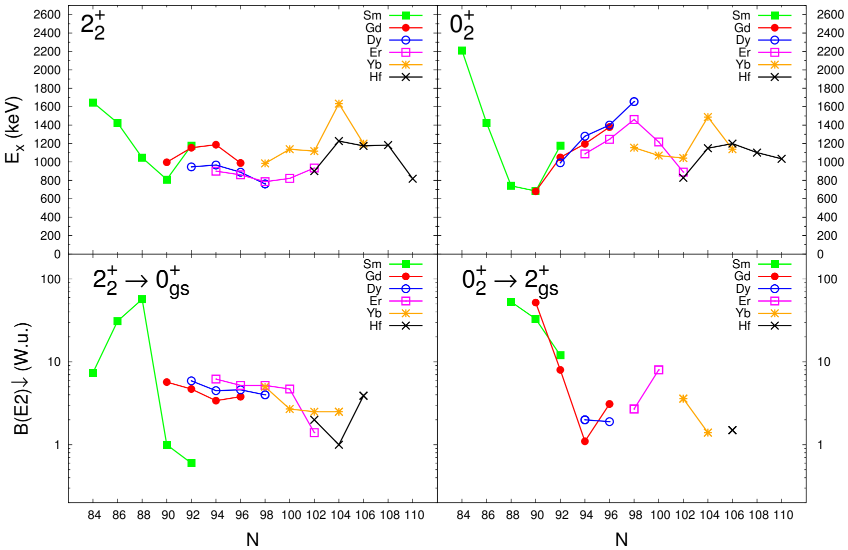

Figure 1. (color online) Systematics of the first excited $K^\pi = 2^+$ "γ" and $K^\pi = 0^+$ bands in several isotopes of Sm, Gd, Dy, Er, Yb, and Hf as a function of neutron number "N" along with the observed $B(E2 : 2^+_{K=2^+} \rightarrow 0^+)$ values for the γ bands and the $B(E2 : 0^+_2 \rightarrow 2^+_{g.s.})$ values for the first excited $K^\pi = 0^+$ bands.

on the identification and characterization of 0^+ excitations in deformed nuclei and to some extent due to the interpretation of what is expected of a β vibration.

The discussions on the existence or absence of $K^\pi = 0^+$ 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, to a redefinition of what a β vibration should be [36]. In the IBM [37–39], the first excited 0^+ and 2^+ bands of pure S(U3) or deformed limit, are members of the same representation whereas a recent development describes nuclei at the point of phase change from spherical to deformed in terms of β and γ shape parameters, or the SU(3) symmetry [16, 22, 24] or the pseudo-SU(3) [29].

These studies and others on the nature of $K^\pi = 0^+$ bands in deformed nuclei show widely varying levels of collectivity for the depopulation of the first excited 0^+ states [1]. Recent experiments have also shown enhanced collectivities in transitions connecting even higher excited states to the first excited 0^+ states [18, 23, 30, 32]. The other aspect is the lack of complete or sufficient experimental data to definitively exclude the other interpretations. The landscape has been changing significantly in recent years with results from the Munich Q3D spectrometer that have led to the discovery of a large number of previously unobserved 0^+ states in deformed nuclei of the rare earth region and a growing number of lifetime measurements.

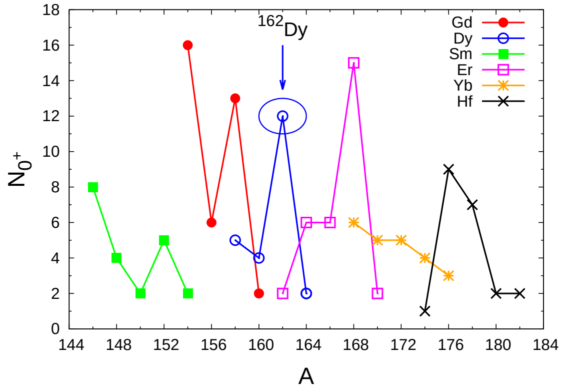

Figure 2. (color online) The number of 0^+ states observed in the rare earth region of nuclei. These large variations are not due to structural differences for these nuclei, but rather they point to the existing experimental situation where measurements have been made at the Q3D in Munich uncovering a large number of 0^+ states. The rare earth region of nuclei is one of the largest well known regions of deformation on the chart of nuclides. Typically, well deformed nuclei with $4^+/2^+$ energy ratios above 3 exhibit the expected rotational behavior with varying results for the superimposed vibrational excitations. These large variations are not due to structural differences for these nuclei, but rather they point to the existing experimental situation where measurements have been made at the Q3D in Munich uncovering a large number of 0^+ states.

The number of 0^+ states in the rare earth region is shown in Figure 2. These large variations are not due to structural differences for these nuclei, but rather they point to the existing experimental situation where measurements have been made at the Q3D in Munich uncovering a large number of 0^+ states. The rare earth region of nuclei is one of the largest well known regions of deformation on the chart of nuclides. Typically, well deformed nuclei with $4^+/2^+$ energy ratios above 3 exhibit the expected rotational behavior with varying results for the superimposed vibrational excitations.

In this paper, we discuss new lifetime measurements using the GRID (Gamma-Ray-Induced-Doppler broadening technique) to report on the lifetimes of several 0^+ states in the ^{156}Gd nucleus. The Gd nuclei from $A = 154$ to $A = 160$, exhibit $4^+/2^+$ energy ratios of approximately 3.0 or higher and in each case, there are several 0^+ states observed. In the ^{154,158}Gd nuclei, the 0^+ states were identified by the (p,t) reaction at the Munich Q3D spectrometer [20, 26]. In every nucleus of this range, several 0^+ states have been identified both below and above the pairing gaps. Also, a recent paper on the ^{160}Gd reported on lifetime measurements of the two excited 0^+ states [40], the missing case for a complete systematic picture of these isotopes was ^{156}Gd. The ^{156}Gd nucleus was studied extensively and with high precision using bent crystals GAMS 2/3 for (n,γ), the BILL electron spectrometer for (n,e^-) measurements [41], and the early tests of the GRID (GammaRay Induced Doppler broadening) technique [42–44] using the GAMS4 spectrometer at the Institut Laue Langevin in Grenoble, and by (d, t) and (d, p) reactions at the Munich Tandem Accelerator [41]. Other studies include, electron, proton, and photon scattering [45, 46]. The ^{156}Gd nucleus was used for the early tests of the Interacting Boson Model numerical studies for the SU(3) limit [47]. This nucleus is well known up to an excitation energy of 2.35 MeV with six excited $K^\pi = 0^+$ bands, four of them below the pairing gap at approximately 2 MeV. The lifetime measurement of these 0^+ states is the focus of this study. This paper reports on the lifetimes of three excited 0^+ states and the resulting B(E2) values in this work.

2 Gamma Ray Induced Doppler Broadening Technique of Lifetime Measurements

The experiment was performed at the Institut Laue-Langevin (ILL) neutron High Flux Reactor in Grenoble, France. The ^{156}Gd nucleus was populated by neutron capture on a 5.349 g of Gd_2O_3 placed into thin graphite boxes. The GRID technique [43] of lifetime measurements is based on measuring the broadening of decay gamma-ray lines using perfect crystals to measure the associated wavelength of a γ ray. The broadening is due to the initial recoil velocity of the nucleus where the width of a given gamma-ray transition emitted in flight results from the competition between the slowing down process and the level lifetime. 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 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 lower limit is extracted by assuming that the missing feeding comes from the unplaced low energy transitions that were measured in this nucleus. The more realistic scenario would probably lie somewhere in the middle of the lifetimes resulting from these intentionally extreme feeding assumptions. Table 1 lists the lifetimes of the three excited 0^+ states that we were able to measure.

3 Results

Twelve level lifetimes were measured in this work. The three 0^+ states that are the bandheads for $K^\pi = 0^+$ excitations at 1048.479, 1168.190, and 1715.181 keV are discussed in this work. Figure 3 shows the resulting B(E2) values for all the measured level lifetimes and their depopulating transitions. Table 1 shows the results of the lifetime measurements along with the range of lifetimes for one level that was previously measured [41]. In general, the lowest of the two 0^+ bandheads at 1049 and 1168 is connected with more intense B(E2) values to

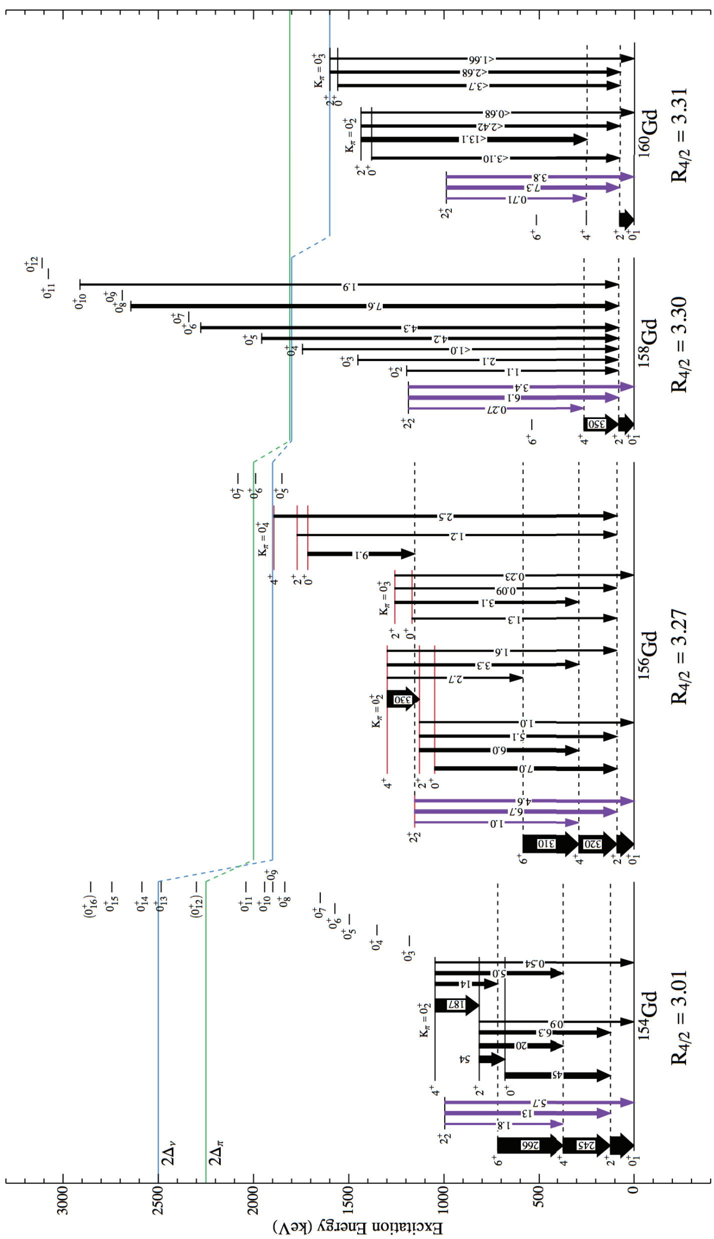

Figure 3. Systematics of the Gd nuclei from A= $154 - 160$ with the B(E2) values where lifetimes exist for the various levels.

Table 1. The level energies and the measured lifetime ranges for the three excited 0^+ states. This table shows the full ranges of extracted lifetimes, a column showing $\tau = 0.6\tau_{max}(ps)$ used in calculating the B(E2) values connecting bands of interest in Weisskopf units shown in Figure 3. The 0.6 factor is an arbitrary factor chosen to match the measured ranges in this experiment with previous measurements.

E_x(keV)	$\tau_{GRID}(ps)$	$0.6\tau_{max}(ps)$	Prev. Meas.
1049.479	$1.81 < \tau < 4.75$	2.85	$1.39 < \tau < 12.97$
1168.190	$3.00 < \tau < 14.69$	8.81	
1715.181	$0.02 < \tau < 7.08$	4.25	

the ground state band. The third 0^+ state at 1715 keV has an excitation band that seems to be connected by an order of magnitude larger B(E2) values to the $K^\pi = 2^+$ band than the ground state band indicating that it is an excitation built on the $K^\pi = 2^+$ γ band. Table 2 shows a brief summary of the excitation energy ratios as well as the B(E2) value ratios of the $K^\pi = 4^+$ and $K^\pi = 0^+$ excitations that are most strongly connected to the $K^\pi = 2^+$ γ band.

Table 2. The experimental energy and B(E2) ratios for the proposed single and double phonon excitations.

$E(4^+_{\gamma\gamma})/E(2^+_\gamma)$	1.31
$E(0^+_{\gamma\gamma})/E(2^+_\gamma)$	1.49
$B(E2{:}4^+_{\gamma\gamma} \rightarrow 2^+_\gamma)/B(E2{:}2^+_{\gamma\rightarrow 0^+_{g.s}})$	0.39
$B(E2{:}0^+_{\gamma\gamma} \rightarrow 2^+_\gamma)/B(E2{:}2^+_{\gamma\rightarrow 0^+_{g.s}})$	1.96

4 Conclusions

Lifetime measurements are an important component of the nuclear data necessary to resolve the outstanding question in nuclear structure regarding the nature of the first excited $K^\pi = 0^+$ bands and the β vibrations in deformed nuclei. This paper reports on new lifetime measurements to contribute to the discussion. The excitation energy ratio of the $K^\pi = 4^+$ to $K^\pi = 2^+$ γ band is 1.31 and the ratio of the $K^\pi = 0^+$ at 1715 keV to the $E(2^+_\gamma)$) is 1.49. The harmonic value for the excitation energies of two phonon to one phonon excitations is exactly two. A similar situation is found for the B(E2) values given in Table 2. The ratios of B(E2) values found for the levels of interest are $B(E2{:}4^+_{\gamma\gamma} \rightarrow 2^+_\gamma)/B(E2{:}2^+_{\gamma\rightarrow 0^+_{g.s}})$ and the $B(E2{:}0^+_{\gamma\gamma} \rightarrow 2^+_\gamma)/B(E2{:}2^+_{\gamma\rightarrow 0^+_{g.s}})$ are 0.39 and 1.96, respectively. The harmonic values for the very same B(E2) ratios are 2.78 and 5.0, respectively. The only other case for negative anharmonicities is observed in the ^{232}Th nucleus in the actinide region of nuclei [48, 49] where the excitation energy ratio for the $K^\pi = 4^+$ to $K^\pi = 2^+$ γ ratio is 1.8 and the

B(E2:$4^+_{\gamma\gamma} \rightarrow 2^+_\gamma$)/B(E2:$2^+_{\gamma \rightarrow 0^+_{g.s}}$) ratio was determined to be 4.1±1.0 [49]. In this case, the B(E2) ratio was very close to the harmonic value of 2.78. Further work is ongoing on the ^{156}Gd analysis and interpretation.

Acknowledgments

This work was supported by the National Science Foundation under contract PHY-1419765. The authors would like to acknowledge the hospitality and scientific help of the ILL team at Grenoble, France.

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