Compound and Rotational Damping in Warm Deformed Rare-Earth Nuclei

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The γ decay in the quasicontinuum from selected configurations of the rotational nucleus 163Er has been measured with the EUROBALL array. A new analysis technique has allowed for the first time to directly measure the compound and rotational damping widths Γµ and Γrot. Values of Γµ ≈ 20 keV and Γrot ≈ 200 keV are obtained in the spin region I ≈ 30–40ℏ, in good agreement with microscopic cranked shell model calculations. A dependence of Γµ and Γrot on the K-quantum number of the nuclear states is also presented.

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The strong electromagnetic quadrupole transitions along low-lying rotational bands in well deformed nuclei represent one of the most striking manifestations of collective motion in finite quantum systems. Microscopically, such bands are associated with simple configurations, corresponding to a few particle-hole excitations in the deformed mean field. As the excitation energy U and the level density at a given angular momentum increase, the mean-field configurations mix under the action of the residual interaction, acquiring a compound damping width Γµ. For large values of U (U ≈ 8 MeV), the study of neutron resonances has shown that nuclear compound states represent one of the best examples of quantum chaotic systems, with spectral properties well described by Gaussian orthogonal ensemble statistics [1]. The compound width Γµ is also found of particular relevance in connection with the damping of the vibrational collective motion (giant resonances) [2].

The evolution of γ-detection arrays has made it possible to address the basic issue of how collective motion is modified, in going from cold, well resolved bands into the region of interacting bands. Both theoretical and experimental studies have demonstrated that rotational correlations persist, at least up to U = 2–3 MeV. However, quadrupole γ transitions are damped: the decay from a given initial state acquires a distribution, whose FWHM is the rotational damping width Γrot. This width reflects the different rotational properties of the mean-field configurations which are mixed through the residual interaction [3]. The knowledge of the two widths Γµ and Γrot should allow one to characterize in a given deformed nucleus the transition from order to chaos, which can affect in different ways the level statistics and the rotational decay [4]. Much effort has been devoted in order to obtain a quantitative estimate of Γrot from the experimental spectra, based on a simple simulation of the rotational decay or on a simple parametrization of the spectral shape (cf. e.g., [5,6]). However, microscopic cranked shell model calculations (CSM) have recently indicated that such spectra are sensitive to both widths Γrot and Γµ. Especially, the strength function of two consecutive transitions, that is the two-dimensional (2D) strength function of transitions I → (I - 2) → (I - 4), carries fairly direct information about both the rotational and compound damping widths Γrot and Γµ [7,8]. In this Letter, we determine values for these two basic widths simultaneously and for the first time. This analysis is particularly valuable, considering that Γµ has only been estimated, with large uncertainties, from measurements of the single particle spreading width [2,9]. The analysis is carried out in the case of the nucleus 163Er, which is a typical representative of well deformed nuclei in the rare-earth region. A possible dependence of Γrot and Γµ on the K-quantum number of the intrinsic nuclear configurations could also be investigated.

CSM calculations show that the strength function for two consecutive γ transitions contains two components, an uncorrelated one with spherical contours, Fig. 1(a), and a correlated one with elliptic contours, Fig. 1(b). These two components are clearly visible in the calculated spectrum, Fig. 1(c), projected onto the Eγ\textsuperscript{p}-Eγ\textsuperscript{c} direction. While the wide width Γ\textsubscript{wide} is ≈ √2Γrot, the narrow width
Such spectra depend on four parameters: the damping widths \( \Gamma_{\text{rot}} \) and \( I_{\text{nar}} \), the intensity \( I_{\text{nar}} \) of the narrow component, and the number \( N_{\text{step}} \) of decay steps considered. Figure 1(d) shows that the calculated multiple steps pure \( E2 \) spectrum (histogram) is well accounted for by the analytical approximation (solid line). If one leaves out the narrow component, as was previously done in Ref. [6], the \((E_{\gamma 1}, E_{\gamma 2})\) spectrum contains just one Gaussian valley, as illustrated by the dashed line of Fig. 1(d).

Actual \( \gamma \) cascades of rapidly rotating nuclei also contain \( E1 \) transitions, which cool the nucleus and disperse its excitation energy. This results in a spectrum including stronger energy correlations stemming from transitions in the coldest parts of the cascades along regular rotational bands. A realistic test of the analytic expression for the spectrum should take into account the whole cascade including the competition between \( E1 \) and \( E2 \) transitions in each step, and this is presently done by a Monte Carlo code [12]. The simulations make use of levels and \( E2 \) transition probabilities microscopically calculated for the specific case of the \(^{163}\text{Er}\) nucleus, in which the \( K \)-quantum number of the intrinsic states is also taken into account, in an approximate way [10]. Each \( \gamma \) cascade is started from Gaussian distributions in internal energy \( U \) and spin \( I \), with centroids and widths reproducing the experimental conditions of the \(^{163}\text{Er}\) experiment lately discussed (i.e., \( \langle U \rangle = 4 \text{ MeV}, \text{FWHM}_U = 4 \text{ MeV}, \langle I \rangle = 44 \text{h}, \) and \( \text{FWHM}_I = 20 \text{h} \)).

Two different simulated \( E_{\gamma 1} \times E_{\gamma 2} \) matrices of \(^{163}\text{Er}\) have been calculated. One, named discreate, is obtained updating \( \gamma \) between regular rotational bands, requiring that the branching number \( n_h \) of \( E2 \) branches out of a given state is less than 2 [7]. The second matrix, named damped, is obtained by subtracting the discreate one from the \( \gamma \text{-} \gamma \) spectrum collecting all coincidences between \( E2 \) transitions in a cascade. Figure 2(a) shows a 60 keV wide cut on the discreate (bottom) and damped (top) simulated matrices. The projections are taken across the diagonal \( E_{\gamma 1} = E_{\gamma 2} \), at the average transition energy \( \langle E_{\gamma} \rangle = 960 \text{ keV} \), corresponding to the spin value \( I = 32\hbar \). Both spectra display a ridge-valley structure typical of rotational nuclei, with a separation between the two most inner ridges equal to \( 8h^2/\mu^2 \), \( \mu^2 \) being the dynamic moment of inertia of the bands. While in the discreate case the ridges are sharp and strongly pronounced, a more smooth pattern is observed in the damped spectrum, with weaker and wider ridges and a central valley partially filled, quite similar to the spectra shown in Fig. 1(d). The smooth line superposed on the damped spectrum is the best fit by the analytical expression, obtained by a \( \chi^2 \) minimization with respect to the parameters \( \Gamma_{\text{rot}}, I_{\text{nar}}, N_{\text{step}} \). The fitting procedure is found to be very stable and corresponds to \( N_{\text{step}} = 5 \) and \( I_{\text{nar}} = 0.1 \). The extracted values of \( \Gamma_{\text{nar}} \) and \( \Gamma_{\text{rot}} \), of the order of 40 and 200 keV, respectively, are presented in Figs. 2(b) and 2(c). The error bars shown in Fig. 2 denote
the uncertainties of the fit and are different for the various quantities, depending also on the selected energies. The fitted values are compared to CSM calculations corresponding to the levels 11 to 100, with \( \langle E_\gamma \rangle \approx 1.4 \text{ MeV} \) (solid line), and to the levels 101 to 300, with \( \langle E_\gamma \rangle \approx 2 \text{ MeV} \) (dashed line). Good agreement is found, in particular, with the calculation related to the colder energy region, which is where the simulated \( \gamma \)-decay flow mostly goes for this spin interval. This clearly demonstrates the internal consistency of the present analysis technique.

The experiment was carried out using the EUROBALL array at the IReS Laboratory (France), employing the reaction \(^{18}\text{O} + ^{150}\text{Nd}\), at \( E_{\text{beam}} = 87, 93 \text{ MeV} \). The \(^{150}\text{Nd}\) target was made of a stack of two thin foils for a total thickness of \( 740 \mu \text{g/cm}^2 \). The corresponding maximum angular momentum reached in the reaction has been calculated to be \( 40h \) and \( 45h \), respectively. Energy-dependent time gates on the Ge time signals were used to suppress background from neutrons. A total of \( \approx 3 \times 10^9 \) events of triple and higher Ge folds were finally obtained, with \(^{162,163}\text{Er}\) as main evaporation residues.

The data have been sorted into a number of \( \gamma-\gamma \) matrices in coincidence with specific \( \gamma \) transitions of \(^{163}\text{Er}\) [13]. In particular, a matrix collecting the entire decay flow of \(^{163}\text{Er}\) (named total) has first been constructed by gating on the three cleanest low spin transitions. In addition, seven matrices gated by transitions belonging to the low-\( K \) bands (\( K = 5/2 \)) labeled \( A, B, E, \) and \( F \) in Ref. [13], and by the high-\( K \) bands (\( K = 19/2 \) labeled \( K1, K2, \) and \( K4 \) in Ref. [13] have been sorted, together with their corresponding 2D background. Finally, all known peak-peak and peak-background coincidences have been subtracted with the help of the Radware software [14]. A correction for the detector efficiency has then been applied to the spectra.

The separately gated matrices have been added together in one low-\( K \) (\( A + B + E + F \)) and one high-\( K \) \((K1 + K2 + K4)\) matrix. Finally, the pure \( E2 \) rotational correlations should be isolated from the experimental \( \gamma-\gamma \) coincidence matrices, which also contains a background of \( E1 \times E1 + E1 \times E2 + E2 \times E1 \) correlations. This two-dimensional background has been constructed assuming an exponential shape \( \sim E_\gamma^4 \exp(-E_\gamma/T) \) for the \( E1 \) statistical component, \( T \) being the temperature of the nuclear system. In the present case \( T \) is \( \sim 0.45 \text{ MeV} \), as deduced from an interpolation of the spectrum tail at \( E_\gamma > 2 \text{ MeV} \), which is dominated by the \( E1 \) decay.

Cuts perpendicular to the \( E_{\gamma_1} = E_{\gamma_2} \), diagonal, 60 keV wide, have been made on the \( E2 \times E2 \) component of the total, low-\( K \) and high-\( K \) \( \gamma-\gamma \) coincidence spectra. The projections are taken at \( \langle E_\gamma \rangle = 900, 960, 1020, 1080, \) and \( 1140 \text{ keV} \), corresponding to the spin range 30\( h \) to 40\( h \). Examples of such spectra are shown in Fig. 3. In all cases a rather smooth ridge-valley profile is observed, very similar to one displayed in the \( \text{damped} \) simulated matrix of Fig. 2(a) (apart from the \( \approx 25% \) difference in the values of \( J^{(2)} \)). The smooth curves in Fig. 3, well reproducing the experimental data, correspond to the best fits of the two-component spectral function. In all cases the parameter \( N_{\text{step}} = 5 \), while the intensity \( I_{\text{nar}} \) is in average 0.1 for both total and low-\( K \) and 0.17 for high-\( K \) data. The obtained \( I_{\text{nar}} \) and \( I_{\text{rot}} \) values for the total spectrum are shown in Fig. 2(b) and 2(c) by open circles. As one can see, the experimental data are in good agreement with the calculations.
agreement with the theoretical prediction for $\Gamma_{\text{rot}}$ and $\Gamma_{\text{nar}}$ from the rather cold region of $\langle U \rangle = 1.4 \text{ MeV}$, crossed by the $\gamma$-decay flux.

The results of the spectral shape analysis on the low-$K$ and high-$K$ data are shown in Fig. 4, in comparison with the corresponding low-$K$ ($K \approx 8$) and high-$K$ ($K > 8$) predictions at the excitation energies $\langle U \rangle = 1.4$ and $2 \text{ MeV}$. Even for these more selective data, satisfactory agreement is obtained with the theory with $\langle U \rangle = 1.4 \text{ MeV}$. In addition, while the measured values of the narrow width are found of the order of $40 \text{ keV}$ regardless of $K$ (leading to a compound width estimate $\Gamma_{\mu} = \Gamma_{\text{nar}}/2 \approx 20 \text{ keV}$), the rotational damping width $\Gamma_{\text{rot}}$ is found to depend on the $K$ value, being $\approx 200 \text{ keV}$ for low-$K$ and $\approx 150 \text{ keV}$ for high-$K$ states, in agreement with the calculations. This points to a shift towards higher energies of the onset of rotational damping for high-$K$ states, which also in the calculations are found to keep their rotational structures even up to $1.5 \text{ MeV}$ internal energies, where the damping mechanism is otherwise largely dominating [10].

In conclusion, the present Letter shows the first measurement of both compound and rotational damping widths $\Gamma_{\mu}$ and $\Gamma_{\text{rot}}$ and therefore represents a step forward in the understanding of the order to chaos transitions in the atomic nucleus. For the nucleus $^{163}\text{Er}$ we have found $\Gamma_{\text{rot}} = 200 \text{ keV}$ and $\Gamma_{\mu} = 20 \text{ keV}$, for angular momenta $h\varpi = 900$ and $960 \text{ keV}$. Panels (a) and (b) show projections on the total $\gamma$-$\gamma$ matrix, while panels (c),(d) and (e),(f) correspond to spectra gated on low-$K$ and high-$K$ configurations of $^{163}\text{Er}$. The $(\sim 150, 150) \text{ keV}$ interval shown here is equivalent to the one adopted in Fig. 2(a) [namely $(\sim 200, 200) \text{ keV}$], considering the different values of $8\hbar^2/J^{(2)}$ in the simulated and experimental spectra $(\sim 150$ and $120 \text{ keV}$, respectively).

![FIG. 3. 60 keV wide projections on the $E_\gamma^{-}E_\gamma^{+}$ axis of experimental matrices of $^{163}\text{Er}$, at the average transition energies $E_\gamma = 900$ and $960 \text{ keV}$. Panels (a) and (b) show projections on the total $\gamma$-$\gamma$ matrix, while panels (c),(d) and (e),(f) correspond to spectra gated on low-$K$ and high-$K$ configurations of $^{163}\text{Er}$. The $\gamma_0$ adopted in Fig. 2(a) [namely $(\sim 200, 200) \text{ keV}$], considering the different values of $8\hbar^2/J^{(2)}$ in the simulated and experimental spectra $(\sim 150$ and $120 \text{ keV}$, respectively).]

![FIG. 4. Experimental values of $\Gamma_{\text{nar}}$ and $\Gamma_{\text{rot}}$, as extracted from the spectral shape analysis of experimental low-$K$ [panels (a) and (c)] and high-$K$ [panels (b) and (d)] $\gamma$-$\gamma$ coincidence spectra of $^{163}\text{Er}$. Predictions from cranked shell model calculations [10] for average excitation energies of 1.4 and 2 MeV are shown by the solid and the dashed line, respectively.

in the region $I = 30\hbar$–$40\hbar$ and internal excitation energy $U = 1.4 \text{ MeV}$. In addition, a more selective analysis on spectra gated by high-$K$ and low-$K$ configurations has shown a weak dependence of $\Gamma_{\text{rot}}$ on the $K$-quantum number of the nuclear states.

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