

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 ^{163}Er 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 Γ_μ and Γ_{rot} . Values of $\Gamma_\mu \approx 20$ keV and $\Gamma_{\text{rot}} \approx 200$ keV are obtained in the spin region $I \approx 30\text{--}40\hbar$, in good agreement with microscopic cranked shell model calculations. A dependence of Γ_μ and Γ_{rot} 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 to 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* Γ_μ . For large values of U ($U \approx 8$ 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 Γ_μ 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 $U = 2\text{--}3$ MeV. However, quadrupole γ transitions are damped: the decay from a given initial state acquires a distribution, whose FWHM is the *rotational damping width* Γ_{rot} . 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 Γ_μ and Γ_{rot} 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 Γ_{rot} 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 Γ_{rot} and Γ_μ . Especially, the strength function of two consecutive transitions, that is the two-dimensional (2D) strength function of transitions $I \rightarrow (I-2) \rightarrow (I-4)$, carries fairly direct information about both the rotational and compound damping widths Γ_{rot} and Γ_μ [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 Γ_μ 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 ^{163}Er , which is a typical representative of well deformed nuclei in the rare-earth region. A possible dependence of Γ_{rot} and Γ_μ 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 $E_{\gamma_1}\text{--}E_{\gamma_2}$ direction. While the wide width Γ_{wide} is $\sim\sqrt{2}\Gamma_{\text{rot}}$, the narrow width

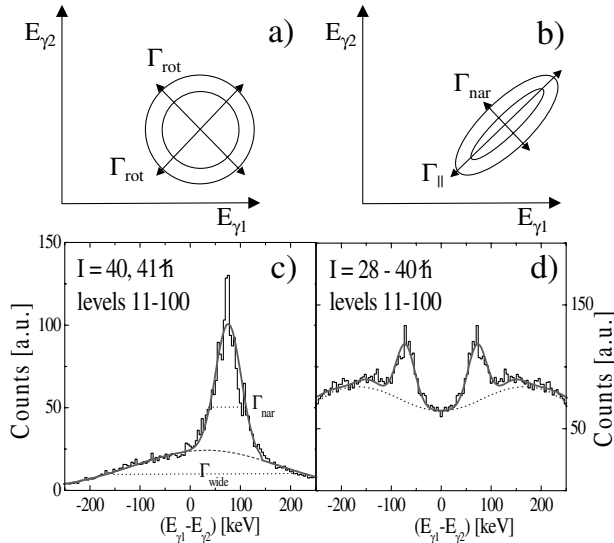


FIG. 1. The spectral shape analysis method. Panels (a) and (b) show schematic contours of the uncorrelated and correlated two steps decay, respectively. (c) Projection on the E_{γ_1} - E_{γ_2} axis of the strength function for two consecutive $E2$ γ rays, obtained by microscopic cranked shell model calculations of ^{163}Er [7,10], for the levels 11 to 100, for each I^π , at spin $I = 40\hbar, 41\hbar$. The full drawn line is the two-component function, which contains a wide and a narrow Gaussian distribution of width $\Gamma_{\text{wide}} \sim \sqrt{2}\Gamma_{\text{rot}}$ and $\Gamma_{\text{nar}} \sim 2\Gamma_{\mu}$, respectively. (d) Projection on the E_{γ_1} - E_{γ_2} axis of a γ - γ spectrum calculated for multiple steps of $E2$ decay, considering levels 11 to 100 only, for each I^π , in the spin range $28\hbar$ - $40\hbar$. The full drawn line is the parametrized 2D spectrum for multiple steps, which incorporates the two-component function, with $\Gamma_{\text{rot}} = 180$ keV, $\Gamma_{\text{nar}} = 44$ keV, and $I_{\text{nar}} = 0.3$, while the dashed line has no narrow component and a width of $\Gamma_{\text{rot}} = 150$ keV.

Γ_{nar} can be related to the compound damping width by $\Gamma_{\text{nar}} \sim 2\Gamma_{\mu}$, as discussed in Ref. [8]. This two-component structure should be reflected in the line shape of two and higher fold γ -coincidence spectra from damped quasicontinuum transitions, as shown in Fig. 1(d) for a schematic calculated spectrum neglecting the $E1$ contribution. The particular ridge structure observed around ± 70 keV originates from the narrow component.

To be able to extract the widths Γ_{rot} and Γ_{μ} from experimental data, a parametrized spectrum function $S(E_{\gamma_1}, E_{\gamma_2})$ is introduced [11]. For two steps, $S(E_{\gamma_1}, E_{\gamma_2})$ is a sum of the correlated component described in terms of a two-dimensional Gaussian function, Fig. 1(b), with relative intensity I_{nar} , and the uncorrelated one, Fig. 1(a), with intensity $(1 - I_{\text{nar}})$ (the width Γ_{\parallel} is related to Γ_{rot} and Γ_{nar} so that the spectrum projected on the E_{γ_1} and E_{γ_2} axes has the same Gaussian form as the uncorrelated component). This spectral function can be extended to multiple steps of $E2$ γ decay, leading to analytical expressions for two- and higher-dimensional spectra which consist of the superposition of many Gaussian functions.

Such spectra depend on four parameters: the damping widths Γ_{rot} and Γ_{nar} , the intensity I_{nar} of the narrow component, and the number N_{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 γ 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}Er nucleus, in which the K -quantum number of the intrinsic states is also taken into account, in an approximate way [10]. Each γ cascade is started from Gaussian distributions in internal energy U and spin I , with centroids and widths reproducing the experimental conditions of the ^{163}Er experiment lately discussed (i.e., $\langle U \rangle = 4$ MeV, $\text{FWHM}_U = 4$ MeV, $\langle I \rangle = 44\hbar$, and $\text{FWHM}_I = 20\hbar$).

Two different simulated $E_{\gamma_1} \times E_{\gamma_2}$ matrices of ^{163}Er have been calculated. One, named *discrete*, is obtained updating γ between regular rotational bands, requiring that the branching number n_b of $E2$ branches out of a given state is less than 2 [7]. The second matrix, named *damped*, is obtained by subtracting the *discrete* one from the a γ - γ spectrum collecting all coincidences between $E2$ transitions in a cascade. Figure 2(a) shows a 60 keV wide cut on the *discrete* (bottom) and *damped* (top) simulated matrices. The projections are taken across the diagonal $E_{\gamma_1} = E_{\gamma_2}$, at the average transition energy $\langle E_{\gamma} \rangle = 960$ 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 $8\hbar^2/J^{(2)}$, $J^{(2)}$ being the dynamic moment of inertia of the bands. While in the *discrete* 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 χ^2 minimization with respect to the parameters Γ_{rot} , Γ_{nar} , I_{nar} , and N_{step} . The fitting procedure is found to be very stable and corresponds to $N_{\text{step}} \approx 5$ and $I_{\text{nar}} \approx 0.1$. The extracted values of Γ_{nar} and Γ_{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

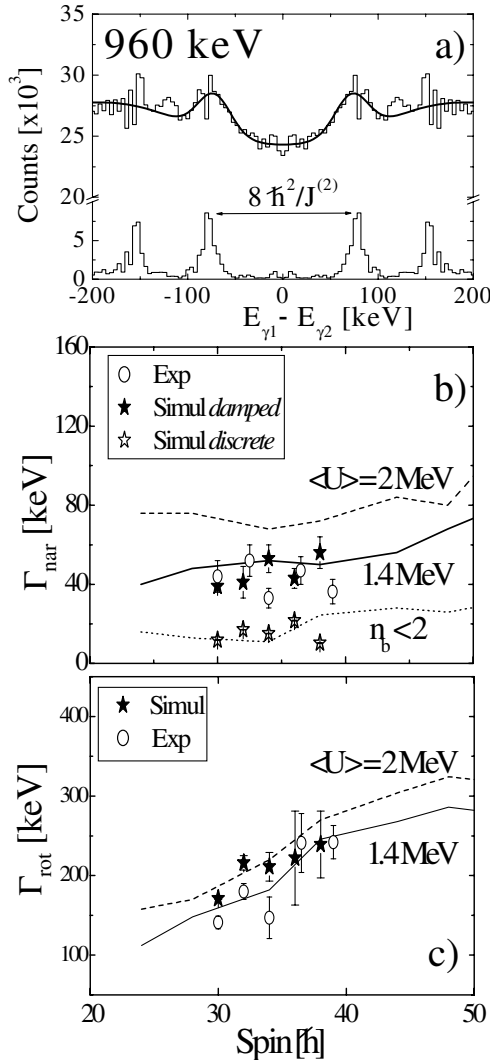


FIG. 2. (a) Example of 60 keV wide projections of simulated γ - γ spectra collecting the $E2$ contributions from discrete rotational bands (bottom) and damped transitions (top), at $\langle E_\gamma \rangle = 960$ keV. The thick solid line superposed on the damped spectrum is the interpolation by the analytical function. (b),(c) Values of Γ_{nar} and Γ_{rot} deduced from damped simulated spectra (full stars), in comparison with cranked shell model predictions at two different excitation energies [1.4 MeV (solid line) and 2 MeV (dashed line)]. The FWHM of the first ridge in the *discrete* matrix is shown by open stars in panel (b), together with the corresponding prediction (dotted line). Experimental values for Γ_{rot} and Γ_{nar} on ^{163}Er are shown by open circles.

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 $\langle U \rangle \approx 1.4$ MeV (solid line), and to the levels 101 to 300, with $\langle U \rangle \approx 2$ MeV (dashed line). Good agreement is found, in particular, with the calculation related to the colder energy region, which is where the simulated γ -decay flow mostly goes for this spin interval. This clearly demon-

strates 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 $E_{\text{beam}} = 87, 93$ MeV. The ^{150}Nd target was made of a stack of two thin foils for a total thickness of $740 \mu\text{g}/\text{cm}^2$. The corresponding maximum angular momentum reached in the reaction has been calculated to be $40\hbar$ and $45\hbar$, 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 residua.

The data have been sorted into a number of γ - γ matrices in coincidence with specific γ transitions of ^{163}Er [13]. In particular, a matrix collecting the entire decay flow of ^{163}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 γ - γ 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 $\sim E_\gamma^3 \exp(-E_\gamma/T)$ for the $E1$ statistical component, T being the temperature of the nuclear system. In the present case T is ~ 0.45 MeV, as deduced from an interpolation of the spectrum tail at $E_\gamma > 2$ 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* γ - γ coincidence spectra. The projections are taken at $\langle E_\gamma \rangle = 900, 960, 1020, 1080,$ and 1140 keV, corresponding to the spin range $30\hbar$ to $40\hbar$. Examples of such spectra are shown in Fig. 3. In all cases a rather smooth ridge-valley profile is observed, very similar to the one displayed by the *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_{step} is ≈ 5 , while the intensity I_{nar} is in average 0.1 for both *total* and *low-K* and 0.17 for *high-K* data. The obtained Γ_{nar} and Γ_{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

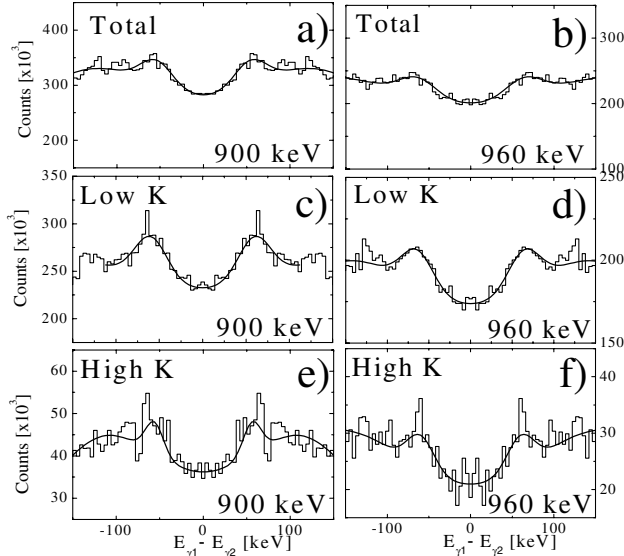


FIG. 3. 60 keV wide projections on the $E_{\gamma_1} - E_{\gamma_2}$ axis of experimental matrices of ^{163}Er , at the average transition energies $E_\gamma = 900$ and 960 keV. Panels (a) and (b) show projections on the total γ - γ matrix, while panels (c), (d) and (e), (f) correspond to spectra gated on low- K and high- K configurations of ^{163}Er . The $(-150, 150)$ keV interval shown here is equivalent to the one adopted in Fig. 2(a) [namely $(-200, 200)$ keV], considering the different values of $8\hbar^2/J^{(2)}$ in the simulated and experimental spectra (≈ 150 and 120 keV, respectively).

agreement with the theoretical prediction for Γ_{rot} and Γ_{nar} from the rather cold region of $\langle U \rangle \approx 1.4$ MeV, crossed by the γ -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 ($K \leq 8$) and high- K ($K > 8$) predictions at the excitation energies $\langle U \rangle \approx 1.4$ and 2 MeV. Even for these more selective data, satisfactory agreement is obtained with the theory with $\langle U \rangle \approx 1.4$ MeV. In addition, while the measured values of the narrow width are found of the order of 40 keV regardless of K (leading to a compound width estimate $\Gamma_\mu = \Gamma_{\text{nar}}/2 \approx 20$ keV), the rotational damping width Γ_{rot} is found to depend on the K value, being ≈ 200 keV for low- K and ≈ 150 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 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 Γ_μ and Γ_{rot} and therefore represents a step forward in the understanding of the order to chaos transitions in the atomic nucleus. For the nucleus ^{163}Er we have found $\Gamma_{\text{rot}} \approx 200$ keV and $\Gamma_\mu \approx 20$ keV, for angular momenta

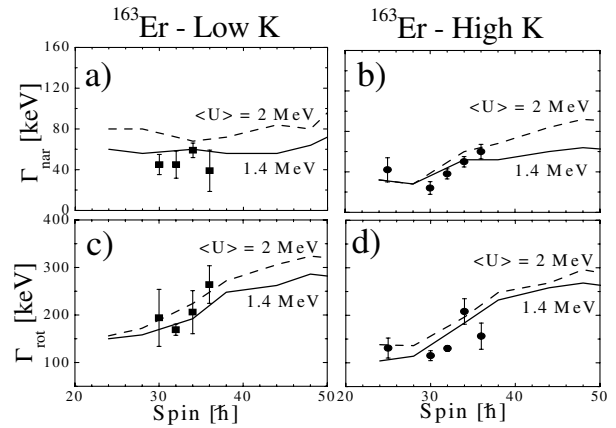


FIG. 4. Experimental values of Γ_{nar} and Γ_{rot} , as extracted from the spectral shape analysis of experimental low- K [panels (a) and (c)] and high- K [panels (b) and (d)] γ - γ coincidence spectra of ^{163}Er . Predictions from cranked shell model calculations [10] for average excitation energies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

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

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