Ergodic bands and motional narrowing in excited superdeformed states of ^{194}Hg

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The E$_\gamma$-E$_\gamma$ coincidence spectra from the electromagnetic decay of excited superdeformed states in ^{194}Hg reveal surprisingly narrow ridges, parallel to the diagonal. 100-150 excited bands are found to contribute to these ridges, which account for nearly all the E2 decay strength. Comparison with theory suggests that these excited bands have many components in their wavefunctions, yet they display a remarkable property in that each state decays mostly to one final state. This phenomenon can be explained in terms of the combination of shell effects and motional narrowing.

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Since the discovery of superdeformation at high spin in ^{152}Dy [1], around 300 discrete superdeformed (SD) rotational bands have been observed in nuclei ranging from ^{36}Ar to ^{198}Po [2]. The existence of highly elongated ellipsoids is due to quantum shell effects, which create a secondary minimum in the potential energy surface of the nucleus at very large deformation. SD nuclei are produced in fusion reactions at high angular momentum and excitation energy. The hot compound nucleus cools by evaporating neutrons, then by emitting γ-rays. As the temperature decreases, a small fraction (typically $\sim$1%) of the γ cascades are trapped in the SD minimum. Rotation of the resulting elongated nucleus gives rise first to unresolved collective electric quadrupole (E2) transitions [3–5] and then to an impressively long series of $\sim$20-25 discrete, nearly equi-spaced E2 transitions, which reveal one of nature's best rotors.

The above process represents a transition from a chaotic system, where symmetries and quantum numbers (apart from spin and parity) are broken, to a cold, ordered system. The resolved SD bands can be assigned the quantum numbers of states in a rotating mean field [6]. Given the robustness of collective rotation exhibited by SD bands, it is interesting to explore if the change from chaos to order evolves through an ergodic [7, 8] regime. This represents a situation where the wavefunctions are complicated, representative of a chaotic system, yet collective rotation and flow is preserved, e.g., with Porter-Thomas flucutations in the strengths of all transitions except the collective E2 γ rays [7]. The present letter addresses the transition from chaos to order by investigating the structure of excited states in the SD well, which itself is an excited minimum (false vacuum). Previous work [5] has demonstrated an intense pronounced broad bump of collective rotational E2 transitions in ^{194}Hg, centered at 760 keV. Here we report on the study of the correlations of these E2 transitions, as revealed in an E$_\gamma$-E$_\gamma$ matrix. We find exceptionally narrow ridges, which reveal rotational bands connecting unique states with spins differing by $2\hbar$, even though the wave functions of the eigenstates are complicated, containing many mean-field configurations.

The experiment, which was originally dedicated to the study of the ΔI=2 staggering in the SD bands of ^{194}Hg [9], was carried out at the 88" cyclotron facility in Berkeley. The reaction ^{150}Nd(^{48}Ca,4n)^{194}Hg was used at a bombarding energy of 201 MeV. To avoid Doppler broadening of the γ lines emitted by nuclei as they slow down in a backing, a self-supporting target was used. The photons emitted in the reaction were detected in Gammasphere [10], which comprised 70 Compton-shielded Ge detectors at the time. A total of $\sim 0.9\times10^9$ events of Compton-suppressed fold ≥ 4 were collected. To isolate only the cascades which get trapped in the SD minimum, coincidence gates were set on two transitions of the yrast SD band and any two additional coincident transitions were recorded into a two-dimensional spectrum (matrix). Background was removed by subtracting a fraction (85%) of the corresponding uncorrelated matrix [11]. A matrix of about the same quality is obtained if one removes Compton-scattered events by a double unfolding procedure [12].

Fig. 1 shows a portion of the matrix in the region of transition energy 650-900 keV. Clear rotational correlations show up in the form of 2-3 ridges running parallel to the diagonal in the interval 650 to 900 keV. Transitions contributing to the ridges can be sampled by cutting slices of the matrix and projecting along the E_1-E_2 coordinate, as indicated on Fig. 1a), with the result displayed on Fig. 1c) and 1d). The absolute intensity present in the ridges is given in Fig. 2a) together with the intensity of the one-dimensional E2 bump [5] and of the yrast SD band intensity. Three other properties of the first ridge are shown in Fig. 2. First, the energy separation between the first ridge and the diagonal is shown together with that of consecutive transitions in the yrast

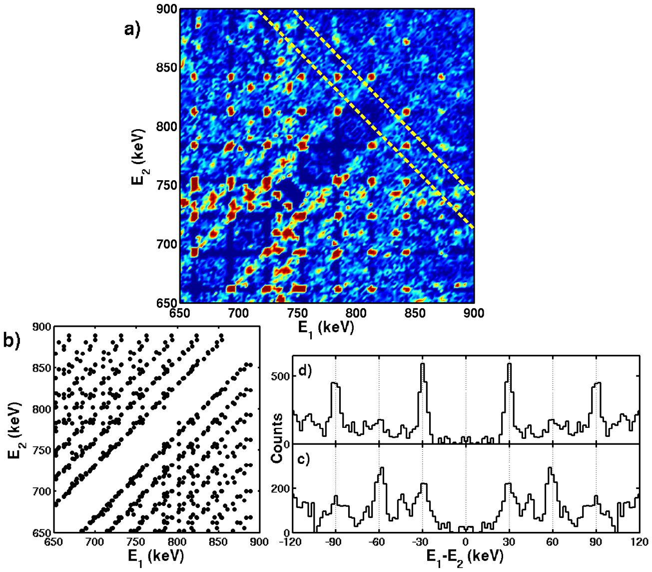

FIG. 1: (Color Online) a) Experimental double SD-gated $E_{\gamma 1}$-$E_{\gamma 2}$ coincidence matrix in ^{194}Hg. The yrast SD band shows up as a regular grid pattern of points. The first and second ridges are clearly visible from 650 to 850 keV. Note that the diagonal contains nearly zero counts. b) Schematic $E_{\gamma 1}$-$E_{\gamma 2}$ coincidence matrix between transitions in 20 SD bands of even-even, odd-odd and odd-even mass 190 nuclei: ^{191}Au, ^{190}Hg, ^{192}Hg, ^{193}Hg, ^{194}Hg, ^{195}Hg, ^{192}Tl, ^{194}Tl, ^{194}Pb, ^{196}Pb, ^{198}Pb. c) and d) Projections perpendicular to the diagonal of the matrix shown in panel a). The diagonal is set at 0 keV and the projections, which are centered at 812 (c)) and 798 keV (d)), cover 20 of the ~30 keV interval between SD peaks. The projection region of panel c), illustrated by the dashed lines in a), has been selected to exclude the contribution of the intense SD yrast band from the first, but not the second ridge. In panel d), the projection instead excludes this contribution from the second, but not the first, ridge.

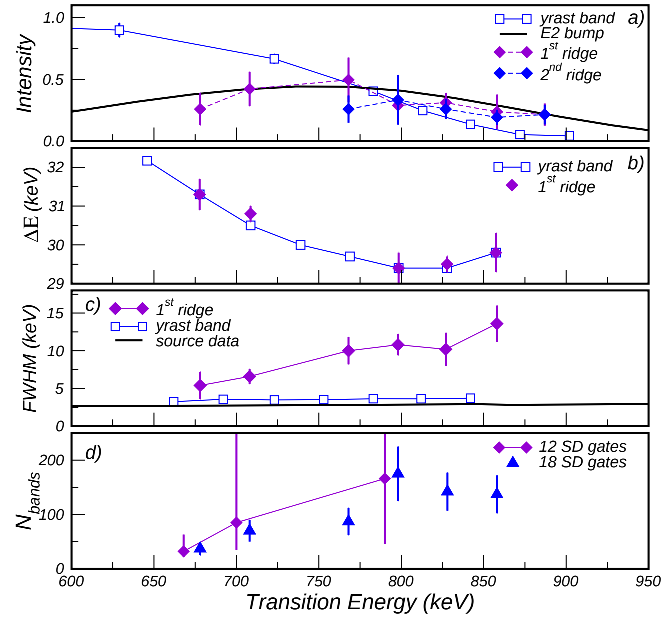

FIG. 2: (Color Online) a) Intensity in units of multiplicity/30 keV present in the first and second ridges, the 1-dimensional quasicontinuum E2 bump and the SD yrast transitions as a function of transition energy (multiplicity $\equiv$ number of transitions per cascade). b) Inverse dynamical moment of inertia for the yrast SD band in ^{194}Hg and for the first ridge as a function of average transition energy. c) Widths (FWHM) of the first ridge, SD lines and calibration peaks. d) Number of bands contributing to the first ridge, obtained from 2 different matrices (see text). The error bars from the SD-gated matrix with 12 gates are due to the large uncertainty in the determination of the second moment μ_2.

SD band of ^{194}Hg (2b)). Secondly, its width is displayed (2c)). Finally, the number of bands (2d)) which contribute to the ridge structure could be extracted from a Fluctuation Analysis [13]. The number of bands, which ranges from 30 to 150, is obtained from perpendicular cuts on the background-subtracted double-SD gated matrix and from the second (μ_2) and first (μ_1) moments over the ridge regions. The cuts were made at different energies and were of variable widths to avoid the SD and ND yrast peaks. Although the ridges are clearly visible in the background-subtracted matrix and in the cross-diagonal spectra (Fig. 1c,d)), their fluctuations are very small, which in most cases allows a determination of only a lower limit for the number of bands present in the ridges. (Small fluctuations imply a large number of pathways). To gain in statistics, we added 6 more SD transitions to the list of 12 original gates. These transitions are known to bring some contaminations into the spectrum but the extra combinations of gates yields a factor ~2.4 more counts in the matrix. The number of bands contributing to the ridges in the less clean matrix is consistent with the number of bands obtained from the original matrix.

The experimental observations imply many new and exciting features. The narrow ridges mean that the energy difference between any two consecutive transitions remains almost constant. The narrow width (Fig. 2c)) is a striking feature when one realizes that of the order of 100-150 bands contribute to the ridge. The ridge separation is a measure of the dynamical moment of inertia, $\mathcal{J}^{(2)}$. Fig. 2b) indicates, extraordinarily, that the moment of inertia from the ridge separation is practically identical to that of the yrast SD band. This is intimately related to the phenomenon of identical SD bands or, more accurately, identical dynamical moments of inertia $\mathcal{J}^{(2)}$ in the mass 190 region [14]. Fig. 1b) shows how the coincidences between transitions in 20 discrete SD bands from the mass 190 region form narrow ridge-like patterns. The overall E_γ-E_γ coincidence matrix resembles that for excited quasicontinuum states in ^{194}Hg, including even giving the same $\mathcal{J}^{(2)}$ value. Hence, the nearly identical $\mathcal{J}^{(2)}$ values for discrete SD bands observed in the A~190 region recurs even for excited SD states in ^{194}Hg. This is quite unexpected since excitations are more complicated, pairs are broken and pairing correlations are reduced, which would normally increase the $\mathcal{J}^{(2)}$ moment of inertia.

The first and second ridge intensities at spin I, $I_{r1,I}$ and $I_{r2,I}$, can be expressed in terms of: a) the total unresolved E2 strength at spin I, $I_{E2,I}$; b) the fraction f_I of the unresolved E2 strength which is of SD character and may contribute to the observed narrow ridges; and c) the probability P_{I-2} and P_{I-4} to remain in a particular band at spin I-2 and I-4:

$$I_{r1,I} = I_{E2,I} f_I P_{I-2} \quad , \quad I_{r2,I} = I_{E2,I} f_I P_{I-2} P_{I-4}$$

From the ridge intensities displayed in Fig. 2, we can deduce that the inband probability P_I is $\sim$1 until feeding is forced into the yrast SD band by the gating conditions and that the fraction f is also $\sim$1, with a slight drop at the highest rotational frequencies. This means that practically all the unresolved E2 strength is concentrated in the SD ridges and that there is little or no branching out from any band to another.

The small width of the ridge and the large number of excited bands found in ^{194}Hg are quite different from all other cases for which rotational energy correlations have been studied. Both for the rotational states in ^{168}Yb and ^{163}Er[15–18], which have normal (smaller) deformation, as well as for the SD bands of ^{143}Eu [19], the fraction of E2 transitions carrying rotational energy correlations is much smaller, typically less than 10%, with the remaining transitions out of each state being fragmented over many weak transitions covering a quite wide energy interval, the rotational damping width (typically around 200 keV). In the feeding of SD bands in ^{152}Dy, the narrow fraction is somewhat larger ($\sim$30% [20]). In the present case of ^{194}Hg, the narrow SD ridge nearly exhausts the entire E2 strength, accounting for $\sim$80-100% of the the E2 transitions in the 1-dimensional spectrum. Also, the number of paths contributing to the ridge, that is the effective number of rotational bands carrying rotational energy correlations, is much larger in ^{194}Hg than in these other nuclei, by a factor of about 3 to 5.

The main results of both the earlier and the present experiments can qualitatively be understood within a common description, in terms of cranked mean-field states interacting via a residual two-body interaction [22]. As pointed out by Yoshida and Matsuo [23], the single particle orbitals around the Fermi surface of the SD shape for nuclei with mass $A \sim 190$ carry exceptionally small alignments of the angular momentum along the cranking axis. Their wave-functions stay coupled to the deformed shape rather than become coupled with the angular momentum vector. Sampling the excited mean field basis states, one finds that their transition energies show little variation among states of given angular momentum. Rephrased in terms of the rotational frequency, the dispersion $\Delta\omega$ among them is very small.

This implies the following picture for the excited rotational bands SD bands in the mass $A \sim 190$ region: at low excitation energy, the bands are truly discrete, the average energy distance between them being much larger than the interaction matrix element. This situation persists up to around energy $U \approx 1.2$ MeV above yrast, where the bands start to mix, but in such a way that the phase and rotational coherence of the wavefunctions is maintained over sequences of angular momenta. Finally, around energy $U \approx 1.8$ MeV above yrast, the transitions start to branch to several states. This is illustrated in Fig. 3, which shows that the bands in ^{194}Hg have many components of intrinsic states in their wavefunction (4 on average but up to $\sim$ 10).

With so many components mixed into the wavefunctions, one could not assign any particular structure or any specific quantum numbers to them other than the energy, angular momentum and parity. In that sense, the bands approach an ergodic situation. The condition for ergodic bands [7] is that the rotational damping width Γ_{rot} is smaller than the average level spacing D. The present calculations show that the condition $\Gamma_{rot} < D$ is not met in the spin domain of the observed ridges (20 to 46 $\hbar$). However, if one considers instead D_2, the average distance between states which interact via the residual two-body interaction, the condition $\Gamma_{rot} < D_2$ is met in the onset region of mixing.

Also, the damping width is reduced relative to the full value $\Gamma_{rot} \approx 4\Delta\omega$, implied by the dispersion $\Delta\omega$ among the unmixed bands. This last effect is called motional narrowing [24, 25], which is achieved when $2\Delta\omega < \Gamma_{\mu}$, where Γ_{μ} is the compound damping width arising from the mixing of mean-field configurations.

For the SD bands in ^{194}Hg, all mixed bands are predicted to carry motional narrowing. This is a peculiar situation and has never been observed before. For the usual case of mixed bands, for which the condition $4\Delta\omega >> D_2$ is fulfilled at the onset of damping, analytic expressions have been derived for the width of the narrow component of the rotational strength function, as well as of its intensity I_{narrow} [21]. However, for the present case of overall motional narrowing, such expressions have not been derived. Instead, we refer to Fig. 3, which shows that the rotational band states in ^{194}Hg typically carry 4 components, and Fig. 5 of reference [23], which shows that the ridge stays rather narrow with increasing energy above yrast, and that it keeps the major part of the intensity of consecutive transitions, in accordance with the present experimental findings.

We should consider the possibility that the ridges arise from discrete bands. However, given the sheer number of bands present in the ridges, it is hard to believe that band mixing could be so weak in ^{194}Hg. Furthermore, this possibility can be precluded by the width of the second ridge, which is close to that of the first ridge. In the case of uncorrelated discrete bands, the second ridge should be twice as wide.

As discussed above, mixed bands with overall motional narrowing offers a better explanation. Especially, with increasing excitation energy above yrast, as is expected for increasing angular momentum, the mixed band states acquire more and more components, as illustrated on Fig.

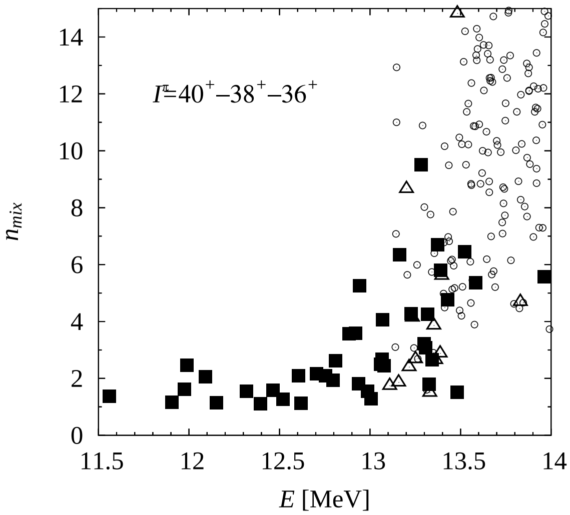

FIG. 3: Number of admixed intrinsic states into ^{194}Hg SD states as a function of their excitation energy. The mixing number is computed for SD states of spin 40 and the symbols denote the amount of coherence in consecutive transitions. Squares indicate states that decay within the same band for two consecutive transitions (branching ratio < 2), triangles indicate states that have a branching ratio < 2 in the first transition, but not in the second, while the circles indicate states which decay to many other bands (branching ratio > 2).

3, and this also results in an increasing width of the ridge, in agreement with the observed results displayed on Fig. 2b).

In conclusion, the present experiment has shown that the unresolved E2 transitions emitted by the SD ^{194}Hg, as it cools down to the yrast line, show unique rotational correlations in that practically all the E2 strength forms unusualy narrow ridges ($\sim$10 keV). This is completely different from what has been measured in all other nuclei, where the E2 strength is predominantly fragmented over a much larger energy interval (>200 keV). Many (30-150) bands are found to contribute to the ^{194}Hg ridges yet rotational coherence is maintained. Theory shows that the wave functions contain many mean-field configurations, so that a chaotic regime is approached, where transition strengths should exhibit Porter-Thomas fluctuations. Yet, as predicted by Mottelson [7], rotational coherence and flow are preserved, with E2 matrix elements connecting unique states with spins I and I-2. This feature gives a completely new insight into the transition from order to chaos through a nearly ergodic regime and the damping of rotational motion. In the particular case of mass 190 nuclei, configuration mixing among excited SD states does not lead to a spread in the rotational strength.

Acknowledgments

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