Fragmentation of the Decay from the Superdeformed Yrast Band in ^{192}Hg

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The decay-out spectrum of the superdeformed yrast band in ^{192}Hg comprises a quasicontinuum, from which about 50 weak discrete transitions of energy between 1 and 3.2 MeV are resolved. The fluctuations of the one-dimensional quasicontinuum spectrum are studied with the fluctuation analysis method, which shows that of the order of a few thousand different transitions are available in the first step of the decay-out cascades. The experimental effective number of transitions is compared to schematic theoretical calculations. [S0031-9007(96)01064-2]

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The existence of superdeformed (SD) nuclei is made possible by the presence of a second minimum in the potential energy surface at very large deformation ($\beta = 0.4$–0.6), caused by a shell gap in the single-particle spectrum [1]. The first experimental evidence of superdeformed states was the observation of fission isomers in the actinide region [2], and, later, of rotational bands in rapidly rotating nuclei in several mass regions, most notably around mass numbers 150 and 190 [3]. Despite the fact that more than 100 SD rotational bands have been observed, discrete transitions out of bands directly into resolved low lying states of normal deformation (ND) have been found in only a few cases [4–7]. A quasicountinuum spectrum of unresolved decaying transitions was recently observed in the ^{192}Hg nucleus [8]. This supports a statistical decay scenario [9], in which the SD states decay because of a small admixture with one (or a few) ND compound state(s). The decay out then proceeds as a γ cascade with many possible transitions, whose strengths should be governed by Porter-Thomas fluctuations [10,11].

We report here a first investigation of the number of transitions sampled by the ^{192}Hg nucleus in its decay out from the SD yrast band, by application of the fluctuation analysis method (FAM) [11,12].

The SD states in ^{192}Hg were populated with the reaction ^{160}Gd(^{36}S, $4n$). The 159 MeV beam was delivered by the Vivitron accelerator in Strasbourg. A ^{160}Gd gold-backed target (1 mg/cm^2 on 10 mg/cm^2) was used in order to distinguish between the fully Doppler-shifted γ rays that feed the SD states and the stopped γ rays that deexcite them. The γ rays were detected by the newest implementation of the Eurogam 4π γ multidetector array, comprising 30 large volume Compton suppressed Ge detectors and 24 new polarization-sensitive BGO shielded clovers [13,14]. The event trigger required at least four coincident Compton-suppressed γ rays, resulting in a total of 0.9×10^9 quadruple- and higher-fold coincidences.

To obtain enough statistics in the decay spectrum, a one-dimensional spectrum containing all the events in coincidence with at least two SD transitions was constructed according to the prescription in Ref. [15]. It was background subtracted by removing a proportion of a single-SD-gated spectrum and corrected for the detector response [16]. Figure 1 shows the resulting spectrum as well as the sum of four single ND-gated spectra (the gates were set on the 6^+-4^+, 8^+-6^+, 5^--4^+, and 22^+-20^+ transitions). The background spectrum for the ND-gated spectrum was chosen to be a fraction of the spectrum containing all the events in the experiment. Both spectra are normalized to give the same integral (multiplicity) in the 2^+-0^+ line. One sees that with this absolute normalization the SD- and ND-gated spectra display almost identical intensity as well as slope above 3 MeV. Between 1 and 3 MeV, the SD spectrum lies above the ND spectrum and exhibits a broad component with intermediate-width structures and discrete lines. This excess of intensity has been previously identified [8] as containing the γ rays connecting the SD and ND states. Above 1 MeV, the ND spectrum, stripped of all discrete high-energy lines, is then smoothed and taken to represent the spectrum of statistical γ rays feeding the SD band. This experimental approximation is encouraged by the close identity of the statistical tails of the SD- and

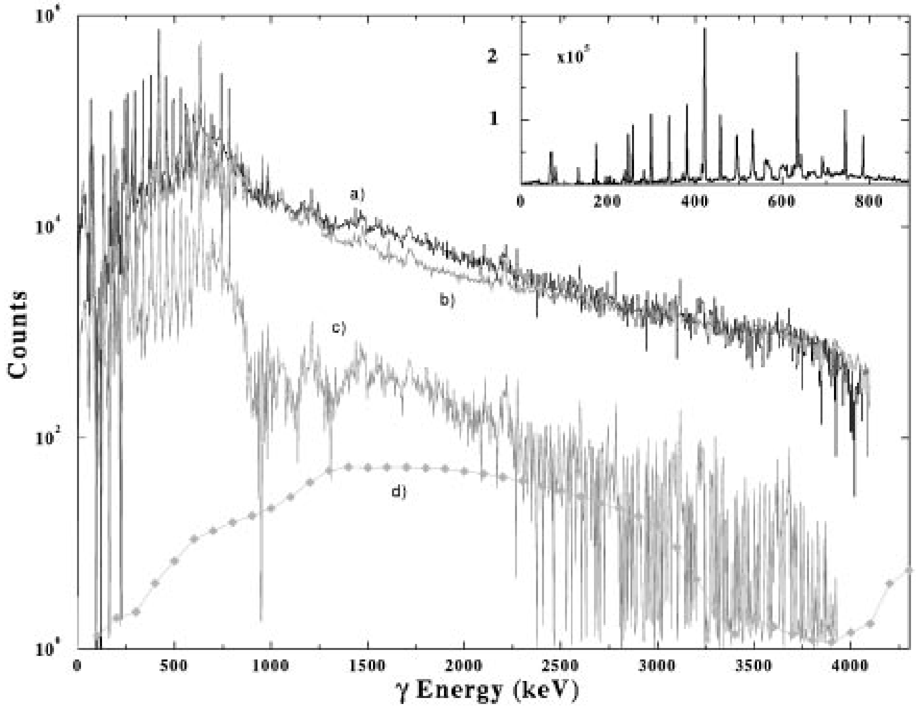

FIG. 1. Double-SD-gated spectrum (a) and ND-gated spectrum (b), both normalized to the same intensity in the 2^+-0^+ ND line. For the purpose of the figure, the two spectra have been corrected for the detector efficiency and compressed by 4. The efficiency-corrected experimental decay spectrum (c) is shown together with the calculated statistical decay spectrum of an even-even paired nucleus (d). Both spectra have been divided by 10 and the theoretical spectrum has been adjusted to the experimental spectrum by compressing it to 4 keV/channel. The inset shows the double-SD-gated spectrum (a) from 0 to 900 keV.

ND-gated spectra above 3 MeV, but it cannot be strictly justified, since the initial distribution of angular momenta (and possibly also of excitation energies) of the cascades will be quite different for the feeding into ND states as compared to the SD band [17]. Nevertheless, this experimental approximation of the statistical feeding spectrum above 1 MeV is identical to the simulated spectrum of Lauritsen *et al.* [17]. The portion above 1 MeV in Fig. 1(c), obtained by subtracting the smoothed ND-gated spectrum from the SD-gated spectrum, is then the decay spectrum from the SD band in ^{192}Hg. The bulk of the intensity in this spectrum lies between 1 and 3 MeV and has a multiplicity of $\gamma_{\mathrm{mult}} = 2.6 \pm 0.4$. This is to be compared to 3.2 ± 0.6 extracted from the total decay spectrum [8].

In the top panel of Fig. 2 the background-subtracted double-SD-gated spectrum is displayed in more detail. For γ cascades containing the SD band, the nucleus slows down during its decay along the band from the full recoil velocity to a complete stop in the target. All other than in-band transitions are then emitted with the full Doppler shift or from a stopped nucleus. The figure displays pronounced (within 2σ) discrete lines, corresponding to γ rays emitted at rest. Altogether, 51 stopped linking transitions are identified within the 1 to 3.2 MeV range, and they have all been firmly established to be in coincidence with the SD band as well as with low lying ND lines. Their total intensity is 40% of the intensity in the SD band. Hence, above 1 MeV, the resolved and unresolved transitions comprise 15% (i.e., 0.4/2.6) and 85% of the decay spectrum, respectively. Apparent structures in the bottom panel of Fig. 2 do not relate to the SD band by the proper coincidence requirements. A careful search for high-energy single step γ rays has also been carried out, without success. The upper limit on the recorded γ-ray energy in the experiment was 4 MeV, dictated by the acquisition system, and the highest lying discrete prominent transition is at 3118 keV, carrying $(0.8 \pm 0.1)\%$ of the SD band intensity. However, no experimental evidence of this being a single step path down close to the ND yrast line has been found. This may be expected, since the excitation energy of the SD 10^+ state, from which the decay out takes place, is estimated to be 4.3 ± 0.9 MeV [8].

The fluctuation analysis method is a powerful tool to go further in the study of the quasicontinuum component of the decay spectrum. It relies on the fact that the number of transitions available for the decay, although large, is finite. Because of the high statistics collected in this experiment, the more intense of the transitions of our decay spectrum will be counted in many events. This will enhance the fluctuations of the spectrum relative to those generated by pure counting statistics. The aim of the fluctuation analysis method is to determine N_t, the number of paths, or effective number of transitions sampled in the decay from the SD band. N_t is given by $(\sum_t w_t^2)^{-1}$, where w_t is the probability that a particular transition is used in the cascade. This number should be evaluated within an energy interval of the order of the characteristic energy scale of the cascades, in our case the temperature.

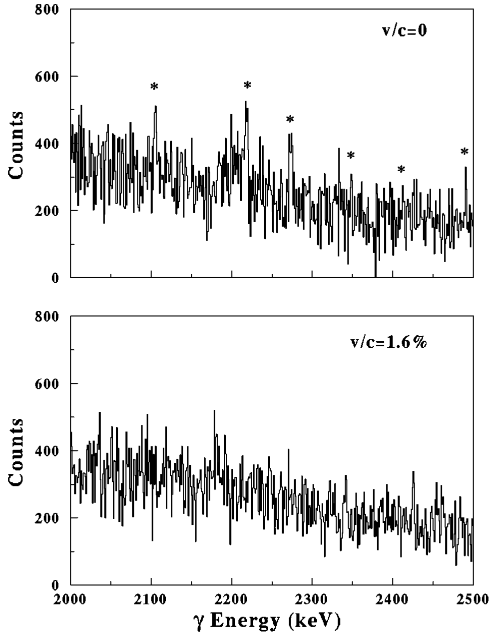

FIG. 2. The top panel represents the double-SD-gated spectrum (background subtracted and unfolded) with no Doppler shift correction, in which discrete linking transitions are indicated with a star. The bottom panel shows the same spectrum after correction for the compound nucleus velocity.

A typical value of the temperature is 0.4 MeV, and we will use an interval width of 0.2 MeV.

Experimentally, the effective number of transitions N_t is extracted from the first and second moments μ_1 and μ_2 of the count distribution in the spectrum [11]:

$$N_t = 2pf^2 \frac{N_{\mathrm{evt}}(A)\mu_1(A)}{\mu_2(A) - \mu_1(C_{\mathrm{raw}}) - g^2\mu_1(B_{\mathrm{raw}})}. \quad (1)$$

The letter A denotes the Compton- and background-subtracted spectrum obtained by subtracting from the gated spectrum C a background-gated spectrum B scaled by the factor g, and then correcting $C - gB$ for the detector response. $N_{\mathrm{evt}}(A)$ is the number of recorded events in spectrum A. The factor 2 arises from Porter-Thomas fluctuations, p is a correction factor for finite detector resolution, and f accounts for any underlying smooth spectrum. $\mu_1(C_{\mathrm{raw}})$ and $\mu_1(B_{\mathrm{raw}})$ refer back to the original raw spectra, and their appearence in the expression (1) accounts for the uncorrelated counting statistics, which will remain in the spectra after all subtractions. The spectra used for the fluctuation analysis should not be corrected for detector efficiency, since this destroys the balance between the fluctuations due to the finite number of decaying transitions and the fluctuations due to pure counting statistics.

The decay-out spectrum is superposed on the statistical feeding spectrum, and f is the fraction of decay out to total events $f = N_{\mathrm{evt}}(\mathrm{decay})/N_{\mathrm{evt}}(\mathrm{total})$. This factor is computed for every 0.2 MeV interval and varies from approximately 0.4 to 0.1, as can be read from Fig. 1. Taking into account the underlying spectrum by means of the f factor is justified when the following condition is met: $(1 - f)^2 N_t(\mathrm{decay}) \ll f^2 N_t(\mathrm{stat\ feeding})$ [11]. Figure 3(a) displays the experimental effective number of transitions extracted from the decay-out spectrum. The error bars are evaluated as described in Ref. [11], assuming also a 20% uncertainty on the f-factor estimate. The factor of the order of 10 to 100 more transitions in the feeding spectrum justifies the use of the f factor.

The initial stage of the SD decay out is expected to be fundamentally different from that of the feeding cascades with respect to fluctuations. In the weak coupling limit, where the SD state interacts only with its nearest neighboring ND state [9] the decay-out cascade should start from one (or a few) initial state(s), whereas the feeding cascade starts from a multitude of initial states populated by the neutron decay. Furthermore, with increasing transition energy, a decreasing number of final states are available for the primary γ rays in both types of cascades. The fluctuations in the high-energy part of the decay spectrum should thus be dominated by these first-step transitions since the following steps have many more paths. This would cause the number of transitions in the SD decay-out spectrum to decrease at high energies, in proportion to the level density of final states $\rho(U_{\mathrm{final}})$, where U denotes the energy above yrast. In the feeding case, the equivalent number of transitions is the product $\rho(U_{\mathrm{initial}})\rho(U_{\mathrm{final}})$, which would yield a more slowly varying behavior with γ-ray energy.

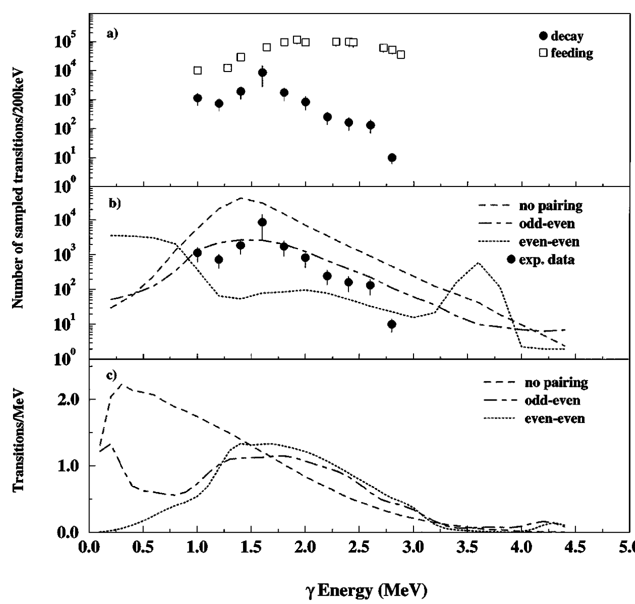

FIG. 3. (a) Experimental number of transitions sampled by the nucleus per 200 keV energy bins. The results are shown for the spectrum of γ rays deexciting the SD band as well as for our experimental approximation of the spectrum of statistical γ rays feeding the SD band. (b) Calculated number of transitions sampled in the decay from an excited state at an energy of 4.3 MeV above the yrast line, for even-even and odd-even nuclei with pairing and for an even-even nucleus with no pairing. These are displayed together with the corresponding experimental points. (c) Statistical decay spectra calculated from the different cases described in (b).

The experimental results in Fig. 3(a) clearly confirm this expected behavior of the number of decaying transitions at high γ-ray energies.

In Fig. 3(b), the effective number of transitions in the superdeformed decay-out spectrum is compared to the calculated number of transitions in three different cases. The calculations are all based on the model described in Ref. [18]. In this schematic model, quasiparticle energies are calculated, starting from equidistant single-particle levels, with pairing treated using the BCS method, followed by particle-number projection and diagonalization. The number of transitions for even-even and odd-even nuclei, as well as for an even-even nucleus with no pairing, are shown in Fig. 3(b). In the calculations, the single path probability w_t varies greatly, for example, being much larger for transitions in the first decay step than for transitions with the same energy emitted in the second decay step. The corresponding decay spectra, discussed and described in Ref. [18], are shown in Fig. 3(c).

The low-energy γ rays tend to come from the last decay steps which originate from a region of low level density. This causes the initial increase in the calculated number of transitions at low energy. A maximum is then reached around 1.7 MeV, followed by a decrease at higher energy, which is explained above. For the even-even case, the peculiar behavior of the calculated number of transitions in the very weak parts of the decay spectrum, below 1 MeV and above 3 MeV, is caused by the pairing gap of about 1.3 MeV in the even-even nucleus. The transitions in these regions consist of "second chance" γ rays, which have many initial states, and only one final state.

More quantitatively, one notes that the experimental data points for the number of decaying transitions are situated between calculated curves for the even-even and the odd-even nuclei and, in fact, lie closer to the odd-even curve. This is most probably due to the reduction of the pairing correlations by finite angular momentum, which makes the rotating even-even nucleus more similar to a nonrotating odd-even nucleus. More realistic calculations, in which the level density is altered by the symmetry of the potential [19,20], the cranking of the potential [20], and shell effects [21] can change the actual calculated values. Within this uncertainty, the agreement between data and calculations can be considered as satisfactory. It is reasonably straightforward to extract the number of first-step transitions above 2 MeV, where they dominate the spectrum (as discussed above). From Fig. 3(a), we can deduce that there are of the order of 1000 final states available for transitions above 2 MeV. This number can be compared with that derived by dividing the total number of transitions in the 1 to 3 MeV range [roughly 9000, from Fig. 3(a)] by the average number of steps connecting SD and ND states in the same energy interval (2.6). This procedure gives roughly a total of 3000 transitions at each step of the decay. However, this number is probably overestimated for the first and last steps since the transitions in either case stem from, or lead to, fewer states than the transitions in the second step of the decay. The large number of pathways obtained by the FAM provides additional evidence for the fragmentation and statistical nature of the deexcitation of the SD band in ^{192}Hg.

In conclusion, we have characterized the decay spectrum [8] of the SD yrast band in ^{192}Hg in three respects: (i) 51 discrete transitions without Doppler shift have been identified. (ii) The fluctuation analysis shows that the highly excited SD state has of the order of 1 to 3000 different transitions to choose from in the first step of its decay. (iii) The effective number of decaying transitions decreases with increasing γ-ray energy above 2 MeV, showing that the decay-out cascade is initiated from only one or a few initial states.

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[1] V. M. Strutinsky, Nucl. Phys. **A95**, 420 (1967).
[2] S. M. Polikanov *et al.*, Sov. Phys. JETP **15**, 1016 (1962).
[3] B. Singh, R. B. Firestone, and S. Y. F. Chu, Report No. LBL-38004, 1995.
[4] S. Lunardi *et al.*, Phys. Rev. C **52**, R6 (1995).
[5] M. A. Deleplanque *et al.*, Phys. Rev. C **52**, R2302 (1995).
[6] T. L. Khoo *et al.*, Phys. Rev. Lett. **76**, 1583 (1996).
[7] A. Lopez-Martens *et al.*, Phys. Lett. B **380**, 18 (1996).
[8] R. G. Henry *et al.*, Phys. Rev. Lett. **73**, 777 (1994).
[9] E. Vigezzi *et al.*, Phys. Lett. B **249**, 163 (1990).
[10] C. E. Porter and R. G. Thomas, Phys. Rev. **104**, 483 (1956).
[11] T. Dossing *et al.*, Phys. Rep. **268**, 1 (1996).
[12] B. Herskind and S. Leoni, Nucl. Phys. **A520**, 539c–554c (1990).
[13] P. M. Jones *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **362**, 556 (1995).
[14] P. J. Nolan *et al.*, Ann. Rev. Nucl. Part. Sci. **45**, 561 (1994).
[15] C. W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **364**, 560 (1995).
[16] D. C. Radford *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **258**, 111 (1987).
[17] T. Lauritsen *et al.*, Phys. Rev. Lett. **69**, 2479 (1992).
[18] T. Dossing *et al.*, Phys. Rev. Lett. **75**, 1276 (1995).
[19] S. Bjørnholm, A. Bohr, and B. Mottelson, in *Proceedings of the IAEA Symposium on Physics and Chemistry of Fission, New York, 1973* (IAEA, Vienna, 1974).
[20] T. Døssing and A. S. Jensen, Nucl. Phys. **A222**, 493–511 (1974).
[21] S. Åberg, Nucl. Phys. **A477**, 18 (1988).