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Dynamic moment of inertia of the ^{192}Hg superdeformed band at high rotational frequencies

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The superdeformed band in ^{192}Hg has been extended to higher transition energies from a new analysis of a large set of double and triple coincidence data. Contrary to the results of cranked shell model calculations including monopole pairing, the dynamic moment of inertia $\mathcal{J}^{(2)}$ is found to continue to increase with rotational frequency.

The evolution of dynamic moments of inertia $\mathcal{J}^{(2)}$ as a function of the rotational frequency $\hbar\omega$ for the superdeformed (SD) bands in the mass $A=150$ region is characterized by pronounced isotopic and isotonic variations [1]. These variations have been attributed to differences in the occupation of specific high-N intruder orbitals [2] (i.e. high-N orbitals located two major shells higher in energy in a spherical nucleus, which plunge down as a function of deformation and are near the Fermi surface for the SD shape). In contrast, all but two of the SD bands in the mass $A=190$ region display the same overall behavior: a smooth andrather pronounced increase of $\mathcal{J}^{(2)}$ with $\hbar\omega$ is always present [1]. It has been shown that the occupation of specific high-N intruders cannot account for this observed rise [1,3–5] in $\mathcal{J}^{(2)}$ and it has been suggested that quasiparticle alignments and the resulting changes in pairing play an essential role [4–7].

The nucleus ^{192}Hg is often regarded as the doubly-magic SD nucleus in the $A=190$ region as large shell gaps are calculated [6,8] to occur in the single-particle spectrum for $Z=80$ and $N=112$, at a quadrupole deformation $\beta_2\sim0.5$. A single SD band has been found in this nucleus [4,9] and the measurement of the lifetimes of the individual SD states [10] conclusively shows that a change in deformation with $\hbar\omega$ (centrifugal stretching) cannot explain the observed $\sim40\%$ rise in $\mathcal{J}^{(2)}$, within the frequency range covered by the experiment. In ref. [10], it was shown that calculations using the cranked Woods–Saxon Strutinsky model with pairing are able to account for the general trend seen in the data. The rise in the calculated $\mathcal{J}^{(2)}$ can be ascribed to the combined alignment of a pair of $N=6$ ($i_{13/2}$) protons and a pair of $N=7$ ($j_{15/2}$) neutrons. It is a direct consequence of this type of calculation that, after the quasiparticle alignments have taken place, $\mathcal{J}^{(2)}$ will exhibit a downturn with increasing $\hbar\omega$ and will approach the value of the static moment of inertia $\mathcal{J}^{(1)}$. This property is well known from the study of quasiparticle alignments (associated with the backbending phenomenon) in rare-earth nuclei [11]. A similar downturn in $\mathcal{J}^{(2)}$ is also predicted in the calculations of ref. [7], where changes of pairing correlations with $\hbar\omega$ are treated in a schematic model.

In the present work, the SD band of ^{192}Hg has been

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extended to a frequency $\hbar\omega \sim 0.44$ MeV, i.e. the highest frequency reached in this mass region, hereby providing a test of the calculations mentioned above. A smooth increase of $\mathscr{J}^{(2)}$ with $\hbar\omega$ is observed over the entire frequency range, thus raising questions about the adequacy of the calculations.

In order to investigate the highest frequencies in the ^{192}Hg SD band, i.e. a domain where the γ-ray transitions are expected to have intensities below 0.1% of the fusion cross section, a very large data set is essential. This was achieved here by adding the results of five experiments originally performed to study the population of the ^{192}Hg SD band [12,13] in the ^{160}Gd(^{36}S,4n) reaction at beam energies varying from 154 to 167 MeV. The data were taken with a stack of two 500 μg/cm^2 isotopically enriched (97%) targets located at the center of the Argonne–Notre Dame BGO γ-ray facility, a spectrometer consisting of an inner multiplicity-sum energy array of fifty BGO detectors surrounded by 12 Compton suppressed Ge detectors. At each beam energy, only high-multiplicity events were stored on magnetic tape by requiring a minimum of four inner array detectors to fire in prompt coincidence with at least two suppressed Ge detectors. The total data set comprised 2.8×10^8 coincidence events, of which $\sim 7\%$ are of higher order (mainly triple γ–γ–γ events).

In the analysis, a coincidence matrix was constructed where events corresponding to high-multiplicity cascades in ^{192}Hg were enhanced by careful selection of conditions on the γ-ray multiplicity and on total energy recorded in the array. These conditions were adjusted at each beam energy, in order to reflect corresponding changes in input angular momentum and excitation energy. The final matrix obtained in this way contained 2.0×10^7 events, of which 69% are in ^{192}Hg; the main "contaminant" channels still present in the data were those leading to ^{191}Hg (19%) and ^{193}Hg (12%). The triple coincidence events were also sorted separately in a so-called coincidence cube where the energies recorded in the three detectors are stored each along one of the principal axes. As in the case of the double coincidences, multiplicity and sum-energy selection was applied. The total number of triple coincidence events analyzed was 4.2×10^6. In order to investigate the highest spin states, single gated planes or double gated spectra were extracted from the cube.

In the analysis of the γ–γ coincidence matrix, gates were placed on the known SD transitions [4,9] in order to search for additional γ rays. The spectrum obtained by adding the cleanest coincidence spectra (gates placed on the 257, 300, 341, 381, 496, and 602 keV γ rays) is shown in fig. 1. The sixteen SD lines and the yrast transitions reported earlier [4] are clearly visible. Beyond $E_\gamma \sim 800$ keV, three transitions appear with respective energies of 820.7, 847.6 and 874.0 keV: they can be regarded as candidates for an extension of the SD band on the basis of the observed energy spacings. These γ-rays also appear in individual coincidence spectra even though they are very weak. Coincidence spectra gated on the three new candidates themselves are too weak to be conclusive. Thus, there is a need for further confirmation from the analysis of the γ–γ–γ triple events. The highest part of the coincidence spectrum obtained from the cube by placing double gates on known SD band members is shown in fig. 2a, and compared with the double coincidence spectrum in fig. 2b. The triple coincidence spectrum confirms the presence of the transitions at 821 and 848 keV and makes the assignment of the highest transition at 874 keV plausible, but not certain. The intensity pattern for all the SD transitions, as obtained from the 341 keV coincidence gate, is shown as an inset in fig. 1. While the relative intensity of the highest transition known previously (792 keV) is 14% with respect to the intensity of the 381 and 458 keV transitions (normalized to 100%), the respective intensities for the three new γ-rays are only 8%, 5%, and 2%. Thus, the feeding of the highest new SD state reported here corresponds to less than 0.04% of the total γ-ray intensity flowing through the ^{192}Hg. Finally, minor differences between the earlier reports [4,9] on the ^{192}Hg SD band were examined on the basis of the present data set. A 215 keV γ ray, for which there was no conclusive evidence in ref. [4], was proposed as the bottom transition of the SD band in the work of ref. [9]. No indication for this transition could be found in the triple coincidence data discussed here. On the other hand, the weak decay branch from the SD structure into the 10^+ yrast presented in ref. [9] is confirmed by the present analysis, albeit with an intensity smaller than that originally reported by a factor of ~ 2.

The results presented above allow an examination of the behavior of the dynamic moment of inertia $\mathscr{J}^{(2)}$

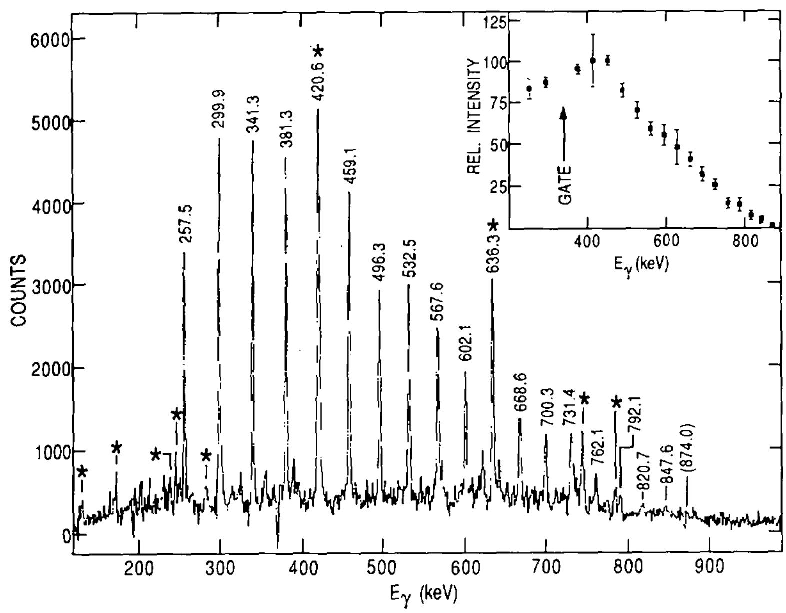

Fig. 1. γ-ray spectrum in ^{192}Hg obtained by summing the cleanest coincidence gates placed on the 257, 300, 341, 381, 496, and 602 keV transitions in the γ-γ coincidence matrix described in the text. Known ^{192}Hg yrast transitions [4] are identified with an asterisk. The inset shows the relative intensity of the SD lines as measured in the 341 keV coincidence spectrum.

at rotational frequencies $\hbar\omega \geqslant 0.4$ MeV. A comparison between the data and the calculations of refs. [7,10] is presented in fig. 3. In contrast with the expectations based on cranked-Strutinsky models, $\mathcal{J}^{(2)}$ keeps rising over the entire $\hbar\omega$ range. This observation points to the need to question the alignments indicated by the model and to reexamine the underlying physics.

As stated above, cranked shell model calculations have been quite successful in explaining some of the general features related to superdeformation near $A=190$, and there is reason to believe that they address some of the physics correctly. For example, there is little doubt that the important high-N intruder orbitals have been identified properly: they have a major impact on the average value of $\mathcal{J}^{(2)}$ which is reproduced properly in all SD bands near $A=190$. In fact, the shell structure in the vicinity of the Fermi surface appears to be well understood as the measured excitations in the second well are reproduced satisfactorily using quasiparticle diagrams derived with the cranked Strutinsky approach [1]. From comparisons between neighboring odd and even nuclei, there is also compelling evidence that pairing plays a significant role in the SD bands of this region. For example, the observed differences in the behavior of $\mathcal{J}^{(2)}$ with $\hbar\omega$ in ^{193}Tl and ^{191,192}Hg can be accounted for satisfactorily when blocking arguments are invoked: see refs. [1,5,14] for a detailed discussion. Within the cranked shell model, variations of several parameters which influence the evolution of $\mathcal{J}^{(2)}$ with $\hbar\omega$ have been explored. Small changes in the deformation parameters β_2 and β_4 allowed by the lifetime measurements of Moore et al. [10] result in minor changes in the frequency at which the high-N proton and neutron intruders align. These changes will, however, not delay the downturn of $\mathcal{J}^{(2)}$ beyond the frequency range under consideration. The importance of octupole correlations in this SD region has been demonstrated recently [15–17]: both experiment and calculations suggest strong octupole correlations in ^{193}Hg. The effects of introducing a static octupole deformation β_3 has been studied recently in the case of ^{190}Hg [18] and similar conclusions apply for ^{192}Hg. The interaction strength between crossing levels increases with β_3 for neutrons and decreases for protons. Again, the effects on $\mathcal{J}^{(2)}$ remain small and are unable to account for the con-

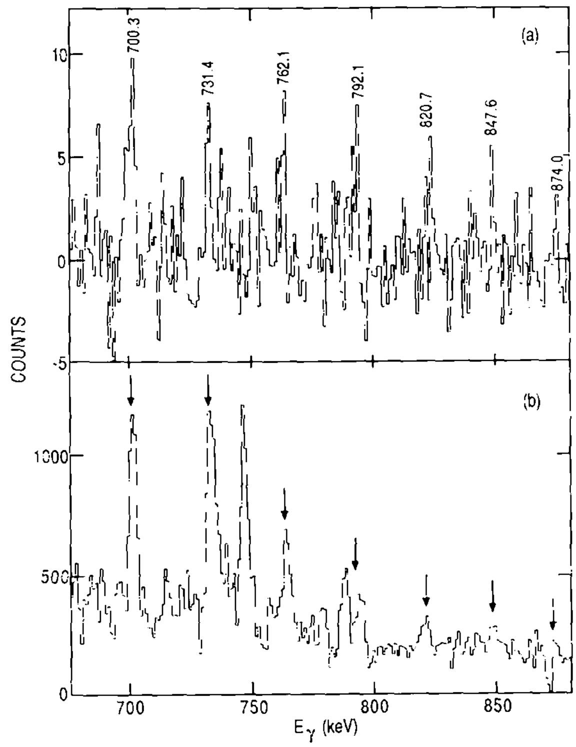

Fig. 2. (a) High energy part of the summed coincidence spectrum obtained from the triple coincidence cube (see text for detail). (b) Enlarged section of the γ-ray spectrum of fig. 1 is shown for comparison.

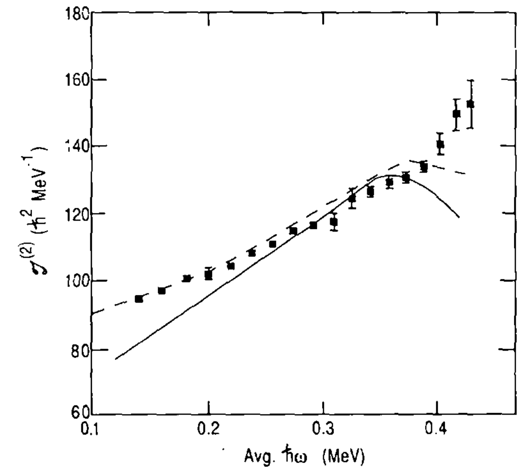

Fig. 3. Comparison between the measured and calculated (solid line from ref. [10], dashed line from ref. [7]) dynamic moments of inertia $\mathscr{J}^{(2)}$ as a function of rotational frequency $\hbar\omega$ in the SD band of ^{192}Hg. As customary for this type of figure, the frequencies are calculated from the average of two consecutive transition energies.

tinued smooth rise with $\hbar\omega$. In ref. [18] it was proposed that a strong residual neutron–proton interaction may be present which would result in a lowering in energy of the yrast SD configuration with respect to all other orbitals and would shift the interaction frequency. The shift implied by the present ^{192}Hg data is much larger than the one envisaged in ref. [18] and is hard to justify without detailed calculations which are currently lacking.

In most cranked-shell model calculations which attempt to reproduce the evolution of $\mathscr{J}^{(2)}$ with $\hbar\omega$ in the $A=190$ region, the most critical parameter appears to be the monopole pairing strength. In order to reproduce $\mathscr{J}^{(2)}$ values in ^{191,192,194}Hg, the neutron pairing strength had to be reduced considerably (to 30% of its ground state value), while the proton strength was kept at its groundstate value or was even slightly enhanced [5,6,10]. However, a similar scaling of the pairing could not reproduce the data for the SD band in ^{190}Hg (see ref. [18] for details). These observations show that pairing has thus far mainly been treated as a parameter for which a detailed microscopic treatment is not yet available. Reduced pairing is to be expected on the basis of general arguments. Pairing is sensitive to the overlap between orbitals of interest. At very large deformation, states originating from different shells approach the Fermi surface, and these states should have a reduced coupling through the pairing interaction. If the monopole pairing strength is indeed reduced, higher order corrections such as quadrupole pairing may become important. Efforts to explore this possibility are currently under way for the SD nuclei [19,20]. We note that higher order corrections have already been found to be important for the $j_{15/2}$ orbital at normal deformation in actinide nuclei [21].

To summarize, the new analysis of data on the SD band of ^{192}Hg has shown that the dynamic moment of inertia $\{\mathscr{J}^{(2)}$ keeps rising with rotational frequency beyond the point where cranked Strutinsky calculations predict a downturn. This suggests a need for a better understanding of pairing at large deformations.

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