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Highly deformed nuclear shapes: Recent results from experiment and theory

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1. INTRODUCTION

Evidence for the existence of excited states in nuclei which are associated with highly deformed (superdeformed) shapes has been available for over thirty years. The first examples were discovered in the actinide region as fission isomers. Strutinsky, using his shell correction method, showed that these isomers represented states in a secondary minimum of the nuclear potential corresponding to large quadrupole deformations [1]. One had to wait until 1986 and the identification of the first superdeformed (SD) rotational band in ^{152}Dy [2] for another SD region to be discovered, even though, theoretical calculations predicting the existence of other regions had been available for some time. The quadrupole deformation of this rotational band was shown to be as large as that of the fission isomers with a major to minor axis ratio for the prolate nucleus of 2:1. Since this discovery, SD rotational bands have been found in Ce–Nd nuclei around mass 130 [3] and in Hg–Pb nuclei near mass 190 [4] with major to minor axis ratios of 1.5:1 and 1.7:1, respectively.

While much theoretical and experimental work has been done over the past several years on SD nuclei, a new era in the study of nuclei at high angular momentum has begun with the recent construction of three large γ-ray spectrometers: GAMMASPHERE, EUROGAM and GASP. The contributions to this conference of P. Twin [5] and D. Bazzacco [6] discuss the EUROGAM and GASP devices, respectively. GAMMASPHERE is currently being assembled at the Lawrence Berkeley Laboratory's 88" cyclotron. When completed it will consist of 110 Compton suppressed Ge (CSGe) detectors with relative efficiencies ranging from 70 to 85% allowing for the efficient detection of 4 and 5 fold CSGe coincidence events. The spectrometer has been operating in the Early Implementation configuration since March of 1993 and currently consists of 36 CSGe detectors. The next phase of the spectrometer will begin in the fall of 1994 with 50 CSGe detectors, and all 110 detectors should be in place by the fall of 1995.

Since the new arrays, when fully loaded, are characterized by a gain in detection sensitivity of better than an order of magnitude over previous capabilities, these instruments are especially suitable for the study of SD bands which are weakly populated in heavy-ion induced fusion reactions. It is in fact very encouraging that, even though, GAMMASPHERE and EUROGAM have operated at 30-40% of their full capacity, unexpected new results have already emerged and the remainder of this paper, as well as the contributions of P. Twin and D. Bazzacco [5,6], will discuss several of these.

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2. THE DECAY OF SUPERDEFORMED BANDS

One of the outstanding experimental problems in the study of SD nuclei concerns their decay to the ground state. In both the mass 150 and 190 regions, the behavior of all SD bands with respect to their decay is essentially the same, i.e. after a long sequence of in-band transitions, a rapid decay out occurs over 2–4 states, and transitions linking the SD band to known levels in the first well are unobserved. As a result, the excitation energy, spin and parity of the levels in the SD well are unknown. Theoretically, two different mechanisms for the decay have been suggested. The first proposes that statistical mixing between states in the SD well and highly excited states in the first well is responsible for the depopulation of the SD band, and if correct, the resulting decay spectrum would have a statistical shape [7,8]. The other suggests that the decay is governed by the overlap between the collective wavefunctions of states in the two wells, and the predicted decay spectrum would consist of discrete E2 transitions directly connecting near-yrast and SD states [9].

Many groups have searched without success for experimental evidence of discrete transitions connecting the SD band to the known states. However, a recent study of the SD band in ^{143}Eu [10] has presented evidence for 5-6 "sum peaks" in coincidence with the SD band. These sum peaks are extracted from 3-fold CSGe data by requiring one of the three detected γ rays to be a member of the SD band, summing the other two transitions and histogramming the result. Since the excitation energy of the SD band is a constant, the sum spectrum could contain peaks associated with a two-step decay of the SD band towards the yrast line. The sum peaks of ref. [10] are observed at the 1.5 σ level with energies ranging between 3.15 and 3.95 MeV. These peaks place the excitation energy of the first level in the SD band at 8.582 MeV. The probable spin of this level is given as $35/2\hbar$ and lies 3.635 MeV above the yrast $35/2\hbar$ state.

While the procedure described above has deduced the excitation energy of the SD band in ^{143}Eu, it has not yielded information concerning the nature of the decay. A recent experiment at EUROGAM has attempted to answer this question by measuring the total spectrum of γ rays coincidence with the SD band of ^{192}Hg [11]. This spectrum was obtained from three-fold gamma coincidence data by requiring two of the observed γ rays to be members of the SD band and histogramming the third transition into a one-dimensional spectrum. The final spectrum, shown in the top panel of fig. 1, was generated by performing proper background subtraction for 3-fold coincidences and correcting for neutron interactions, coincident summing, detector response and photopeak efficiency. The spectrum associated with the decay of the SD band is shown in the bottom panel of fig. 1 and results from subtracting the following components from the total spectrum: (1) lines associated with γ-ray transitions between levels in the SD band and between states in the first well; (2) components associated with the feeding of the SD band namely an E2 bump peaking around 600 keV and a low energy M1/E2 distribution; and (3) a simulated statistical E1 component (smooth curve in the top panel). This statistical component must be calculated, since it is not discernable from the decay spectrum, and the model used has been shown to reproduce all observables associated with the feeding of the SD band in ^{192}Hg [12].

The decay spectrum shown in fig. 1 exhibits a statistical distribution and supports the

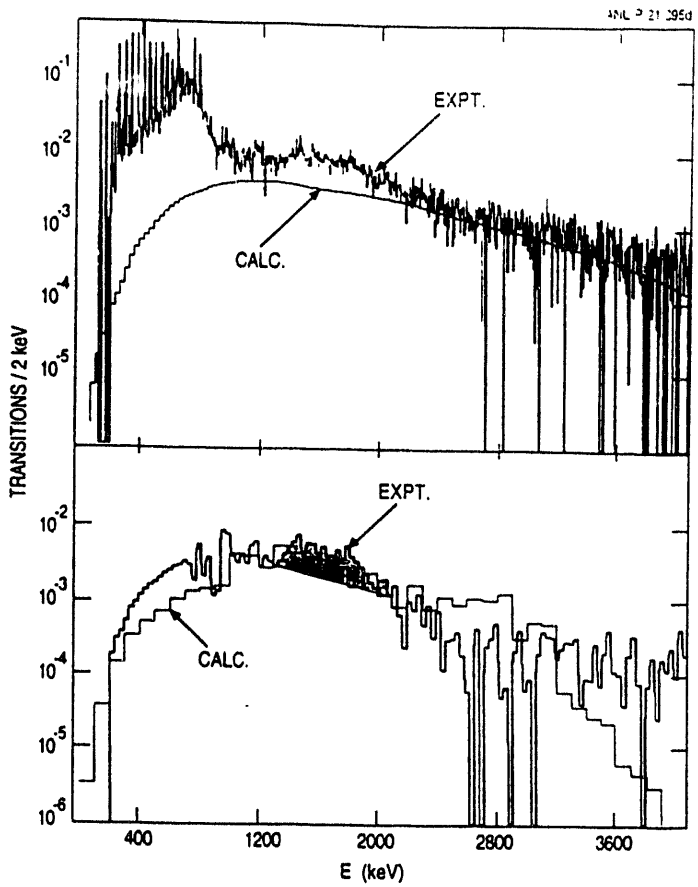

Figure 1. The top panel shows the total spectrum in coincidence with the SD band of ^{192}Hg. Also shown is the calculated E1 statistical spectrum which feeds the SD band. The bottom panel shows the spectrum attributed to the decay of the SD band (compressed relative to total). Also given is the spectrum calculated by Dossing using a model which self-consistently treats the weakening of pairing with increasing number of quasiparticle excitations.

suggestion of refs. [7,8] that the decay of the SD band is governed by the mixing of SD states with highly excited levels in the first well. Other quantities extracted from the spectrum are: (i) the average number of transitions in the decay of the SD band to the yrast line (3.2 $\pm$ 0.6), and (ii) the excitation energy and spin of the SD band at the point of decay (4.3 $\pm$ 0.9 MeV and 10.1$\pm$ 0.7$\hbar$). The decay spectrum also contains a noticeable bump between 1.3 and 2.2 MeV (shaded region) which sits on top of the statistical spectrum. A recent calculation by Dossing based on a model which self-consistently treats the weakening of pair correlations with increasing number of quasiparticle excitations is able to reproduce the decay spectrum including this bump as illustrated in fig. 1 [13] . In the calculation, the bump arises from a combination of transitions from the sequential steps of the de-excitation cascade and from the last step of the decay where the statistically fed continuum states must cross the pair gap to the ground band.

3. A NEW RESULT ON IDENTICAL BANDS

One of the more fascinating aspects to come out of the study of SD nuclei is the discovery that nuclei which differ by one or two mass units can have SD bands with nearly identical transition energies over large spin intervals of 20–30$\hbar$. Presently, a number of examples have been discovered in both the A=150 and A=190 regions [4]. Also, a re-examination of existing data has shown that so-called identical bands also occur at normal deformation. However, the spin range over which the bands are identical is more restricted than in the SD case. [14,15]

While many examples of identical bands have been uncovered, there is at present no universally accepted description of these observations. Theoretical suggestions range from the possible manifestation of a new symmetry [16] to subtle cancellation effects between mass and pairing terms in the collective hamiltonian [17], from the continuous readjustment of the self-consistent mean field with angular momentum [18] to a balance between residual p-n and pairing interactions [19]. One clue to the manifestation of this phenomenon accompanied the identification of the first pair of identical SD bands found between ^{152}Dy and ^{151}Tb [20]. It was pointed out in ref. [21] that within the strong coupling limit of the particle rotor model a rotational band in ^{151}Tb could have identical transition energies with ^{152}Dy if (i) it is built on an intrinsic excitation with Ω=1/2, (ii) has a decoupling parameter of a=+1 and (iii) has an identical moment of inertia to that of the core. It was further shown that the value a=+1 is achieved for the ^{151}Tb case if the pseudo SU(3) coupling scheme is valid at large deformation.

Also in ref. [21], it was pointed out that an orbital with Ω=1/2 and a= −1 in the pseudo SU(3) representation is located near the Fermi surface in the neutron single-particle system at the SD shape for ^{151}Dy. In the asymptotic limit, the energies in the SD band corresponding to this excitation would lie half way between the γ-ray energies of the SD band in ^{152}Dy. Subsequently, a number of experiments were performed to look for this band without success.

Recently, ^{151}Dy has been re-examined at GAMMASPHERE. In addition to the previously known SD band reported in ref. [22], four new SD bands have been identified in this nucleus. One of new these bands is shown in fig. 2 along with the original SD band of ^{152}Dy. In the bottom panel of the figure, the energy differences between the average of consecutive transitions in ^{152}Dy and the γ rays observed in ^{151}Dy are presented while the differences in γ-ray energy of transitions in ^{152}Dy and the excited SD band in ^{151}Tb are shown in the upper inset. As fig. 2 indicates, the transitions in ^{151}Dy are very close to the midpoint energies of the ^{152}Dy SD band, and the degree of similarity is the same as that seen in the (^{151}Tb*, ^{152}Dy) case. Thus, it has been proposed in ref. [23] that this band in ^{151}Dy corresponds to an excitation involving the [3$\tilde{1}$0]1/2 pseudospin orbital coupled to the ^{152}Dy core and marks the first identification of an SD band with a decoupling parameter a=−1. As advocated in ref. [21], this result can be regarded as further evidence for the presence of the pseudo SU(3) symmetry at extreme conditions of large elongation and high spins. Whether an interpretation in terms of this symmetry provides a general explanation for all identical bands for only to a selected subset of nuclei in the vicinity of ^{152}Dy remains to be established.

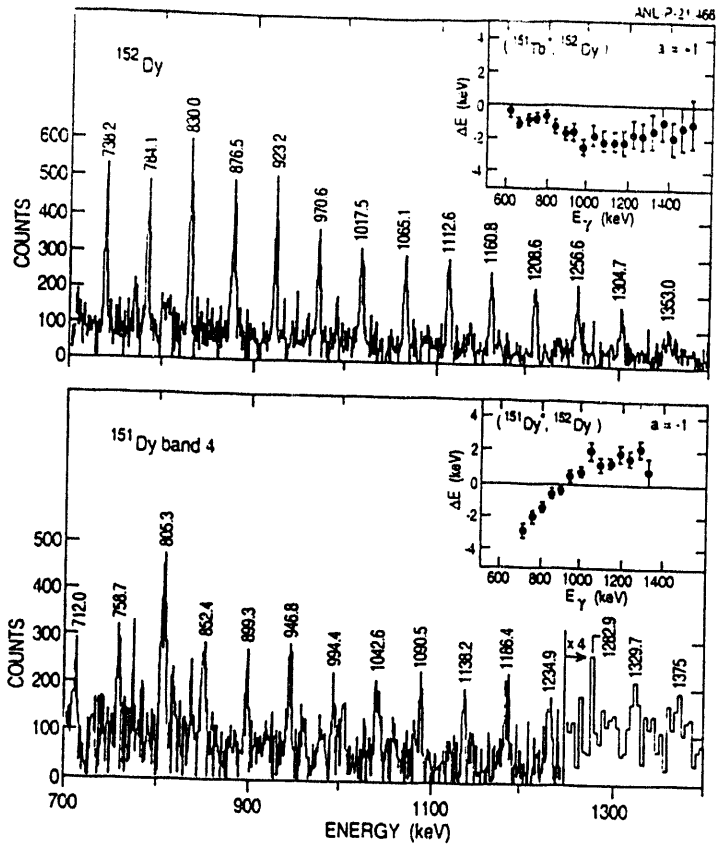

Figure 2. Spectra for the SD band in ^{152}Dy (top panel) and the pseudospin band of ^{151}Dy (bottom panel). The inset in the top panel shows the difference in transition energy for the (^{151}Tb*,^{152}Dy) pair. The energy differences presented in the inset of the bottom panel were obtained by subtracting the average energies of consecutive transitions in ^{152}Dy from the γ-ray energies of the pseudospin band of ^{151}Dy

4. PAIRING IN THE SECOND WELL

In the study of nuclei at high spin, information about the intrinsic structure of a rotational band can be inferred from various quantities which depend on either the excitation energy or the angular momentum of the individual rotational levels in the band. Unfortunately, these quantities are generally not known for SD nuclei, and, as a result, bands are usually represented by a quantity referred to as the dynamical moment of inertia $\mathcal{J}^{(2)}$. This quantity is equivalent to the second derivative of the excitation energy with respect to spin ($\frac{d^2E_x}{dI^2}$). Experimentally, it is represented as $4/\Delta E_\gamma$ where ΔE_γ is the energy difference between successive transitions in a rotational band.

The evolution of the dynamic moment of inertia as a function of $\hbar\omega$ ($\omega = E_\gamma/2$) for SD bands in the mass 150 region is characterized by pronounced isotopic and isotonic variations which have been attributed to differences in the occupation of specific high-N intruder orbitals, namely $j_{15/2}$ neutrons and $i_{13/2}$ protons [24]. This realization represented one of the early theoretical successes in understanding the underlying single-particle nature of SD bands. In contrast, the vast majority of the SD bands in the mass 190 region display the same smooth and rather pronounced increase of $\mathcal{J}^{(2)}$ with $\hbar\omega$. It is generally

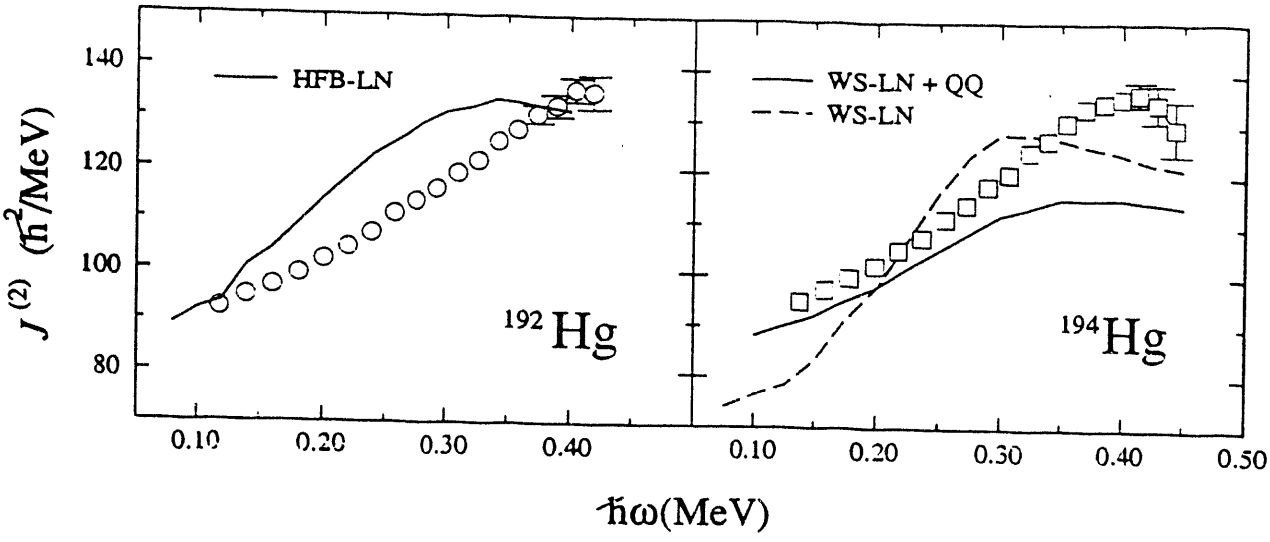

Figure 3. Dynamic moments of inertia for the yrast band in ^{192}Hg (left panel) and ^{194}Hg (right panel) as a function of $\hbar\omega$. For ^{192}Hg, results from a Hartree-Fock-Bogoliubov cranking calculation using the Lipkin-Nogami approach (HFB-LN) are compared with the data [25]. For ^{194}Hg, results from a cranked Wood-Saxon calculation + Lipkin-Nogami with (solid line) and without quadrupole pairing (dashed line) are presented [27].

accepted that this rise is due to quasiparticle alignments of the same high-j intruder orbitals referred to above. Thus, it is even more of a surprise that identical SD bands are found in a frequency range where such dynamical effects are taking place.

Recent results from GAMMASPHERE and EUROGAM have extended the yrast SD bands in ^{192,194}Hg to higher spins [25,26]. The resulting dynamic moments of inertia are shown in fig. 3. For ^{194}Hg, the SD band shows a leveling off and a subsequent decrease in $\mathcal{J}^{(2)}$ at the highest frequencies. For ^{192}Hg, a leveling off at the highest spins is clearly present. This observation has been predicted by standard cranked shell-model calculations with pairing, but always at lower frequencies than observed. From a theoretical viewpoint, this change in $\mathcal{J}^{(2)}$ indicates at which rotational frequency the quasiparticle alignments have been completed.

Two new sets of theoretical calculations have attempted to (i) reproduce the new data, and (ii) address deficiencies of previous calculations. The first set are cranked Hartree-Fock-Bogoliubov calculations using a Skryme type interaction in which monopole pairing is calculated self-consistently using the Lipkin-Nogami approach. Results from these calculations are shown in fig. 3 for ^{192}Hg. The overall agreement with experiment is quite good, however, the calculation rises too quickly with respect to the data, and this is attributed to the early alignment of the quasiparticles.

The other set of calculations [27] is an extension of the cranked Wood-Saxon calculations performed for example in ref. [26] (dashed curve in fig. 3) and include a quadrupole pairing (QQ) term in the Hamiltonian. It has been suggested that such a term may be important

for SD nuclei where states originating from different shells approach the Fermi surface at very large deformations. These states should have a reduced pairing interaction. If the monopole pairing strength is reduced significantly, higher order corrections, which are configuration dependent, may play an important role. The results of these new cranking calculations are shown in fig. 3 (solid line) for the ground SD band in ^{194}Hg. As the figure shows, the addition of the QQ term leads to an increase in $\mathcal{J}^{(2)}$ at low frequencies bringing the calculated values in line with experimental results. One also observes in the calculation a reduction in alignment of the high-j orbitals and a slight shift to higher $\hbar\omega$ of the $j_{15/2}$ crossing frequency. Overall, the agreement with experiment is quite good but there is a clear discrepancy at the higher frequencies which is linked to the reduced alignments.

Whether such higher order pairing effects are needed in the Hartree-Fock calculations remains to be seen. If they are not necessary, the two approaches would be at odds with one another. Our ability to account for identical bands in the mass 190 region may well rest on the degree with which the rise of the moments of inertia in these bands, the role of pairing and of quasiparticle alignments can be understood.

5. EVIDENCE FOR VIBRATIONAL EXCITATIONS IN THE SUPERDEFORMED WELL

There are many instances in the A=150 and A=190 regions where two or more SD bands are observed in the same nucleus. The band which is populated with the highest intensity is assumed to correspond to the yrast band, while the other bands have been described quite successfully as excited bands built on quasiparticle or particle-hole excitations. In contrast, there has been no evidence until recently for SD bands built on collectively vibrating band-heads. This has been somewhat of a surprise since rotational bands associated with quadrupole and octupole vibrations are commonplace features of nuclei at normal prolate deformation. Several recent theoretical investigations have suggested that collective octupole vibrations play a significant role in the SD wells of the A$\sim$150 and A$\sim$190 nuclei due to the presence near the Fermi surface of many pairs of orbitals with opposite parity and $\Delta l = 3$ [29–31].

Recent evidence for an SD band built on an octupole vibrational state has been presented following an experiment performed at GAMMASPHERE. In this study, states in the SD well of ^{190}Hg were populated, and the analysis of the data showed conclusively that a second SD band is decaying into the yrast SD states over at least three levels. Also, the transitions linking these two SD bands have been tentatively identified. Such a pattern of decay is unlike any observed for SD states. Based on the branching ratios to the yrast SD band, the multipolarity of the linking transitions has been given an E1 assignment and transition matrix elements of approximately $8\times10^{-}3$ Weiskoff units have been deduced. This E1 rate is three orders of magnitude larger than that typically observed in heavy deformed nuclei, but similar to those observed in the octupole-unstable actinide nuclei. It is also in agreement with calculations for the neighboring nucleus ^{192}Hg which predict a strength of 11×10^{-3} W.u. for transitions from an octupole-vibrational state in the SD well to the yrast SD band [29,31]. As a result, ref. [28] has suggested that the excited SD band in ^{190}Hg is, in fact, built on a one-phonon octupole vibration in the SD well.

6. SUMMARY

Even though the new γ-ray spectrometers have been in use for only a short period of time and at less than 50% of their full capacity (for EUROGAM and GAMMASPHERE), interesting new results have emerged. Outstanding questions concerning the decay of SD states, the role of pseudospin in identical bands, the nature of pairing in the second well, and the presence of vibrational states at large deformation have already been addressed. The future looks very promising and more challenges lie ahead. For example, new calculations [32] looking at systems with even larger deformations indicate that hyperdeformed nuclei should be accessible to experiments.

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