IDENTICAL BANDS: WHAT IS NEW FROM LARGE ARRAYS? *

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The phenomenon of identical bands is studied by analyzing the distributions of fractional changes in the dynamical moments of inertia for pairs of bands in superdeformed (SD) nuclei. These distributions show that there exists a significant excess of identical bands in SD nuclei compared to normally-deformed nuclei at low spins. This is attributed to the weaker pairing correlations and the stabilizing role of intruder orbitals on the structures of SD bands. To go into further details, precise level lifetimes have been measured for various superdeformed bands in ^{148,149}Gd and ^{152}Dy with the Doppler-shift attenuation method. From the derived quadrupole moments, Q_0, we find large differences in deformation between the yrast bands and some excited bands in the gadolinium isotopes. Moreover, two of the excited Gd bands and the ^{152}Dy yrast band, which have identical moments of inertia, have similar Q_0 moments, supporting the picture that alignment and deformation effects cancel in identical bands. Calculations performed with the cranking-Hartree-Fock model show that the charge moments calculated with respect to the doubly magic SD core ^{152}Dy can be written as independent contributions from the individual orbitals.

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1. Introduction

The discovery, some years ago, of different rotational bands which have nearly the same moments of inertia has been one of the most challenging problem in the domain of low-energy nuclear physics. The first example of such pair of bands was found [1] in superdeformed (SD) nuclei of the rare earth region using the TESSA3 gamma-ray spectrometer. This exciting finding was followed by other examples, firstly at SD shapes and, secondly

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in normally deformed nuclei [2–4], raising the question of the influence of nuclear superfluidity. Indeed, due to the presence of an odd particle, the pairing correlations are expected to be reduced leading to an increase of 10–15 % in the moments of inertia of odd-A nuclei. The observation of identical bands (IB's) in adjacent nuclei is, therefore in contradiction of such an effect. Since then, the new generation of highly efficient gamma-ray arrays began to be operational (Eurogam, Gammasphere, and Ga.Sp) and a large number of experiments have been performed in order to learn something about the puzzle of IB's. The question is then: what have we learnt on IB's from these large arrays ? Indeed, with the availability of larger set of data on IB's (especially in the mass regions $A \sim 130$, $A \sim 150$, and $A \sim 190$), it is possible to address several questions: first, is there an excess of IB's at SD shapes compared to normal deformed nuclei, or not? Second, if the answer is positive, can it be traced back to if significant differences were observed, can they be correlated any shell effects or other specific properties manifesting in SD nuclei? In this contribution, I shall try to answer these questions by means of a statistical approach [5]. In the second part I shall go further into details through lifetime measurements of some pairs of IB's and, finally make a point on the latest related developments in theory.

2. A statistical approach

As I said, the avalaible dataset made possible new investigations, and in particular, it is now possible to see whether there is a surplus of IB's in SD nuclei compared to normally deformed ones. Indeed, with a statistically significant dataset, it is expected to observe a "certain number" of IB's. The question is then: is the number of IB's observed in SD nuclei sufficiently larger than this "statistical quantity"? To address this question we first have to define a criterion in order to *measure* the similarity of two bands and second, to set conditions on it to *decide* about their sameness. Many parameters have been used to assess the similarity between two bands. In this work, since the physics of IB's is intimately related to masses, we have adopted the most general definition that two bands are identical if they exhibit an anomalously small difference (as defined later) in their $\mathcal{J}^{(2)}$ moment of inertia ($\mathcal{J}^{(2)}$ is defined as $4/\Delta E_\gamma$, where ΔE_γ is the difference in the energies of two consecutive γ rays in a band composed of stretched E2 transitions.) To determine the degree of similarity of band (n) in nucleus X and band (m) in nucleus Y we have evaluated the fractional change (FC) in their $\mathcal{J}^{(2)}$:

$$FC_{\mathrm{X(n),Y(m)}} \equiv \left[\mathcal{J}^{(2)}_{\mathrm{X(n)}} - \mathcal{J}^{(2)}_{\mathrm{Y(m)}}\right] / \mathcal{J}^{(2)}_{\mathrm{X(n)}} = \Delta\mathcal{J}^{(2)} / \mathcal{J}^{(2)}_{\mathrm{X(n)}} \,.$$

Furthermore, in order to conserve the physical meaning of the sign of FC, the nucleus Y, to which the reference band belongs, was taken to be the lighter of the two nuclei. Adopting this definition, there exists a special subset of IB's which consist of bands having the same γ-ray energies (*isospectral*) or which have (as shown later) a half-integer or integer relative alignment. Thus any element of this subset form identical bands, whereas the inverse is not always true.

Since $\mathcal{J}^{(2)} = dI/d\omega = 4/\Delta E_\gamma$ where $\hbar\omega = E_\gamma/2$ is the rotational frequency and $i(\omega) = I_{\mathrm{X(n)}}(\omega) - I_{\mathrm{Y(m)}}(\omega)$ is the alignment, then:

$$FC_{\mathrm{X(n),Y(m)}} = di/dI_{\mathrm{X(n)}}\,.$$

The quantity FC has the advantage of being independent of the *absolute* spin I. Instead, it depends only on the relative spin alignments of the two bands. Since the absolute spin values of SD bands have not yet been experimentally determined, one can alternatively use the effective spin alignment:

$$i_{\mathrm{eff}} = i \bmod 1 = \overline{FC}_{\mathrm{X(n),Y(m)}} I + i_0\,.$$

In this work, we have extracted $\overline{FC}$ via a linear least-squares fit to i_{eff}. This technique is particularly relevant when comparing the moments of inertia of SD bands which typically consist of long cascades (~15 transitions on average) of γ rays. In order to select IB's, we ensure a good quality of the least-squares fit procedure by requiring the standard deviation to be less than 0.05. When local discontinuies originating from band interaction, backbending effects, etc... have some influence on the global behaviour of $\mathcal{J}^{(2)}$, we allow at most 20% of the data points to be removed from the fit. Finally, to be identical, the $\overline{FC}$ of the two bands must be less than half the expected change in the moment of inertia of two rigid bodies due to their mass difference (ΔA).

The available dataset consisted of 54 SD bands in the mass $A \sim 150$ region and, 45 SD bands for mass $A \sim 190$. By comparing *each* band with *all* the other ones, we generate 1250 (790) pairs of bands in the mass $A \sim 150$ (190) region. Among these, 32% (61%) exhibit a good linear fit and 6% (12%) are found to be identical. The resulting $\overline{FC}$ distribution obtained in the two mass regions are shown in Fig. 1. These all exhibit a nearly Gaussian peak centered at $\overline{FC}\sim 0$.

In SD nuclei in the mass $A\sim150$ region, pairing correlations are believed to be greatly reduced [7, 8]. Consequently, the labelling of SD bands in this region in terms of high-$\mathcal{N}$ intruder occupation quantum numbers is relevant. ($\mathcal{N}$ is the principal oscillator quantum number and the intruder orbitals are those orbitals which originate from the higher-lying shells which

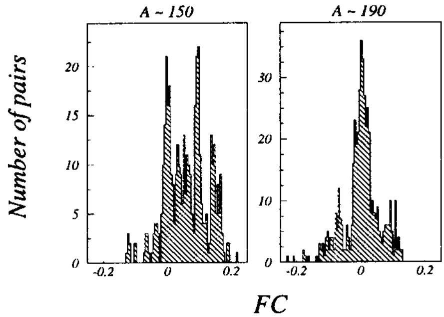

Fig. 1. Distributions of average fractional changes ($\overline{FC}$) in the moments of inertia of pairs of SD bands in the mass $A{\sim}150$ and $A{\sim}190$ regions. All possible pairs of bands belonging to nuclei in a given region which could be fitted with a standard deviation of $\sigma < 0.05$ are shown in these plots.

have a larger $\mathcal{N}$.) For example, the yrast band ^{152}Dy(1), and the excited bands ^{151}Tb(2) and ^{151}Dy(4) in the adjacent nuclei all contain 4 protons from the $\mathcal{N}$=6 and two neutrons from the $\mathcal{N}$=7 shells. (This configuration will be denoted as $\pi 6^4 \nu 7^2$.) In this mass region, as shown in Fig. 1, only a small number of pairs have negative values for $\overline{FC}$, indicating that the moments of inertia are indeed generally increasing with mass. In Fig. 2, the number of pairs of IB's is plotted as a function of the mass difference which extend up to $\Delta A = 7$ with a maximum at $\Delta A = 2$. Using configuration assignments based on cranked shell model calculations, [7, 9, 10] it appears that 85% of the 73 pairs of IB's have the same high-$\mathcal{N}$ intruder content. In adjacent nuclei, this high-$\mathcal{N}$ content is preserved by the creation of a single particle or hole in a low-$\mathcal{N}$ orbital, the usual situation for excited bands. This explain why most of the IB's are found to have a difference of two mass units.

Another interesting feature observed in Fig. 1 is the presence of two other well defined peaks centered at $\overline{FC} \sim 0.10$ ($\overline{FC} \sim 0.16$). Surprisingly, the vast majority of the pairs that comprise these peaks differ by 2 (3) high-$\mathcal{N}$ orbitals, irrespective of their mass difference. Again these correlations clearly highlight the predominant influence of the high-$\mathcal{N}$ orbits on the moments of inertia of SD bands in the mass $A \sim 150$ region.

In a second step, we restrict the comparison to adjacent nuclei ($A_{\rm Y} = A_{\rm X} - 1$) with the additional requirement that at least one of the bands has to be yrast in either nucleus $A_{\rm X}$ or $A_{\rm Y}$. The distribution of $\overline{FC}$ values obtained in this case is plotted in Fig. 3. Again all the 17 pairs of IB's comprising the peak at $\overline{FC} \sim 0$ are predicted to have the same structure in terms of high-$\mathcal{N}$ content. Another unexpected result is the other distinct peak centered at

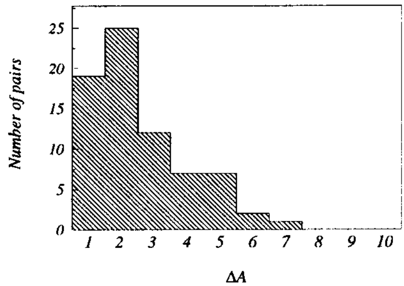

Fig. 2. Histogram of mass difference distribution ΔA for pairs of IB's. The maximum of the distribution is reached for $\Delta A = 2$ where 25 pairs of bands are found to be identical.

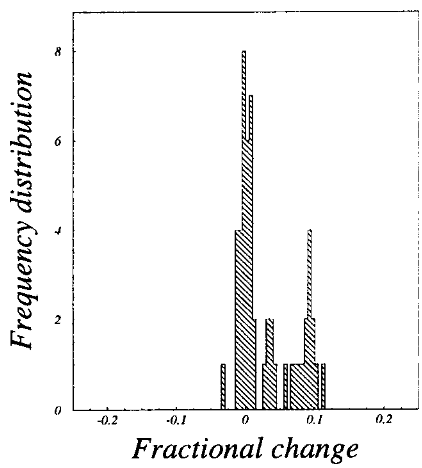

Fig. 3. Distributions of average fractional changes ($\overline{FC}$) in the moments of inertia of pairs of SD bands in the mass regions A~150. Bands in a nucleus X with mass A_X are compared with bands in the neighbouring nucleus with A_X-1, one of the bands being restricted to the yrast configuration.

$\overline{FC} \sim 0.10$ even though the mass difference is only $\Delta A = 1$. Therefore, just at the opposite of the IB phenomenon, this value is one order of magnitude too large.

A similar analysis has been performed in the mass region $A \sim 190$ leading to different conclusions. The distribution of $\overline{FC}$ for all possible pair combinations is plotted in Fig. 1. In contrast to what is observed in the rare earth region, it exhibits a single symmetric broad peak centered at $\overline{FC} \sim 0$. Also many negative values are observed and no secondary structures emerge. Finally many of the pairs that are found to be identical are predicted to have very different configurations. These results show that most of the active orbitals have a constant alignment and that the condition of identical high-$\mathcal{N}$ content is no longer a good criterion for selecting IB's. This means that the configuration-mixing interactions are strong enough to smooth out the single particle occupancy reducing the predominant influence of the intruder orbitals. Another factor is that these latter orbitals have larger K-values in the Hg-Pb region compared to the Gd-Dy one (K is the projection of the single-particle angular momentum on the symmetry axis). These intruder orbitals, therefore, do not significantly change the deformation of the core and are only weakly influenced by the Coriolis interaction.

But the key question remains: do we have a surplus of IB's in SD nuclei? To address this question we have to define a "good" reference. We have used the study described in Refs. [11, 6]. The results of these two surveys have been combined to obtain the distribution of $\overline{FC}$ values for the odd-A normal-deformed bands (neutron numbers $\mathcal{N}$=90-109 and proton numbers Z=62-78).

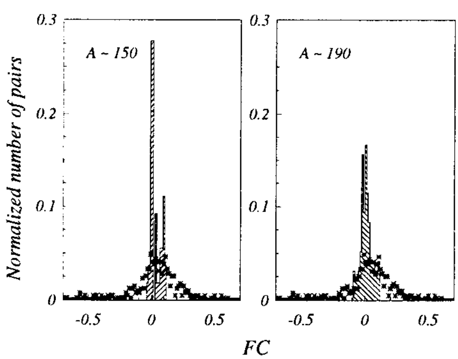

Fig. 4. Distributions of average fractional changes ($\overline{FC}$) in the moments of inertia of pairs of SD bands in the mass regions A~150 (left) and A~190 (right). Bands in a nucleus X with mass A_X are compared with bands in the neighbouring nucleus with A_X-1, one of the bands being restricted to the yrast configuration. The stars show the corresponding distribution for nearly 400 odd-A normal-deformed bands in the rare-earth region. All three distributions are normalized separately to have a total count of one.

In Fig. 4, this distribution (stars) is superimposed on the corresponding distributions of $\overline{FC}$ values for SD bands in the A~150 and 190 regions. This histogram, represents an approximately Gaussian distribution centered around $\overline{FC}\simeq$5%, which is considerably wider than that for the SD bands. The most striking feature is the presence of a clear excess of IB's in SD bands as compared to the low-spin normal-deformed bands. Again, this difference can be attributed to pairing correlations: the present analysis of the odd-A rare-earth bands covers the low-spin states where pairing correlations are indeed very important.

To summarize, the distributions of fractional changes in the moment of inertia of both SD and normally-deformed bands are found to exhibit a nearly Gaussian peak centered at approximately zero. The widths of these distributions increase from 0.025 for SD bands in $A\sim150$, to 0.05 for SD bands in $A\sim190$, to 0.28 for normally-deformed bands in the rare-earth region. As a result, there exists a large excess of identical bands in SD nuclei compared to normally-deformed nuclei at low spins. This is attributed to the increasing strength of pairing correlations. The rotational structures in the $A\sim150$ mass region, which correspond to large deformations and very high spins, are very diabatic. This means that their underlying shell structure (*i.e.*, their high-$\mathcal{N}$ intruder content) is clearly reflected in their moments of inertia. Indeed, there exists a very nice correspondence between the theoretical single-particle shell structure, occurrence of IB's, and the observed fine structures (peaks) in the distribution of fractional changes. Consequently, the weak coupling limit (the situation where the valence particles or holes are passive spectators) is met more often than previously anticipated. At lower angular momenta and smaller deformations, the picture becomes more adiabatic and bands lose their individuality. This is also the case in the $A\sim190$ SD bands where configuration mixing due to pairing correlations smears out the individuality of each band.

3. Lifetime measurements in the rare earth region

Even though many excited SD bands are known in the mass $A\sim150$ region, which allow the previous statistical analysis to be preformed, very little is known on their properties. For example, because of their weaker intensities compared to the yrast SD structures, lifetime measurements were not possible until now. Such experiments are even more crucial since the remarkable discovery of pairs of IB's with almost identical $\mathcal{J}^{(2)}$-values in nuclei which differ by one to several mass units (see Fig. 2.). The Gd isotopes are of particular interest from this point of view since several of these excited bands are IB's. For example the pairs $\{^{152}Dy(1), ^{149}Gd(4)\}$ and $\{^{152}Dy(1), ^{148}Gd(5)\}$ are found to exhibit $\overline{FC}$ values very close to 0. By measuring accurately the lifetimes of SD levels in ^{152}Dy and ^{148,149}Gd isotopes we can investigate whether the predicted deformation changes associated with different single-particle configurations do indeed exist. Furthermore, a precise quadrupole moment determination of the yrast SD band in ^{152}Dy will enable us to establish the deformations associated with IB's in nuclei differing by 3 and 4 mass units. To measure the lifetimes of SD states

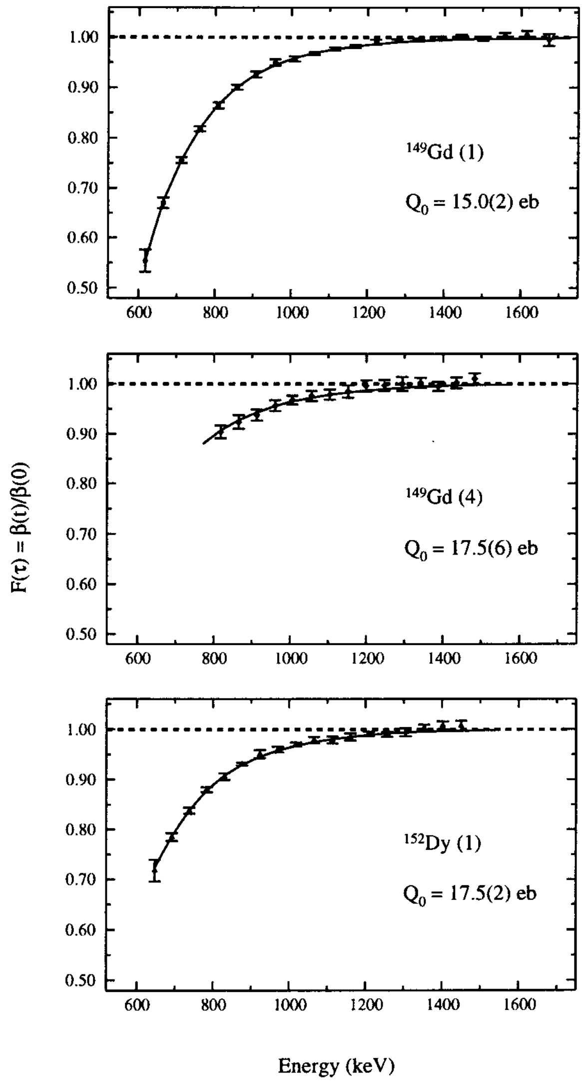

Fig. 5. Measured fractional shifts F for SD bands in ^{149}Gd and ^{152}Dy together with the calculated fractional shifts for a constant in-band quadrupole moment indicated in each panel (see [12]). Centroid shifts were determined by comparing γ-ray triple-gated coincidence spectra measured at $\theta = 22°$ and $158°$ or $\theta = 46°$ and $134°$. The measured F-values were obtained from double-gated γ-ray spectra in the case of ^{152}Dy(1).

we have used the Doppler Shift Attenuation Method (DSAM) [12]. Because these lifetimes are expected to be less than 200 fs, the γ-rays connecting SD states are Doppler shifted as a function of the angular position relative to the beam axis (θ), and the recoil velocity of the emitting nucleus ($\beta(\mathrm{t})$). By accurately measuring these shifts, it is possible to deduce the fractional shift:

$$\mathrm{F}(\tau) = \beta(\mathrm{t})/\beta(0)\ ;\ \mathrm{E}_\gamma(\theta_i) = \mathrm{E}_{\gamma 0}(1+\beta(0)\mathrm{F}(\tau)\cos(\theta_i))\ ,$$
$$\mathrm{F}(\tau) = (\mathrm{E}_\gamma(\theta_1) - \mathrm{E}_\gamma(\theta_2))/\mathrm{E}_{\gamma 0}\beta(0)(\cos(\theta_1) - \cos(\theta_2))\ .$$

An experimental F-value represents the average recoiling velocity and hence the mean time at which a given level depopulates. To extract a lifetime for this particular nuclear state, it is necessary to know the time history over which it is fed. In the plateau region, where the SD transitions have relative intensities of $\sim$ 100%, the problem greatly simplifies since the population of the levels proceed via observed states. In our experiments the initial recoil velocities of the ions and stopping media were either identical or very similar: ^{124}Sn(^{30}Si,5n)^{149}Gd, ^{124}Sn(^{30}Si,6n)^{148}Gd and, ^{120}Sn(^{36}S,4n)^{152}Dy. Therefore, there will be cancellation of some systematic errors, such as the uncertainty in the stopping powers, when relative Q_0-values are compared. Experimental F-values for SD bands in ^{149}Gd and ^{152}Dy are plotted in Fig. 5 as a function of the γ-ray energies of the SD transitions. To calculate F-values, the side-feeding has been simulated by constructing a rotational band on each SD state. These bands had a common moment of inertia and their intrinsic quadrupole moment $(Q_0)_{SF}$ could be varied from band to band. The intensity of each side-feeding band was constrained to reproduce the experimental values. The best fits to all bands require $(Q_0)_{SF} \simeq 15$ eb in a short cascade of no more than two or three transitions (for more details on how the slowing down history of the recoils was treated can be found in Refs. [12]).The analysis of the decay curves proceeded from the top of the bands. The free in-band and side-feeding quadrupole moment parameters $(Q_0)_B$ and $(Q_0)_{SF}$ were varied in a 2-dimensional minimization of χ^2 for the F-values in a particular band. Microscopic calculations using the Nilsson–Strutinsky cranking model and the modified oscillator potential with the parametrization of Ref. [13] have been performed. The extracted theoretical values for Q_0 at spin $I \sim 40\ \hbar$ are listed in Table I together with the experimental values. In general, the calculated values are larger than the measured ones by approximately 10%. Because of experimental uncertainties on the absolute values, this discrepancy is not serious, and we have concentrated on relative values.

The quadrupole moment for the yrast band in ^{149}Gd is found to be 15.2 $\pm$ 0.2 eb which is significantly less than the values, 17.5 $\pm$ 0.6 eb and 17.8 $\pm$ 1.3 eb for ^{149}Gd(4) and ^{148}Gd(5) respectively. Starting from

^{152}Dy, we can remove particles in upsloping equatorial orbitals, making configurations assigned to *excited* bands in lighter nuclei. The most extreme case is ^{148}Gd(5) where we predict a very large deformation $\varepsilon_2 \approx 0.618$ for ^{148}Gd(5) which is much larger than that of the yrast band, ^{148}Gd(1). These data most elegantly illustrate the polarisation effects of the occupation of the high-$\mathcal{N}$ orbitals on the SD shape.

Finally, one of the main issues is whether IB's have the same deformation or whether deformation changes compensate [14] the alignment brought in by the extra particle(s)? In the present data, the extracted quadrupole moments for ^{148}Gd(5), ^{149}Gd(4) and, ^{152}Dy(1) are equal within the uncertainties. Nevertheless, this does not mean that they have the same deformation. Just the opposite, although the calculated deformation is smaller in ^{152}Dy than in the IB's of ^{148}Gd and ^{149}Gd, we obtain very similar quadrupole moments, (Table I). This supports the picture that alignment and deformation effects cancel [14] in IB's.

TABLE I

Q_0 quadrupole moment values (in eb) derived for SD bands in ^{148,149}Gd and ^{152}Dy compared with calculated values at spin $I \approx 40\ \hbar$. The quadrupole deformation ε_2 is also indicated.

		Q_0(exp)	Q_0(calc)	ε_2
^{149}Gd	Band 1	15.0 (2)	16.5	0.555
	Band 2	15.6 (3)	16.7	0.556
	Band 3	15.2 (5)	17.4	0.576
	Band 4	17.5 (6)	19.3	0.612
^{148}Gd	Band 1	14.6 (2)	16.0	0.545
	Band 2	14.8 (3)	16.0	0.545
	Band 5	17.8 (13)	19.6	0.618
^{152}Dy	Band 1	17.5 (2)	18.9	0.582

4. Some insights in theory

From the theoretical point of view, calculations of multipole moments have been performed in the Dy region [15]. In this work, both quadrupole and hexadecapole moments have been calculated in the cranking Skyrme–Hartree–Fock model. More than 200 SD bands have been analyzed using the SkM* and SkP effective interactions. This study indicates that the proton quadrupole moments (Q_{20}) show very weak dependence with rotational frequency in the range $\hbar\omega \sim 0.2 - 0.5$ MeV for either the positive and the negative signature nuclear orbits.

For reasons as yet unclear, the calculations systematically overestimate by $\sim$ 10% the measured Q_{20} values. This is also true for Nilsson–Strutinsky [12] and relativistic mean-field [16] models. The experimental absolute values also suffer from a sytematic 10–15% error from stopping powers. Thus, to avoid these large uncertainties Satula et al. alternatively used the relative values defined as :

$$\delta Q_\lambda(\mathrm{X(n)}) = Q_\lambda(\mathrm{X(n)}) - Q_\lambda(^{152}\mathrm{Dy}(1))\,.$$

This quantity "measures" the particle/hole polarizabilities and can be compared with relative experimental values since, as described previously, it is sometime possible to eliminate some systematic errors. As shown in Ref. [15] the agreement between measurements and theoretical predictions is excellent. This work also indicates that the results are very similar using SkM* or SkP. But the most interesting point is that $\delta Q_{20}(\mathrm{X(n)})$ can be written as a sum of independent contribution from single-particle/hole states around ^{152}Dy. This means that the relative charge multipole moments can be described by the "extreme shell model" formula:

$$\delta Q_{20}(\mathrm{X(n)}) \simeq \sum_{[Nn_z\Lambda]} \delta Q_{20}^{[Nn_z\Lambda]}\,.$$

This approximation works surprisingly well since the quoted deviation is less than 0.04 eb for more than 90% of the SD bands considered in this work. As already shown in the $\overline{FC}$ analysis, this additivity of polarization effects confirms that SD bands around ^{152}Dy are a perfect example of an almost unperturbed single particle- motion.

5. Conclusions

As a general conclusion, it has been shown that the phenomenon of the IB's is definitely relevant since there is a clear excess of IB's in SD nuclei compared to normal-deformed nuclei at low spins. The $\overline{FC}$ analysis has also shown that the shell structure of SD nuclei in the mass $A \sim 150$ region is very well reflected in the moments of inertia, a situation which is very different in the mass $A \sim 190$ region. Through the lifetime measurements, it has been shown that IB's have identical Q_0's implying different quadrupole deformations. Again, the particular role of the high-$\mathcal{N}$ orbitals has been underlined since they are at the origin of strong polarization effects on the SD shape. Finally, an analysis looking at the contribution of each single-particle/hole states to the total multiple moments of SD nuclei in the rare earth region has been performed in the same spirit as for the $\overline{FC}$ analysis. This shows that "extreme shell model" works very well around the ^{152}Dy core. This however remains to be investigated for the $\mathcal{J}^{(2)}$ moments of inertia by comparing the experimental $\overline{FC}$ with a theoretical reference.

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