SUPERDEFORMATION IN THE MASS 150 REGION: NEW RESULTS WITH THE EUROGAM ARRAY*

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New and unexpected results have been obtained with the Eurogam spectrometer. In the mass 150 region, several excited superdeformed bands have been discovered which show that models implying a scaling of the moment of inertia with mass are difficult to justify locally. The decay-out mechanism has been studied in detail through a systematic investigation of nuclei for which accurate data are available. This study shows that the high-N intruder configurations play a major role in the deexcitation process. A very weak perturbation on the yrast superdeformed energy levels of ^{149}Gd has been measured and this observation may be interpreted as the remnant of a quantum number associated with a 4-fold symmetry.

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1. Introduction

The first experimental evidence for the existence of superdeformed (SD) shapes, corresponding to an elongated ellipsoid with an axis ratio close to 2:1, came with the discovery [1] of fission isomers in 1962. About five years later, these exotic shapes were associated [2] with a second minimum in the potential energy surface originating both from shell correction effects and a reduced contribution of the Coulomb force due to a larger average separation between protons. In lighter nuclei it has been suggested [3] that this latter contribution can be caused by the increasing influence of the Coriolis force at high spins and calculations predicted a deep second minimum at high angular momentum in nuclei in the vicinity of proton and neutron shell

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closures $Z = 66$ and $N = 86$, respectively. At high rotational frequency, the orbitals which have a high intrinsic angular momentum, empty at zero deformation, often dive very close to the Fermi surface and, may even become yrast. The occupancy of these so-called "high-N intruder" orbitals ($N = 6$ proton and $N = 7$ neutron in the mass 150 region) have such a strong influence on the behaviour of SD nuclei that we can classify the SD configurations in terms of high-N intruder labelling [4]. For example, the configuration of the first SD band which has been found [5] in the nucleus ^{152}Dy can be noted as $\pi 6^4 \nu 7^2$ (4 protons in $N = 6$ orbitals and 2 neutrons in $N = 7$ orbitals).

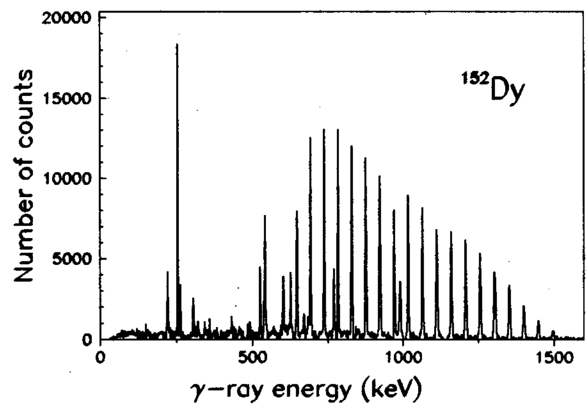

Fig. 1. γ-ray spectrum of the first SD band observed in ^{152}Dy. This spectrum has been obtained from 3-fold Eurogam coincidences with an additional trigger on the delayed γ rays emitted by the 60 ns isomer.

The experimental signature of the SD structure observed in this nucleus is shown in Fig. 1. It consists of a long γ-ray cascade of about 20 transitions exhibiting a highly rotational behaviour with a very regular energy spacing between two successive γ rays of the order of $\Delta E_\gamma \sim 50\,\mathrm{keV}$ in the mass 150 region. Up to now, no discrete transitions between normal deformed (ND) and SD states have been established. This means that it is presently not possible to assign spins and parities to SD energy levels and thus, the only observables which can be used in order to compare experiment and theory are the γ-ray energies and the intensities of the transitions.

To overcome this problem we define the dynamical moment of inertia, by analogy with classical mechanics, noted $\Im^{(2)} = 4/\Delta E_\gamma$ which has the enormous advantage to be independent of spin. This quantity is obviously very sensitive to the spacing between two consecutive γ rays and, also, to the high-N intruder orbital occupancy. We call "excited SD band" a band which is located at higher excitation energy compared to the yrast

SD band. These excited SD bands are based on the promotion of one (or more) particle up to an orbital lying at higher excitation energy compared to the yrast configuration. In the following pages, the yrast band will be noted band 1, the first excited band 2, *etc.* ... and they are labelled in brackets following the nucleus (*e.g.*: ^{152}Dy(1) is the yrast band of ^{152}Dy). In the mass 150 region, 12 yrast SD bands and 31 excited bands have been discovered so far (status in August 1993), with the advent of the large γ-ray array Eurogam that I shall briefly describe in the next section.

2. The Eurogam array

Funded jointly in the frame of a France-U.K. collaboration, the Eurogam array [7] in its phase 1 version has been operational at Daresbury Laboratory until March 1993. It was composed of 45 large volume Ge detectors of about 70% relative efficiency, compared to a 3"×3" NaI, at a γ-ray energy of 1.33 MeV. Each Ge detector was surrounded by bismuth germanate scintillator (BGO) to efficiently suppress the γ rays scattered from the Ge detector to the BGO shield. This leads to a peak-to-total ratio of about 0.55 with a cobalt source and to a full energy peak efficiency of $\sim$ 4.5% for the 1.33 MeV cobalt line. With this high efficiency, it is possible to select 3, 4 and even 5 coincident γ rays (resp : γ^3, γ^4 and γ^5) to study in detail the nuclear structure at extreme rotational frequencies. The possibility to set multiple gates (2, 3 or 4), considerably improves the resolving power of the device [8]. This resolving power represents the ability of an array to "extract" a peak from the background.

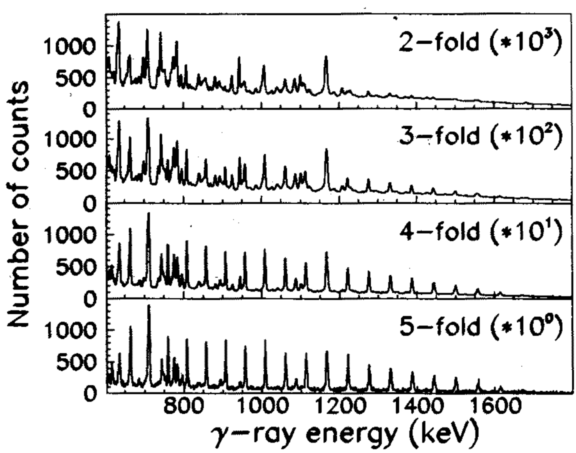

Fig. 2. Single,double,triple and quadruple gated γ-ray spectrum of ^{149}Gd(1) band. The resolving power is strongly improved when the required fold is increased by one unit, but at the same time the statistics is reduced by a factor of 10.

In order to have an idea of the power of a multidetector like Eurogam, linked to the high efficiency and to the use of high fold coincidences, Fig. 2 represents the ^{149}Gd(1) band [9] analysed using γ^2, γ^3, γ^4 and γ^5 data. The effect of increasing by one unit the required fold is a loss of about one order of magnitude in statistics, but the peak-to-backround ratio is strongly improved and thus we have to find the best compromise between the improvement of the quality and the loss of statistics. In the following studies, we have essentially used the 4-fold coincidences.

3. Identical bands

Two SD bands are called "identical bands" when they have a similar $\Im^{(2)}$ moment of inertia and if they are composed of γ rays with the same energies within 2 keV. More generally, two SD bands observed in nuclei A and B are called identical if their γ rays are linked by the relation:

$$E_\gamma^A(I') = E_\gamma^B(I) + k\Delta E_\gamma^B(I)\,, \tag{1}$$

with $k = 0; {}^1\!/_4; {}^1\!/_2$ or ${}^3\!/_4$. This means that the γ-ray spectra for these two SD bands are the same with an offset being a quantized amount of the spacing between two successive γ rays. The first example of identical bands had been found [10] in the ^{151}Tb–^{152}Dy isotopes and initiated a wide effort of theoretical groups all over the world.

But what is the problem? Most of the models used to describe the atomic nucleus involve a scaling factor in mass for the moment of inertia $\Im \sim mR^2 \sim A^{5/3}$. This scaling in mass can be tested quantitatively with γ-ray energies and for two nuclei differing by one mass unit around $A = 150$ we have:

$$\frac{\Delta\Im}{\Im} = \frac{\Delta E_\gamma}{E_\gamma} \sim 0.01\,. \tag{2}$$

Experimentally we are able to measure a difference of less than 2 keV in the same mass region which leads to $\Delta E_\gamma / E_\gamma \sim 0.001$ and, thus, the discrepancy between measurement and calculations reaches a factor of 10. Several theoretical arguments have been put forward to explain this identity between ^{151}Tb(2) and ^{152}Dy(1) such as pseudo-SU3 symmetry [11], supersymmetry [12], quantized pseudo-spin alignment [13], continuous readjustment of the self consistent mean field [14], cancellation of terms which contribute to the $\Im^{(2)}$ [15], ... but no definitive explanation has yet emerged. One can also say that this case is just a coincidence.

But using the Eurogam spectrometer, we have performed an experiment with the goal to study the ^{149}Gd nucleus *via* the ^{124}Sn(^{30}Si,5n)^{149}Gd reaction at a beam energy of 158 MeV. Seven excited SD bands have been identified in this nucleus, and it appears that for each of these bands we can find an yrast SD band (the reference) which has a very similar $\Im^{(2)}$ [16]. Even more intriguing Table I lists the values of the k coefficient obtained by comparing the γ-ray energies of one excited SD band of ^{149}Gd and its yrast SD band of reference.

TABLE I

Comparison of the identity of bands 3 to 8 of ^{149}Gd with yrast bands of neighbouring nuclei. The value of the k coefficient indicates that the offset between the two compared γ-ray spectra is always a quantized amount of the spacing between two successive γ rays.

Compared SD bands	k coefficient
^{149}Gd(3) / ^{150}Tb(1)	0
^{149}Gd(4) / ^{152}Dy(1)	3/4
^{149}Gd(5) / ^{152}Dy(1)	1/4
^{149}Gd(6) / ^{148}Gd(1)	3/4
^{149}Gd(7) / ^{150}Tb(1)	1/2
^{149}Gd(8) / ^{150}Tb(1)	3/4

It is clear now that the first observed case is not just a coincidence and the experimental evidence of a quantized phasing between two different nuclei with a difference in mass of three units (^{149}Gd(4) and ^{152}Dy(1)) is totally unexpected. Furthermore, ^{152}Dy(1) and ^{153}Dy(2) are identical; this shows that three holes $(2p-1n)$ and one particle $(1n)$, which is a difference of four units of mass, have the same effect on ^{152}Dy core. This indicates that if the scaling of the moment of inertia with mass in $A^{5/3}$ is correct in a first approximation it is certainly not valid locally.

4. Decay-out

The decay-out is certainly one of the poorly known aspects in the field of superdeformation and many tentative experiments have been performed, unsuccessfully, to look for discrete transitions linking ND and SD states. Instead we chose to study the mechanism associated to the decay-out [17]. In a first step we focus on the ^{151}Tb experiment performed with Eurogam. We used the ^{130}Te(^{27}Al,6n)^{151}Tb reaction at a beam energy of 154 MeV, to produce the residual nuclei. The identity between ^{151}Tb(2) and ^{152}Dy(1) has been extended and it is maintained, on average, to about 1.3 keV over 20 transitions. We used the alignment approach of Ragnarsson [18] to assign a set of absolute spins to the bands and this enables a comparison of the change in their relative excitation energy as function of spin. The intensity of band 2 is about half of that of band 1 and therefore it lies at higher excitation energy in the feeding region. Assuming that the two bands have the same excitation energy at $I = {}^{129}/_2\hbar$, which is conservative, data show (Fig. 3) that band 2 is over 500 keV in excitation energy when it decays out. This surprising effect is certainly related to structure effects since it indicates that the excitation energy in the 2nd potential well is not the predominant factor for deciding the spin at which an SD band de-excites.

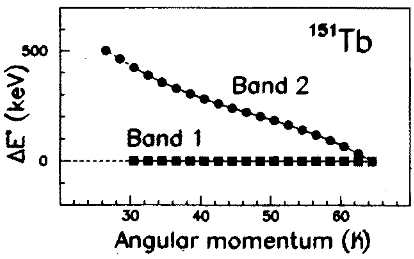

Fig. 3. Relative excitation energy (ΔE^*), plotted as a function of spin, between the yrast (band 1) and the first excited (band 2) superdeformed bands in ^{151}Tb, assuming that the bands have the same excitation energy at the highest spin of 64.5 $\hbar$. To extend the comparison to the lowest spins, the dynamical moment of inertia of the yrast band has been smoothly extrapolated.

The relative intensities of the γ rays in band 2 have been accurately measured and the comparison with ^{152}Dy(1) shows that they are identical within experimental uncertainties [17]. Because the statistical distribution is expected to be different [19], this is another surprise which shows that the distribution of states in the first well has very little effect on the decay-out mechanism. Instead we conclude that there is strong evidence for the high-N intruder configuration to play a major role.

In a second step, in order to investigate these surprising features, we have extended our analysis to neighbouring nuclei. We define the decay-out spin as being the spin of the state emitting the transition with about 20% intensity. The de-excitation patterns of SD bands for which we have accurate enough data [17], are shown in Fig. 4 as function of spin. In the bottom panel of Fig. 4, we find SD bands with configuration $\pi 6^n \nu 7^1$, with $n = 1$, 2 and 3, and all of them de-excite at the same spin of $\sim$ 25.5 $\hbar$. This means that the decay-out is insensitive to the occupancy of the high-N proton orbitals and therefore to the shape of the barrier between the ND and the SD potential wells. All the bands of the top panel of Fig. 4 have a $\pi 6^n \nu 7^2$ configuration. Those with $n = 2$ or 3, complete their de-excitation 6$\hbar$ higher than the bands with the $\nu 7^1$ neutron configuration which leads to a decay-out spin of $\sim$ 32 $\hbar$. This difference in spin is certainly related to

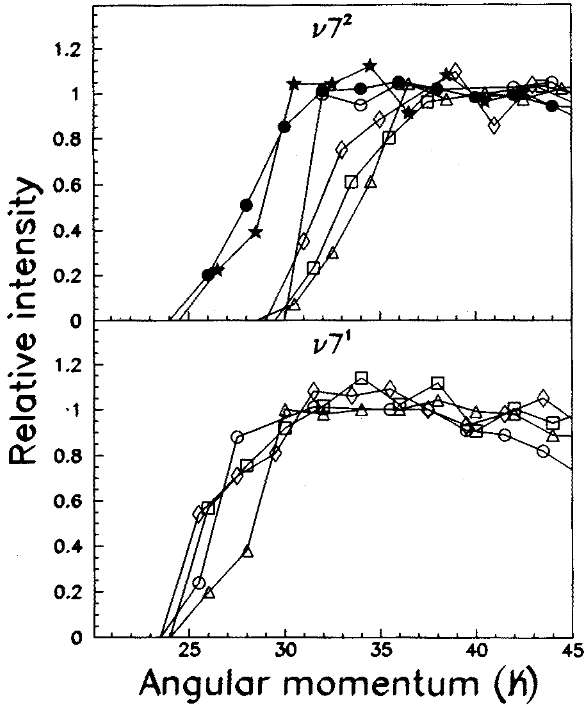

Fig. 4. De-excitation patterns of superdeformed bands in the $A \sim 150$ mass region as a function of spin for different high-N intruder configurations. The neutron intruder orbital occupancy is indicated at the top of each panel.

the occupancy of the high-$N = 7$ neutron intruder orbitals since the pairing forces are partially blocked for $\nu 7^1$ configuration whereas it is not the case when two neutrons occupy these $N = 7$ orbitals. But in this top panel we also find two SD bands with a $\nu 7^2$ intruder occupancy and a decay-out spin of $\sim 26\hbar$ instead of the expected $\sim 32\hbar$. These two SD bands are both associated with the doubly closed shell configurations $\pi 6^4 \nu 7^2$ which reduce the effects of pairing correlations and strongly stabilize the SD nuclei, driving down the decay-out spin.

From this extensive work implying a large amount of accurate data, we conclude that in the mass 150 region, the decay-out mechanism is strongly affected by nuclear structure effects and that pairing correlations play a predominant role in the statistical tunnelling mechanism.

5. Higher symmetry

This section is dedicated to the experimental observation [20] of a 4-fold symmetry in SD nuclei. I will concentrate again on the ^{149}Gd experiment and, even more restrictive, on the yrast band of this nucleus.

With the very high quality data set that we obtained, it is possible to determine the γ-ray energies within $\sim$ 0.1 keV. The plot of the $\Im^{(2)}$ moment of inertia as function of rotational frequency exhibits an anomalous staggering which is very regular from $\hbar\omega \sim 0.5$ MeV up to $\hbar\omega \sim 0.75$ MeV, and definitively outside the error bars.

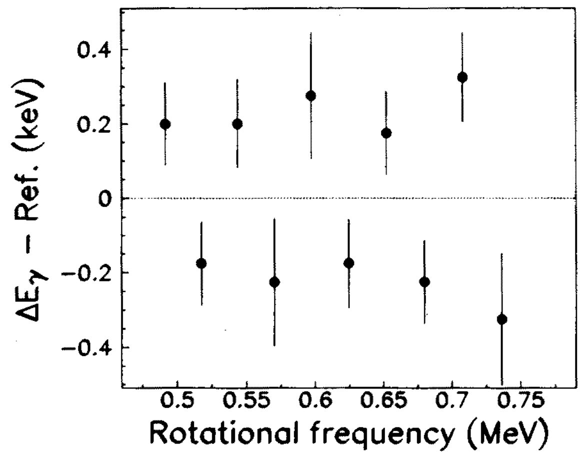

Fig. 5. Energy differences ΔE_γ between two consecutive γ-ray transitions of the yrast superdeformed band in ^{149}Gd as a function of rotational frequency after subtraction of a smooth reference (see text).

In order to determine the magnitude of these oscillations, we chose a smooth reference giving the unperturbed values for ΔE_γ^{ref} and located at the good angular momenta (which is not the case of the trivial arithmetic average between two successive points). The analytical expression for this reference is given by :

$$\Delta E_\gamma^{ref}(I) = \frac{\Delta E_\gamma(I-2) + 2\Delta E_\gamma(I) + \Delta E_\gamma(I+2)}{4} . \tag{3}$$

The plot of the difference $\Delta E_\gamma - \Delta E\gamma^{ref}$ (Fig. 5) clearly shows that it is alternatively positive and negative with a magnitude of 0.23 ± 0.06 keV. Certainly such an effect is due to a perturbation on the SD energy levels and it can be reproduced by an alternating shift of 0.12 ± 0.03 keV of the γ-ray energies of ^{149}Gd(1) compared to the unperturbed transitions of the reference. The corresponding perturbation on the yrast SD energy levels is half of this last value and we eventually get the scenario where the SD energy levels are alternatively shifted up and down by the same amount of $e \sim 58 \pm 11$ eV. (Considering the fact that the SD levels are located around $\sim 20 - 30$ MeV, the measured perturbation is of the order of $e/E^* \sim 10^{-6}$.)

Other exotic scenarios may exist which reproduce this experimental feature but, whatever the scenario is, the very important message is that the same perturbation occurs every second level ($4\ \hbar$). This indicates the remnant of a quantum number associated with a 4-fold symmetry, *i.e.* a system invariant by a rotation of $\pi/2$ around the rotation axis instead of the usual $\Delta I = 2\hbar$ for rotational states implying a symmetry of π. This C_4 symmetry could be generated by the coupling to the hexadecapole field.

6. Conclusion

The new and sometimes unexpected results obtained with Eurogam show that the possibility of using high fold coincidences with good statistics considerably enlarges the available domain of physics: we are now able to analyse in details nuclear structure effects and their consequences, and to measure, for example, perturbations of the order 10^{-6} on the Halmitonian of the system. However, several crucial points like the observation of the linking transitions between SD and ND states, the hyperdeformation or the entrance channel effects are still not clarified. With its large efficiency and high granularity, the Eurogam phase 2 array allows us to address soon these questions and to reach new domain of physics.

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