Proton Backbend in the Doubly-Magic Superdeformed Nucleus ^{144}Gd

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A discrete superdeformed rotational band has been discovered in ^{144}Gd following the reaction ^{100}Mo(^{48}Ti,4n)^{144}Gd at 221 MeV. The dynamical moment of inertia shows a sharp irregularity at $\hbar\omega=0.45$ MeV. The intensity of the γ-ray transitions suggests that the irregularity can be associated with a backbend, which is interpreted in terms of the $N=6$ proton band crossing. The experimental results are in good agreement with cranked mean field calculations, which indicate the presence of large shell gaps for both protons and neutrons.

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The occurrence of large shell gaps in atomic nuclei often reflects the existence of dynamical symmetries of the nuclear mean field. An example are the degeneracies of the deformed harmonic oscillator which become most pronounced at deformations where the oscillator frequencies are in the ratios of small integers, e.g., if $\omega_\perp/\omega_3=1{:}1$ (spherical shape), 1:2 (superdeformed), 1:3 (hyperdeformed), etc. [1]. Also in realistic nuclear potentials, like the modified harmonic oscillator (MHO) or Woods-Saxon (WS), the normal parity states form a pseudo-oscillator pattern [2,3]. Many basic features of the simple deformed harmonic oscillator model are retained, in particular the existence of shell gaps at the superdeformed (SD) shape. By extension of the concept used for spherical systems, certain nuclei can therefore be considered as doubly magic in the regime of superdeformation. The position (deformation, nucleon number) of these shell gaps, however, depends on the details of the model. Several cranked-Strutinsky calculations, using a WS potential [3-5], showed that ^{144}Gd, ^{152}Dy, and ^{192}Hg are the best examples for SD doubly-magic nuclei. Following these predictions superdeformation was in fact identified in ^{152}Dy [6] and ^{192}Hg [7]. The spectroscopy in the neighborhood of these nuclei turned out to be extremely rich and confirmed that very large shell gaps are present, at SD shape, for $Z=66$, $N=86$ and $Z=80$, $N=112$, respectively [8]. On the other side, none of the several attempts [9,10] performed in order to find SD bands in ^{144}Gd was successful and this case remained a challenge to the experimentalist.

Only very recently [11], two sequences of γ rays have been suggested as candidates for discrete SD bands in ^{144}Gd. However, the high-statistics dataset presented here, as well as a recent experiment performed at Daresbury [12], do not confirm the presence of these transitions. Several explanations were put forward to account for the failure in finding a SD band in ^{144}Gd: (a) The nucleus was populated [9] at a too high temperature, a condition which prevents the decay flow from being trapped in the second potential well; (b) an extremely low population of the SD band is expected in ^{144}Gd in accord with the observed almost linear decrease of the intensity of SD bands in Gd isotopes as the neutron number decreases [13]; (c) the strong band crossing predicted in ^{144}Gd at $\hbar\omega=0.45$ MeV [14] implies that the energy distance between two consecutive γ rays is far from being constant and that the "constant spacing" criterion used when searching for weak SD bands is not applicable. As a consequence of the failure to observe superdeformation in ^{144}Gd the question was also raised to what extent the predictions of large shell gaps at $N=80$ and $Z=64$ were correct.

Recently, in agreement with calculations of Refs. [14] and [15], the first evidence of SD bands in the mass $A=140$ region was obtained in the nuclei ^{143}Eu [16] and ^{142}Sm [17] which have the same neutron number 80 as ^{144}Gd. These results gave confidence that the advent of the new generation of γ-detector arrays (i.e., GASP, EUROGAM, and GAMMASPHERE), would allow one to prove the superdeformed character also of ^{144}Gd. In this Letter we report on the first discovery of a SD band in this nucleus. As predicted, the band shows a pronounced

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backbending at $\hbar\omega = 0.45$ MeV, while at higher frequencies it displays a remarkably constant energy spacing of about 55 keV between consecutive transitions. The $J^{(2)}$ moment of inertia above the crossing amounts to $72\hbar^2$ MeV^{-1} which is the highest value observed in the mass 140 region.

We have populated the nucleus ^{144}Gd through the reaction ^{100}Mo+^{48}Ti at a beam energy of 221 MeV. The target consisted of three self-supporting foils of ^{100}Mo with a total thickness of 1.1 mg/cm^2. The beam was provided by the Tandem XTU accelerator of Legnaro National Laboratories and gamma rays have been detected using the GASP array with all the 40 high efficiency Compton suppressed germanium detectors and the 80 bismuth germanium oxide (BGO) detectors of the inner ball in operation. Events were collected when at least 3 suppressed Ge detectors and 3 inner ball detectors fired in coincidence. With such conditions the event rate was ≈ 6 kHz with a beam current of 4 particle-nA and a 8 kHz singles rate in the germanium detectors. After unfolding, 3.2×10^9 and 1.7×10^9 events of doubles and triples data, respectively, were available for the off-line analysis. In order to search for discrete SD rotational bands, we have produced a γ-γ matrix from the doubles data requiring a multiplicity larger than 23 in the BGO ball. In this matrix (which contained 4×10^6 events) we could easily identify the known SD band of ^{143}Eu [16] which is produced strongly in the ^{100}Mo+^{48}Ti reaction after $p4n$ evaporation. A careful search performed channel by channel in the energy region 900–1300 keV revealed the presence of ≈ 10 mutually coincident transitions with an average spacing of ≈ 55 keV above 1 MeV. The spacing between consecutive γ rays was found to decrease to ≈ 40 keV at 0.9 MeV. In order to increase the selectivity of the analysis, the data have been sorted off line into a fully symmetrized cube with proper conditions on the fold and sum energy of the BGO ball. The spectrum of Fig. 1 has been obtained by gating twice on the transitions assigned to the band. Energies and relative intensities of the 14 γ rays of the new SD band are reported in Table I. The assignment of the band to ^{144}Gd follows from the observation, in coincidence with the band, of the strong ^{144}Gd lines lying above the 10^+ isomer [18,19]. The intensity of the 1139 keV transition, where the population of the band is almost constant at its maximum value, was estimated to be $\approx 0.2\%$ of the total population of the ^{144}Gd nucleus. The small intensity of the band can explain why it escaped detection in the previous experiments. With the same procedure outlined above, we have searched for the two possible sequences reported in Ref. [11], but the existence of these bands has not been confirmed. We note here that the observed intensity fits into the systematics of the SD band population in Gd isotopes [13] which shows an odd-even staggering and a decrease when going to lower mass number. Large shell gaps in the single particle spectrum are expected to yield a low excitation energy of the strongly deformed minimum relative to the absolute minimum and also a large well depth. Both these facts are important for the intensity of SD bands. The weak intensity of the ^{144}Gd band is therefore not understood and demands further study.

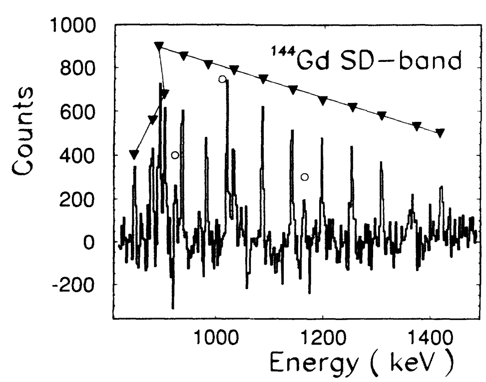

FIG. 1. Sum of double-gated coincidence spectra showing the SD band in ^{144}Gd. Gates have been set in the cube produced from the triples data on all transitions of the SD band between 892 and 1364 keV. The band members are marked by ▼ and known transitions in ^{144}Gd are denoted by ○.

From Fig. 1 it is evident that the band undergoes a backbending at $\hbar\omega = 0.45$ MeV, where the band intensity is still at its maximum (even if the errors reported in Table I are large, the 902 keV transition always shows an intensity lower than that of the 892 transition and accordingly we place it below the 892 transition). Two other transitions with energies of 846 and 879 keV always appear in coincidence with the band. Their intensity is also reported in Table I and we assign both lines to the SD band below the backbending. The decay out of the band is occurring over three transitions and starts just at the backbending.

TABLE I. Gamma-ray energies (E_γ) and intensities (I) for the ^{144}Gd SD band. The transitions are ordered following their position in the band.

E_γ (keV)	I/I_{933} (%)
846.3(7)	36(10)
878.9(4)	64(12)
901.7(2)	89(13)
891.7(3)	99(14)
933.3(2)	100
979.7(2)	93(12)
1031.0(3)	95(12)
1084.3(2)	100(12)
1139.6(3)	97(11)
1194.9(3)	72(10)
1250.5(4)	79(10)
1306.6(5)	69(11)
1363.9(7)	52(10)
1418.1(9)	34(12)

The SD bands have been classified according to the occupation number of high-N intruder orbitals, where N is the main oscillator quantum number [14,20]. In ^{152}Dy four protons occupy the $N=6$ $i_{13/2}$ orbital and two neutrons are in the $N=7$ $j_{15/2}$ one; in a short notation this is written as $\pi 6^4 \nu 7^2$. In the SD band of ^{144}Gd none of these high-N orbitals is occupied at low frequency. The second well arises essentially from the very favored shell structure at large deformation at $N=80$ and $Z=64$. However, when cranking the nuclear potential, the aligned $\pi 6^2$ configuration approaches the Fermi surface. The observed sharp band crossing in ^{144}Gd is thus interpreted as a crossing of the $\pi 6^0 \nu 7^0$ vacuum with the aligned $\pi 6^2 \nu 7^0$ configuration. The band crossing is very sharp, indicative of a small interaction between the two SD structures. The present experiment nicely confirms the predictions of Ref. [14], where this band crossing and the corresponding $J^{(2)}$ moment of inertia were discussed in detail. This is the first experimental observation of a backbend, related to the alignment of a proton pair, in a SD band. We mention here that very recently the first example of a backbend due to the alignment of a neutron pair has been reported in one of the excited SD bands of ^{149}Gd [21].

We have improved the calculations of Ref. [14], treating both deformation and pairing self-consistently. The energy in the rotating frame of reference (Routhian) is minimized on a deformation lattice and the pairing Hamiltonian is solved by means of the Lipkin-Nogami procedure at each deformation point and frequency [22]. Our results are shown in Fig. 2. The occupation of the aligned $N=6$ protons drives the nucleus to a more deformed shape, resulting in a jump in β_2 [Fig. 2(a)]. The change in β_2 is accompanied by a similar change in β_4 (0.047–0.051), not shown in our figure. In our model the sharpness of the crossing is directly related to the change in deformation. At larger deformation ($\beta_2 \approx 0.50$), the proton crossing is expected to be more smooth.

The middle panel shows the $J^{(2)}$ moment of inertia, directly extracted from our lattice calculations. According to the calculations, the $N=6$ protons cross the vacuum configuration at $\hbar\omega \approx 0.4$ MeV. There is further indication of a smooth hump in the neutron system, which relates to the alignment of $i_{13/2}$ neutrons. Experimentally this hump is not observed, implying that the neutron band crossing is more smooth or occurs at the same frequency as the corresponding proton crossing. Also in the isotone ^{143}Eu a similar alignment is expected but the experimentally observed $J^{(2)}$ moment of inertia is completely flat. However, as both protons and neutrons align the same kind of high-j quasiparticles, one might deal with residual effects not present in standard mean field calculations [23].

The next band crossing, which is predicted at $\hbar\omega = 0.75$ MeV, is related to the occupation of the aligned $N=7$ neutrons. Experimentally we see a small rise at the highest frequency, which could be taken as an indication of the onset of the next crossing. The present statistics, however, does not allow us to further speculate on this possibility. This crossing will drive the nucleus to an even larger deformation. The weakness of the intensity of the band might thus be related to a fragmentation of the SD band in the feeding region due to the $N=7$ neutron crossing. From the presence of the calculated large shell gaps it is not easy to understand otherwise why the intensity of the band is that small. We expect that more spectroscopic information might clarify this issue.

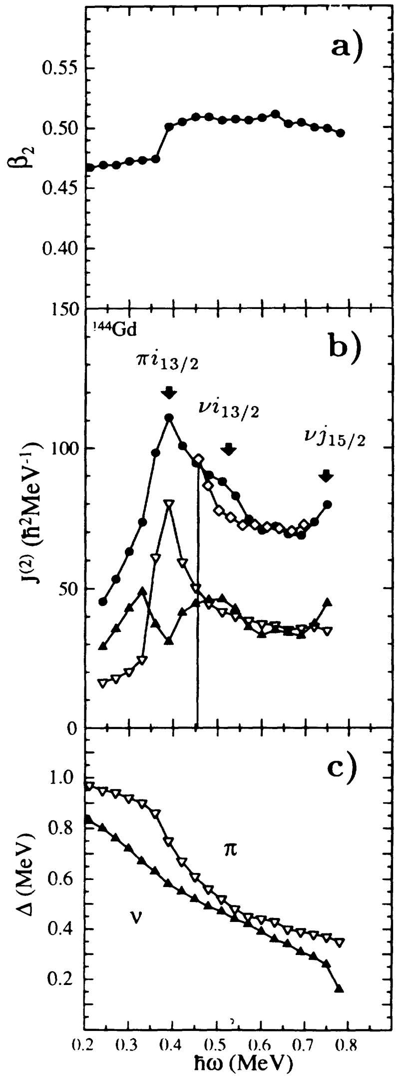

FIG. 2. Results of pairing and deformation self-consistent calculations for ^{144}Gd as a function of $\hbar\omega$: (a) Deformation trajectory (β_2) of the SD band; (b) experimental (◇) and calculated (●) dynamical moments of inertia. Proton (▽) and neutron (▲) contributions are depicted separately. The relevant band crossings due to quasiparticle alignments are marked by arrows. (c) Calculated neutron and proton pairing gaps.

The lower panel finally depicts the behavior of the pairing gaps with frequency, following the self-consistent deformation trajectory. The proton band crossing results in a pronounced drop, typical of band crossing in normal deformed nuclei. The neutron pairing, however, decreases smoothly with frequency, although the $i_{13/2}$ neutron band crossing, as discussed above, is calculated to occur in this frequency range. At the highest frequency, where the neutron pairing almost vanishes due to the onset of the $j_{15/2}$ neutron crossing, our solution might not be reliable any more.

In summary, after a long chain of unsuccessful experiments, we finally have unambiguously assigned a SD rotational band to the nucleus ^{144}Gd. The band exhibits a sharp backbend at low frequency, which is interpreted in terms of the alignment of a $N=6$ proton pair that triggers a shape change towards increased quadrupole deformation. Pairing and deformation self-consistent calculations are in rather good agreement with the present dataset. This agreement supports theoretical calculations that predicted large shell gaps at superdeformed shapes for $N=80$ and $Z=64$. The low intensity of the SD rotational band might be accounted for by a predicted sharp level crossing of the $N=7$ neutrons in the feeding region. Future spectroscopy in the vicinity of the doubly-magic nucleus ^{144}Gd might shed more light on the shell structure at superdeformed shape in this mass region.

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