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A new phenomenon: shifted identical yrast bands in neighboring even-even nuclei

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Identification of the levels in ^{160}Sm and ^{162}Gd in spontaneous fission studies led to the discovery of a new phenomenon, shifted identical bands (SIB). SIBs are yrast bands in neighboring nuclei (a,b) with moments of inertia which are identical when shifted by a constant amount $\kappa = -\Delta J_1/J_1$, so $J_{1a}(1+\kappa) = J_{1b}$, from 2^+ to 8^+ and higher to 16^+. Building on that work, an analysis of yrast bands in even-even proton to neutron rich Xe to Pb nuclei was carried out. In over 700 comparisons, fifty-five SIBs were found for ground bands in stable to the most neutron rich Ce – W nuclei with $|\kappa|$ between 1.5% and 13%, where the spread in κ is less than ±1%, and only four identical bands ($\kappa \cong 0$). As examples, we find for ^{158}Sm – ^{160}Gd (from 2^+ to 10^+), $\kappa = -3.2^{+0.1}_{-0.2}\%$ (where the ± is the total spread in κ from –3.1 to –3.4) and $\Delta J_2/J_2 = 3.0 \pm 1.2\%$; ^{158}Sm - ^{160}Sm, $3.4^{+0.5}_{-0.3}\%$; and ^{154}Nd – ^{158}Gd, -10.4±0.2%. After the shifts, these J_1 and J_2 values have smaller spreads than do the outstanding examples of identical bands. The J_1 values were fitted to a variable moment of inertia model with parameters J_0 and C whose values correlate with the SIB J_1 values. The SIBs are not correlated either with deformation, $E(4^+)/E(2^+)$, or the N_pN_n product. Some excited bands are SIBs and IBs in proton rich Pt-Pb where nuclear shape coexistence is important.

1. INTRODUCTION

A major highlight of nuclear structure research in the 1990s was the discovery of identical bands (IB) in both superdeformed and normal deformed bands [1]. Bands are classified as identical when bands in two neighboring nuclei have essentially equal transition energies and moments of inertia for every spin state. These IBs test our theoretical understanding of large

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amplitude collective motion and demand more precise microscopic approaches to the calculation of moments of inertia [1]. Almost all IBs involve even-even and even-odd proton rich neighboring nuclei [1]. Nearly "IBs" were reported for the α chain ^{156}Dy to ^{172}W compared to ^{180}Os [2], where the energy similarities were somewhat correlated with N_pN_n. In neutron rich nuclei, only ^{98,100}Sr and $^{108-110}$Ru [3] are observed to have ground state IBs.

We have discovered a new phenomenon, which we call shifted identical band (SIB) in our investigation of the structures of neutron rich nuclei populated in the spontaneous fission of ^{252}Cf. Levels in ^{160}Sm and ^{162}Gd were identified [2,4], as well as new high spin states in the heavy partners in neutron rich Xe to Gd nuclei [3]. We observed the ^{160}Sm and ^{162}Gd yrast transition energies to be very similar to ^{158}Sm and ^{160}Gd, respectively. These data initiated a comparison of the moments of inertia of neighboring even-even nuclei from Xe to Pb, from proton to neutron rich nuclei, and to some excited superdeformed bands. We classify shifted identical bands as occurring when two yrast cascades in nuclei separated by 2n, 2p, 4n, 4p, α, α+2n, α+2p, 2α, or 2n-2p have their transition energies and moments of inertia (J_1 and J_2) become identical when E_γ or J_1 for one nucleus is shifted by a constant amount κ with less than ±1% total spread in κ, so that $J_{1a}(1+\kappa) = J_{1b}$ for every state from 2^+ to 8^+ and higher to 16^+. A total of 55 SIBs were found in over 700 comparisons. The SIBs are found in stable to the most neutron rich Nd to Hf nuclei known, while SIBs and IBs are not seen in their lighter mass nuclei nor in Xe, Ba, Ce, or Os nuclei, except for ^{152}Ce. Some IBs and SIBs are seen in excited bands from 4^+ to 14^+ states in the Pt–Pb very neutron deficient nuclei where shape coexistence occurs [5]. This new phenomenon of SIBs provides new challenges for microscopic theories.

2. PROCEDURES

The percentage differences in transition energies E_γ and in the kinematic moment of inertia J_1 between corresponding pairs of levels in two neighboring nuclei were calculated as:

$$J_{1VMI} = \frac{1}{6}\left(2J_0 + \left(\frac{54x}{C} + 8J_0^3 - 6\sqrt{\frac{3x\left(27x + 8CJ_0^3\right)}{C^2}}\right)^{1/3} + \left(\frac{54x}{C} + 8J_0^3 + 6\sqrt{\frac{3x\left(27x + 8CJ_0^3\right)}{C^2}}\right)^{1/3}\right)$$

where nuclide b is the heavier mass nuclide. Thus, $E_{\gamma a} = (1+\kappa)E_{\gamma b}$ and $J_{1a}(1+\kappa) = J_{1b}$. An identical band is defined as one in which $\Delta E_\gamma/E_\gamma$ remains constant within ±1% of zero, and a shifted identical band as one that is constant within ±1% of a $\kappa \geq 1\%$. These limits are in general even more restrictive than those used to classify IBs. For the SIBs observed, the absolute value of κ falls between one and thirteen percent. The experimental J_1 values were fitted by the variable moment of inertia (VMI) model [6]. We also calculated $\Delta J_2/J_2$.

In the VMI model [6], J_1 is allowed to vary as a function of two parameters: J_0, the ground-state moment of inertia, and C, the restoring force constant that measures the hardness of a nucleus to stretching (the smaller C, the softer the nucleus). In the VMI model, assuming no component of angular momentum I along the symmetry axis, J_{1VMI} is

$$\frac{\Delta E_\gamma}{E_{\gamma b}} = \frac{\left(E_{\gamma_{nuclide\ a}} - E_{\gamma_{nuclide\ b}}\right)}{E_{\gamma_{nuclide\ b}}} = \kappa = -\frac{\Delta J_1}{J_{1a}} = -\frac{\left(J_{1\,nuclide\ a} - J_{1\,nuclide\ b}\right)}{J_{1\,nuclide\ a}}$$

where x = I(I+1). A least squares fit for the J_{1VMI} values vs. the J_{1exp} values at each spin was obtained by adjusting the J_0 and C values. The root-mean-squares of the differences between the J_{1VMI} and J_{1exp} values were calculated along with $\Delta J_{1VMI}/J_{1VMI}$ for each point.

3. RESULTS

As a test of our approach, VMI fits were made to the data for superdeformed bands SD-1 – SD-1 and SD-1 – SD-3 in superdeformed double magic (at high spins) ^{192}Hg and its neighbor ^{194}Hg, which have "one of the most spectacular examples of IBs" [1]. The average $\Delta E_\gamma/E_\gamma$ values from 14^+ to 46^+ and average $\Delta J_2/J_2$ values from 14^+ to 44^+ for the two SD-1 bands are (1.0±0.2)% and (–1.4±1.7)% and for the SD-1 – SD-3 bands are $(-0.1^{+0.3}_{-0.9})$% and $(-0.1^{+2.2}_{-2.4})$%. The J_1 and J_2 shifts are correlated with the J_0 differences 0.9% and 0.2%, respectively, between the two pairs of bands in ^{192}Hg and ^{194}Hg. The first case is an SIB with small κ and the second case is the "spectacular" IB [1]. The $\Delta J_2/J_2$ values always have greater spreads than $\Delta J_1/J_1$ values. Superdeformed nuclei are considered very hard, and the SD-1 bands of ^{192,194}Hg have large C = 4.62, 4.46, respectively. Surprisingly, even larger values of C are found for a number of SIB bands reported here. Values of C are nearly equal for shifted identical bands, as they are for ^{192,194}Hg.

The values of $\Delta E_\gamma/E_\gamma$ were calculated for the following even-even nuclei separated by 2n, 2p, α, 4n, 4p, α+2n, α+2p, 2α, and 2n-2p: $^{114-144}$Xe, $^{126-148}$Ba, $^{128-152}$Ce, $^{128-156}$Nd, $^{132-160}$Sm, $^{138-162}$Gd, $^{148-166}$Dy, $^{150-170}$Er, $^{154-178}$Yb, $^{160-184}$Hf, $^{164-186}$W, $^{170-192}$Os, $^{176-184}$Pt, $^{178-186}$Hg, $^{186-188}$Pb, and the 1p, 1n, 1n-1p, 2n-1p cases involving $^{176-184}$Pt, $^{177-185}$Au, $^{178-186}$Hg, and $^{183-187}$Tl nuclei.

In essentially all cases, as the neutron number increases for a given Z, there is a progression from very uncorrelated yrast transition energies where there are no SIBs (the total spreads in κ are typically 5% to over 100%) to strongly correlated energies, which we have termed shifted identical bands, in stable to the most neutron rich nuclei known, as seen in Figs. 1 and 2. Note that the Er sequence is somewhat

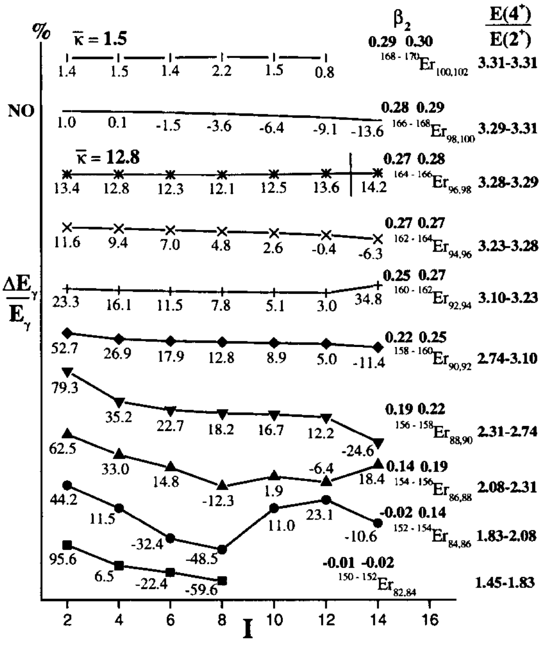

Figure 1. Percentage differences in transition energies for isotopes of Er (Z = 68), separated by 2n. κ̄ is given for the SIBs. Theoretical β_2 deformations are given. Each line has a different scale.

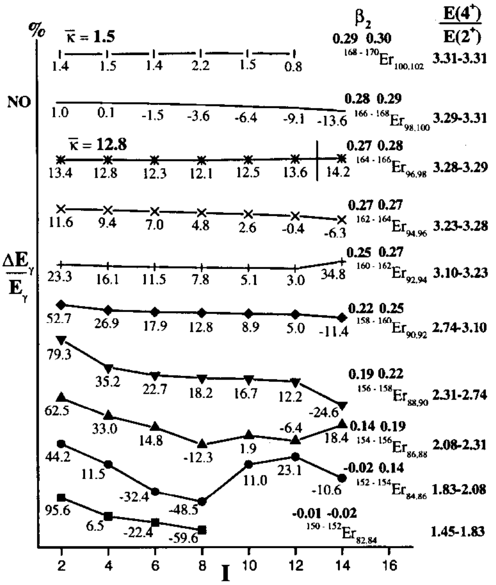

Figure 2. Percentage differences in transition energies for $^{158-178}$Yb and $^{160-180}$Hf, separated by 2p. κ̄ is given for the SIB. Theoretical β_2 deformations are given. The experimental values show the same peaking effect as the theoretical values. Each line has a different scale.

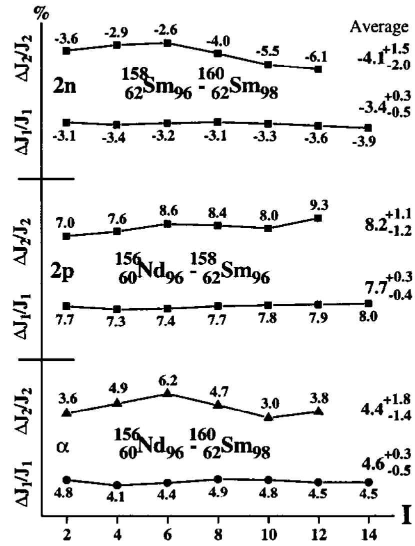

Figure 3. Percent differences in the kinematic and dynamic moments of inertia for the comparisons $^{158-160}$Sm, ^{156}Nd-^{158}Sm, and ^{156}Nd-^{160}Sm. Note for the SD-1 - SD-3 IBs in $^{192-194}$Hg, the J_1 and J_2 spreads are 1.2% and 4.6%.

unusual in that $^{166-168}$Er is not an SIB but $^{168-170;\ 164-166}$Er are SIBs. Fig. 3 shows examples of $\Delta J_1/J_1$ and $\Delta J_2/J_2$. All the SIB data were fitted by the VMI model. A few identical bands were found where $J_{0a} \sim J_{0b}$ and large $C_a \sim C_b$. Shifted identical bands occurred with large $C_a \sim C_b$ but the J_0's differed by κ. Note that SIBs only occurred for large C values, corresponding to hard nuclei with small stretching. For example, ^{134}Sm and ^{136}Sm are both soft nuclei, that is, they have small values of C (while calculated for different spin ranges, both have $C = 2.23\text{x}10^{-3}$ MeV$^3/\hbar^4$), and these yrast bands are not SIBs. As shown in Fig. 4, $^{158-160}$Sm SIBs have C values larger than those in the $^{192-194}$Hg IB, with $E_\gamma(^{158}\text{Sm}) = 1.034E_\gamma(^{160}\text{Sm})$ for every transition from the 2^+ to the 14^+ state, and a spread of only 1.031 to 1.039. An example of 2p separation SIBs is given in Fig. 5. Nearly the same constancy found in $\Delta J_1/J_1$ is also found in $\Delta J_2/J_2$ where J_2 is the dynamic moment of inertia, as seen in Fig. 3. The $\Delta J_2/J_2$ spreads are larger than those of $\Delta J_1/J_1$ for SIB, as for superdeformed IBs. Remarkably, the SIB J_1 and J_2 spreads are often smaller (Fig. 3) than the J_1 and J_2 spreads for SD bands. So, after shifting, these new SIBs are more identical than the "most spectacular" IBs.

Tables 1 – 3 show the IBs and SIBs that start at 2^+ for the 2n, 2p, and α separations. No IB or SIB occurs for any combination with Xe, Ba, or Os nuclei, and only one case each for the most neutron rich Ce and W isotopes. In over 700 comparisons in Xe – Os nuclei, 55

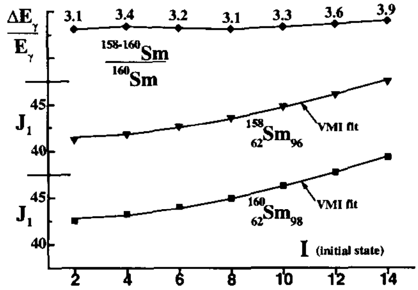

Figure 4. VMI fits and $\Delta E_\gamma/E_\gamma$ for 2^+ to 14^+. For 2n separation, $\Delta E_\gamma/E_\gamma$ and $\Delta J_{1th}/J_{1th}$ in % are $3.4^{+0.5}_{-0.3}$, -3.4 ± 0.3 where the + and – values give the total spread. J_0 in $\hbar^2$/MeV, C in MeV$^3/\hbar^4$, $\sqrt{(J_{1th}-J_{1ex})^2}$ in $\hbar^2$/MeV = 41.5, 5.63x10^{-3}, 0.147; 42.8, 4.86x10^{-3}, 0.131 for ^{158}Sm, ^{160}Sm, respectively.

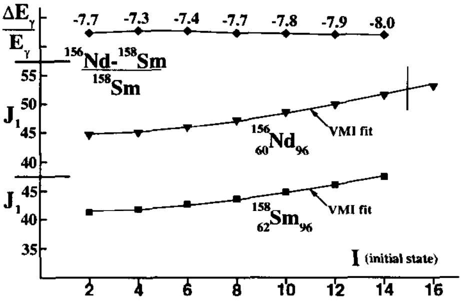

Figure 5. VMI fits and $\Delta E_\gamma/E_\gamma$ for 2^+ to 14^+. For 2p separation, $\Delta E_\gamma/E_\gamma$ and $\Delta J_{1th}/J_{1th}$ in % are $-7.7^{+0.4}_{-0.3}$, $7.6^{+0.2}_{-0.1}$ where the + and – values give the total spread. J_0 in $\hbar^2$/MeV, C in MeV$^3/\hbar^4$, $\sqrt{(J_{1th}-J_{1ex})^2}$ in $\hbar^2$/MeV = 44.8, 4.21x10^{-3}, 0.127; 41.5, 5.63x10^{-3}, 0.147 for ^{156}Nd, ^{158}Sm, respectively.

cases of SIBs that begin at the 2^+ state were found and all involve stable to the most neutron rich known nuclei with N = 90 – 112 (Table 4). There are only four ground state identical bands seen in even-even Xe to Pb nuclei, so SIBs are a different phenomenon. There are marked differences in magnitude (factors up to 9) and sign of κ for neighboring pairs for 2n, 2p, and α separations. All β_2 values for SIB nuclei range from 0.23 – 0.30 theoretically and somewhat larger up to 0.35 experimentally, corresponding to well-deformed nuclei. In very proton rich W, Pt, Au, Hg, Tl, and Pb nuclei known, there are about equal numbers of SIBs and IBs starting at 4^+ or 6^+ for one, two, and four nucleon separations, which are not considered in this paper. Their 2^+ and sometimes 4^+ states are perturbed by shape coexistence, so these bands are built on excited states. For example, for ^{178}Pt – ^{182}Hg – ^{186}Pb, both α pairs are IB and the 2α is IB for the excited deformed states.

We observed 55 cases of ground state SIBs: one case in ^{152}Ce; 9 in $^{152\text{-}156}$Nd; 20 in $^{152\text{-}160}$Sm; 21 in $^{154\text{-}162}$Gd; 18 in $^{160\text{-}166}$Dy; 14 in $^{160,164\text{-}170}$Er; 17 in $^{170\text{-}178}$Yb; 9 in $^{168,176\text{-}184}$Hf; and one in ^{186}W (note there is double counting since each of the 55 cases involves a pair of isotopes). Eighty-two percent of SIBs occur in the stable to most neutron rich, well deformed Sm to Yb nuclei. However, in the same region other nuclei with equally large deformations do not exhibit SIBs. The 2n SIBs are nearly uniformly spread from Sm to Hf, the 2p SIBs cluster in Sm and Gd (11 of 22), and the α SIBs are clustered in Gd to Er (13 of 20), somewhat correlated with the 2p cases. Since the results to some degree cluster around neutron mid shell, where the saturation of collectivity is expected, one could expect that saturation may play a role. Clearly there is no correlation with $A^{5/3}$, for example, for ^{158}Sm – ^{160}Sm, κ = 3.4 and for ^{158}Sm – ^{160}Gd, κ = -3.2, so adding 2p gives the opposite sign to adding

Tables 1-2. $\Delta E_\gamma/E_\gamma$ for examples of SIB and IB in ground state yrast bands for 1α and 2p separation. The identical bands (IB) are marked with a *.

1α Separation in Yrast Bands			
Z / N	Pair	I_{max}	$\Delta E_\gamma/E_\gamma$(%)
60-62/94-96	^{154}Nd-^{158}Sm	10	$-4.0^{+1.4}_{-1.6}$
/96-98	^{156}Nd-^{160}Sm	14	$-4.6^{+05}_{-0.3}$
62-64/94-96	^{156}Sm-^{160}Gd	10	$0.1^{+0.7}_{-0.6}$ *
/96-98	^{158}Sm-^{162}Gd	10	$1.9^{+1.1}_{-0.9}$
		8	$1.6^{+0.7}_{-0.6}$
64-66/94-96	^{158}Gd-^{162}Dy	12	$-1.8^{+0.4}_{-0.2}$
/96-98	^{160}Gd-^{164}Dy	8	$3.0^{+1.0}_{-0.4}$
/98-100	^{162}Gd-^{166}Dy	8	$-6.9^{+1.0}_{-0.9}$
66-68/94-96	^{160}Dy-^{164}Er	10	-5.7±0.7
/98-100	^{164}Dy-^{168}Er	8	$-8.8^{+0.8}_{-1.0}$
68-70/94-96	^{162}Er-^{166}Yb	12	$-0.4^{+0.4}_{-1.0}$ *
/98-102	^{166}Er-^{170}Yb	8	$-5.1^{+0.7}_{-1.1}$
/100-102	^{168}Er-^{172}Yb	14	$1.9^{+0.9}_{-0.6}$
70-72/94-96	^{164}Yb-^{168}Hf	8	$0.5^{+0.9}_{-1.0}$ *

2p Separation in Yrast Bands			
Z / N	Pair	I_{max}	$\Delta E_\gamma/E_\gamma$(%)
60-62/94	^{154}Nd-^{156}Sm	10	$-7.0^{+0.7}_{-1.0}$
/96	^{156}Nd -^{158}Sm	14	$-7.7^{+0.4}_{-0.3}$
62-64/90	^{152}Sm -^{154}Gd	14	$-1.5^{+0.6}_{-0.4}$
/94	^{156}Sm -^{158}Gd	10	$-3.6^{+1.2}_{-1.0}$
		8	$-3.9^{+0.9}_{-0.7}$
/96	^{158}Sm -^{160}Gd	10	$-3.2^{+0.1}_{-0.2}$
/98	^{160}Sm -^{162}Gd	10	$-1.3^{+1.1}_{-0.8}$
64-66/98	^{162}Gd -^{164}Dy	14	$-1.5^{+1.0}_{-0.7}$
		10	-1.8±0.4
66-68/100	^{166}Dy -^{168}Er	12	-3.9±0.3
68-70/102	^{170}Er -^{172}Yb	12	0.3±0.5*
70-72/108	^{178}Yb -^{180}Hf	10	$-9.3^{+1.2}_{-0.7}$
		8	$-9.7^{+0.7}_{-0.3}$
72-74/112	^{184}Hf -^{186}W	8	$-11.4^{+0.6}_{-1.0}$

2n and has the opposite change in E_γ and J_1. More importantly, there is no correlation with deformation. For example, look at the two $^{158\text{-}160}$Gd – $^{162\text{-}164}$Dy α cases of SIB where $\kappa = -1.8$ and +3.0, respectively. The experimental β_2 for Gd are 0.348 and 0.353, and for Dy are 0.341 and 0.348, respectively. The Gd deformations are larger in both cases and so one expects their transition energies to be smaller. This is consistent with the first case but exactly opposite in the latter case. Note in Fig. 1 that the pair $^{166\text{-}168}$Er is not an SIB, even though its deformations are intermediate between the deformations of $^{164\text{-}166}$Er and $^{168\text{-}170}$Er, both of which are SIBs. Note also the factor of nearly 10 difference in $\bar{\kappa}$ for the two Er SIBs with similar deformations. In the 2p chain of Yb to Hf shown in Fig. 2, the deformations peak at midshell around N = 102 but no IBs or SIBs are seen there. The only SIB is in the most neutron rich nuclei known with N = 108 and lower deformation. Thus, collectivity and saturation of collectivity are not correlated with SIB occurrence. Also note in Table 4 where the $E(4^+)/E(2^+)$ ratios are given, there is no correlation with this ratio and the occurrence of SIBs, except that the number approaches 3.33.

Now look at the N_pN_n scheme suggested earlier [2], where N_pN_n are the smaller number of particles or holes from the nearest magic numbers. First the "identical bands in widely dispersed nuclei" noted earlier [2] in the ^{156}Dy to ^{172}W α chain compared to ^{180}Os do have

Tables 3.
$\Delta E_\gamma/E_\gamma$ for examples of SIB and IB in ground state yrast bands for 2p separation.

2n Separation in Yrast Bands			
Z / N	Pair	I_{max}	$\Delta E_\gamma/E_\gamma$(%)
62/94-96	$^{156\text{-}158}$Sm	14	3.2±1.0
/96-98	$^{158\text{-}160}$Sm	14	$3.4^{+0.5}_{-0.3}$
64/96-98	$^{160\text{-}162}$Gd	10	$5.3^{+1.0}_{-0.9}$
66/96-98	$^{162\text{-}164}$Dy	14	$9.1^{+0.8}_{-0.6}$
/98-100	$^{164\text{-}166}$Dy	8	$-5.0^{+0.8}_{-1.2}$
68/96-98	$^{164\text{-}166}$Er	12	$12.8^{+0.8}_{-0.7}$
/100-102	$^{168\text{-}170}$Er	12	1.5±0.7
70/102-104	$^{172\text{-}174}$Yb	14	$2.6^{+0.4}_{-0.3}$
/104-106	$^{174\text{-}176}$Yb	12	$-6.5^{+1.3}_{-0.4}$
		10	-6.7±0.2
/106-108	$^{176\text{-}178}$Yb	8	$-2.6^{+0.4}_{-0.8}$
72/104-106	$^{176\text{-}178}$Hf	12	$-5.4^{+0.9}_{-0.6}$
/108-110	$^{180\text{-}182}$Hf	8	-3.7±0.9

Table 4.
$E(4^+)/E(2^+)$ ratios where the SIBs for ranges 2^+, to 8^+, 10^+, 12^+, or 14^+ are shaded. This is a composite of all SIBs e.g. not all 2n from N = 96 – 102 Er are SIB and only ^{178}Yb to ^{180}Hd is a SIB. For each Z, the isotope with the highest N is the most neutron rich isotope whose levels are known to 8^+.

N \ Z	58	60	62	64	66	68	70	72	74
88	2.59	2.49	2.32	2.19	2.23	2.31	2.33	2.31	
90	2.86	2.93	3.01	3.01	2.93	2.74	2.63	2.56	2.48
92	3.15	3.25	3.25	3.24	3.21	3.10	2.92	2.79	2.68
94	3.23	3.29	3.29	3.29	3.27	3.23	3.13	2.97	2.82
96		3.31	3.30	3.30	3.29	3.28	3.23	3.11	2.95
98			3.29	3.29	3.30	3.29	3.27	3.19	3.06
100					3.31	3.31	3.29	3.25	3.15
102						3.31	3.31	3.27	3.20
104							3.31	3.28	3.24
106							3.31	3.29	3.26
108							3.31	3.31	3.29
110								3.29	3.27
112								3.26	3.24

relatively small average κ's but their spreads in κ are large, $0.2^{+6.1}_{-5.4}$, $-0.2^{+7.2}_{-4.7}$, $-0.5^{+7.1}_{-6.2}$, $-1.6^{+6.9}_{-4.7}$, and $-7.1^{+4.2}_{-2.3}$, respectively. So, they are not really identical in the usual sense. In Table 5 are shown the six pairs with the same $(N_pN_n)(N'_pN'_n)$ values noted earlier [2], ^{156}Dy – ^{172}W, ^{160}Er – ^{168}Hf, ^{158}Dy – ^{170}Hf, ^{162}Er – ^{166}Yb, ^{160}Dy – ^{168}Yb, and ^{162}Dy – ^{166}Er along with eight other such cases, and six of eight Gd – Er cases, which form a long chain of identical N_pN_n nuclei that go from spherical ^{148}Gd – ^{152}Er to well deformed ^{162}Gd – ^{166}Er. As seen in Table 5, in the earlier noted six cases [2] there is one SIB and two IBs but with the exception of an SIB in ^{162}Gd – ^{162}Dy, all the others have large $\bar{\kappa}$ with large spreads, including all the Gd – Er chain with two cases left out. Note (Table 5) four of the earlier six cases [2] have multiple other pairs with the same N_pN_n, all with large $\bar{\kappa}$ and large spreads. The N_pN_n for the SIB nuclei go from 80 to 288 but many similar products in this range are not SIBs. The absence of SIBs in many cases and of any consistency for equal N_pN_n nuclei suggest that the global collective features tracked by N_pN_n cannot account for the observed SIBs.

Finally, the SIBs for α, α+2n, α+2p, 4n, 4p, and 2n-2p separations have the following differences: for Nd to Dy SIBs, their $\Delta E_\gamma/E_\gamma$ can be obtained by adding, including sign, the SIB 2n and 2p values even when the 2n and 2p values are different in magnitude and sign. However, for Er, Yb, and Hf nuclei, the SIBs for α separation are the result of combining 2n and 2p neighboring nuclei with no SIB where the $\Delta E_\gamma/E_\gamma$ change in 2n is in the opposite direction so as to cancel the 2p non-SIB variation. For example, in ^{160}Dy – ^{164}Er, from 2^+ to

Table 5.
Examples of $\Delta E_\gamma/E_\gamma$ values for comparisons of ground state yrast bands in nuclei with identical N_pN_n values. Different pairs with the same $(N_pN_n)(N_pN_n)$ are labeled by a, b, c, d.

Type	Pair	$(N_p,N_n)(N_p,N_n)$	Range	$\Delta E\gamma/E\gamma(\%)$
4α	^{156}Dy - ^{172}W	(16,8)(8,16)	2 - 14	$7.8^{+4.1}_{-3.3}$
3α	^{158}Dy - ^{170}Hf	(16,10)(10,16)	2 - 14	$1.0^{+2.5}_{-2.9}$
2α	^{160}Dy - ^{168}Yb	(16,12)(12,16)[a]	2 - 14	$0.5^{+1.9}_{-1.6}$
2α	^{160}Er - ^{168}Hf	(14,10)(10,14)[b]	2 - 12	$1.5^{+0.4}_{-0.5}$
α	^{162}Dy - ^{166}Er	(16,14)(14,16)[c]	2 - 8	$0.8^{+1.0}_{-0.7}$
α	^{162}Er - ^{166}Yb	(14,12)(12,14)[d]	2 - 12	$-0.4^{+0.4}_{-1.0}$
4p	^{152}Gd - ^{156}Er	(14,6)(14,6)	2 - 12	$-11.8^{+11.7}_{-6.2}$
4p	^{154}Gd - ^{158}Er	(14,8)(14,8)	2 - 12	$-21.2^{+11.2}_{-14.8}$
4p	^{156}Gd - ^{160}Er	(14,10)(14,10)[b]	2 - 12	$-20.1^{+7.9}_{-9.2}$
4p	^{158}Gd - ^{162}Er	(14,12)(14,12)[d]	2 - 12	$-15.8^{+7.6}_{-6.3}$
4p	^{160}Gd - ^{164}Er	(14,14)(14,14)	2 - 10	$-14.8^{+3.5}_{-2.8}$
4p	^{162}Gd - ^{166}Er	(14,16)(14,16)[c]	2 - 10	$-8.9^{+2.8}_{-1.6}$
8p	^{158}Sm - ^{166}Yb	(12,14)(12,14)[d]	2 - 12	$-21.3^{+8.9}_{-7.6}$
8p	^{160}Sm - ^{168}Yb	(12,16)(12,16)[a]	2 - 12	$-13.8^{+8.2}_{-5.7}$
8p-4n	^{156}Gd - ^{168}Hf	(14,10)(10,14)[b]	2 - 14	$-19.0^{+8.2}_{-9.3}$
6p-2n	^{158}Sm - ^{162}Er	(12,14)(12,14)[d]	2 - 12	$-20.9^{+9.6}_{-7.6}$
6p+2n	^{158}Gd - ^{166}Yb	(14,12)(12,14)[d]	2 - 12	$-16.2^{+6.8}_{-6.1}$
4p-4n	^{160}Sm - ^{160}Dy	(12,16)(16,12)[a]	2 - 12	$-14.0^{+6.3}_{-4.3}$
2p-2n	^{158}Sm - ^{158}Gd	(12,14)(14,12)[d]	2 - 12	$-6.2^{+2.9}_{-2.2}$
2p-2n	^{162}Gd - ^{162}Dy	(14,16)(16,14)[c]	2 - 10	$-10.1^{+0.8}_{-0.6}$

10^+, $\Delta E_\gamma/E_\gamma$ for 1α is –5.7±0.7%, but over the same range $\Delta E_\gamma/E_\gamma$ for ^{160}Dy – ^{162}Er goes from -14.9% to -8.7%, and $\Delta E_\gamma/E_\gamma$ for $^{162\text{-}164}$Er goes from 11.6% to 2.6%.

In summary, this new phenomenon of SIBs is found most often in stable to the most neutron rich Sm to Yb nuclei known with N = 94 – 108. Studies of their heavier nuclei could give us insight into the occurrence of such bands but will have to await radioactive ion beam accelerators. Comparisons of SIB with the N_pN_n scheme, $E(4^+)/E(2^+)$, deformation, and its saturation indicate that one must go beyond global collective features to find an understanding of this new phenomenon. These SIBs with remarkably constant E_γ shifts and marked differences in size and sign of κ for even neighboring pairs clearly present challenges for more microscopic theoretical approaches.

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REFERENCES

1. C. Baktash, B. Haas, and W. Nazarewicz, Annu. Rev. Nucl. Part. Sci. 45 (1995) 485.
2. R.F. Casten *et al.*, Phys. Rev. C 45 (1992) R1413.
3. J.H. Hamilton *et al.*, Prog. Part. Nucl. Phys. 35 (1995) 635.
4. E.F. Jones *et al.*, ENAM98, B.M. Sherrill *et al.*, eds., AIP (New York 1998) p. 523.
5. J.H. Hamilton, in "Treatise on Heavy Ion Science", Allen Bromley, ed., Plenum Press (New York 1989) Vol. 8, p. 2.
6. M.A.J. Mariscotti, G. Scharff-Goldhaber, and B. Buck, Phys. Rev. 178 (1969) 1864.