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A New Phenomenon - Shifted Identical Bands

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Abstract

From spontaneous fission data in the prompt γ-ray emission of ^{252}Cf, the isotopes ^{162}Gd and ^{160}Sm were identified and the level schemes of ^{160}Gd and ^{158}Sm were extended. From over 700 comparisons of even-even yrast bands from Xe to Os separated by 2n, 2p, α, 4n, 4p, 2α, α+2n, α+2p, 2n-2p, and other cases, from the ground state to 8^+ and sometimes as high as 18^+, 55 ground state shifted identical bands (SIB) and 4 identical bands (IB) were found. After the shift, these SIBs are seen to be more identical than previously known IBs and are not correlated with $(N_pN_n)(N_pN_n)'$, $\beta_2\beta_2'$, $E(4^+)/E(2^+)$, saturation of collectivity, or with the variation in the ground band - s band interaction strength. They are seen only in well-deformed stable to most neutron rich nuclei from Nd to Hf, and are not seen in γ bands.

Level schemes of ^{160}Gd and ^{158}Sm were extended and ^{162}Gd and ^{160}Sm were discovered by analysis of new spontaneous fission data from the prompt γ-ray fission of ^{252}Cf. It was noted that each γ-transition energy in ^{162}Gd is 5% lower than its counterpart in ^{160}Gd. This was the starting point for our analysis which led to the discovery of shifted identical bands.

The equations which we use to characterize SIBs express percentage differences in transition energies E_γ and moments of inertia between corresponding pairs of levels in two neighboring nuclei, a and b, as follows:

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

where nuclide b is the heavier mass nuclide. The kinematic moments of inertia, J_{1a} and J_{1b}, and the transition energies are related by the expressions $E_{\gamma a} = (1+\kappa)E_{\gamma b}$ and $J_{1a}(1+\kappa) = J_{1b}$.

We define IBs as those in which $|\bar{\kappa}| \leq 1\%$ and the total spread in $\kappa \leq \pm1\%$. This definition is more restrictive than those used previously to characterize identical bands [1]. We define shifted identical bands as those in which $|\bar{\kappa}| > 1\%$ and the total spread in $\kappa \leq \pm1\%$. As examples of SIBs, ^{172}Yb - ^{174}Yb has $\bar{\kappa} = 2.6^{+0.4}_{-0.3}\%$, ^{156}Nd - ^{158}Sm, $-7.7^{+0.4}_{-0.3}\%$, and ^{156}Nd - ^{160}Gd, $-10.6^{+0.4}_{-0.2}\%$.

From ten comparisons of $\Delta E_\gamma/E_\gamma$ of $^{132--160}$Sm, only the two most neutron rich comparisons, $^{158-160}$Sm and $^{156-158}$Sm, with $\bar{\kappa} = 3.4^{+0.5}_{-0.3}\%$ and 3.2±1.0%, respectively, are SIBs. These two cases of SIB are seen to have much smaller total spreads than those of the proton rich to stable cases of Sm where the total spreads range from 5.7% to 167%. From ten cases of percentage differences in transition energies for $^{150--170}$Er separated by 2n, the most neutron rich case, $^{168-170}$Er with $\bar{\kappa} = 1.5\pm0.7\%$, and the third most neutron rich case, $^{164-166}$Er with $\bar{\kappa} = 12.8^{+0.8}_{-0.7}\%$ are SIBs. However, the second most neutron rich case, $^{166-168}$Er, is not an SIB, in spite of the fact that it has intermediate β_2 values and $E(4^+)/E(2^+)$ ratios, suggesting no correlation of occurrence of SIBs with β_2 values or $E(4^+)/E(2^+)$ ratios. From eleven comparisons of percentage differences in E_γ for 2p separation of $^{158--178}$Yb and $^{160--180}$Hf, only the most neutron rich case with N = 108, ^{178}Yb - ^{180}Hf, is an SIB with $\bar{\kappa} = -9.3^{+1.2}_{-0.7}\%$. However, β_2 is a maximum at N = 102 (^{172}Yb - ^{174}Hf), where there is no SIB. This suggests no correlation of the occurrence of SIBs with β_2 or saturation of collectivity. Again in these cases of 2p separation

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of Yb and Hf isotopes, the total spreads for the more proton rich non-SIB cases range from 10.3% to 74.4%, much larger than the total spread of the SIB.

Variable Moment of Inertia [2] fits were made to all the data. This is the theoretical equation used in the VMI model, assuming no component of I along the symmetry axis:

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

where x = I(I+1). It is characterized by two parameters: the ground state deformation $J_0(\hbar^2/\mathrm{MeV})$, and the nuclear softness or stretching parameter $C(\mathrm{MeV}^3/\hbar^4)$. The SIBs all had large C values, corresponding to hard nuclei with small stretching. Values of J_0 and C correlate with the SIB J_1 values and were adjusted to obtain a least squares fit for the J_{1VMI} values vs. the J_{1exp} values at each spin over the range where $\Delta E_\gamma/E_\gamma$ is constant. 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.

In a 2n comparison of the SD-1 band of ^{192}Hg and the SD-3 band of ^{194}Hg, which has been termed "one of the most spectacular examples of IBs" [3], we note remarkably small and constant values of κ where $\bar{\kappa}$ = -0.1$^{+0.3}_{-0.9}$% and total spreads in $\Delta E_\gamma/E_\gamma$ and $\Delta J_2/J_2$ are 1.2% and 4.6%, respectively. In the 2n SIB separation of $^{158-160}$Sm, the total spreads in $\Delta E_\gamma/E_\gamma$ and $\Delta J_2/J_2$ are 0.5% and 2.9%, respectively, for 2p SIB separation of ^{156}Nd - ^{158}Sm, the total spreads are 0.6% and 1.6%, respectively, and for α SIB separation ^{156}Nd - ^{160}Sm, total spreads are 0.8% and 3.2%, respectively. These total spreads are even smaller than the total spreads in the Hg SD bands. Thus, after the shifts, the SIBs are more identical than "spectacular" ^{192,194}Hg IBs.

In the 2n separation cases, there is a sign change and magnitude difference in $\bar{\kappa}$ even within comparisons of different isotopes of the same elements. For $^{162-164}$Dy, $\bar{\kappa}$ = 9.1$^{+0.8}_{-0.6}$%, but for $^{164-166}$Dy, $\bar{\kappa}$ = -5.0$^{+0.8}_{-1.2}$%. For $^{164-166}$Er, $\bar{\kappa}$ = 13.0$^{+1.2}_{-0.9}$%, but for $^{168-170}$Er, $\bar{\kappa}$ = 1.5±0.7%, a large difference in magnitude. In the 1α separation cases, we likewise have noted a change in sign between comparisons of different isotopes of the same elements. For ^{158}Gd - ^{162}Dy, $\bar{\kappa}$ = -1.8$^{+0.4}_{-0.2}$%, but for ^{160}Gd - ^{164}Dy, $\bar{\kappa}$ = 3.4$^{+1.4}_{-0.8}$%, and for ^{162}Gd - ^{166}Dy, $\bar{\kappa}$ = -7.2$^{+1.3}_{-1.1}$%. There is a sign change between the two cases of SIBs in the 2n separation of ^{158}Sm - ^{160}Sm with $\bar{\kappa}$ = 3.4$^{+0.5}_{-0.3}$% and 2p separation of ^{158}Sm - ^{160}Gd with $\bar{\kappa}$ = -3.2$^{+0.1}_{-0.2}$%, and yet the β_2 values and $E(4^+)/E(2^+)$ ratios are essentially equal for these isotopes. For the α separation cases of SIBs ^{158}Gd - ^{162}Dy and ^{160}Gd - ^{164}Dy, β_2 values as well as $E(4^+)/E(2^+)$ ratios are constant and in both Gd - Dy comparisons, β_2 is greater in Gd than in Dy. However, again there is a sign change between these two cases of SIBs. This indicates no correlation of the occurrence of SIBs with β_2 values and $E(4^+)/E(2^+)$ ratios. Out of 20 comparisons of nuclides which have the same N_pN_n products, we found only two SIBs and two IBs, so these SIBs and IBs are not correlated with the N_pN_n products.

The new phenomenon which we have termed shifted identical bands is seen only in well-deformed stable to most neutron rich nuclei from Nd - Hf. SIBs are not correlated with $(N_pN_n)(N_pN_n)'$, $\beta_2\beta_2'$, $E(4^+)/E(2^+)$, with saturation of collectivity, or with the variation in the ground band - s band interaction strength [4]. There is no systematic variation in the quantity $\bar{\kappa}$ which characterizes SIBs, and $\bar{\kappa}$ can vary in magnitude up to a factor of 10 and in sign in neighboring pairs of isotopes. This phenomenon poses new challenges for microscopic models.

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