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Unexpected rapid variations in odd-even level staggering in gamma-vibrational bands

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Abstract. Triple-γ coincidence data were used to study the γ-vibrational bands to 14^+ in $^{104-106}$Mo, to 13^+ in ^{108,110}Ru and 17^+ in ^{112}Ru, and to 13^+, 15^+ in $^{112-116}$Pd. The even-odd spin energy level splittings show rapid variations with spin and neutron number in these nuclides. With one exception, the Sm-Pt nuclei show no such reversal and much smaller staggering.

PACS. 21.10.Re Collective levels – 27.60.+j Properties of specific nuclei listed by mass ranges: $90 \leq A \leq 149$

We used our γ-γ-γ data (5.7×10^{11} triples and higher folds) from the spontaneous fission of ^{252}Cf to study the γ-type vibrational bands in $^{104-106}$Mo, $^{108-112}$Ru, and $^{112-116}$Pd. The γ bands are extended from 8^+, 8^+ [1] to 14^+, 14^+ in $^{104-106}$Mo, from 9^+ [2] to 13^+, 13^+, 17^+ in ^{108,110,112}Ru, and from 6^+, 5^+ to 15^+, 15^+ in $^{114-116}$Pd. Lalkovski *et al.* [3] looked at the γ-band systematics in the $^{104-110}$Ru to the 8^+ levels and in ^{108,110,116}Pd to 8^+ and ^{112,114}Pd to 11^+ and 10^+. They noted that there were definite signature splittings in the γ bands in both these Ru and Pd nuclei and drew several conclusions. We have likewise analyzed the signature splittings in ^{104,106}Mo, ^{108,110,112}Ru, and ^{112,114,116}Pd to higher spin. As we will show, some of their conclusions [3] are not correct, in particular their conclusions "iii.) the even-spin levels in the γ band are depressed with respect to the odd-spin levels (staggering effect) for all Ru and Pd nuclei", "iv.) the energy of transitions between states with even spin increases with the angular momentum (with exception of ^{104}Ru, ^{108}Pd, ^{112}Pd)" and their later conclusions "The staggering amplitude in Ru isotopes is lower than that in Pd isotopic chain" and "the irregular behavior of the odd-spin levels of the γ bands in ^{112,114,116}Pd can be explained by the back bending effect". Our higher-spin data are important in changing some of the conclusions and in giving a clearer picture of what is happening in these γ bands. The even-odd spin energy level splittings, *e.g.* $\Delta E = E_{3^+}$-E_{2^+}, E_{4^+}-$E_{3^+}, \ldots$, show striking and rapid variations with N to indicate the need for a microscopic description.

Gupta and Kavathekar [4] investigated the the $K^\pi = 2^+$ γ-vibrational bands and odd-even staggering from Sm to Pt nuclei. They conclude that "The sign of the odd-even energy staggering (OES) index in the γ bands distinguishes between the rigid triaxial rotor shape and the γ-soft vibrator or the $O(6)$ symmetry. Its absolute magnitude indicates the degree of deviation from an axial rotor. This OES index $S(4)$ is large for the shape-transitional nuclei and is much reduced for well-deformed nuclei." Similar conclusions about the changing usefulness of the above models because of a prolate-oblate phase transition in the Hf-Hg region were discussed recently [5]. We analyzed the γ-vibrational bands in Sm to Pt nuclei and came to similar conclusions. With one exception, the Sm-Pt nuclei show no such reversal in staggering pattern as seen in Mo, Ru, and Pd, and much smaller staggering.

In fig. 1(a), a comparison of the γ bands of ^{104,106,108}Mo shows a clear difference between ^{104}Mo and ^{106}Mo, with ^{104}Mo showing a marked staggering to spin 12^+. A little of this effect is seen at low spins in ^{106}Mo but

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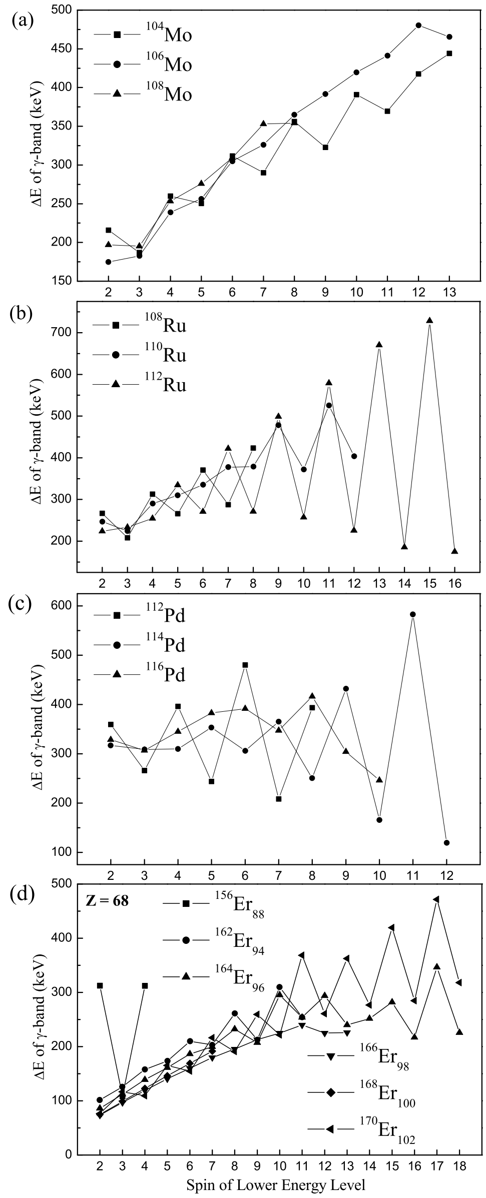

Fig. 1. Energy-level differences of the γ bands of (a) ^{104,106,108}Mo, (b) ^{108,110,112}Ru, (c) ^{112,114,116}Pd, and (d) $^{156-170}$Er.

it smoothes out at higher spins until spin 13^+. The ^{108}Mo staggering starts similar to ^{104}Mo and then smoothes out.

For the γ bands of ^{108,110,112}Ru in fig. 1(b), the staggering in ^{108}Ru is the same as in ^{104}Mo with the odd-spin levels pushed up to the even-spin levels. The ^{110}Ru staggering starts out similar to ^{108}Ru, then smoothes out like ^{108}Mo, and then looks like ^{112}Ru at higher spins. The ^{112}Ru staggering starts smooth but, starting at 4^+, exhibits an opposite staggering to ^{108}Ru with the even-spin levels pushed up to the odd-spin levels. At high spin, ^{112}Ru has the largest energy staggering seen in these nuclei. While ^{112}Pd looks similar to ^{104}Mo and ^{108}Ru, ^{114}Pd starts smooth then exhibits the opposite staggering to ^{112}Pd but similar to ^{112}Ru. These data clearly suggest the role of triaxial shapes, but the fluctuations indicate that it is a very microscopic phenomenon. In going from ^{108}Ru to ^{112}Ru, we see a clearly changing pattern that is not easily reproduced within any one theoretical model.

As noted in refs. [3] and [4], the Davydov and Fillipov model has the (2^+,3^+), (4^+,5^+) grouping while the Wilets and Jean model has (3^+,4^+), (5^+,6^+). One would need the Wilets and Jean model for ^{104}Mo, ^{108}Ru, and ^{112}Pd, and the Davydov and Fillipov model for ^{112}Ru and ^{114}Pd. Actually the low-spin data analyzed by Lalkovski *et al.* [3] already showed this effect but it was ignored in their summary (iii.)). Moreover their iv.) conclusion is also not true for ^{114}Pd and ^{116}Pd (see fig. 1(c)). Both the even- and odd-spin Pd sequences are irregular. The back bending of the γ bands cannot explain the switch in staggering patterns. Finally, one notes that the staggering in fact is greater at high spin in ^{112}Ru, not less than in the Pd as earlier claimed [3].

The region of Sm to Pt level energies were taken from [6]. For $^{154-166}$Dy level-energy differences, strong oscillation is seen only in $N = 88$ ^{154}Dy, which is outside the region of well-deformed nuclei. The others all vary smoothly with no staggering, as expected in the collective model, except at the highest spin. In a comparison of $^{156-170}$Er level-energy differences shown in fig. 1(d), there is strong oscillation again in $N = 88$ ^{156}Er, which is outside the region of deformed nuclei. There are small oscillations above spin 6^+ in ^{162,164}Er. We found that ^{170}Er has the opposite oscillation to ^{162,164}Er, as found in the Ru and Pd nuclei. This is the only case of reversal in the odd-even spin staggering found in the Sm to Pt nuclei. Note ^{170}Er is 6–8 neutrons above ^{162,164}Er, to be compared to only 2, 4 neutron separation for reversal in Ru and Pd.

The three largest energy differences are at the highest spins in ^{112}Ru, 570 keV, ^{114}Pd, 480 keV, and ^{166}Yb, 640 keV. Stable triaxial deformation is likely playing an important role in the rapidly varying and large odd-even spin staggering. It is not clear what causes the sudden complete reversal as found for ^{108,112}Ru and ^{112,114}Pd. This is a new phenomenon not generally seen for Sm to Pt γ bands, except for ^{170}Er. Clearly, the data call for a more microscopic description of γ-vibrational bands, including γ-soft and stable triaxial deformations.

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