Systematic features of signature inversion in doubly odd nuclei

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The signature inversion phenomenon in odd-odd nuclei is reviewed for the regions of mass numbers $A \simeq 80$, 130, and 160. The angular momentum, frequency, and moment of inertia estimated at the signature inversion point are analyzed. The correlations found of these quantities with other nuclear parameters are discussed.

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I. INTRODUCTION

Among the features exhibited by the rotational spectra of doubly odd nuclei the signature inversion deserves special attention.

The signature quantum number is associated with the rotation of a deformed nucleus around a principal axis by 180°. A rotational band splits into two sequences with $I-j_n-j_p$ = even and $I-j_n-j_p$ = odd according to the signature, where I is the total angular momentum and j_n (j_p) is the spin of the odd neutron (proton) quasiparticle. The action of the Coriolis force in the rotating system in general is to decrease the energy of the $I-j_n-j_p$ = even states with respect to the others, and for this reason it receives the name of favored band and the other one the unfavored partner. The energy shift between both bands at a given rotational frequency $\hbar\omega$ is called the signature splitting, and it is characterized by a level staggering.

By following the evolution of this couple of bands as a function of spin or angular frequency one may observe that sometimes the favored and unfavored bands cross each other producing the so-called signature inversion phenomenon.

The nuclear structure of ^{76}Br [1,2] revealed, for the first time, an anomaly in the level staggering that now is interpreted as a band crossing of different signature. From this early work until now numerous studies of the nuclear structure of doubly odd nuclei found this effect in different mass regions such us $A \simeq 80$, 130, and 160. As a result of this experimental effort several mechanisms have been proposed to describe it.

In the following paragraph a summary of these theoretical studies is reported.

Bengtsson *et al.* [3] explained it by the effect of the γ deformation in a cranked shell model calculation. Hamamoto [4] using the particle-plus-rotor model suggested that the γ deformation may not be so important. The work of Jain and Goel [5] within the framework of the axially symmetric rotor–plus–two-particle model suggests the mechanism of Coriolis mixing between a large number of bands and Hara and Sun [6] proposed the crossing of decoupled bands to describe it. In addition, other studies analyze the effect of including the proton-neutron interaction between the odd nucleons such as the works of Matsuzaki [7] and Tajima [8] and the effect of the different dynamical symmetries of the interacting boson model such as the work of Yoshida *et al.* [9].

Concluding, there are several proposed mechanisms, but still there is not a single model, indicating that the signature inversion is still an open question.

The purpose of this work is twofold. The first is to collect all the experimental information available in the literature for certain bands in doubly odd nuclei in which the signature inversion is observed. The selected bands are described by the $\pi g_{9/2} \otimes \nu g_{9/2}$, $\pi h_{11/2} \otimes \nu h_{11/2}$, and $\pi h_{11/2} \otimes \nu i_{13/2}$ nuclear structures for the $A \simeq 80$, 130, and 160 mass regions, respectively. The second is to analyze this information with the purpose of finding some global features, along different mass regions, that might help to develop a model to explain this phenomenon.

II. ANALYSIS

With the purpose of analyzing the experimental information let us first define the physical variables at the point in which the signature inversion takes place as indicated by the word ''critical'' before the name of the parameter. For instance the angular momentum at the point in which both bands of different signature cross each other is simply denoted as the ''critical angular momentum'' or ''critical spin.''

The determination of the critical spin is sometime difficult to perform. The complex nuclear structure of doubly odd nuclei near the ground state complicates the experimental procedure of assigning the angular momentum to the low energy levels, some of them, the head of collective bands. As a consequence, the lack of a reliable bandhead spin measurement makes the critical spin not well determined.

There are studies that try to overcome this problem by analyzing a mass region and, according to the argument of excitation energy systematics, assign the spin of the lowest state such as for the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands around mass $A \simeq 130$ [10] and the bands $\pi h_{11/2} \otimes \nu i_{13/2}$ in the mass region $A \simeq 160$ [11]. Most of the experimental data used in the present work were obtained from these review works and completed with recent results. For the $\pi g_{9/2} \otimes \nu g_{9/2}$ bands in the mass $A \simeq 80$ region a similar study was performed [12].

In the following we describe how the different critical parameters used in the present study were obtained from the nuclear band structure.

In general, the normal procedure to represent the signature inversion is to plot the energy difference between two consecutive energy states in a band such as $[E(I)-E(I-1)]/2I$ versus I. Then the points corresponding to odd values of I fall on one curve and the points corresponding to even values of I on another curve. The critical angular momentum (I_c) is easily determined measuring the angular momentum in which both curves cross each other. Sometimes, as a result of a complicated level structure below the critical point, the crossing is determined from the information of states that lie at higher spins. Following this procedure the degree of uncertainty in the determination of the critical spin is estimated of around $0.25\hbar$.

Another parameter related to the crossing point of the two bands of different signature is the frequency. Unlike the critical spin, which is obtained through a graphical procedure, the frequency ($\hbar\omega_c$) needed a more elaborate one.

The frequency is defined through the canonical relation $(dE/dI)=\hbar\omega$. Because we deal with discrete energies and spins, the experimental frequency is defined as

$$\hbar\omega(I)=\frac{E(I+1)-E(I-1)}{A(I+1)-A(I-1)}, \tag{1}$$

where $A(I)$ is the total angular momentum projection along the rotational axis, the so-call alignment,

$$A(I)=\sqrt{(I+1/2)^2-K^2}, \tag{2}$$

and K is the spin projection on the symmetry axis.

Then the critical frequency is determined using the following procedure. From the energy of two consecutive states of a single signature, one higher and the other lower than the critical spin, it is possible to calculate one frequency. Doing the same thing for the other signature band we obtain two frequencies in the vicinity of the crossing point. According to that, by fitting a straight line between both frequencies it is possible to obtain the value of the frequency at the critical spin by linear interpolation. Following the last procedure along the many nuclei in the mass 80, 130, and 160 regions it was possible to obtain the critical frequency for a total of 48 nuclei.

Another procedure is to determine the critical frequency at which the experimental Routhians of the two signatures cross each other. The two methods give the same results.

The critical frequencies $\hbar\omega_c$, critical spins I_c, and the data sources are reported in Tables I and II.

III. DISCUSSION

In the present work we shall focus our attention on a search of some correlations between these critical angular momenta and frequencies with other nuclear parameters.

As an example of this attempt we report in Fig. 1 the critical spin I_c as a function of the neutron number. As can be observed the critical spin is divided into three groups of points, one for each mass zone, and spans an angular momentum region from $8.9\hbar$ up to $21.5\hbar$.

The analysis of the individual trend of I_c versus N shown in Fig. 1 reveals that for the mass 80 region the critical spin

TABLE I. The calculated critical spins and frequencies of the $\pi g_{9/2}\otimes\nu g_{9/2}$ and $\pi h_{11/2}\otimes\nu h_{11/2}$ bands for the $A\simeq 80$ and 130 mass regions, respectively. The $K=4$ quantum number was adopted.

Nuclei	I_c ($\hbar$)	$\hbar\omega_c$ (MeV)	Nuclei	I_c ($\hbar$)	$\hbar\omega_c$ (MeV)
^{74}Br [17]	9	0.378	^{118}Cs [29]	14.5	0.340
^{76}Br [18]	10.5	0.463	^{120}Cs [29]	16.5	0.401
^{78}Br [19]	11.3	0.569	^{122}Cs [29]	17.5	0.458
^{76}Rb [20]	10	0.379	^{124}Cs [29]	18.5	0.507
^{78}Rb [21]	9.7	0.365	^{126}Cs [29]	21.5	0.561
^{80}Rb [22]	10.5	0.469	^{124}La [30]	18.5	0.472
^{82}Rb [23]	11.7	0.603	^{126}La [31]	19.5	0.567
^{84}Rb [24]	11.6	0.656	^{128}Pr [32]	18.5	0.384
^{80}Y [25]	8.9	0.341	^{130}Pr [32]	18.5	0.425
^{82}Y [26]	9.5	0.377	^{132}Pr [33]	18.5	0.463
^{84}Y [27]	11.5	0.533	^{134}Pr [10]	17.5	0.511
^{86}Nb [28]	10.7	0.475	^{134}Pm [34]	17.5	0.425

shows a tendency to increase with increasing neutron number. On the other hand, the mass 160 region presents the reverse direction, the critical spin decreases with increasing neutron number, and the mass 130 region shows a sort of intermediate behavior between both mass regions. In particular, for the mass 130 region we find that some of the nuclei, namely, the Cs and the La isotopic chains, increase the critical spin and the Pr isotopic chain shows an almost constant value or slightly decreases with neutron number, respectively.

Furthermore, if we now analyze the critical frequency, instead of the critical spin, as a function of the neutron number outlined in Fig. 2, it shows a tendency to increase the value for the mass 80 and 130 regions and decrease for the mass 160 region with an increment of neutron number.

Similar results are obtained in the analysis of the critical spin and frequency as a function of the atomic (Z) and mass (A) parameters, instead of the neutron number.

Some of these previous results were already pointed out by other authors which analyzed the critical spin parameter in the the mass 130 region [10] and mass 160 region [11] and in particular the evolution of the critical frequency with neutron number for nuclei in the mass 160 region [13].

The error bars shown in Fig. 2 represent the degree of uncertainty in $\hbar\omega_c$ because its value depends on the determination of both the K quantum number and the critical spin. The K values are determined from a systematic study of the different rotational bands found in the neighboring nuclei. In this review we adopted the K quantum number suggested by the literature and assigned a dispersion of $\Delta K=0.5$. In turn the value of the critical spin was obtained by the graphical procedure described before and the dispersion was estimated as $\Delta I_c=0.25\hbar$. Then the sum of both effects, the uncertainty in the K and I_c parameters, produces an uncertainty in the critical frequency.

One of the purposes of this work is to find some global correlation between the critical frequency and some other parameters preserved along the different mass regions. To this end, instead of using the parameters N, Z, or A to analyze the experimental information, we used a parameter that

TABLE II. The critical spins, K quantum numbers, and critical frequencies of the $\pi h_{11/2} \otimes \nu i_{13/2}$ bands for the $A \simeq 160$ mass region.

Nuclei	I_c ($\hbar$)	K	$\hbar\omega_c$ (MeV)	Nuclei	I_c ($\hbar$)	K	$\hbar\omega_c$ (MeV)
^{152}Eu [35]	14	5	0.210	^{164}Lu [44]	18.1	6	0.306
^{154}Tb [36]	16.8	5	0.272	^{166}Lu [11,45]	16.6	8	0.249
^{156}Tb [11,36]	14.2	5	0.239	^{168}Lu [46]	15.7	8	0.222
^{156}Ho [37]	18.6	5	0.330	^{170}Lu [47]	12.6	8	0.165
^{158}Ho [38]	16.3	5	0.259	^{166}Ta [48]	18	7	0.312
^{160}Ho [39]	14.3	6	0.201	^{168}Ta [11,49]	19.4	7	0.310
^{158}Tm [40]	15	5	0.257	^{170}Ta [50]	16.6	7	0.260
^{160}Tm [41]	17.8	5	0.313	^{172}Ta [51]	14.3	8	0.212
^{162}Tm [41]	16.4	6	0.256	^{174}Ta [52]	12.7	8	0.174
^{164}Tm [42]	14.3	6	0.205	^{176}Ta [53]	11.9	8	0.159
^{166}Tm [43]	12.1	6	0.158	^{176}Re [54]	15.4	8	0.252
^{162}Lu [44]	20.3	5	0.366	^{178}Re [54,55]	12.5	8	0.180

was introduced by Casten *et al.* [14] who successfully studied the evolution of the nuclear deformation through the nuclear chart.

They suggested that it is possible to parametrize the nuclear transition of different mass regions by the number N_pN_n. This number is defined as the product of the numbers of valence proton, N_p, and neutron, N_n, particles (or holes past midshell).

Figure 3 shows the critical frequencies as a function of N_pN_n for the three mass regions. As can be seen, the critical frequencies are grouped along a single curve with negative slope. The data are more disperse around the middle of the curve ($60 < N_pN_n < 110$) and rather concentrated in the vicinity of a curve outside the central zone.

Another parameter, derived from the critical spin and frequency that is possible to define, is the following ratio:

$$\Theta_c = \frac{\sqrt{I_c(I_c+1)}}{\hbar\omega_c}.$$

This new parameter Θ_c is simply the moment of inertia estimated at the angular momentum in which the signature inversion occurs and for this reason it is called a critical moment of inertia.

Figure 4 shows that the critical moments of inertia as a function of N_pN_n cluster their values around several curves. These curves are approximately straight lines and differ in the relative positions depending on the mass region. A quantitative measure of the degree of correlation results in 0.93, 0.55, and 0.84 for the $A \simeq 80$, 130, and 160 mass regions, respectively.

The difference in the relative position for the three curves suggests that the ordinate might depend on the average moment of inertia at high spin for each mass region. To explore further this assumption we estimate the average moment of inertia at high spin from the review article of Winchell *et al.* [15]. They found that the moment of inertia at high spin, greater than $18\hbar$, is approximately proportional to $A^{5/3}$ for various mass regions. The comparison between the approximately average of the moment of inertia and in parentheses

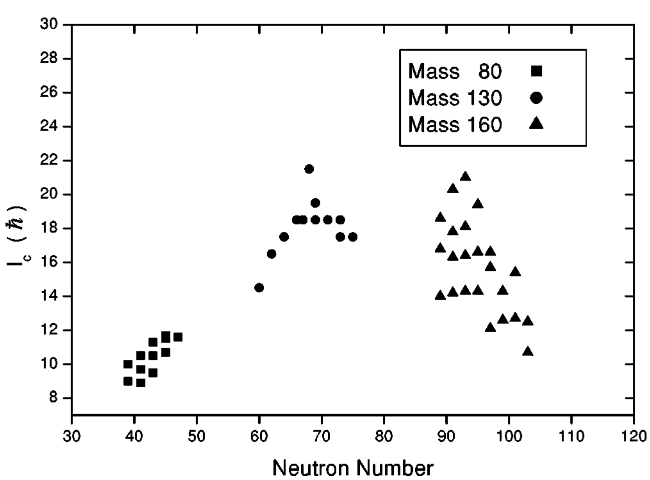

FIG. 1. The critical angular momentum (I_c) versus the neutron number for the mass 80, 130, and 160 regions. The uncertainty is estimated equal to $\Delta I_c = \hbar/4$.

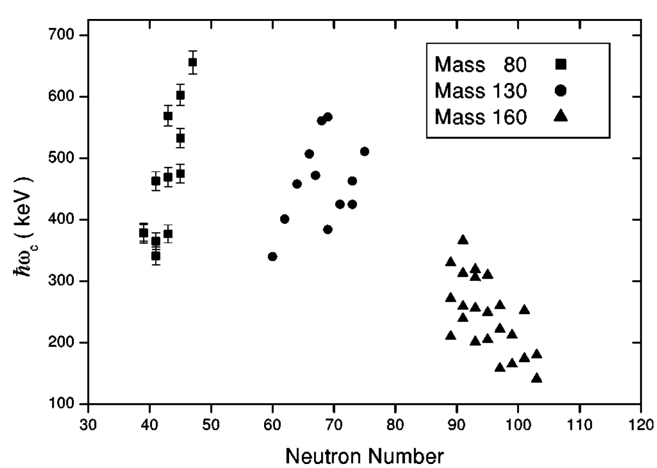

FIG. 2. The evolution of the critical frequency versus the neutron number for the different mass regions. Only the error bars, due to uncertainty in the K quantum number and the critical spin, greater than the size of the symbol are drawn.

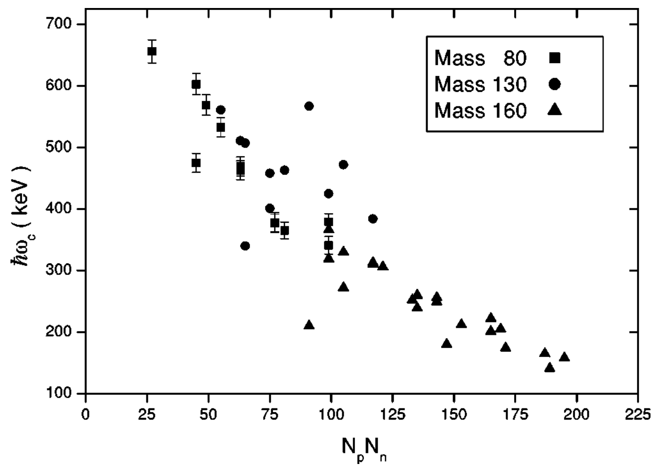

FIG. 3. The critical frequency versus the N_pN_n parameter. Only the error bars greater than the size of the symbol are drawn. The parameters show some correlation except in the region $60 < N_pN_n < 110$.

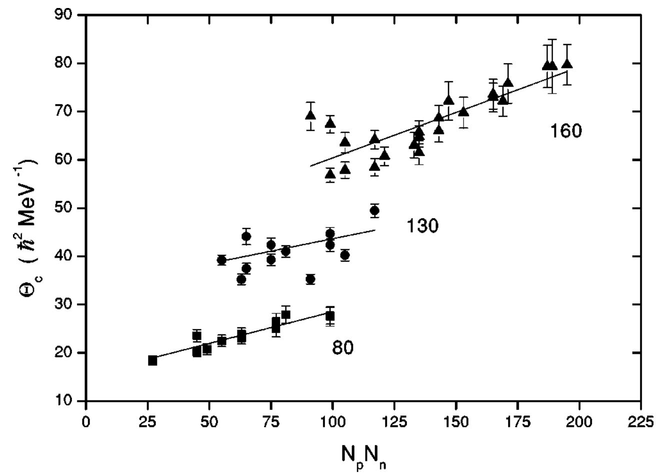

FIG. 4. The critical moment of inertia as a function of N_pN_n for the three mass regions. The curves have been drawn to guide the eye through the different groups. The data points accumulate around several curves with different degrees of correlation.

the average of the critical values obtain from Tables I and II, results 23 (24), 40 (41), and 60 (68) $\hbar^2$ MeV^{-1} for the mass 80, 130, and 160 regions, respectively. As can be seen, both average moments of inertia, one at high spin, and the other at the critical spin are similar and suggest that the previous assumption is reasonable.

Let us analyze in the following another parameter which is the rigid moment of inertia of an axial symmetric nucleus. Their value can be expressed in the form $\Theta_r \propto A^{5/3}(1 + 0.31\beta) + O(\beta^2)$ where β is the deformation [16]. Then if the rigid moments of inertia divided by $A^{5/3}$ results in an expression independent of the mass region and proportional to the deformation in a first order approximation. The last result for the rigid moment of inertia shows similarities when it is compared with the critical moment of inertia shown in Fig. 4.

The ratio of the critical divided by the average moment of inertia at high spin is almost independent of the mass regions and also the relationship between Θ_c and N_pN_n is approximately linear.

This relation is extended even further if we consider that the N_pN_n is a reasonable estimate of the average strength of the p-n interaction. And this interaction, especially in highly overlaping orbits, is the dominant factor that induces the nuclear deformation [14] measured by the parameter β.

IV. SUMMARY

In conclusion, from a systematic study of the critical spin of the doubly odd nuclei a clear feature emerges. The critical moment of inertia, Θ_c, as a function of the N_pN_n parameter shows a rather regular behavior through very different mass regions and can be interpreted as a possible global parameter to describe the signature inversion phenomena.

The remarkable correlation found between the pair of parameters Θ_c and N_pN_n suggests that the change of the critical moment of inertia in which the signature inversion takes place is influenced by the average strength of the p-n interaction.

Finally, from the present systematic study it is possible to predict, with a certain error, for each doubly odd nuclei the range in moment of inertia for which the crossing of bands with different signatures is more likely to occur. We expect that this work might promote theoretical studies directed to analyze global features rather than specific calculations for particular nuclei and contribute to increase our knowledge about this interesting phenomenon.

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