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SIGNATURE INVERSION IN ODD–ODD NUCLEI*

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Trends in the energy staggering of the $\pi h_{11/2}\nu i_{13/2}$ and $\pi h_{11/2}\nu h_{11/2}$ bands in the mass 160 and 130 regions, respectively, have been investigated in order to better understand the origin of signature inversion. While the $A \approx 160$ nuclei behave in a consistent manner, a more complicated scenario is observed in the mass 130 region. As a result of our experiments on the lightest Pr nuclei, the systematics of these $Z = 59$ nuclei have been extended, which aids in the understanding of the latter region. Triaxial deformation, a pn interaction, and quadrupole pairing are considered as possible contributors to this effect. As all the chiral-twin bands that are known have signature inversion in the favored band, a possible link between the two phenomena should be considered.

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1. Introduction

The energy splitting between the two signatures of a rotational band in a deformed nucleus is a key indicator of the structure underlying the band. The signature splitting is generally small or zero for a band of high K (the projection of the total angular momentum on the nuclear symmetry axis), but large for bands built on quasiparticles of high j and small K. This trend is a result of the mixing of the $K = 1/2$ component of a high-j shell into the valence orbital, giving significant signature splitting. However, even for Fermi levels in mid or high shell for a high-j particle, there can be substantial signature splitting as a result of small deformation or significant softness of the nucleus. Signature splitting is thus an indicator of the shape of the nucleus.

An even more sensitive indicator of nuclear structure can be the inversion of the signature in a rotational band, when the signature favored to be low in energy is shifted higher than the unfavored signature. This can happen at low spins ($\mathrm{I} < j_1 + j_2$) as a result of angular momentum couplings [1]. A signature inversion that extends to higher spins is a more interesting nuclear structure case, and is the subject of this paper.

Signature inversion has been observed in rotational bands in odd–odd deformed nuclei in a number of cases, and theories have been advanced to explain it. Bengtsson *et al.* [2] discussed the inversion in the $\pi h_{11/2} \nu i_{13/2}$ band in ^{152}Eu and ^{154}Tb and attributed this to nuclear asymmetry, specifically $\gamma = 11°$ for the former and $14°$ for the latter. Semmes and Ragnarsson [3] have shown that a proton–neutron residual interaction in a particle-rotor Hamiltonian can also reproduce signature inversion in many cases. More recently Xu, Satula, and Wyss [4] have demonstrated that even for axially symmetric nuclei a quadrupole pairing interaction can lead to signature inversion. It is these three theories that will be used in this paper. Other theoretical approaches include the crossing of bands in the projected shell model [5] and the horizontal expansion to mix states of different tilted cranking angles [6]. Also, Tajima [7] has combined two of these approaches (γ deformation and a *pn* residual interaction) to do calculations on specific nuclei (Cs and La).

This paper explores the trend of signature inversion in two regions, $\pi h_{11/2} \nu i_{13/2}$ bands for $A \sim 160$ and $\pi h_{11/2} \nu h_{11/2}$ structures for $A \sim 130$. The latter region is especially complicated and our recent measurements on three odd–odd Pr nuclei help to elucidate the relative contributions of γ deformation, *pn* residual interaction, and quadrupole pairing to signature inversion. A connection between this effect and the occurrence of chiral-twin bands around $N = 75$ is also proposed.

2. $\pi h_{11/2}\nu i_{13/2}$ systematics

The occurrence of signature inversion in odd–odd nuclei can best be illustrated by the partial level scheme of ^{154}Tb [8] shown in Fig. 1. The favored component of an odd–odd rotational band has signature quantum number $\alpha_f = 1/2[(-1)^{j_p-1/2} + (-1)^{j_n-1/2}]$. Therefore, in the $\pi h_{11/2}\nu i_{13/2}$ band even spins should be favored. This is not the case for ^{154}Tb, as odd spins are lower in energy than expected until around $I = 18\hbar$. To quantify the amount of splitting between the two signatures, one can use the expression $E(I) - 1/2[E(I+1) + E(I-1)]$ which compares the energy of a level with the average of the energies of the levels one spin higher and lower (of the other signature). The signature which has a negative value of this function is the favored signature in the band. A plot of this staggering function for the $\pi h_{11/2}\nu i_{13/2}$ band in ^{154}Tb and many adjacent nuclei is given in Fig. 2. The amount of signature inversion is largest at $N = 89$ and decreases as N increases. This trend is compatible with the calculations of Bengtsson *et al.* [2], who attribute the inversion to be a result of $\gamma > 0$. Nuclei become less γ soft as one departs the $N = 90$ region, so it is reasonable that the amount of signature inversion decreases.

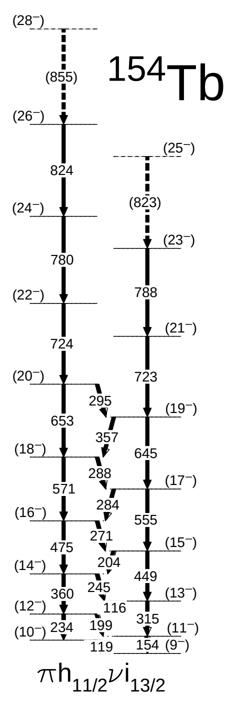

Fig. 1. Partial level scheme of ^{154}Tb showing the $\pi h_{11/2}\nu i_{13/2}$ band [8].

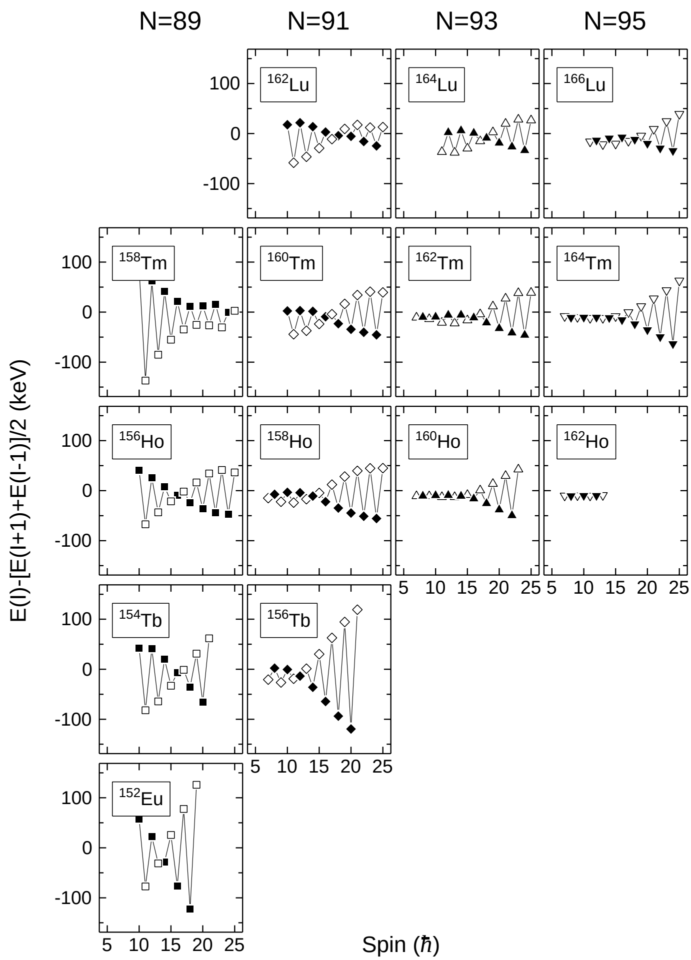

Fig. 2. Energy staggering function measured for the $\pi h_{11/2}\nu i_{13/2}$ bands in various rare-earth nuclei. Filled symbols refer to the even-spin sequence, which is favored in energy when those symbols are low in the plot.

A closer look at the effect of γ deformation on signature can be obtained by considering the systematics of signature splitting in the rotating frame of the nucleus (Fig. 3). The $\pi h_{11/2}$ bands have γ slightly negative for Eu and Tb ($K = 5/2$). However, γ becomes more negative for N = 88–90 Tm and Lu due to increasing softness of the nucleus, even though the Fermi level has moved into the higher part of the $\pi h_{11/2}$ shell ($K = 9/2$). Hamamoto has calculated that $\gamma = -21°$ is needed to explain the large signature splitting seen for N = 90 ^{171}Lu [9]. The coupling of the $i_{13/2}$ neutron orbital to proton $h_{11/2}$ has the effect of driving the nucleus to $\gamma > 0$, which removes

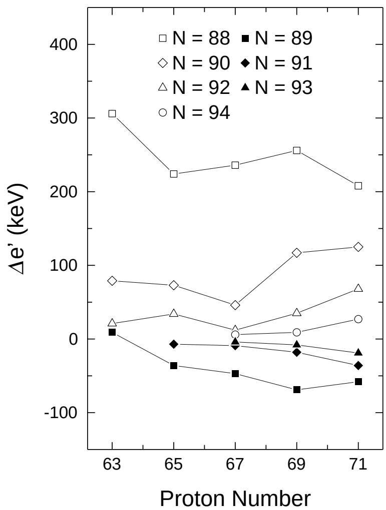

Fig. 3. Splitting between the signatures of the $\pi h_{11/2}$ band observed throughout the rare-earth region at a rotational frequency of 0.20 MeV. The even-N values refer to odd-A nuclei, odd-N to odd–odd $\pi h_{11/2}\nu i_{13/2}$ bands. Negative values of $\Delta e'$ indicate signature inversion.

the large signature splitting of odd-A nuclei and even inverts the signature in adjacent odd–odd isotopes. So, it appears reasonable to associate the large change in signature splitting with the γ softness of the nucleus.

At $N = 95$ there is no signature inversion in the yrast $\pi h_{11/2}\nu i_{13/2}$ band of ^{164}Tm, but there is a large inversion in the excited $\pi h_{9/2}\nu i_{13/2}$ band up to I $= 19\ \hbar$ [10]. This is probably not a γ effect, since $N = 95$ nuclei have well deformed shapes. Instead this is an excellent illustration of the effect of the pn residual interaction on signature. Semmes has performed particle-rotor calculations with a surface-delta pn residual interaction [10]. The calculated results for ^{164}Tm show no inversion of signature for the $\pi h_{11/2}\nu i_{13/2}$ band but a sizeable amount for $\pi h_{9/2}\nu i_{13/2}$, matching the measurement. The reason for this is related to the fact that the V_{pn} matrix element is attractive for a proton-particle neutron-particle pair, but repulsive for a proton-particle neutron-hole pair. Since the $h_{9/2}$ proton is largely particle in nature while the $i_{13/2}$ is quasiparticle, there is an addition of terms that results in the lowering of the unfavored signature. In contrast, both $\pi h_{11/2}$ and $\nu i_{13/2}$ are quasiparticle in nature, with no resulting inversion of signature. Similar effects have been seen for the $\pi h_{9/2}\nu i_{13/2}$ band in other odd–odd nuclei in this region [11].

3. $A \sim 130$ region

The relative success in understanding the pattern of signature inversion in the $A \sim 160$ region has encouraged the application of these ideas to the yrast band in odd–odd nuclei in the $A \sim 130$ region: $\pi h_{11/2}\nu h_{11/2}$. The $\nu h_{11/2}$ band in odd-N nuclei has small signature splitting, medium K, and should be equivalent to $\pi h_{11/2}$ in the $A = 160$ region, *i.e.* drive the nucleus to $\gamma < 0$. The $\pi h_{11/2}$ band in odd-Z nuclei has large signature splitting, low K, and should be equivalent to $\nu i_{13/2}$ *i.e.* drive the nucleus to $\gamma > 0$. The question is whether the odd–odd nuclei behave in same way in these two regions.

While a number of odd–odd nuclei have been measured in the $A \sim 130$ region, we have undertaken measurements to investigate the lightest (and most deformed) Pr nuclei. A series of experiments has been performed to populate high-spin states in neutron-deficient odd–odd ^{126,128,130}Pr. The ^{40}Ca + ^{92,94}Mo reactions were used to produce these $Z = 59$ isotopes. Rotational structures in ^{126,128}Pr were identified in an experiment utilizing the new Clarion Ge clover and HyBall CsI charged-particle arrays, along with the Recoil Mass Spectrometer, at the Oak Ridge National Laboratory. In fact, excited states in ^{126}Pr were observed for the first time, which makes it the lightest known odd–odd Pr isotope [12]. The other experiments used Gammasphere, in conjunction with the Washington University Microball, to extend the sequences to high spins ($\sim$40 $\hbar$).

A partial level scheme from our work on ^{130}Pr is shown in Fig. 4. The favored $\alpha = 1$ signature of the $\pi h_{11/2}\nu h_{11/2}$ band does not become low in energy until $I = 17\hbar$. The signature staggerings for this band in ^{126,128,130}Pr from our data are shown in Fig. 5, along with the other such cases known in this region. One can see that signature inversion is present in $\pi h_{11/2}\nu h_{11/2}$ bands in all odd–odd nuclei in this wide range of N and Z, which is different from the experience in the $A = 160$ region. Our data on Pr show that the amount of inversion decreases for smaller N, where the nuclei have larger and stiffer deformations [14]. However, this trend exhibited for Pr is very different than that for the Cs isotopes [15]. This leads to the question of the different effects that seem to be present in these close-lying series of isotopes.

As discussed in the previous section, it is informative to investigate the signature inversion in odd–odd nuclei by comparison to the trend of signature splitting in $\nu h_{11/2}$ bands in adjacent odd-N nuclei. Fig. 6 has a comparison of Routhian energy splittings at $\hbar\omega = 0.27$ MeV. The splitting is always large for odd-N cases, and small and negative for odd–odd nuclei. For the odd-A nuclei the trend of decreasing splitting from ^{119}Ba ($K = 3/2$) to ^{129}Nd ($K = 7/2$) is logical in view of the increasing Fermi level in the $h_{11/2}$ shell. But, the large splitting for $N > 69$ nuclei ($K = 9/2$) must be due

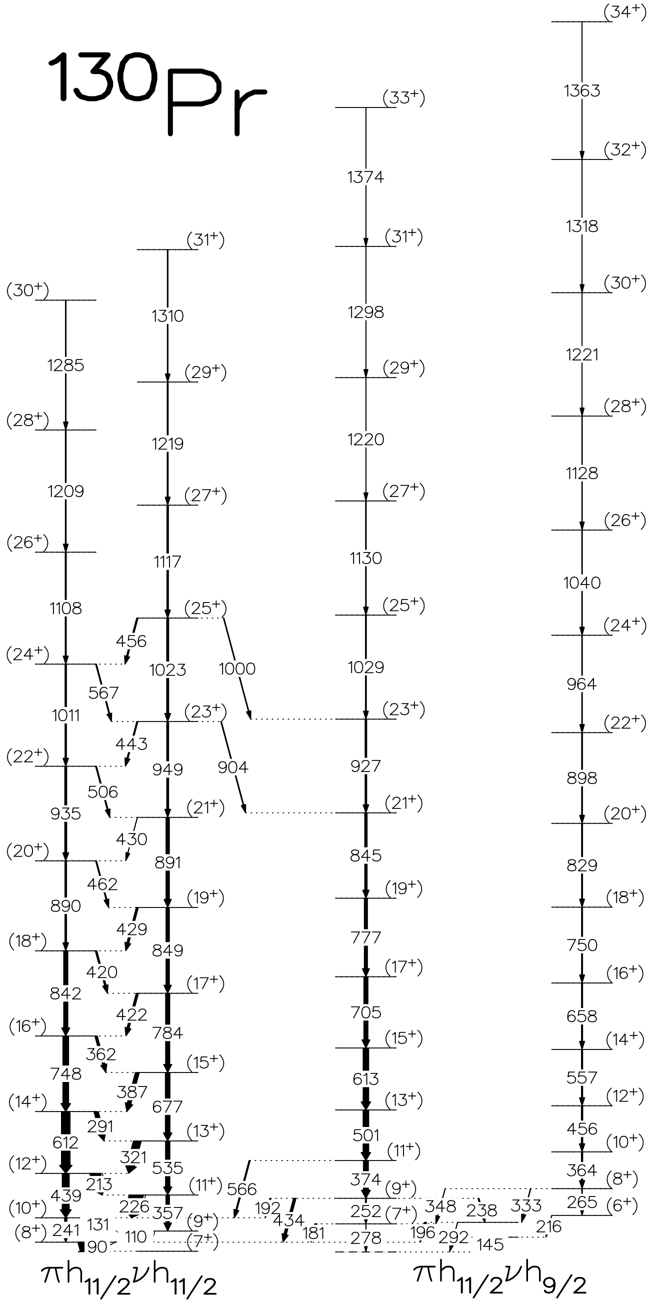

Fig. 4. Partial level scheme of ^{130}Pr showing the $\pi h_{11/2}\nu h_{11/2}$ and $\pi h_{11/2}\nu h_{9/2}$ bands [13].

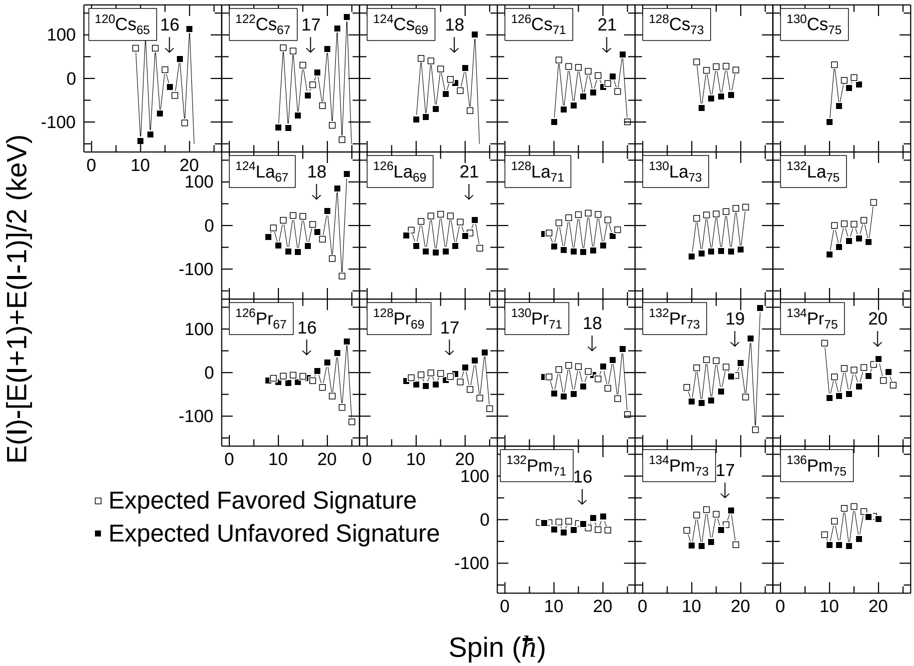

Fig. 5. Energy staggering function measured for the $\pi h_{11/2}\nu h_{11/2}$ bands in odd–odd nuclei. Open symbols refer to the odd-spin sequence, which is favored in energy when those symbols are low in the sequence.

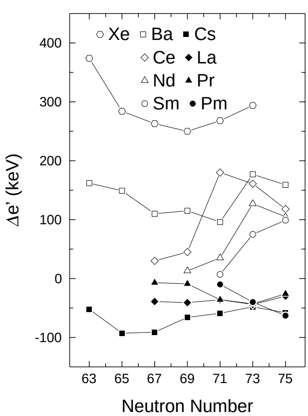

Fig. 6. Splitting between the signatures of the $\nu h_{11/2}$ band observed throughout the $A = 130$ region at a rotational frequency of 0.27 MeV. The odd-N values refer to odd-A nuclei, even-N to odd–odd $\pi h_{11/2}\nu h_{11/2}$ bands. Negative $\Delta e'$ values indicate inversion.

to increasingly negative values of γ. In fact Granderath *et al.* calculate significant negative values of γ for the heavier isotopes of each of these elements, *e.g.* above $N = 71$ for Ce [16]. This increasing γ softness of the heavier isotopes in each of these series can explain the increasing influence of the deformation-driving $h_{11/2}$ proton orbital in the odd–odd $\pi h_{11/2}\nu h_{11/2}$ bands. For example, the signature inversion in $N = 67$ Pr is very small and increases for the heavier Pr nuclei, which are softer to a resulting $\gamma < 0$ for $\nu h_{11/2}$ bands and to $\gamma > 0$ for $\pi h_{11/2}\nu h_{11/2}$ structures in odd–odd nuclei.

But, there must be another major effect at play in Cs nuclei, as the signature inversion in odd–odd cases peaks not for the soft $N = 75$ nuclei (as in Pr and Pm) but instead at $N = 65$. This puzzling trend in Cs nuclei has been examined by several groups [7, 15]. A recent novel approach is to invoke the influence of quadrupole pairing on the signature splitting in $\pi h_{11/2}\nu h_{11/2}$ bands in Cs nuclei [4]. Quadrupole pairing gives maximum inversion in Cs at $N = 65$, which is indeed the case in experiment. The actual inversion is twice as large as that calculated for quadrupole pairing, probably because an equal amount of signature inversion is due to $\gamma > 0$ [4]. The contribution from quadrupole pairing in Cs seems to go to zero for the heaviest Cs isotopes, which means that the remnant signature inversion for $N = 75$ is a $\gamma > 0$ effect as for Pr and Pm.

While the quadrupole pairing calculation helps to explain the trend in Cs, it is not clear how Pr is affected. The same influence should be felt in Pr nuclei, but it is clear that the signature inversion for $N = 67$ Pr is almost zero, where the quadrupole pairing effect is largest for Cs. It is possible that larger β_2 values for Pr compared to Cs lead to a shift of the quadrupole pairing trend to $N < 67$, as yet unobserved.

While we have not discussed *pn* residual interactions in this region, it seems that the general trend should be similar to that of γ. The effect on signature inversion should increase with N as the $\nu h_{11/2}$ orbital becomes a better high-K state, since $\pi h_{11/2}$ is a good particle state. Tajima has included a *pn* residual interaction in his calculations on Cs and La nuclei [7].

4. Chiral-twin bands

The trend elucidated for odd–odd signature inversion in the $A = 130$ region shows the largest effect for the most γ soft nuclei at $N = 75$ (see Fig. 6). It is just at this neutron number that chiral-twin $\pi h_{11/2}\nu h_{11/2}$ bands have been proposed in five isotones [17,18]. The same conditions seem to be necessary for both phenomena — angular momenta along the three principal axes of the soft deformed nucleus. In the limit of strong breaking of the chiral symmetry it is clear that the chiral-twin bands should be degenerate, the M1 transition strengths between bands should equal those within each band, and signature splitting in each band should not exist. However, the observed cases do not have this complete symmetry breaking. In fact, there is an energy splitting between the two chiral bands, and there also seems to be signature inversion in the lower of the two bands up to the spin at which the higher band is seen. Whether signature inversion is a true indicator for chirality or just simply a related effect of the γ deformation is difficult to say at this time. However, the coincidence of the two phenomena should be considered as chiral solutions are further studied.

5. Conclusions

The inversion of the signature of a band in an odd–odd nucleus results from several effects involving high-j states. One is a soft nucleus driven from $\gamma< 0$ in a one-quasiparticle band to $\gamma > 0$ by a high-j low-K particle in an odd–odd structure: $\nu i_{13/2}$ for $A \sim 160$ nuclei and $\pi h_{11/2}$ for $A \sim 130$. Another is the pn residual interaction when one high-j particle is in mid to high shell and the other is low in the shell. In fact these two are often related and should qualitatively give the same trend as a function of N and Z, as in the $A \sim 130$ region. A third effect is based on quadrupole pairing in the system of the non-deformation-driving particle, *e.g.* $\nu h_{11/2}$ for Cs nuclei. This effect occurs even for axially symmetric nuclei, and has been shown by Xu *et al.* to be quite important in explaining the Cs trend [4]. The consideration of these three effects with the newly established trend for odd–odd Pr nuclei (our new measurements) leads for the first time to a qualitative understanding of the pattern of signature inversion throughout the complicated $A \sim 130$ region. However, more calculations are needed to add wide quantitative understanding to this pattern. Specifically, the influence of quadrupole pairing must be different for Pr nuclei compared to Cs, in view of the very different measured trends. Also, more calculations on the pn residual interaction in Pr and Pm nuclei are needed.

An even more important concept to be investigated theoretically is the proposed linkage between signature inversion and chiral-twin bands. This may open another important experimental measure of the occurrence of chiral twin bands.

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