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$\pi g_{9/2}$ structures in odd-odd ^{130}Pr and alignment processes in superdeformed praseodymium nuclei

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Two strongly coupled bands with large dynamic moment of inertia values have been observed for the first time in the neutron-deficient odd-odd nucleus ^{130}Pr using Gammasphere and the Microball charged-particle detector array. These bands involve the important $g_{9/2}[404]9/2$ proton orbital. This new information on ^{130}Pr coupled with Projected Shell Model calculations provide valuable insight on rotational alignment processes taking place in this mass region, the size of the $N=72$ deformed shell gap, and the position of the $i_{13/2}[660]1/2$ neutron intruder orbital at the boundary of the $A=135$ superdeformed region. [S0556-2813(97)50409-2]

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For nuclei with $A\simeq135$, the stabilization of highly deformed shapes has been generally associated with the occupation of one or more $N=6$ $i_{13/2}$ neutron intruder orbitals [1]. Recently, it has been shown for certain strongly coupled bands in the odd-proton nuclei $^{131}_{59}\mathrm{Pr}_{72}$ and $^{133}_{61}\mathrm{Pm}_{72}$ that bands involving the $g_{9/2}[404]9/2$ proton orbital with a stabilized core arising from the $Z=58,60$, $N=72$ deformed shell gaps can also have large deformation [2–4]. Furthermore, it has been suggested that the two proton holes in the $g_{9/2}$ subshell for $Z=58$ help produce the well-developed superdeformed shapes in the Ce nuclei [4]. Two strongly coupled superdeformed bands found recently in $^{132}_{59}\mathrm{Pr}_{73}$ involve both these strong deformation driving proton ($g_{9/2}[404]9/2$) and neutron ($i_{13/2}[660]1/2$) orbitals [5]. The nucleus $^{130}\mathrm{Pr}_{71}$ lies just below the proposed $N=72$ deformed shell gap ($\beta_2\simeq0.30-0.45$) at the boundary where the $i_{13/2}$ neutron is thought to play a significant role. It is therefore an ideal case in which to test whether or not the lowest energy superdeformed bands include this $i_{13/2}$ neutron as in ^{132}Pr. The identification of highly deformed structures based on the $g_{9/2}[404]9/2$ proton orbital, with or without the lowest $i_{13/2}$ neutron orbital, will help clarify the relative importance of the $g_{9/2}[404]9/2$ proton orbital and $i_{13/2}$ neutrons in driving the nucleus towards large deformation and give information on the size of the $N=72$ deformed gap as well as the position of the $i_{13/2}$ neutron intruder orbital.

In this article we report the first observation of strongly coupled bands with a large dynamic moment of inertia ($\Im^{(2)}\sim60\hbar^2$/MeV) in the odd-odd nucleus $^{130}_{59}\mathrm{Pr}_{71}$. These new bands in ^{130}Pr complete a series of bands in ^{129}Pr [6,7], ^{131}Pr [2], ^{132}Pr [5], and ^{133}Pr [8] which involve the $\pi g_{9/2}[404]9/2$ orbital. The present results for the coupled bands in ^{130}Pr are unusual as they represent the *only* case observed at both low and high rotational frequencies ($0.17\leqslant\hbar\omega\leqslant0.56$ MeV), thus offering special insight regarding the interpretation of existing superdeformed bands in this region. In addition, extensive Projected Shell Model [9] calculations were performed to investigate in detail the rotational alignment processes taking place in these highly deformed odd-Z nuclei.

The ^{105}Pd(^{35}Cl,$xnypz\alpha$) reaction at 180 MeV populated high-spin states in many nuclei with $A\simeq135$ and $Z\simeq60$. LBNL's 88-in. Cyclotron facility provided the beam incident on a 500 μg/cm^2 enriched ^{105}Pd foil. Emitted γ rays were collected using 58 HPGe detectors of the Gammasphere array [10] and evaporated charged particles were identified with the Microball charged particle detector array [11]. A multitude of nuclei were produced, and only the ability to select specific charged particle channels allowed a detailed study of $^{130}_{59}\mathrm{Pr}_{71}$. The particle channel gated on 2α (2.6% of the total data) contained a total of 48×10^6 events of a fold $\geqslant3$. The nucleus ^{130}Pr accounted for $\simeq33\%$ of the cross section in the 2α data set.

A total of 7 rotational bands with a dynamic moment of inertia consistent with large deformation in this region [12,13] have been observed in the 2α data set. These include the known bands in ^{129}Pr ($2\alpha3n$)(2 bands) [6,7], ^{131}Pr ($2\alpha n$)(2 bands) [2], and ^{129}Ce ($2\alpha p2n$)(1 band) [14]. The two remaining bands had not been previously observed and are assigned to ^{130}Pr ($2\alpha2n$) from their observed coinci-

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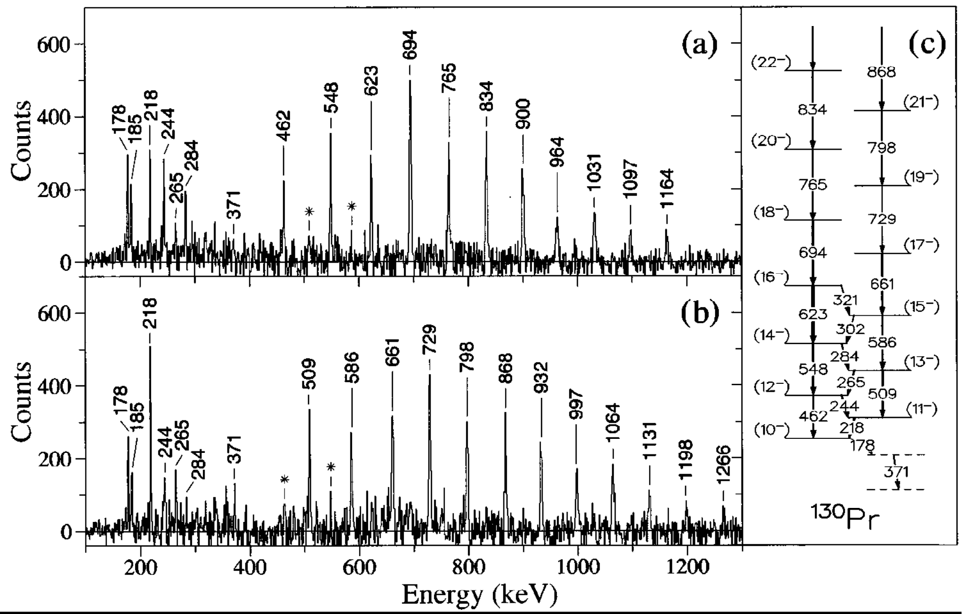

FIG. 1. Summed γ-ray triple coincidence spectra for (a) band 1 of $^{130}_{59}\mathrm{Pr}_{71}$ and (b) band 2 of $^{130}_{59}\mathrm{Pr}_{71}$. [* in (a) and (b) indicates peaks from signature partner], (c) partial level scheme for the coupled bands in ^{130}Pr.

dences with known transitions in ^{130}Pr [15] as well as the observed relative populations of bands among the different reaction channels. Bands 1 and 2 each carry $\simeq 2.2\%$ of the intensity of the ^{130}Pr reaction channel. The in-band transitions for these new structures span energies from approximately 450 keV to 1250 keV and are shown in Figs. 1(a) and 1(b). The energies of the peaks from band 1(2) fall at the midpoints between transitions from band 2(1). Cross-linking transitions between the two bands, assumed $M1$ in character, are also observed, leading to the conclusion that bands 1 and 2 are coupled signature partners as shown in the level scheme in Fig. 1(c). These two bands exhibit essentially zero ($\leqslant 3$ keV) signature splitting over their entire energy range.

The assignment of spins and parities for these new bands faces two difficulties and thus they are placed in parentheses in Fig. 1(c). First, the spins and parities of the normal deformed bands are not known for ^{130}Pr [15]. A recent paper by Liu *et al.* [16] has reassigned the spins in the $\pi h_{11/2} \otimes \nu h_{11/2}$ normal deformed band in ^{130}Pr, which bands 1 and 2 decay to, from those suggested in [15] using energy level systematics. These new assignments (a spin change of $-1\hbar$ compared to [15]) are the spin values adopted in the present work, although it is stressed that these normal deformed spins are still tentative. Second, the exact decay sequence out of bands 1 and 2 into the normal deformed states is not determined. One strong 178 keV transition and one weaker 371 keV transition are seen in coincidence with both bands 1 and 2 and low lying normal deformed transitions (see Fig. 1). The 178 keV transition is either the strongest of the decay out transitions or it may be a continuation of the dipole sequence towards a band head. The 184.5 keV, $(9^+) \rightarrow (8^+)$ [15,16] normal deformed transition is seen in coincidence with the transitions in bands 1 and 2 placing them in the ^{130}Pr nucleus.

The dynamic moment of inertia for bands 1 and 2 in ^{130}Pr is shown in Fig. 2(a). Note that all the other high spin bands observed in ^{130}Pr have much lower values of $\mathfrak{J}^{(2)} \sim 30$–40 $\hbar^2$/MeV. The $\mathfrak{J}^{(2)}$ values for bands 1 and 2 show a gradual climb with increasing rotational frequency. The coupled bands in the odd-Z ^{129,131,132,133}Pr [7,2,5,8] shown in Figs. 2(b) and 2(c) are believed to be based on excitations involving the $g_{9/2}$[404]9/2 proton orbital. The similarity of these bands, in terms of small signature splitting, consistent $B(M1)/B(E2)$ ratios of reduced transition probabilities (see below), and high moment of inertia values, with bands 1 and 2 in ^{130}Pr suggest that these new bands are also based on the $\pi g_{9/2}$[404]9/2 orbital. Comparing the $\mathfrak{J}^{(2)}$'s in Fig. 2(a) with the odd-proton neighbors ^{129,131}Pr [Fig. 2(c)], the odd-neutron neighbor ^{129}Ce and odd-odd ^{132}Pr [Fig. 2(b)], it is clear that the behavior of ^{130}Pr at low frequencies is like that of the one-quasiparticle bands in its neighboring isotopes ^{129,131}Pr.

The question is which neutron orbital is coupled to the $g_{9/2}$[404]9/2 proton in ^{130}Pr? The available neutron orbitals near the Fermi surface at these large deformations are the $h_{11/2}$[523]7/2, $h_{9/2}$[541]1/2, $f_{7/2}$[530]1/2 and the $i_{13/2}$ [660]1/2 [1,2,4]. In order to investigate this question, branching ratio measurements were performed for bands 1 and 2 of ^{130}Pr. The experimental $B(M1;I \rightarrow I-1)/B(E2;I \rightarrow I-2)$ ratios are shown in Fig. 3 along with calculated ratios for the above mentioned neutron orbitals coupled with the $g_{9/2}$ [404]9/2 proton. The theoretical values were calculated using the prescription of Dönau [17] and Frauendorf [18]. The value of $Q_0 = 5.9$ eb was taken from averaging the measured values of the highly deformed bands in the odd proton neighbor ^{131}Pr (5.5 ± 0.8 eb) [2] and the odd neutron neighbor ^{129}Ce (6.3 ± 0.4 eb) [14].

The calculations predict a clear difference in the $B(M1)/B(E2)$ ratios for the different neutron candidates. The most satisfactory reproduction of the experimental values comes from the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration. This is in contrast to the results recently published for ^{132}Pr [5] where the $B(M1)/B(E2)$ values for bands involving the $\pi g_{9/2}$ or-

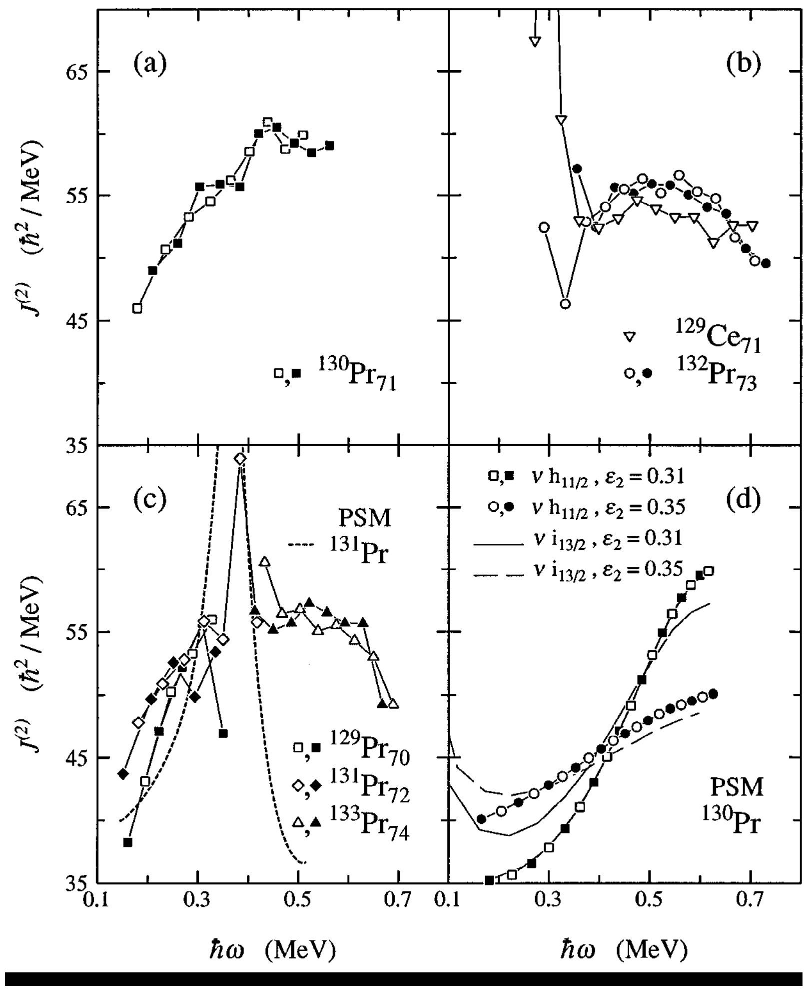

FIG. 2. The dynamic moment of inertia as a function of rotational frequency $\hbar\omega$ for bands involving the $g_{9/2}[404]9/2$ orbital (except for ^{129}Ce): (a) bands 1 and 2 in ^{130}Pr, (b) the decoupled SD band in the odd neutron neighbor ^{129}Ce [14] and ^{132}Pr [5], (c) ^{129}Pr [7], ^{131}Pr [2], and ^{133}Pr [5,8], and the PSM calculations for ^{131}Pr (dashed line) with $\varepsilon_2=0.35$, (d) PSM calculations for the $g_{9/2}[404]9/2$ proton orbital coupled to an $h_{11/2}[523]7/2$ or an $i_{13/2}[660]1/2$ neutron at deformation values of $\varepsilon_2=0.31$ and 0.35.

bital have much larger values around 1.6 $(\mu_N/e\,\mathrm{b})^2$ for spins $\simeq$16–28 $\hbar$ indicating that a different neutron orbital, most likely $\nu i_{13/2}$, is occupied. These observations lead us to suggest a configuration of $\pi g_{9/2}[404]9/2\otimes\nu h_{11/2}[523]7/2$ for bands 1 and 2 in ^{130}Pr. Additionally, the $B(M1)/B(E2)$ ratios were extracted from the same data set for the coupled one-quasiparticle $\pi g_{9/2}$ band in ^{129}Pr [7] and are shown in the inset of Fig. 3. These values are similar to those found in ^{131}Pr [2] and, as in ^{132,133}Pr, are considerably larger than those measured in ^{130}Pr. Such a high degree of consistency between experimental $B(M1)/B(E2)$ measurements and theoretical expectations for this wide region of Pr isotopes gives us confidence in not only assigning configurations to these bands, but also that these $\pi g_{9/2}$ bands all have large deformations. Indeed, TRS calculations [1] predict a minimum at a deformation of $\beta_2=0.35$ for this $\pi g_{9/2}[404]9/2\otimes\nu h_{11/2}[523]7/2$ configuration in ^{130}Pr.

To exhaust fully any other possible configurations that might possess the properties described above for bands 1 and 2 in ^{130}Pr, note that the couplings of the $g_{7/2}[413]5/2$ proton orbital with either the $h_{9/2}[541]1/2$ or the $i_{13/2}[660]1/2$ neutron orbitals are the only other local candidates that could produce a pair of bands with small signature splitting and a

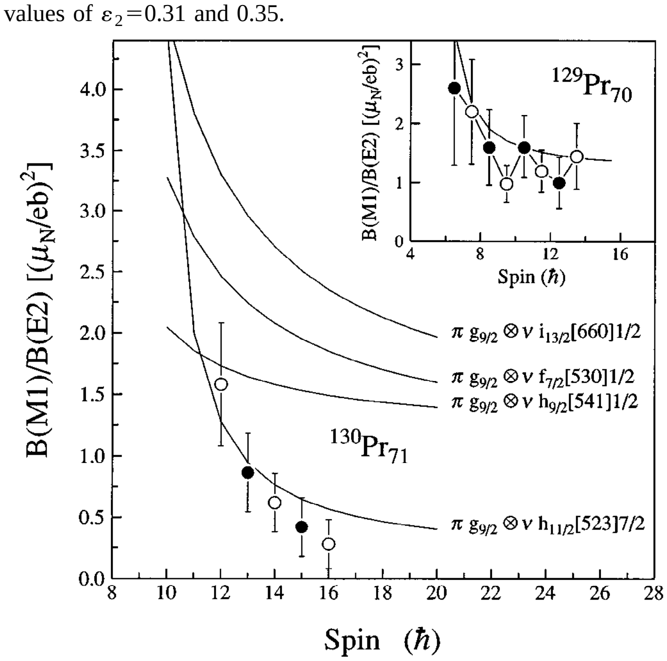

FIG. 3. $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios both calculated and experimental for ^{130}Pr and ^{129}Pr (inset). Calculated values assume a quadrupole moment of 5.9 e b for both ^{130}Pr and ^{129}Pr.

high moment of inertia. However, the experimental branching ratio measurements rule these possibilities out since calculations predict $B(M1)/B(E2)$ values in the 0.1 $(\mu_N/eb)^2$ range for spins 8–12 $\hbar$.

A unique feature of these bands involving the $\pi g_{9/2}$ orbital in ^{130}Pr is that they are observed over the rotational frequency range of $\hbar\omega=0.17$–0.56 MeV. This is in sharp contrast especially with the even-N Pr nuclei which are observed at either low frequency (^{129,131}Pr) or high frequency (^{133}Pr) with anomalous behavior occurring in each near $\hbar\omega=0.30$–0.40 MeV, see Fig. 2(c), presumably signaling the onset of a band crossing. In ^{133}Pr this behavior has been associated with the rotational alignment of a pair of $i_{13/2}$ neutrons and $h_{11/2}$ protons [8]. Support for an $i_{13/2}$ alignment comes from ^{132}Pr where the $\pi g_{9/2}\otimes\nu i_{13/2}$ band in this frequency range is unperturbed, consistent with the ν $(i_{13/2})^2$ crossing being Pauli blocked. It might therefore become tempting to continue and associate the erratic behavior of ^{131}Pr near $\hbar\omega=0.35$ MeV also to include an $i_{13/2}$ crossing. However this cannot be true since an $i_{13/2}$ alignment is neither blocked nor observed (at least up $\hbar\omega\simeq0.60$ MeV) in the $\pi g_{9/2}[404]9/2\otimes\nu h_{11/2}[523]7/2$ configuration in ^{130}Pr.

Instead these results offer convincing evidence for the occurrence of a large deformed shell gap for $\beta_2\simeq0.30$–0.45 at neutron number $N=72$. Cranked shell model calculations show that for the $i_{13/2}$ neutron orbital, which lies above the $N=72$ gap, the ν $(i_{13/2})^2$ alignment frequency changes quite dramatically from $N=74$ to $N=71$. For $N=71$ with a deformation of $\beta_2=0.35$ the ν $(i_{13/2})^2$ crossing frequency is at $\hbar\omega\simeq0.65$ MeV, just above the point where the ^{130}Pr experimental data end. Therefore, an explanation of the anomalies in the moments of inertia in ^{129,131}Pr near $\hbar\omega\simeq0.35$ MeV in terms of a $\pi h_{11/2}$ alignment [2] is thus more likely (see below for further discussion).

In order to pursue some of these questions, Projected Shell Model (PSM) calculations [9] were performed, with specific emphasis on configurations involving the $g_{9/2}[404]9/2$ proton orbital. Calculations were performed at two starting deformation values ($\varepsilon_2=0.31$ and 0.35) in order to test any sensitivity to this input parameter. Results for the $\pi g_{9/2}\otimes\nu i_{13/2}$ and $\pi g_{9/2}\otimes\nu h_{11/2}$ two-quasiparticle configurations in ^{130}Pr are shown in Fig. 2(d). (At this time PSM calculations are limited to a one-quasiparticle space for both protons and neutrons for odd-odd nuclei.) While the different deformations change the theoretical $\mathfrak{J}^{(2)}$ values slightly, the overall smooth upsloping behavior in the $\pi g_{9/2}\otimes\nu h_{11/2}$ configuration is consistent with experimental observations. The gradual upsloping is a consequence of the Coriolis Anti-Pairing effect. It is interesting to note that while the calculated $\mathfrak{J}^{(2)}$ for the $\pi g_{9/2}\otimes\nu i_{13/2}$ configuration is rather similar to that for the $\pi g_{9/2}\otimes\nu h_{11/2}$ curve, it is predicted to lie lower at high frequency, a result consistent with our observations [see Figs. 2(a) and 2(b)] and configuration assignments in ^{130,132}Pr [5] (although this is rather subtle and could be caused by small differences in deformation between the two odd-odd nuclei). The PSM also predicts in ^{130}Pr the relative excitation energy of the $g_{9/2}$ proton coupled to various neutron orbitals at these large deformation values. In these calculations, the $\pi g_{9/2}\otimes\nu h_{11/2}$, $K=8$, band is indeed predicted to lie lowest in energy.

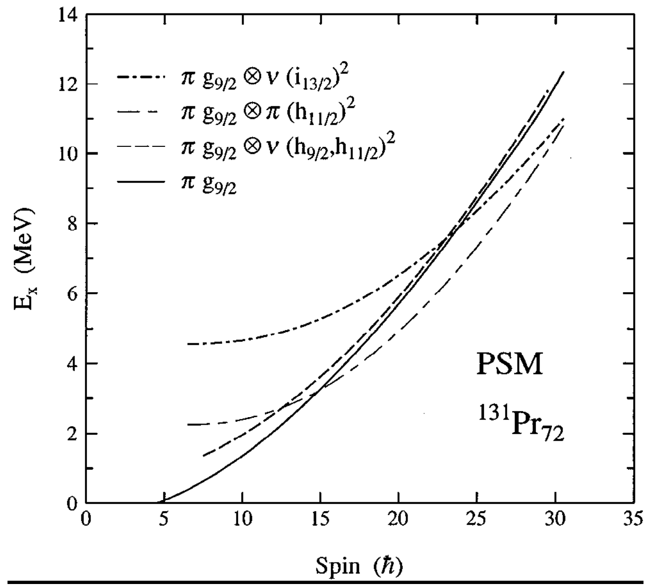

FIG. 4. Calculated excitation energy as a function of spin for various highly deformed configurations involving the $g_{9/2}[404]9/2$ orbital in ^{131}Pr.

For ^{131}Pr, detailed PSM calculations were also made to investigate thoroughly the possible alignment processes taking place and to suggest the cause of the anomalous $\mathfrak{J}^{(2)}$ behavior near $\hbar\omega\sim0.35$ MeV. The crossing of the one-quasiparticle $\pi g_{9/2}$ band was calculated for all the aligned three-quasiparticle configurations, involving the $\pi g_{9/2}$ orbital, expected to be near the Fermi surface. Alignments involving pairs of $h_{11/2}$ protons, $i_{13/2}$ neutrons, and mixed $h_{11/2}/h_{9/2}$ neutrons were considered. The results are shown in Fig. 4. The first one to three-quasiparticle crossing is calculated near $I=16\hbar$ ($\hbar\omega=0.38$ MeV) and involves the alignment of a pair of $h_{11/2}$ protons. The theoretical dynamic moment of inertia for this alignment is plotted along with the experimental values in Fig. 2(c). The $\nu(i_{13/2})^2$ alignment is not predicted to occur until much higher spin and frequency supporting the earlier discussion. The aligned $\nu h_{11/2}/\nu h_{9/2}$ configuration is not predicted to cross the yrast line. Similar results were obtained for ^{129}Pr.

Bringing all these calculations together with the experimental observations in ^{129,130,131}Pr, we are led to conclude that in all these nuclei the $\pi(h_{11/2})^2$ crossing takes place near $\hbar\omega\simeq0.35$–0.40 MeV, but in ^{130}Pr the interaction strength would seem to be somewhat stronger than in ^{129,131}Pr. In fact, in other superdeformed nuclei in this region, this $\pi(h_{11/2})^2$ alignment has been shown to occur smoothly with a large interaction strength [19,20]. One possible explanation for the observed differences in the Pr isotopes is the deformation dependence of the interaction matrix element, $V_{\rm int}$. This is expected theoretically and observed experimentally as the normal lower deformation structures in this region exhibit sharp backbending for the $\pi(h_{11/2})^2$ alignment near $\hbar\omega\simeq0.3$ MeV. Thus if ^{130}Pr has larger deformation than ^{129,131}Pr, then this could result in a larger $V_{\rm int}$ and therefore a smoother crossing. Another possibility is that there is a significant interaction between the odd $h_{11/2}$ neutron in ^{130}Pr and the aligning $h_{11/2}$ protons which affects the $V_{\rm int}$ between the crossing bands. Such effects caused by residual proton-neutron interactions have already been discussed in this mass region [21] in association with anomalous $\pi(h_{11/2})^2$ alignment. Another way of looking at the possible differences between odd-odd and odd-even nuclei around the crossing region is to note the higher density of aligned four-quasiparticle bands in the odd-odd case may lead to a different overlap with the yrast two-quasiparticle band as compared with the same alignment in the odd-even case.

One other possible explanation of the $\Im^{(2)}$ behavior in ^{129,131}Pr at $\hbar\omega \simeq 0.30$–0.35 MeV is that the $\pi g_{9/2}$ structures in these nuclei could simply be crossed by other (non-$\pi g_{9/2}$) configurations of the same parity and signature which interact with and perturb them, where in ^{130}Pr this close degeneracy of levels does not occur. In ^{129}Pr the relative excitation energies of the various bands are not known. However, in ^{131}Pr a high-K, positive parity, three-quasiparticle band approaches the $\pi g_{9/2}$ sequence at high spin and has states that are within about 50 keV at spins $35/2^+$ and $37/2^+$ of the $\pi g_{9/2}$ levels which is exactly where the dynamic moment of inertia of the latter begins to deviate from smooth behavior. This suggestion is supported by the fact that this same three-quasiparticle band displays the ''remarkable anomaly'' [2] of decaying into the superdeformed $\pi g_{9/2}$ band at lower spin in preference to other lower lying normal deformed states caused by another close degeneracy of levels at spin $23/2^+$. Extending these bands to higher frequency seems an important goal to resolve fully the true character of the high spin perturbations that take place in these odd-Z, even-N nuclei.

In conclusion, two weakly populated sequences with large dynamic moments of inertia have been observed in the odd-odd nucleus ^{130}Pr. These new strongly coupled bands are assigned the configuration $\pi g_{9/2}[404]9/2 \otimes \nu h_{11/2}[523]7/2$ based on their moment of inertia behavior, $B(M1)/B(E2)$ ratios, and small signature splitting. These particular bands in ^{130}Pr are unusual in Praseodymium nuclei, in that they range from low to high rotational frequency thus allowing useful comparisons with other large deformation bands involving the important $\pi g_{9/2}[404]9/2$ orbital in ^{129,131}Pr and ^{132,133}Pr, respectively. The lack of any sharp alignments in the ^{130}Pr bands offers strong support for the occurrence of a large shell gap at $N=72$ which pushes any $\nu(i_{13/2})^2$ alignment to very high frequency, $\hbar\omega > 0.6$ MeV, thus placing a constraint on the placement of this orbital. It is suggested that a $\pi(h_{11/2})^2$ alignment occurs in ^{130}Pr and the neighboring ^{129,131}Pr isotopes near $\hbar\omega \sim 0.38$ MeV. Several possible reasons for the different behavior of ^{129,131}Pr as compared to ^{130}Pr at high spin were discussed.

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