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# Proton orbital effects in the second minimum of doubly odd $^{132}$Pr

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Second minimum structures have been observed for the first time in the doubly odd nucleus $^{132}_{59}$Pr. Two new bands are interpreted as based on the $\pi g_{9/2}[404]9/2 \otimes \nu i_{13/2}[660]1/2$ configuration and a third as the $\pi h_{11/2}[532]5/2 \otimes \nu i_{13/2}[660]1/2$ configuration. Signature splitting effects observed in the $\pi(g_{9/2})^{-1}$ bands provide new information regarding the positive parity proton orbitals at large deformation. Results from the extracted $B(M1)/B(E2)$ ratios are consistent with a large deformation for the $\pi(g_{9/2})^{-1}$ bands.
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The study of high angular momentum structures [1,2] in the so-called ''superdeformed'' second minimum remains a most exciting and challenging frontier in nuclear spectroscopy. In the $A \approx 130$ superdeformed region, the same fascinating physics questions that are being asked in the other superdeformed regions are present, for example, the phenomenon of identical bands, the decay out of the second potential energy well, the need to determine the excitation energies and spin/parities of bands, the role of pairing, and the puzzle of $\Delta I = 2$ energy staggering. In addition, being able to assign configurations to the observed bands, thereby identifying the active orbitals at the Fermi surface, and measuring their deformation driving characteristics is of vital importance. The new generation of $\gamma$-ray spectrometers [3–5] has allowed significant progress to be made in this region in the last few years. These experiments have included the first observation of excited superdeformed bands in individual nuclei, the first unambiguous observation of identical bands in neighboring nuclei, the systematic study of the decay out from the yrast highly deformed structures in Nd nuclei, evidence for $\Delta I = 2$ energy staggering effects in Ce nuclei, and detailed quadrupole moment measurements [6–18].

In an experiment aimed at furthering our understanding of the properties of second minimum structures in the $A \approx 130$ region, the high efficiency and resolving power of the $\gamma$-ray spectrometer Gammasphere [3] was combined with the selectivity of the charged particle detector array Microball [19]. The $^{35}$Cl + $^{105}$Pd reaction at a beam energy of 180 MeV was employed. The target consisted of a single foil of enriched $^{105}$Pd of thickness 500 $\mu$g/cm$^2$. A wide range of nuclei from $Z = 58$ to 62 were populated via $xp$, $y\alpha$, and neutron emission. The selection capabilities of the Microball allowed the clean separation of the different charged particle channels. A large number of superdeformed bands ($>25$) in a wide range of nuclei ($>10$) have been observed, with the discovery of over 15 new superdeformed bands in this region. In this paper results for the $\alpha 2p$ channel, which comprised $\approx 6\%$ of the total reaction cross section are reported,

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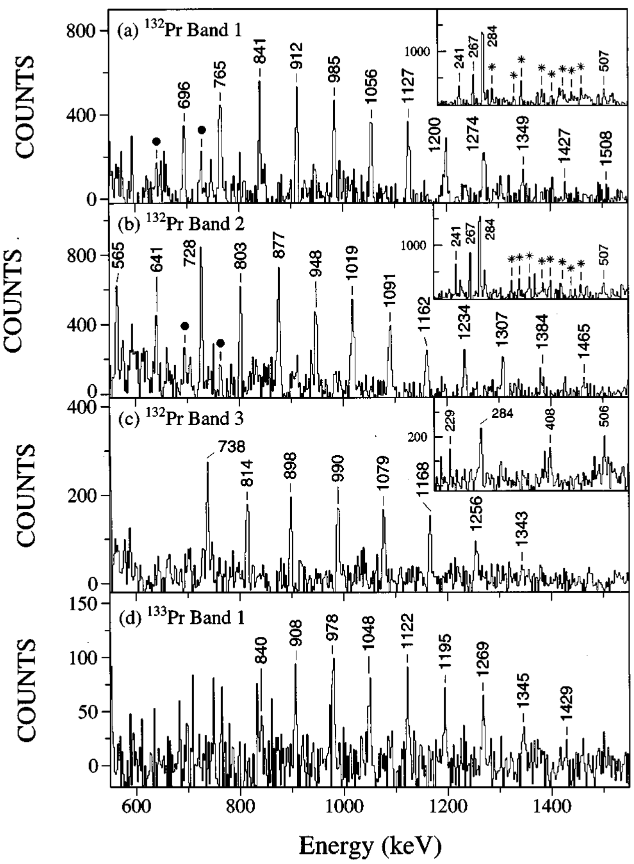


FIG. 1. (a) and (b) Summed $\gamma$-ray triple coincidence spectra for bands 1 and 2 in $^{132}$Pr. Peaks corresponding to the signature partner band are labeled with circles. The insets contain the low-energy (200 keV to 550 keV) part of the spectra. The strongest transition in $^{132}$Pr (the 284 keV peak) is seen as well as other transitions in the yrast positive parity band up to $I=11\hbar$. Dipole transitions between bands 1 and 2 are marked with a star. (c) Summed triple coincidence spectrum of band 3 in $^{132}$Pr along with the low-energy insert showing transitions in the yrast negative parity band. (d) Summed triple coincidence spectrum of band 1 in $^{133}$Pr.

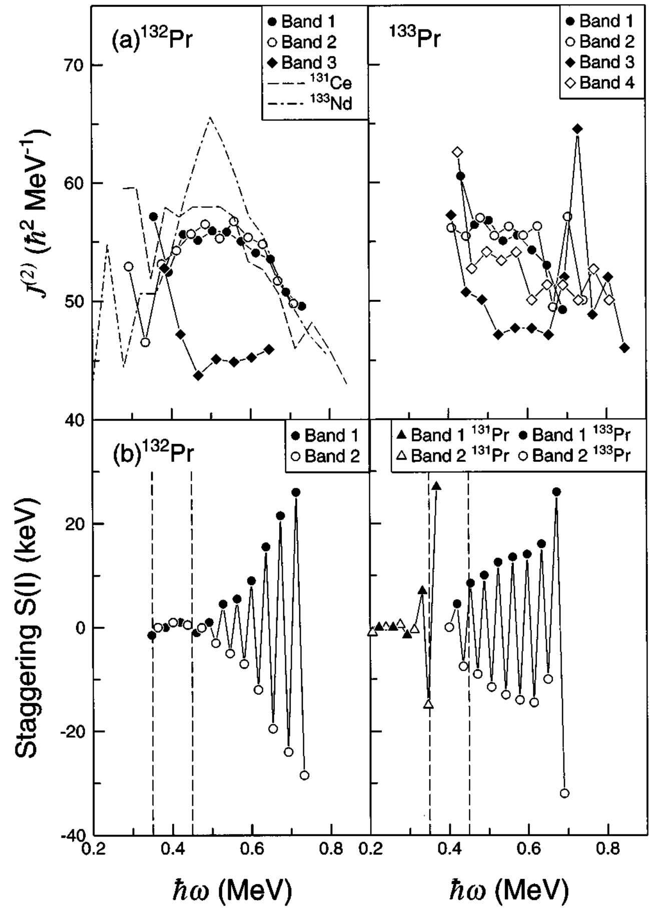


FIG. 2. (a) Plot of the dynamic moment of inertia $\mathfrak{J}^{(2)}$ for superdeformed bands in $^{132}$Pr as a function of rotational frequency $\hbar\omega$. The superdeformed bands from $^{131}$Ce, $^{133}$Nd, and $^{133}$Pr are included for comparison. (b) Signature splitting effects from the bands involving the $g_{9/2}[404]9/2^+$ proton orbital in both $^{132}$Pr (left) and $^{131,133}$Pr (right). It should be noted that the data for band 1 in $^{133}$Pr came from this experiment and the data for bands 2, 3, and 4 in $^{133}$Pr are from Ref. [14].

with the first observation of superdeformed bands in doubly-odd $^{132}_{59}$Pr. A total of $1.13\times10^8$ triple or higher fold suppressed events were collected in this $\alpha 2p$ channel. In addition to these new bands in $^{132}$Pr, we will discuss certain aspects of the known superdeformed bands in $^{133}$Pr [14] which were also populated.

Two bands with high moment of inertia values have been observed in $^{132}$Pr spanning a transition energy range of approximately 650 to 1500 keV [see Figs. 1(a) to 1(b)]. The transition energies (accurate to 0.3 keV) for band 1 are 695.5, 764.8 840.7, 912.3, 984.6, 1055.9, 1127.4, 1199.9, 1273.8, 1348.5, 1427.3, and 1508.1 keV. Band 2 has transition energies of 565.3, 641.0, 727.6, 802.9, 876.5, 948.3, 1019.0, 1091.4, 1161.8, 1234.0, 1307.0, 1384.4, and 1464.8 keV. The maximum intensity of these bands has been measured to be 1.4% of the population intensity of the $^{132}$Pr reaction channel. The energy spacing for consecutive transitions in bands 1 and 2 is $\approx$75 keV which is consistent with the known superdeformed bands in this region [1,2]. A third new band (band 3) of intensity 1.2% with transition energies of 738.3, 813.7, 898.4, 989.9, 1078.6, 1167.8, 1256.2, and 1343.3 keV has also been observed [Fig. 1 (c)]. Also shown in Fig. 1(d) is the strongest superdeformed band in $^{133}$Pr. The energies of the top four transitions of this band are different from those proposed in Ref. [14]. A plot of the dynamic moments of inertia $\mathfrak{J}^{(2)}$ of these bands and the superdeformed bands in the neighboring odd-*Z* and odd-*N* nuclei $^{133}$Pr, $^{131}$Ce, and $^{133}$Nd is shown in Fig. 2(a). Tentative spin assignments for the $^{132}$Pr bands have been estimated through analysis of where the bands feed into the previously known normal deformed structure [20–22]. The low-energy spectra (shown as inserts in Fig. 1) indicate that bands 1 and 2 feed into the positive parity yrast band at a spin of $\approx 11\hbar$. The 565.3 keV transition in band 2 has been tentatively assigned as the $(14^+)\rightarrow(12^+)$ decay, and the 695.5 keV transition in band 1 as a $(17^+)\rightarrow(15^+)$ decay. The presence of transitions from the negative parity yrast band in the spectrum for band 3 [see insert of Fig. 1(c)] leads to the tentative assignment of spin values from $(14^-)$ to $(30^-)$ for the band.

Transitions in band 2 are observed to fall virtually at the midpoint between adjacent peaks in band 1 and vice versa (Fig. 1). In fact some peaks from the other band (denoted by circles) are present in the spectra for bands 1 and 2 demonstrating that there is cross talk between these bands, thus

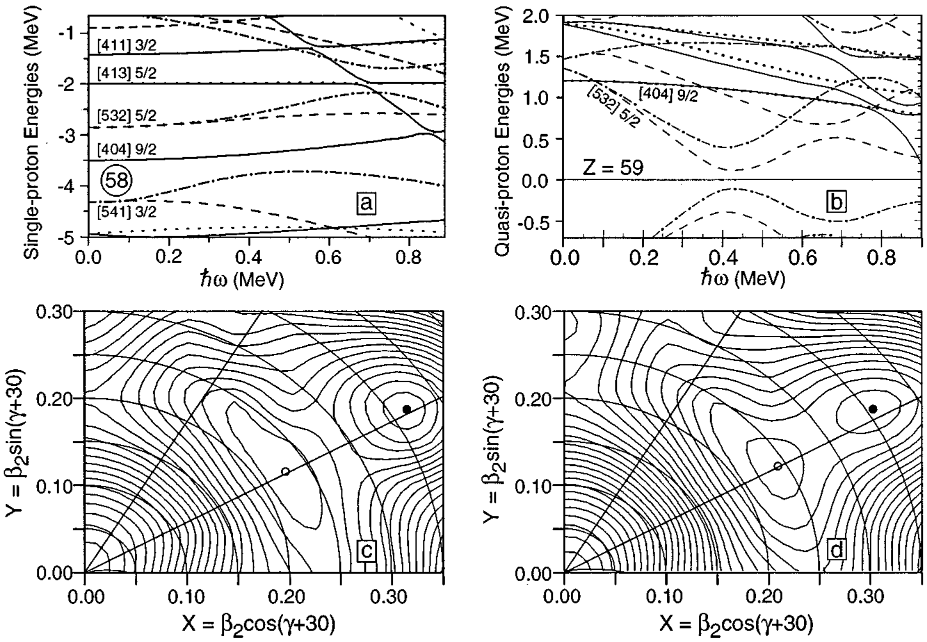


FIG. 3. (a) Single-particle Routhians for protons in $^{132}$Pr, calculated at $\beta_2=0.36$, $\beta_4=0.012$, and $\gamma=1.4°$. Lines are defined in terms of parity and signature $(\pi,\alpha)$ as follows: solid=$(+,+)$, dotted=$(+,-)$, dash-dotted=$(-,+)$, dashed=$(-,-)$. (b) Quasiparticle Routhians for protons in $^{132}$Pr, calculated with the same parameters as in (a). Note the down sloping behavior of the second lowest $(+,+)$ trajectory relative to the [404]9/2 orbital. Lines are defined in the same manner as in (a). (c) Total Routhian surface (TRS) calculation for $(+,+)$ configurations at a rotational frequency of $\hbar\omega=0.29$ MeV. The filled circle denotes the minimum in the superdeformed well, while the open circle represents the minimum of the normal deformed well. (d) TRS calculation performed in a similar manner as (c), but for $(-,+)$.

indicating they are signature partners. The energy splitting between the two signatures of the strongly coupled, superdeformed bands in $^{131,132,133}$Pr is shown in Fig. 2(b) using the staggering parameter $S(I)$ (defined as $S(I)=E(I)-E(I-1)-\frac{1}{2}[E(I+1)-E(I)+E(I-1)-E(I-2)]$) as a function of rotational frequency, $\hbar\omega$. In $^{131,133}$Pr these bands have been assigned [8,14] to an excitation based on the $g_{9/2}$[404]9/2 proton orbital coupled to zero and two $i_{13/2}$ neutrons, respectively. In Fig. 2(b) the $^{131}$Pr bands do not display any splitting until the upper limits of the bands at a rotational frequency of $\hbar\omega\approx0.35$ MeV. We suggest these deviations may be associated with the onset of the $i_{13/2}$ neutron alignment [23] at $\hbar\omega\approx0.4$ MeV. The $\pi(h_{11/2})^2$ alignment which also occurs near this rotational frequency, as indicated in Fig. 3(b), is known to take place with a large interaction strength and thus unlikely to cause the sudden splitting effects in $^{131}$Pr [24–26]. This is supported in $^{132,133}$Pr nuclei where the $\mathfrak{I}^{(2)}$ values for the $g_{9/2}$[404]9/2 bands are all considerably larger than the corresponding $\pi h_{11/2}$ [532]5/2 bands (see below) in which this gradual $\pi(h_{11/2})^2$ alignment is blocked. The proposed $i_{13/2}$ band crossing scenario is also consistent with the fact that the $^{133}$Pr bands, which are associated with two $i_{13/2}$ neutrons in their configuration, are only observed above a frequency of $\hbar\omega\approx0.4$ MeV. These data thus indicate that a band crossing involving $i_{13/2}$ neutrons takes place at $\hbar\omega\approx0.4$ MeV consistent with theoretical expectations. The observation that bands 1 and 2 in $^{132}$Pr pass straight through this frequency range without any apparent perturbation [between the dashed vertical lines in Fig. 2(b)] is consistent with Pauli blocking arguments which indicate that an $i_{13/2}$ neutron is occupied in these $^{132}$Pr bands. This latter suggestion is further supported by the experimental results for the neighboring isotone $^{133}$Nd where the superdeformed band associated with the $i_{13/2}$ [660]1/2 neutron orbital is yrast by more than 500 keV at $I=30\hbar$ [7].

With regard to signature effects, it may be observed that there is essentially no splitting at lower frequencies for $^{132}$Pr, but at $\hbar\omega\approx0.5$ MeV, the bands begin to gradually separate from each other [see Fig. 2(b)]. The increase in splitting at higher frequencies in $^{132}$Pr which is also observed in $^{133}$Pr could indicate that the nucleus moves towards triaxiality. Indeed in Ref. [27] it is suggested that bands involving $i_{13/2}$ neutrons become triaxial for nuclei with $N>75$. However, total Routhian surface (TRS) [23] calculations do not predict a triaxial shape in $^{132}$Pr or that any significant difference occurs in $\gamma$ deformation for either signature of the $g_{9/2}$[404]9/2 orbital. We suggest an alternative possibility that the splitting may be caused by a gradual mixing of positive parity orbitals at the Fermi surface. Figure 3(a) shows the single-proton Routhians calculated using a Woods-Saxon potential at a quadrupole deformation of $\beta_2\approx0.36$ typical of superdeformed bands in this region. Above $Z=58$ the active orbitals are the $h_{11/2}$ [532]5/2 for negative parity and the $g_{9/2}$[404]9/2 for positive parity. It is the latter orbital which the odd-proton occupies to form bands 1 and 2 in $^{131\text{-}133}$Pr nuclei. However, in such a calculation no splitting of the two signatures of the $g_{9/2}$[404]9/2 orbital occurs. It is only when the influence of pairing correlations are included that a possible explanation of the observed signature splitting in bands 1 and 2 of $^{132,133}$Pr arises. In Fig. 3(b), a quasiparticle Routhian is plotted for $Z=59$. We suggest that it is the influence of the next highest positive parity, positive signature $(\pi,\alpha)=(+,+)$ orbital in this calculation that decreases in energy with increasing rotational frequency and interacts with the positive signature of the

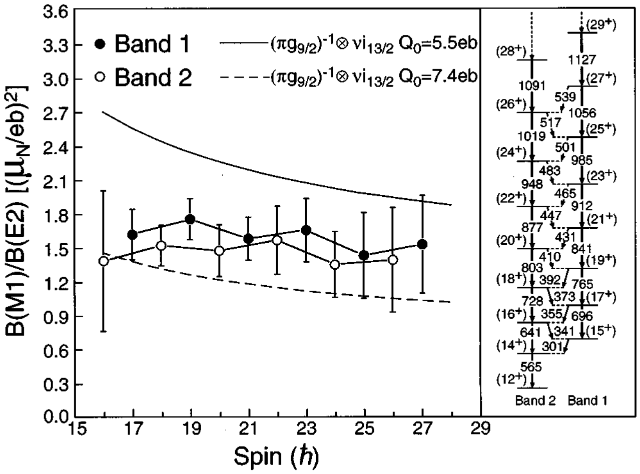


FIG. 4. $B(M1)/B(E2)$ ratios for bands 1 and 2 in $^{132}$Pr. The theoretical calculations are for the $\pi(g_{9/2})^{-1}\otimes \nu i_{13/2}$ configuration with two different quadrupole moment values. A partial level scheme of bands 1 and 2 is also shown.

$g_{9/2}$[404]9/2 orbital which could lead to the experimentally observed signature splitting. However, it is clear in the present calculations that this occurs at too high a rotational frequency compared to experiment. This is evidence that perhaps these two orbitals are closer in energy than the theory predicts or that their interaction strength is stronger. Returning once more to the discussion of possible triaxial shape, our calculations do show that even a small value of $\gamma$ ($\approx$10°) is sufficient to bring the two (+,+) orbitals discussed in Fig. 3(b) closer together such that they cross near $\hbar\omega$=0.5 MeV. The fact that the energy splitting in bands 1 and 2 in $^{132,133}$Pr are of similar magnitude is evidence that they have similar quadrupole (and possibly triaxial) deformations since any change in deformation alters the relative position of these two (+,+) orbitals and hence their mixing.

The above discussion leads to the interpretation that bands 1 and 2 in $^{132}$Pr have the predominant configuration $\pi g_{9/2}[404]9/2\otimes \nu i_{13/2}[660]1/2$. Further evidence consistent with this assignment is discussed below. Similar structures involving the $\pi(g_{9/2})^{-1}$ orbital in odd-odd nuclei within this region have been observed in $^{130}$Pr [28] and possibly $^{136}$Pm [29,30] also in this experiment.

Reliable lifetime measurements [31] cannot be extracted from these data due to insufficient statistics for the bands. However, it is still possible to suggest that the quadrupole moment for bands 1 and 2 in $^{132}$Pr is large from the extracted $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios of reduced transition probabilities. These experimental $B(M1)/B(E2)$ ratios have been compared with theoretical predictions using the framework discussed by Dönau [32] and Frauendorf [33]. The results for bands 1 and 2 as well as the theoretical curves for the $\pi(g_{9/2})^{-1}\otimes \nu i_{13/2}$ configuration and a corresponding level scheme are displayed in Fig. 4. In order to perform the calculations, the gyromagnetic ratios were determined as prescribed in Ref. [33]. Alignment values of 6.5$\hbar$ and 0.5$\hbar$ were used for the $i_{13/2}$ neutron and $g_{9/2}$ proton orbitals, respectively. The quadrupole moment values are taken from measured values for the superdeformed $\pi g_{9/2}$[404]9/2 bands in $^{131}$Pr ($Q_0$=5.5±0.8 $e$ b) [8] and the yrast superdeformed band in $^{131}$Ce ($Q_0$=7.4±0.3 $e$ b) [15] which is based on the $\nu i_{13/2}$[660]1/2 orbital. The values for $^{132}$Pr fall within the region bounded by these values adding plausibility to our suggestion that these bands are associated with a large deformation. The only other configuration involving orbitals close to the Fermi surface with large deformation [23] that give a similar $B(M1)/B(E2)$ ratio is the $\pi(g_{9/2})^{-1}\otimes \nu h_{9/2}$ configuration. However, the arguments given previously we believe are sufficiently strong to rule out this possibility.

Total Routhian surface calculations [23] were performed for positive parity configurations at different rotational frequencies. The potential energy surfaces at a rotational frequency of $\hbar\omega$=0.29 MeV, shown in Fig. 3(c), display two distinct co-existing minima. One minimum which occurs at $\beta_2$=0.22 dominates at low frequency. This is associated with the normal deformed structures in $^{132}$Pr. At $\hbar\omega\approx$0.25 MeV, a second minimum forms at $\beta_2$=0.36. This is associated with the occupation of an $i_{13/2}$ neutron orbital and is the suggested basis of the superdeformed bands discussed in this work. This second minimum continues to be the favored minimum at higher rotational frequencies. The calculations also predict a negative parity superdeformed structure in $^{132}$Pr [Fig. 3(d)] which we believe may be associated with band 3 as discussed below.

By comparing the $\mathfrak{J}^{(2)}$'s for $^{132}$Pr in Fig. 2 with those of $^{133}$Pr [14], one can note not only the similarities of the $\pi(g_{9/2})^{-1}$ bands (i.e., bands 1 and 2 in $^{132}$Pr compared with $^{133}$Pr bands 1 and 2), but also band 3 in $^{132}$Pr with band 3 in $^{133}$Pr. In Ref. [14] it was suggested that this band in $^{133}$Pr is the favored band associated with the $\pi h_{11/2}$ [532]5/2 orbital coupled to a pair of $i_{13/2}$ neutrons. We suggest that band 3 in $^{132}$Pr is most likely the same negative parity $\pi h_{11/2}$ orbital, but this time coupled to a single $i_{13/2}$ neutron. This proposal is consistent with the quasiproton diagram of Fig. 3(b). (Although a $\pi h_{11/2}\otimes \nu[(h_{9/2})(i_{13/2})^2]$ configuration cannot be completely ruled out.) Unfortunately, the unfavored $\pi h_{11/2}\otimes \nu i_{13/2}$ partner which would correspond to band 4 in $^{133}$Pr has not yet been found in $^{132}$Pr. This failure to observe a fourth band in $^{132}$Pr can be explained by the fact that band 3 in $^{133}$Pr is three times as intense as band 4 in $^{133}$Pr; thus it was unlikely for us to find this fourth band in our data. However, in the calculations [Fig. 3(b)] the unfavored $\pi h_{11/2}$ trajectory is predicted to be lower in energy than the $g_{9/2}$[404]9/2 levels. Thus, there seems to be some incompatibility between theory and experiment with regard to the superdeformed bands involving the $h_{11/2}$ proton orbital. Once again, band 3 in $^{132}$Pr cannot be positively identified as being associated with a large deformation until lifetime measurements are performed. This band shows striking similarities to band 3 in $^{133}$Pr indicating that it is reasonable to suggest the bands involve similar orbitals.

In comparing the energies of bands 1 and 2 in $^{132}$Pr with bands 1 and 2 in $^{133}$Pr, respectively, a constant difference of $\approx$5 keV is observed over a wide energy range of 840→1340 keV. Additionally, it has been found that band 2 in $^{132}$Pr is also, to the same degree, isospectral to band 3 in $^{132}$Ce [13] over a similarly large frequency range. Is this evidence for band 3 in $^{132}$Ce being based on a proton excitation? The implications of these identities are not fully understood at this time. No convincing evidence for any

$\Delta I=2$ staggering effects, which have been observed in neighboring Ce nuclei [16], are observed in $^{132}$Pr.

In summary, two (possibly three) weakly populated superdeformed bands in $^{132}$Pr have been observed for the first time. The observation of intraband transitions between bands 1 and 2 has allowed signature splitting effects and $B(M1)/B(E2)$ ratios to be inspected. This information along with results from neighboring odd-$N$ and odd-$Z$ nuclei and cranked shell model calculations suggest that bands 1 and 2 are based on a $\pi(g_{9/2})^{-1}\otimes\nu i_{13/2}$ configuration and can firmly be associated with a large deformation. For a third new band, a $\pi h_{11/2}\otimes\nu i_{13/2}$ configuration seems most appropriate. In addition, the high-energy transitions of the strongest band in $^{133}$Pr have been modified. Signature splitting effects observed in the $\pi(g_{9/2})^{-1}$ bands in $^{132,133}$Pr offer new information regarding the relative placement of positive parity proton orbitals at large deformation.

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