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Highly deformed rotational structures in ^{136}Pm

J. Pfohl,[1,*] R. W. Laird,[1] M. A. Riley,[1] F. G. Kondev,[1,†] D. E. Archer,[1,‡] T. B. Brown,[1,§] R. M. Clark,[2] M. Devlin,[3,∥] P. Fallon,[2] D. J. Hartley,[1,7] I. M. Hibbert,[4,¶] D. T. Joss,[5,**] D. R. LaFosse,[3,††] P. J. Nolan,[5] N. J. O'Brien,[4] E. S. Paul,[5] D. G. Sarantites,[3] R. K. Sheline,[1] S. L. Shepherd,[5] J. Simpson,[6] R. Wadsworth,[4] Y. Sun,[7] A. V. Afanasjev,[8] and I. Ragnarsson[8]

[1]*Department of Physics, Florida State University, Tallahassee, Florida 32306*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[3]*Department of Chemistry, Washington University, St. Louis, Missouri 63130*
[4]*Department of Physics, University of York, Heslington, York Y01 5DD, United Kingdom*
[5]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[6]*CLRC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[7]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[8]*Department of Mathematical Physics, Lund Institute of Technology, P.O. Box 118, S-22100 Lund, Sweden*

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Four highly deformed structures in the odd-odd nucleus $^{136}_{61}\mathrm{Pm}_{75}$ were observed via the ^{105}Pd(^{35}Cl,2p2n) reaction at 180 and 173 MeV using the GAMMASPHERE γ-ray spectrometer and the Microball charged-particle detector array. Quadrupole moment measurements were performed on all of the bands. In contrast to lighter odd-Z Pm and Pr nuclei, bands based on the $g_{9/2}$[404]9/2 proton orbital were not observed. Instead, the four observed sequences are assigned as a coupling of an $i_{13/2}$ neutron with the low-Ω $h_{11/2}$ and mixed $d_{5/2}g_{7/2}$ orbitals. Comparisons with neighboring highly deformed structures are discussed and cranked Nilsson-Strutinsky calculations for ^{136}Pm are presented.

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Recently, much attention has focused on highly deformed second-minimum structures in the odd-Z praseodymium ($Z=59$) chain of nuclei near mass $A=130$. A number of rotational sequences with characteristics consistent with super or highly deformed ($\epsilon_2\sim 0.27-0.40$) shapes were previously observed [1–13]. These studies have demonstrated that the $g_{9/2}$[404]9/2 proton orbital also plays a critical role in driving the nucleus to ''enhanced'' prolate deformation values regardless of the involvement of the $i_{13/2}$[660]1/2 neutron orbital that was previously associated with large-deformation structures in this region [14–16]. In an effort to extend the understanding of highly deformed structures in odd-Z nuclei in this region, a series of experiments were performed to study the $N=74$ and 75 promethium ($Z=61$) nuclei [17]. These experiments continue the quest to expand the $A=130$ Ce-Nd highly deformed region towards the $A=140-150$ superdeformed nuclei [18], and build upon the studies of the $N=72$, 73, and 75 Pm nuclei by Galindo-Uribarri *et al.* [1], Wadsworth *et al.* [4], and Riley *et al.* [19], respectively. This article reports on the observation and quadrupole moment measurements of four highly deformed sequences in ^{136}Pm. These structures are interpreted as involving particular proton orbitals coupled to the energetically favored signature ($\alpha=+1/2$) of the $i_{13/2}$[660]1/2 neutron orbital. One pair of bands shows behavior consistent with the $\pi h_{11/2}\otimes\nu i_{13/2}$ configuration. It is argued that while highly deformed sequences involving the $\pi g_{9/2}$[404]9/2 orbital are observed in ^{133,135}Pm [1,20], the second pair of observed bands in ^{136}Pm is best understood as the mixed $d_{5/2}g_{7/2}$ proton orbital coupled to the $i_{13/2}$ neutron.

High-spin states in a wide range ($Z=58-62$) of nuclei were populated after fusion of a ^{35}Cl beam with ^{105}Pd target nuclei. Thin and backed target experiments were performed at the 88-Inch Cyclotron Facility at the Lawrence Berkeley National Laboratory. Beam energies of 180 MeV (thin target) and 173 MeV (backed target) were used. The thin target was an isotopically enriched ^{105}Pd foil with a thickness of 500 μg/cm^2. The backed target was a 1 mg/cm^2 thick ^{105}Pd foil mounted on a 17 mg/cm^2 Au backing. Emitted γ rays were collected using the GAMMASPHERE spectrometer [21,22] consisting of 57 (thin target experiment) and 97 (backed target experiment) Compton suppressed hyperpure Ge detectors. The evaporated charged particles were identified with the Microball detector system [23] allowing a clean separation of the different charged-particle exit channels. For the ^{105}Pd(^{35}Cl,2p2n)^{136}Pm reaction, which is approximately 13% of the total reaction cross section, 2×10^8 suppressed γ

*Present address: Sandia National Laboratories, Albuquerque, NM 87185.

†Present address: Physics Division, Argonne National Laboratory, Argonne, IL 60439.

‡Present address: Lawrence Livermore National Laboratory, Livermore, CA 94550.

§Present address: Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506.

∥Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.

¶Present address: Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, U.K.

**Present address: School of Sciences, Staffordshire University, Stoke on Trent ST4 2DE, U.K.

††Present address: Department of Physics, SUNY Stony Brook, Stony Brook, NY 11794.

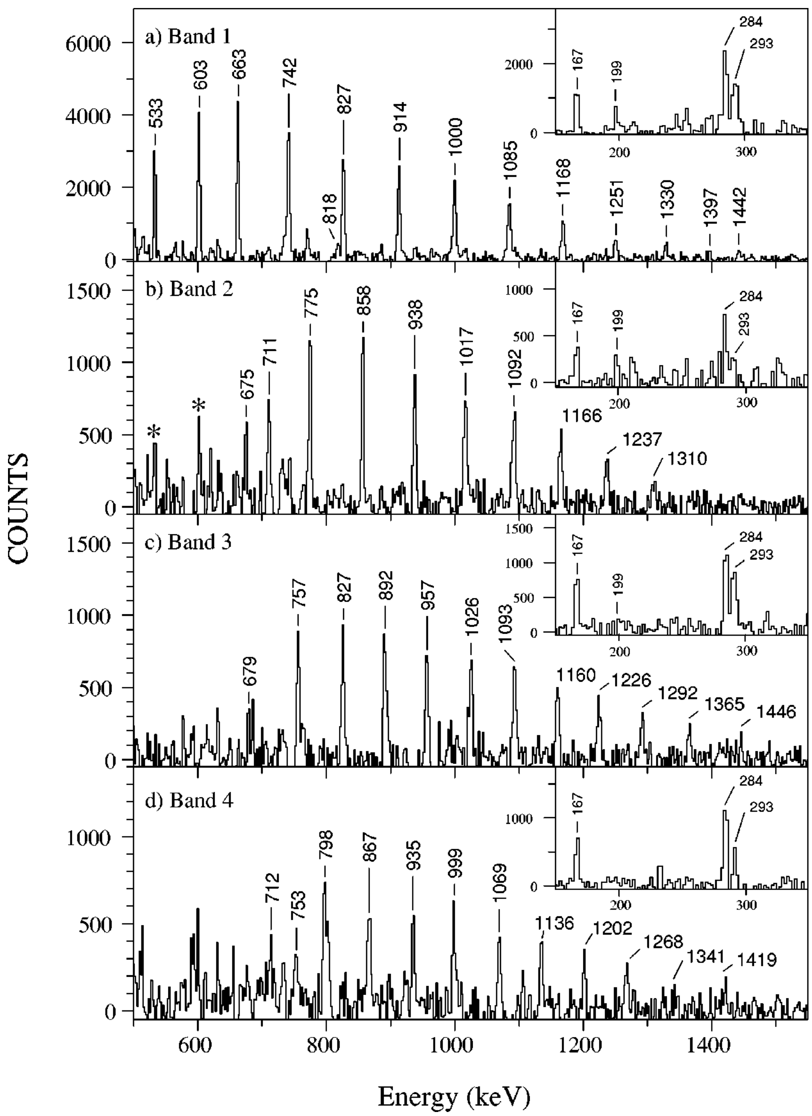

FIG. 1. Summed γ-ray triple-coincidence spectra for bands in ^{136}Pm. The insets contain the low-energy (150 keV to 350 keV) part of the spectra. Low-spin normal deformed transitions in ^{136}Pm are also labeled. The *'s in (b) indicate transitions in band 1. In (d) band 4 the 753 and 712 keV transitions are parallel at the bottom of the band.

events of fold three and above were collected in the thin target experiment, while for the thick target experiment 3×10^8 such events were collected.

Four rotational bands, three of them observed for the first time in this Rapid Communication, all with moments of inertia similar to known highly deformed structures in this mass region were observed in ^{136}Pm (Fig. 1). The maximum intensities of bands 1, 2, 3, and 4 compared with the total intensity of the ^{136}Pm reaction channel are estimated as 9%, 3%, 3%, and 2%, respectively. Although no firm connections are observed between the highly deformed bands and the normal deformed levels [17,24], in the thick target data a stopped 818 keV transition is prominent in the gated spectra of band 1 indicating that this transition can be firmly associated with the decay process of this band. Note also that there is evidence in Fig. 1(b) that band 2 feeds into the lower members of band 1, supporting the suggestion that these two bands are signature partners. The dynamic moment of inertia ($J^{(2)}=dE/dI$) plot for these four sequences in ^{136}Pm and some highly deformed bands for the neighboring nuclei ^{133}Pm [1], ^{132}Pr [2], and ^{135}Nd [25,26] is presented in Fig. 2. For comparison normal-deformed structures in ^{136}Pm have $J^{(2)}$ values of $\sim 30\hbar^2$/MeV.

The most intense cascade, band 1, was previously observed up to the 1168 keV transition [19]. It was suggested that this band involved a coupling of the lowest $i_{13/2}$ neutron orbital ([660]1/2, $\alpha=+1/2$) with the favored signature of the $h_{11/2}$ proton orbital ([532]5/2, $\alpha=-1/2$). For $N=75$ nuclei it is established that this particular neutron orbital plays a dominant role in highly deformed structures and this behavior is also expected in ^{136}Pm. For example, in ^{135}Nd the highly deformed $\nu i_{13/2}$ band is observed to become yrast above spin $25\hbar$ and is more than 400 keV lower in excitation energy than any other sequence at spin $I=40\hbar$. For this important reason, along with moment-of-inertia observations and lifetime measurements (discussed below), the other three bands observed in ^{136}Pm are also assigned an $i_{13/2}$ neutron content. This suggestion is consistent with cranked shell model calculations, although, until firm parities and spin values are experimentally determined, the involvement of the $f_{7/2}h_{9/2}$ [541]1/2 neutron orbital cannot be completely ruled out. The $J^{(2)}$ behavior of band 2 is similar to band 1 indicating that it most likely involves the unfavored signature of the [532]5/2 orbital. Note that in Ref. [19] the lower than usual moment of inertia for band 1, compared with other neighbor-

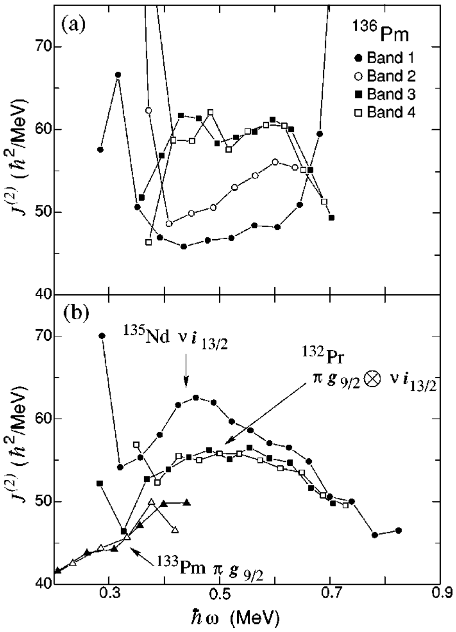

FIG. 2. The dynamic moment of inertia as a function of rotational frequency, $\hbar\omega$, for highly deformed structures in ^{136}Pm and (b) highly deformed bands in ^{135}Nd, ^{133}Pm, and ^{132}Pr.

ing highly deformed sequences, was explained as a ''blocking effect'' for the alignment of the first pair of $h_{11/2}$ protons which is known to occur near $\hbar\omega \sim 0.45$ MeV. The same argument also holds, as indeed it should, for band 2.

Quadrupole moment values were extracted for all four bands from the thick target data using the centroid-shift Doppler-shift attenuation method [27]. For the more intense bands (bands 1 and 2), the data were sorted into two-dimensional matrices of γ-ray energies, in which one axis consisted of the ''forward'' (31.7° and 37.4°) or the ''backward'' (142.6° and 148.3°) group of detectors and the other axis was any coincident detector. Spectra were generated by summing gates on the cleanest, fully stopped transitions at the bottom of the band of interest and projecting the events onto the ''forward'' and ''backward'' axes. These spectra were then used to extract the fraction of the full Doppler-shift, $F(\tau)$, for transitions within the band of interest. In order to extract information for the weaker bands (bands 3 and 4), and to check the results for bands 1 and 2, double gates were also set on in-band ''moving'' transitions in any ring of detectors and data were again incremented into separate spectra for events detected at ''forward,'' ''90°,'' and ''backward'' angles. Finally, for the strongest bands (bands 1 and 2) coincidence gates were set on only the highest spin transitions within the band, making it possible to eliminate the effect of side feeding for states lower in the cascade. Approximately a 10% increase in the deduced deformation was found using the latter method compared with the value extracted by gating on the stopped transitions at the bottom of the band. Similarly, a 5% increase was observed when using coincidence gates set on transitions throughout the band (as for bands 3 and 4). This is consistent with the measurements on the highly deformed bands in ^{133,135}Nd [28]. It is estimated that the side feeding lifetimes of the highly deformed bands in ^{136}Pm and ^{133,135}Nd are similar and about 1.3–1.4 times slower than those for the in-band levels which agrees with recent measurements by Clark *et al.* [29] for highly deformed structures in ^{131,132}Ce. Figure 3 shows the measured fractional Doppler shift, $F(\tau)$, as a function of γ-ray energy for each band, together with that of the known highly deformed band in ^{135}Nd measured in this experiment [28].

In order to extract the intrinsic quadrupole moments from the experimental $F(\tau)$ values, calculations using the code FITFTAU [30] were performed. The $F(\tau)$ curves were generated under the assumption that the band has a constant Q_0 value. In the modeling of the slowing process of the recoiling nuclei, the stopping powers were calculated using the most recent version of the code TRIM [31]. The corrections for multiple scattering were introduced using the prescription given by Blaugrund [32]. Where appropriate, the side feeding into each state was taken into account according to the experimental in-band intensity profile using a rotational cas-

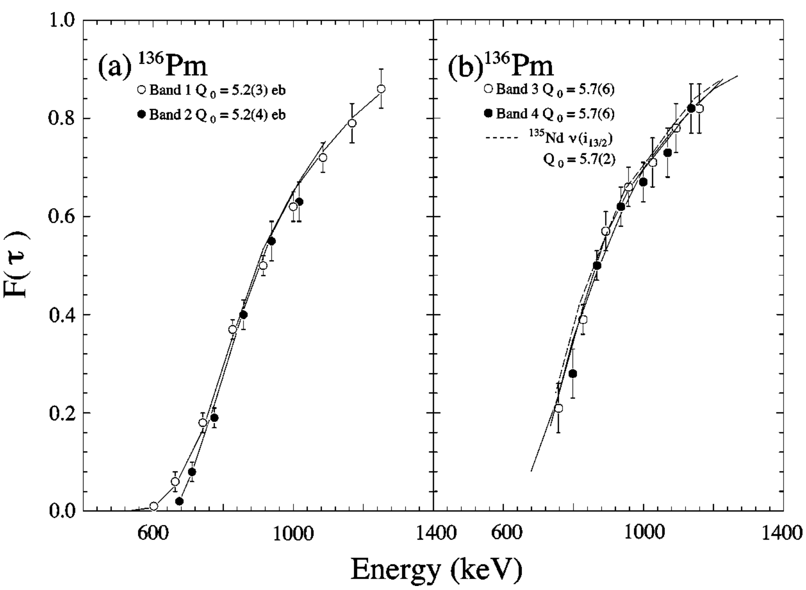

FIG. 3. The experimental and calculated $F(\tau)$ values as a function of γ-ray energy for (a) bands 1 and 2 and (b) bands 3 and 4 in ^{136}Pm. Calculated curves that best fit the data are shown as solid lines along with the corresponding quadrupole moment values. In addition, the $F(\tau)$ curve, extracted from the same data, for the highly deformed band in ^{135}Nd [28] is shown as a dashed line in (b).

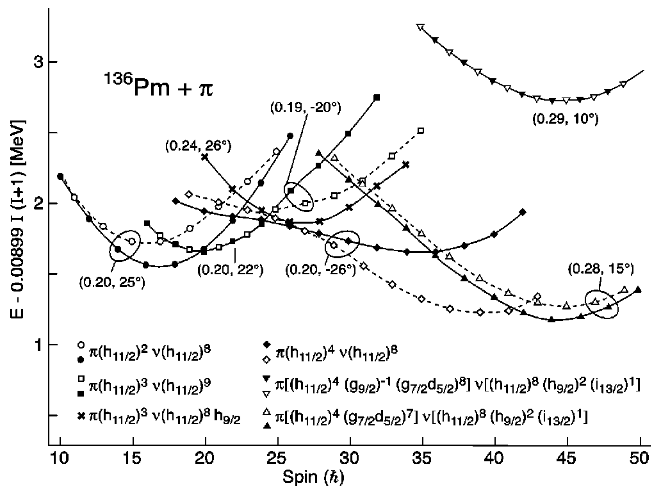

FIG. 4. Calculated excitation energy minus a rigid rotor reference as a function of spin for the lowest energy positive parity configurations in ^{136}Pm. Even and odd spin states are indicated by open and filled symbols, respectively, and signature partner bands are linked by a loop at selected points. Complete theoretical configuration labels for the bands are given in the legend and correspond to the labeling convention used for important band structures in the text in the following manner:

$$\pi[(h_{11/2})^4(g_{9/2})^{-1}(g_{7/2}d_{5/2})^8]\nu[(h_{11/2})^8(h_{9/2})^2(i_{13/2})^1]$$

$$\equiv \pi g_{9/2}\otimes \nu i_{13/2}$$

and

$$\pi[(h_{11/2})^4(g_{7/2}d_{5/2})^7]\nu[(h_{11/2})^8(h_{9/2})^2(i_{13/2})^1]\equiv \pi d_{5/2}g_{7/2}\otimes \nu i_{13/2}.$$

Deformation values (ϵ_2,γ) for the bands are indicated at various spins. Note the position of the $\pi g_{9/2}\otimes \nu i_{13/2}$ configuration (designated by the inverted triangles) is approximately 1.5 MeV above the yrast line.

cade of three transitions with the same Q_0 as the in-band states. Although the uncertainties in the stopping powers and the modeling of the side feeding may contribute an additional systematic error of 15–20 % in the absolute Q_0 values, the relative values are considered to be accurate to a level of 5–10 %. Such precision allows a clear differentiation in the Q_0 values between normal and enhanced deformed sequences, which was used in turn as evidence for the involvement of specific orbitals within a band configuration.

The fact that bands 1 and 2 display such similar $F(\tau)$ curves is further evidence that they are indeed signature partners. This is also true for bands 3 and 4. The high Q_0 values of 5.2(3) (band 1), 5.2(4) (band 2), 5.7(6) (band 3), and 5.7(6) e b (band 4) also support the involvement of the $i_{13/2}$ orbital in these structures. For comparison, the normal deformed sequences were determined to have Q_0 values of $<2.7e$ b since they exhibited little or no Doppler shift at high spin (rotational frequency). Assuming axial symmetry $(\gamma=0°)$ and zero hexadecapole deformation, the Q_0 values correspond to quadrupole deformation values, ϵ_2, of 0.26(2) for bands 1 and 2 and 0.28(3) for bands 3 and 4. However, if a small amount of triaxiality is assumed as suggested from our calculations (see Fig. 4), these ϵ_2 values will increase by about 20%. These Q_0 values fit consistently within the systematic measurements in this region [33] where the effect of the $Z=58$,60 and $N=72$ deformed shell gaps become progressively weaker with increasing Z and N. These experimental observations are also consistent with theoretical predictions, see for example, Refs. [14,15,33] and the calculations presented below.

The above discussion has mentioned several arguments which suggest that the $i_{13/2}$ neutron orbital is involved in all four band configurations. This suggestion is supported by theoretical calculations also, (see below). In addition, the behavior of bands 1 and 2 is consistent with them being based on excitations involving the favored and unfavored $h_{11/2}$ proton orbital (i.e., $\pi h_{11/2}\otimes \nu i_{13/2}$). However, the structure of bands 3 and 4 is less clear. In order to explore the proton orbital candidates that may be involved with bands 3 and 4, the observed structures in ^{133}Pm [1] and ^{135}Pm [20], for which extensive data is now available, is considered. In these odd-Z nuclei, bands involving the π $h_{11/2}$[532]5/2, $d_{5/2}$[411]3/2, $g_{7/2}$[413]5/2, and $g_{9/2}$[404]9/2 orbitals are now established with the $h_{11/2}$ orbital being yrast and the $g_{9/2}$ orbital lying highest in excitation energy. The observed behavior of these orbitals as a function of rotational frequency and spin are very different. For example, the $h_{11/2}$ orbital experimentally displays large signature splitting (>500 keV), while the two $g_{9/2}$ signatures are degenerate to less than 10 keV. The two signatures of the [411]3/2 and [413]5/2 sequences display intermediate energy splitting and have moments of inertia that closely track each other.

In ^{136}Pm, bands 3 and 4 are of similar intensity and display very similar moments of inertia as a function of rotational frequency [Fig. 2(a)]. From the moment of inertia behavior shown in Fig. 2, and the prominent observation of $\pi g_{9/2}$[404]9/2 bands in nearby odd-Z lower mass nuclei, it seems tempting to assign bands 3 and 4 in ^{136}Pm to the $\pi g_{9/2}\otimes \nu i_{13/2}$ configuration because of their similarity to the signature paired bands in ^{132}Pr [Fig. 2(b)]. However, there are several experimental observations that indicate that bands 3 and 4 in ^{136}Pm do not involve the $\pi g_{9/2}$ configuration.

Although no cross linking $\Delta I=1$ transitions are observed between bands 3 and 4, it seems most likely that they are signature partners. If the excitation energies of these two bands are chosen to minimize any energy splitting at low rotational frequency, analyses of their signature-splitting behavior shows them to have nearly an order of magnitude higher energy splitting at $\hbar\omega\sim 0.6$ MeV than examples for highly deformed sequences in ^{129,131,133}Pr, and ^{133,135}Pm based on the [404]9/2 orbital, and also in ^{130,132}Pr where this special proton orbital is coupled with an $h_{11/2}$ and $i_{13/2}$ neutron, respectively. The lack of observed cross transitions between bands 3 and 4 provides additional experimental evidence that the [404]9/2 proton orbital is not involved. For the [404]9/2 orbital in ^{132}Pr, $B(M1)/B(E2)$ transition-strength ratios of ~ 1.6 $(\mu_N/e\,\mathrm{b})^2$ were extracted and $\Delta I=1$ transitions in the energy range of 300–350 keV are observed [2]. It is expected that the same configurations in ^{136}Pm would have slightly lower quadrupole deformation [33] and thus cross transitions should be more easily observable. This argument can be extended further by following the methodology of Donau and Frauendorf [34] to calculate the expected $B(M1)/B(E2)$ values for the two most likely candidates for bands 3 and 4, namely the $\pi[413]5/2\otimes\nu[660]1/2$ or $\pi[411]3/2\otimes\nu[660]1/2$ configurations. Values of $\sim$0.1 and $\sim$0.5 $(\mu_N/e\,\mathrm{b})^2$ were obtained. Since both of these values are much lower than those for the $\pi g_{9/2}\otimes\nu i_{13/2}$ configuration, it seems much more sensible to assign bands 3 and 4 as a mixing of the $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals coupled with the $i_{13/2}$ neutron. It may also be noted that the lowest positive-parity sequence in even-N Pm nuclei is based on the $\pi[413]5/2$ orbital.

In order to support the arguments presented above and shed further light on the high spin structure of ^{136}Pm, projected shell model and cranked Nilsson-Strutinsky calculations were performed. In both cases, the $\pi g_{9/2}\otimes\nu i_{13/2}$ sequences are calculated to lie much higher ($\geqslant$1 MeV) in energy than the $\pi d_{5/2}\otimes\nu i_{13/2}$ and $\pi g_{7/2}\otimes\nu i_{13/2}$ configurations. The latter two configurations are also very close in energy ($\Delta E\leqslant 50$ keV). In the Strutinsky calculations shown in Fig. 4 the deformation of the latter structures was calculated to be $\epsilon_2\approx 0.28$–0.30, $\gamma\sim 15°$ in the $I=30$–$50\hbar$ spin range, which is consistent with the experimental lifetime measurements in the present experiment. This closeness in energy and the sizeable γ deformation suggests that there is significant mixing of the $[411]3/2\otimes\nu i_{13/2}$ and $[413]5/2\otimes\nu i_{13/2}$ sequences in ^{136}Pm at large deformation and spin.

In summary, four sequences with large dynamic moments of inertia are observed in the odd-odd nucleus ^{136}Pm. Quadrupole moment measurements confirm the highly deformed nature of these bands. Configuration assignments to the bands are based on their moment of inertia behavior, large quadrupole moments, estimates of their signature splitting, and consideration of cross-linking dipole transitions. These quantities, together with comparisons with neighboring nuclei and detailed theoretical calculations lead to assignments of $\pi h_{11/2}\otimes\nu i_{13/2}$ for bands 1 and 2, and $\pi d_{5/2}g_{7/2}\otimes\nu i_{13/2}$ for bands 3 and 4. These observations are in sharp contrast to other recent measurements on neighboring light odd-Z Pr and Pm nuclei where highly deformed second-minimum structures involving the $g_{9/2}[404]9/2$ orbital were found. While future measurements should aim to firmly fix the spins and parities of these bands, the present data represent a stepping stone in expanding the realm of the highly deformed $A=130$ Ce-Nd region towards the superdeformed $A=140$–150 Sm-Gd-Dy region.

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