Structure of the yrast band in the odd-odd deformed nucleus ^{156}Pm

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The six-level sequence deduced for the odd-odd nucleus ^{156}Pm in the high-spin studies following spontaneous fission of ^{252}Cf is shown to constitute the $K^\pi = 4^+$ yrast band having the two-quasiparticle configuration $\{p{:}5/2[532] + n{:}3/2[521]\}$. Spin parities $I^\pi = 4^+$ through 9^+ are assigned to the earlier suggested six levels. The location and the decay γ's of the 10^+ level of this band are indicated. It is also pointed out that there are no γ rays common to these postfission high-spin spectra and those seen in the ^{156}Nd β-decay studies.

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Spectroscopic investigations of neutron-rich medium-heavy nuclei are rather scarce, in that these nuclei are usually produced as short-lived radionuclides in spontaneous fission processes. Considering that these n-rich nuclides quickly undergo sequential β decays, studies of level structures of specified individual nuclides require an on-line mass-separator (ISOL) facility along with a sophisticated detector system [1–4]. Alternatively, γ-ray spectroscopy of secondary fission fragments has been pursued using large arrays of Compton-suppressed Ge detectors providing access to yrast or near-yrast structures [5,6]. Recently, the Vanderbilt-Berkeley-Beijing Collaboration [7,8] has carried out spectral studies of n-rich Nd and Pm isotopes produced in a spontaneous fission source of ^{252}Cf using the Gammasphere with 101 Ge detectors. Herein, mass numbers are assigned to new γ transitions in $_{60}$Nd and $_{61}$Pm nuclides, using the triple γ coincidence relationships with the previously known γ transitions emitted from the partner $_{38}$Sr and $_{37}$Rb fragments, respectively, following spontaneous fission of $^{252}_{98}$Cf. In addition to γ-γ-γ coincidences, Hwang *et al.* [8] also applied x(Pm)-γ-γ triple coincidences to investigating high-spin states in Pm isotopes. During these investigations, Hwang *et al.* [7,8] identified numerous γ transitions in ^{91,92,93}Rb and ^{155,156}Pm and also in ^{153,155}Nd following spontaneous fission of ^{252}Cf. Whereas they assigned spin-parities to the related levels for the other six nuclides, and also discussed their structural characterization, no such attempt was made with respect to the six levels introduced by them in the proposed level scheme of the only odd-odd deformed nucleus in their current studies, namely, ^{156}Pm. We address this question in this report.

We have recently reported [9] a detailed critical analysis of all the available data relevant to the characterization of the ^{156}Pm ground state (g.s.) and its 150.3 keV isomer identified in β decays of ^{156}Pm [2,10] and ^{156}Nd [3]. The analysis involved the mapping of the configuration space around the Fermi surface using experimental inputs on locations of neutron and proton Nilsson orbitals in the adjacent isotone and isotope, and also taking into account the Gallagher-Moszkowski (GM) coupling rule [11] and the rotor particle model [12] applicable to odd-odd deformed nuclei. Therein, it was concluded that the ^{156}Pm g.s. has spin-parity $I^\pi = 4^+$ corresponding to the two-quasiparticle (2qp) configuration

$$K^\pi = 4^+\{p_0{:}5/2^-[532\uparrow] + n_0{:}3/2^-[521\uparrow]\}. \qquad (1)$$

We show in the following that the ^{156}Pm levels deduced by Hwang *et al.* [8] constitute the yrast rotational band based on the above mentioned 4^+ g.s., and, thereby, assign spin-parities I^π to these levels.

First, we check how well the excitation energies of their [8] levels can be described using the usual two-parameter formula for the intraband excitation energies E(I, K) of rotational levels relative to the respective bandhead with $I = K$:

$$\begin{aligned} \mathrm{E(I, K)} = \mathrm{A[I(I+1) - K(K+1)]} \\ + \mathrm{B\{[I(I+1)]^2 - [K(K+1)]^2\}}. \end{aligned} \qquad (2)$$

The parameters A and B are determined by a least squares fit to the given energies in Fig. 1 assuming that they relate to a $K = 4$ band. This procedure yields $A = 8.33$ keV and $B = 4.57$ eV. The calculated energies for the $I = 4$ to 10 levels of a $K = 4$ band, using these parameters with Eq. (2), are shown in Fig. 1 in comparison with the experimental energies [8]. The fit yields an rms deviation of <0.3% from the experimental energies, thus confirming band number $K = 4$ and the spin assignments as shown for the various levels as rotational members of this band. Encouraged by the excellent fit to the known level energies, we place the 10^+ level at 803(2) keV, along with its decay γ's of 185 keV and 348 keV as shown in Fig. 1. Experimental identification of these γ's will provide further confirmation of our assignments.

As pointed out by us earlier [9], consideration of the available configuration space around the Fermi surface and the Gallagher-Moszkowski (GM) rule [11] uniquely defines the ^{156}Pm g.s. as having $K^\pi = 4^+$ with the 2qp configuration specified in Eq. (1). Now, we examine specifically whether the $K = 4$ rotational band levels of Fig. 1 are consistent with this characterization. In the two-quasiparticle-rotor model, the yrast band of an odd-odd nucleus $^A_Z\mathrm{X}_N$ is built by the superposition of the valence odd neutron orbital in the $(A-1)$ isotone and the odd proton orbital in the $(A-1)$ isotope. The data on yrast band level energies of the even-even (e-e)

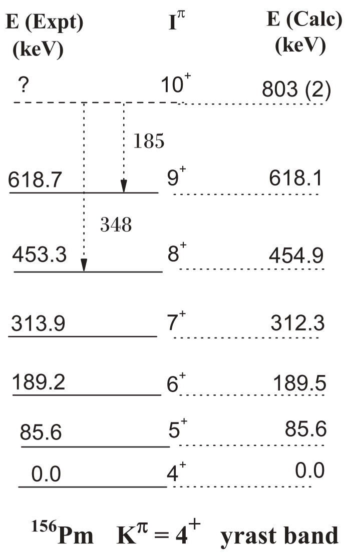

FIG. 1. Our spin-parity assignments and calculated energies $E(I)$ for $K^{\pi} = 4^{+}$ yrast band levels in ^{156}Pm listed on the right are shown in comparison with the experimental [1] level energies on the left.

core nucleus $^{154}_{60}$Nd$_{94}$ [13], the even-odd (e-o) $(A-1)$ isotone $^{155}_{60}$Nd$_{95}$ [7], and the odd-even (o-e) $(A-1)$ isotope $^{155}_{61}$Pm$_{94}$ [8] are plotted in Fig. 2, in comparison with the herein proposed $K^{\pi} = 4^{+}$ yrast band level energies of the odd-odd (o-o) nuclide $^{156}_{61}$Pm$_{95}$. The plots in Fig. 2 clearly reveal that level energies in the ^{156}Pm level scheme given by Hwang *et al.* [8] are fully consistent with their identification as rotational levels of the $K^{\pi} = 4^{+}$ yrast band having the 2qp configuration of Eq. (1).

Additional support for our assignments comes from consideration of the moments of inertia ($\mathscr{I}$) of the four bands shown in Fig. 2. As indicated by Struble *et al.* [14] and by Scharff-Goldhaber and Takahashi [15], these parameters are interrelated as follows:

$$\mathscr{I}_{o\text{-}o} = \mathscr{I}_{o\text{-}e} + \mathscr{I}_{e\text{-}o} - \mathscr{I}_{e\text{-}e}. \quad (3)$$

For our discussion of this factor, we employ the usual rotational band parameters $A(=\hbar^2/2\mathscr{I})$ which are determined from the lowest two levels of the respective band. Using the experimental data for the o-e ^{155}Pm [8], e-o ^{155}Nd [7], and e-e ^{154}Nd [13] nuclides in Eq. (2), we calculate A [o-o ^{156}Pm] = 9.3, to be compared with the experimental A [^{156}Pm] = 8.6. Remembering that the expression in Eq. (2) does not include the contribution from *n-p* interaction in the odd-odd nucleus, the agreement (within 8%) between the experimental and the calculated values is quite reasonable.

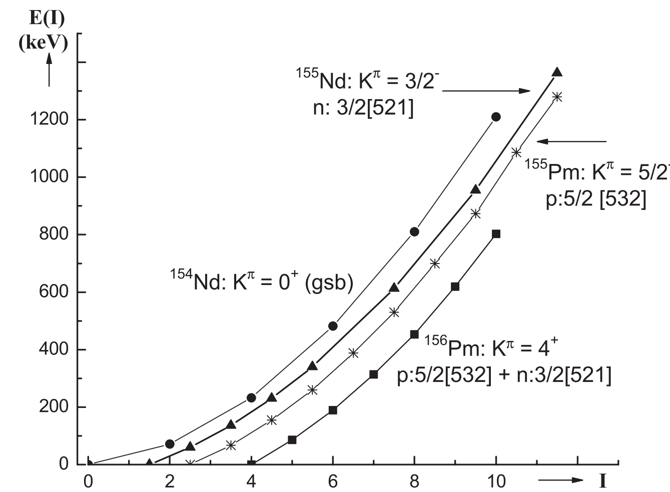

FIG. 2. Experimental level energies $E(I)$ of yrast bands in the e-e core nucleus ^{154}Nd, the e-o $(A-1)$ isotone ^{155}Nd, the o-e $(A-1)$ isotope ^{155}Pm, and the proposed $K^{\pi} = 4^{+}$ band in the o-o ^{156}Pm are plotted as a function of level spin *I*.

Identification of seven γ's in the post-^{252}Cf spontaneous fission decay studies of Hwang *et al.* [8], and their placement in a ^{156}Pm level scheme, as shown in their Fig. 4, are certainly acceptable. However, the identification of their 85.6 keV transition with "the previously known 85.6 keV transition in ^{156}Pm which was determined from the β decay of ^{156}Nd" is not substantiated. The source reference quoted therein for this statement is Greenwood *et al.* [1], which is a compilation of β-decay data for several radionuclides from ^{252}Cf spontaneous fission; however, it does not include any data for ^{156}Nd decay. The closest γ energy to the 85.6(3) keV transition of Hwang *et al.* [8] is that of a very intense 84.7(1) keV γ seen in ^{156}Nd decay [3,10,16,17]; clearly, there is no overlap between the energies of these two transitions. The 85.6(3) keV transition in ^{156}Pm reported, alongside six other γ's, by Hwang *et al.* [8], does not match any γ so far reported from ^{156}Nd β decay. This is not surprising since the focus of Hwang *et al.* [8] is on high-spin states. As shown in our analysis, their 85.6 keV transition originates from the $I^{\pi} = 5^{+}$ level. Intuitively, and realistically, one cannot expect such a high-spin $(I = 5)$ level to be populated in β decay from the $I^{\pi} = 0^{+}$ parent state of ^{156}Nd.

Notwithstanding this oversight, Hwang *et al.* [8] have clearly identified a gamma cascade along with crossover transitions, and proposed a ^{156}Pm level scheme, in this difficult-to-access region. Our analysis and characterization of these six levels as rotational levels with spin-parities $I^{\pi} = 4^{+}$ through 9^{+} of the ^{156}Pm $K^{\pi} = 4^{+}$ ground-state band provide evidence of a well-developed yrast band in this neutron-rich odd-odd transitional $(Z = 61)$ nucleus.

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