Characterization of isomers in the neutron-rich odd-odd nucleus ^{156}Pm

P. C. Sood,[1] M. Sainath,[1,2] R Gowrishankar,[1] and K. Vijay Sai[1]

[1]*Department of Physics, Sri Sathya Sai Institute of Higher Learning, Prasanthi Nilayam (AP) 515 134, India*

[2]*Department of Physics, Rajiv Gandhi University of Knowledge Technologies, Hyderabad (AP) 500 032, India*

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Critical examination of the experimental data from ^{156}Nd and ^{156}Pm β decays and the observed location of relevant neutron and proton orbitals in the neighboring odd-A isotones and isotopes, taken together with the low-lying two-quasiparticle (2qp) structures expected in ^{156}Pm from the rotor-particle model, lead to the conclusion that a consistent description of all the available data is achieved with the $I^{\pi} = 4^{+}$ spin-parity assignment to the 26.7s ^{156}Pm ground state (g.s.) and assignment of $I^{\pi} = 1^{+}$ to its 150.3-keV isomer with the 2qp configuration $4^{+}_{\text{g.s.}}\{p_o:5/2[532\uparrow] \pm n_o:3/2[521\uparrow]\}1^{+}_{150}$. In the process, a two-neutron configuration is also suggested for the 1509-keV 4^{+} level in the daughter nucleus ^{156}Sm. The present analysis reiterates the important question of whether the β-decay log ft value, by itself, can be employed to deduce the relative parity of the β-connected states.

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Structure studies of nuclei in the transitional mass region $A \approx 150$–160 are both challenging and frustrating. This is more so for odd-odd nuclei and for nuclei away from the stability line. Even with spectacular advances in experimental and data analysis facilities, this domain remains very poorly defined. These features are amply illustrated in the spectra of Pm ($Z = 61$) isotopes. The level structures of the $N = 90$ isotope ^{151}Pm provide evidence of reflection-asymmetric shape through identification of four sets of parity doublets [1,2]. In ^{152}Pm, three isomers with comparable half-lives (4.12m, 7.52m, and 13.8m) are known [3], but their relative energies or configurations are still a matter of conjecture. For ^{154}Pm, the latest Nuclear Data Sheets (NDS) evaluation [4] explicitly points out that "there are no definitive data on the relative energies of the two ^{154}Pm isomers (1.73m and 2.68m)," and that "there are conflicts concerning the J^{π} assignments between the experimental data and the detailed model-dependent arguments of Sood and Sheline" [5]. A specific two-quasiparticle (2qp) configuration in terms of Nilsson orbitals (detailed below) was suggested by Hellström *et al.* [6] for the 26.7s β-decaying ground state (g.s.) of ^{156}Pm. However, in their detailed review, Jain *et al.* [7] found this 2qp assignment for ^{156}Pm (g.s.) questionable, because it violated the Gallagher-Moszkowski (GM) rule [8], whereas, according to the criteria for GM validity enunciated by Sood and Singh [9], no violation can occur for this 2qp configuration. The latest NDS evaluation [10] explicitly stated that "the assignment of a configuration to ^{156}Pm (g.s.) and relating it to the 26.7s activity presents problems." We initiated a detailed critical examination of the level structures in odd-odd Pm isotopes [11]. In this Brief Report, we discuss the characterization of the ^{156}Pm isomers—the 26.7s g.s. and more recently identified [12] 150.3-keV $< 5s$ isomer—taking into account other recent experimental results [13–15] and the phenomenological quasiparticle-rotor model estimates for the relevant 2qp bandhead energies [16,17]. Preliminary results of these investigations were reported at a recent symposium [18].

Since our present focus is on the 2qp configuration assignments for low-lying isomers in ^{156}Pm, we first map, in Fig. 1, the available configuration space through a plot of the observed experimental excitation energies [19] of the corresponding single-particle Nilsson orbital $\Omega^{\pi}[Nn_3\Lambda\Sigma]$ in the neighboring odd-A $Z = 61$ isotope for p orbitals and $N = 95$ isotones for the n orbitals. Until recently, no information on level structures in the $N = 95$ isotone ^{155}Nd was available [20]. Hwang *et al.* [13] recently reported a likely 3/2[521↑]-based rotational band in ^{155}Nd having nearly identical transition energies for this band in ^{153}Nd, even though direct experimental evidence for 3/2[521↑] as ^{155}Nd g.s. is still awaited.

In the rotor-particle formulation, 2qp bands in an odd-odd deformed nucleus arise from coupling of 1qp Nilsson orbitals (Ω_p, Ω_n) in accordance with the GM rule [8], wherein the spins-parallel triplet K_T band lies lower in energy than the spins-antiparallel singlet K_S band within the $K^{\pm} = (\Omega_p \pm \Omega_n)$ GM doublet. The low-lying 2qp bands expected in the odd-odd ^{156}Pm nucleus, arising from the coupling of 1qp orbitals of Fig. 1, with $E_p + E_n$ up to 500 keV, are listed in Table I. We now critically examine the experimental inputs and their various interpretations to date toward assigning an acceptable 2qp configuration to ^{156}Pm (g.s.) and its 150.3-keV isomer.

Hellström *et al.* [6] investigated in detail the ^{156}Pm β^{-} decay to various levels in ^{156}Sm. Based on arguments summarized later herein, they concluded that "a consistent picture of ^{156}Pm decay is only found if its ground state is assumed to have $I^{\pi}K = 4^{-}4$." This conclusion was primarily arrived at by considering the following set of β branches [6] to indicated levels in ^{156}Sm:

(A) 16.6% β: log $ft = 5.5 \rightarrow 2526$ keV, $I = 3$ and 8.1% β: log $ft = 5.9 \rightarrow 2519$ keV, $I = 3$;
(B) 3.3% β: log $ft = 9.0 \rightarrow 517$ keV, $I^{\pi}K = 6^{+}0_{\text{gs}}$;
(C) 22.3% β: log $ft = 6.0 \rightarrow 1515$ keV, $I^{\pi} = 5^{-}$;
(D) 11.5% β: log $ft = 6.3 \rightarrow 1509$ keV, $I^{\pi} = 4^{+}$.

They further proposed that "the microscopic composition of the ^{156}Pm g.s. is then most likely given by the configuration"

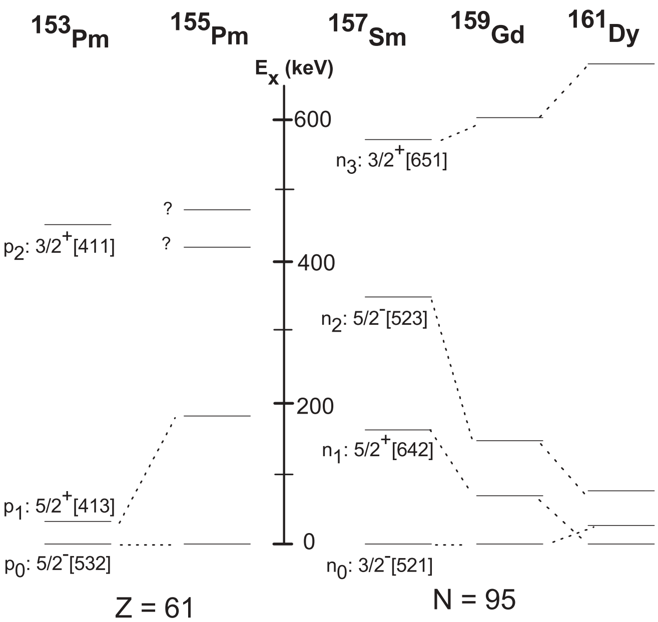

FIG. 1. Observed [19] excitation energies (in keV) of Nilsson orbitals in neighboring $Z = 61$ odd-A isotopes and $N = 95$ odd-A isotones which are the constituents of 2qp bands in the odd-odd nucleus $^{156}_{61}Pm_{95}$.

(using our notation of Fig. 1)

$$K^{\pi} = 4^{-}\{p_1 : 5/2^{+}[413\downarrow] + n_0 : 3/2^{-}[521\uparrow]\}. \quad (1)$$

As is evident in Eq. (1), this combination corresponds to the spins-antiparallel singlet K_S member of the 2qp GM doublet, whose spins-parallel triplet $K_T = 1^{-}$ counterpart has to have lower energy (by the GM rule) and hence constitute ^{156}Pm (g.s.), thus negating Hellström *et al.*'s [6] contention that they studied ^{156}Pm (g.s.) decay and its characterization. According to a critical examination of the criteria for validity of the GM rule by Sood and Singh [9], no violation of the GM rule can occur if $K_T = K^{-}$. Using this criterion, Jain *et al.* [7], and later the NDS evaluator Reich [10], termed the 2qp assignment of Eq. (1) for ^{156}Pm (g.s.) questionable. The recent identification in ^{156}Nd β^{-} decay [12], of a low-spin ($I = 1$) isomer placed at 150.3 keV above the 26.7s $I = 4$ (g.s.), definitely rules out this 2qp configuration (which requires the $I = 1$ level to lie lower in energy) for the ^{156}Pm (g.s.).

Accepting the $I^{\pi} = 4^{-}$ assignment for ^{156}Pm (g.s.), but rejecting its 2qp configuration by Hellström *et al.*, Reich [10] looked for an alternative 2qp configuration. Adopting the $5/2^{-}[532\uparrow]$ proton orbital, "based on systematics of g.s. spins in adjacent odd-A Pm isotopes," as the ^{156}Pm (g.s.) constituent, he observed that $K^{\pi} = 4^{-}$ can occur "only with $K^{\pi} = 3/2^{+}$ neutron orbital and with $3/2^{+}[651\uparrow]$ being the most likely possibility." In this scenario, the ^{156}Pm (g.s.) 2qp configuration, using the notation of our Fig. 1, is

$$K^{\pi} = 4^{-}\{p_0 : 5/2^{-}[532\uparrow] + n_3 : 3/2^{+}[651\uparrow]\}. \quad (2)$$

More recently, Shibata *et al.* [12] identified, in ^{156}Nd β decay, an isomeric state at 150.3 keV in ^{156}Pm which directly deexcites to its ground state with an $M3$ transition. Whereas they [12] discussed in detail isomer half-life (<5 s) and the branching ratio of β decay (<2%) to IT ($M3$), they stated, without any argumentation and just on the basis of the previously suggested ground-state assignment [10], that this isomer is "probably" a 1^{-} state with a likely same configuration as that of the 26.7s ground state; i.e.,

$$K^{\pi} = 1^{-}\{p_0 : 5/2^{-}[532\uparrow] - n_3 : 3/2^{+}[651\uparrow]\}. \quad (3)$$

Evidently this experiment neither determines nor supports negative parity for the ground state or the isomer; it simply concludes that both states have the same parity.

However, it should be noted that, whereas the NDS evaluator [10] invoked the proximity of the constituent proton orbital to the Fermi surface in the adjacent isotope, he somehow overlooked this consideration while suggesting, albeit conditionally, the $3/2^{+}[651\uparrow]$ neutron orbital as a ^{156}Pm (g.s.) constituent. The location of the Fermi surface was also invoked by Reich [10] in terming as incorrect the earlier suggested [6] 2qp configuration for the 1509-keV 4^{+} level of ^{156}Sm. Although he was pointing to the only n orbital, which, on coupling with p_0, would yield $K_T = 4^{-}$, yet the subsequent researchers simply accepted the configuration of Eq. (2) as an NDS assignment for ^{156}Pm (g.s.), without taking note of the inherent constraints. A scan of the latest NDS evaluated database [19] yields the following.

$$\begin{aligned} &\text{Expt } 3/2^{+}[651\uparrow]E_x \text{ (inkeV) in } N = 95 \text{ isotones :} \\ &^{157}\text{Sm}(571),\ ^{159}\text{Gd}(602),\ ^{161}\text{Dy}(678),\ ^{163}\text{Er}(619). \end{aligned} \quad (4)$$

Clearly, any level arising from coupling of this n orbital (at $E_x > 570$ keV) with any p orbital certainly lies above 500 keV in the $N = 95$ odd-odd nucleus. In particular, certainly such a 2qp configuration, e.g., that in Eq. (2), cannot correspond to the ground state of the $N = 95$ ^{156}Pm nucleus.

Having found both earlier assignments of Eqs. (1) and (2) for ^{156}Pm (g.s.) untenable, we now examine the alternative, which is consistent with the observed features of its β decay. Leaving the question of its parity open for the present, we see that the experimentally determined log ft values of <6.0 for the 1515-keV $I = 5$ level and for the two $E_x \approx 2.5$ MeV $I = 3$ levels imply $\Delta I = 1$ from the parent state for these three β branches. This observation unambiguously yields $I = 4$ for the parent state.

Next we proceed to determine the 2qp configuration and then the parity of this $I = 4$ ^{156}Pm (g.s.). For this purpose, we consistently adopt (i.e., for the p as well as the n orbital) the methodology of the NDS evaluator [10] by accepting the

TABLE I. Low-lying (<500 keV) 2qp bands, K_T^{π} and K_S^{π} and their zero-order energies ($=E_p + E_n$) in parentheses, expected in ^{156}Pm. The listed E_p and E_n are the experimental [19] values for ^{155}Pm and ^{157}Sm, respectively. All energies are in keV.

n_i $E_n \rightarrow$ p_i $\downarrow$ E_p	n_0 0.0 $3/2^{-}[521\uparrow]$	n_1 160 $5/2^{+}[642\uparrow]$	n_2 349 $5/2^{-}[523\downarrow]$
p_0 0.0 $5/2^{-}[532\uparrow]$	4^{+} 1^{+} (0.0)	5^{-} 0^{-} (160)	0^{+} 5^{+} (349)
p_1 181 $5/2^{+}[413\downarrow]$	1^{-} 4^{-} (181)	0^{+} 5^{+} (341)	

ground-state configuration in the adjacent odd-A Pm isotope and also in the adjacent Sm isotone, as constituents of ^{156}Pm (g.s.). This procedure yields the following 2qp configuration:

$$26.7s\,^{156}\mathrm{Pm(g.s.)}, \quad K^{\pi} = 4^{+}\{p_0 : 5/2^{-}[532\uparrow] + n_0 : 3/2^{-}[521\uparrow]\}. \tag{5}$$

Extending our horizon beyond the odd-orbital ground states by including other low-lying orbitals in the proximity of the Fermi surface, as shown in Table I, we find that, among all the expected bands, this 2qp configuration ($p_0 + n_0$) of Eq. (5) is the only one that corresponds to the $K_T = 4$ band, which can thus be ^{156}Pm (g.s.); this unique choice has positive parity. We now critically examine the grounds on which a positive parity was "ruled out with a high degree of probability" by Hellström *et al.* [6]. Specifically, we discuss, one by one, the four sets of β branches listed earlier under (A) through (D).

(A) β branches to two $I = 3$, $E_x \approx 2.5$ MeV levels: The two levels around 2.5 MeV in ^{156}Sm have almost identical γ decays to the 2^+ and 4^+ ground band levels and to the 2^- and 4^- levels of the probable $K^{\pi} = 1^-$ octupole band. These γ decays establish $I = 3$ spin assignment to both these levels, leaving the parity undetermined. The observed low (5.5 and 5.8) log *ft* values signify allowed β's with same parity for each of these states as that of the parent. If the parent $I^{\pi} = 4^+$, the $I^{\pi} = 3^+$ assignments follow for both these states. Alternatively, if parent $I^{\pi} = 4^-$, both the daughter states will have $I^{\pi} = 3^-$. These β branches do not, in any way, rule out positive parity of the parent state.

(B) β branch to 517-keV 6^+0_g level: The direct β branch to the 517-keV 6^+ rotational level of the $K^{\pi} = 0^+$ (g.s.) band in ^{156}Sm was classified [6,10] as first-forbidden unique $1^u(\Delta I = 2; \Delta\pi = \text{yes})$ on the basis of the reported log $ft = 9.0$. However, for deformed nuclei, wherein $\Delta K > \Delta I$, there is the additional selection rule of K forbiddenness. This $\Delta K = 4$ transition cannot be simply classified as 1^u (hence $\Delta\pi$ = yes) on the exclusive basis of the reported log $ft = 9.0$ and the I^{π} selection rule, since herein K forbiddenness must also be taken into account. With a quite high Q_{β} (5155 keV) and rather low β intensity (3.3%) in this branch, this log *ft* needs to be reevaluated and the contribution from K forbiddenness must be taken into account, before using this value for classifying this β transition.

(C) β branch to 1515-keV 5^- level: In view of the preceding discussion, the decisive factor for assigning negative parity to the $I = 4$ ^{156}Pm parent state is the observed decay to the 1515-keV 5^- level in ^{156}Pm. As stated by Hellström *et al.* [6], "a positive parity is ruled out with a high degree of probability since the 1515-keV 5^- level is populated with a β-transition having a log *ft* as low as 6.0." This inference is presumably arrived at in consideration of the NDS-adopted strong rule [21] for spin-parity assignment from β decays. This rule states that if log $ft < 5.9$, β transition is allowed: $\Delta I = 0$ or 1; $\Delta\pi$ = no. However, a closer scrutiny of the experimental data reveals that, at least in this transitional mass region, the "strong" rule is not as definitive as stated. For instance, using the comprehensive global compilation [22] of the NDS-evaluated database of log *ft* values, we find that just in the mass range $146 \leqslant A \leqslant 157$ as many as 14 cases of first forbidden (1f) decays, with confirmed $\Delta\pi$ = no and $\Delta I = 0$ or 1, have log $ft \sim 5.9$. As illustrative examples, we list in Table II a few cases of such decays in nuclei neighboring ^{156}Pm. This representative listing, retrieved from the latest Evaluated Nuclear Structure Data File (ENSDF) (November 2010 version) [19], includes two isotopes of Pm, and two nuclei with $A = 157$ and $A = 158$, respectively, from the other side; also this illustrative listing is seen to include two even-A decays and two odd-A decays, including one instance each for β^- and for EC decays. In particular, the 1f classification, even with log $ft = 5.9$, for our core nucleus ^{155}Pm has to be noted. These observations, from the evaluated database [19], permit us to confidently add the following entry in Table II:

$$^{156}\mathrm{Pm}\,4^{+} \to \log ft = 5.95 \to {}^{156}\,\mathrm{Sm 1515 keV} 5^{-}\ \mathrm{1f},$$

confirming the assignment of Eq. (5) to ^{156}Pm (g.s.).

(D) β branch to the 1509-keV 4^+ level: The 1509-keV 4^+ level of ^{156}Sm is rather strongly (11.4%) populated with log $ft = 6.24$ in ^{156}Pm (g.s.) decay. The two-proton configuration $\{p_1 : 5/2^{+}[413\uparrow] + p_2 : 3/2^{+}[411\uparrow]\}$ proposed by Hellström *et al.* [6] for this level was termed "not likely to be correct" by the NDS evaluator [10] on the grounds of the "location of proton Fermi surface." This 2qp configuration is also unacceptable, because, with both the orbitals changing from the NDS suggested [Eq. (2)] or presently proposed [Eq. (5)] 2qp configuration for the parent, the observed strong β^- population of this 4^+ level would not be seen. We suggest the following 2qp configuration for this 4^+ level.

$$^{156}\mathrm{Sm} : 1509 - \mathrm{keV} 4^{+}\ \mathrm{level} : \quad K^{\pi} = 4^{+}\{n_0 : 3/2^{-}[521\uparrow] + n_2 : 5/2^{-}[523\downarrow]\}. \tag{6}$$

With the Eq. (5) 2qp configuration of the parent, the β decay proceeds through $p : 5/2^{-}[532\uparrow] \to n : 5/2^{-}[523\downarrow]$ allowed transition; this is clearly consistent with its strong (11%) population and the observed value of log $ft = 6.24$.

TABLE II. Values of log *ft*, as listed in the latest ENSDF [19], for designated 1f β decays of nuclei neighboring ^{156}Pm.

Parent		log ft	Daughter			β class
^{A}X	I^{π}		^{A}X	I^{π}	E_x	
^{152}Pm	4^-	5.9	^{152}Sm	4^+	2896	1f
^{155}Pm	$5/2^-$	5.9	^{155}Sm	$3/2^+$	1362	1f
^{157}Ho	$7/2^-$	5.9	^{157}Dy	$9/2^+$	162	1f
^{158}Er	0^+	5.95	^{158}Ho	1^-	92	1f
^{158}Er	0^+	5.92	^{158}Ho	$(0,1)^-$	438	1f

With respect to the configuration of the 150-keV isomer, decaying by an $M3$ ($\Delta I = 3$; $\Delta\pi =$ no) transition to this 4^+ (g.s.), clearly the only acceptable K^π is 1^+. Looking at the available bands, as listed in our Table I, we conclude that the only 2qp configuration consistent with these experimental features is as follows.

$$\begin{aligned} &^{156}\text{Pm: } 150.3-\text{keV isomer}: \\ &K^\pi = 1^+\{p_0: 5/2^-[532\uparrow] - n_0: 3/2^-[521\uparrow]\}. \end{aligned} \tag{7}$$

The detailed analysis, as given above, clearly establishes that an assignment of $K^\pi = 4^+$ for 26.7s ^{156}Pm (g.s.) and $K^\pi = 1^+$ for the 150.3-keV isomer, with 2qp configurations given in Eqs. (5) and (7), is fully consistent with all the significant experimental inferences of ^{156}Pm β decay to the various levels of ^{156}Sm. Furthermore, this 2qp configuration is the closest one to the Fermi surface in the respective odd-Z and odd-N adjacent isotope or isotone and is the only one in the proximity of the Fermi surface having $K_T = 4$, thus meeting the prerequisite of being specified as ^{156}Pm (g.s.).

In addition to these conclusions, our present analysis again focuses attention on the fundamental question about the role of β-decay log *ft* values in determining the parities of the involved nuclear states. Earlier we had investigated [23] the overlapping domain of log *ft* values for the allowed and 1f transitions in heavy ($A = 250 \pm 5$) nuclei and identified several instances of 1ff (first forbidden fast) transitions; an operative selection rule describing such 1ff transitions in terms of Nilsson model asymptotic quantum numbers was also suggested. A subsequent comprehensive examination [24] of more than 500 such transitions from the actinide ($A > 228$) region surprisingly revealed that the log *ft* values for the allowed and the 1f transitions of this region have exactly the same central value and the same width. This observation led Sood *et al.* [24] to state that log *ft* values, by themselves, cannot be used as the basis for distinguishing the allowed and the 1f transitions of this region. On the basis of our present analysis, we feel that the preceding observation, earlier made for heavy nuclei, needs to be examined in more detail, especially for nuclei of the transition region ($A \simeq 150$–160).

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