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*Short note*

# High-spin states in $^{166}$Lu

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**Abstract.** Five rotational bands with configurations $\{\pi 7/2^+[404] \otimes \nu 5/2^+[642]\}$ $K = 6$, $\{\pi 9/2^-[514] \otimes \nu 5/2^+[642]\}$ $K = 7$, $\{\pi 1/2^+[411] \otimes \nu 5/2^+[642]\}$ $K = 2$, $\{\pi 1/2^-[541] \otimes \nu 5/2^+[642]\}$ $K = 2$ and $\{\pi 5/2^+[402] \otimes \nu 5/2^+[642]\}$ $K = 5$ were populated through the $^{152}$Sm ($^{19}$F, 5n) $^{166}$Lu reaction at a beam energy of $^{97}$MeV. The last three bands are identified in the present study. A phase change of level staggering is observed and low-spin signature inversion is suggested in the band $\{\pi 1/2^-[541] \otimes \nu 5/2^+[642]\}$ $K$=2. The inversion spin 17.5$\hbar$ (spin at inversion point) of this band fits well to the systematic variation trend of inversion spin, increasing with $N$ and decreasing with $Z$, for the known $\pi 1/2^-[541] \otimes \nu i_{13/2}$ bands observed in odd-odd deformed nuclei around $A = 170$.

**PACS.** 21.10.Re Collective levels – 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

In recent studies on high-spin states of odd-odd deformed nuclei, the phenomenon of low spin signature inversion of $\pi 1/2^-[541] \otimes \nu i_{13/2}$ bands has been studied extensively and great efforts have been made to determine spins of rotational bands by connecting rotational states to the ground state and isomeric states with known spin and parity. The successes in these efforts [1–7] have made it possible to reveal the systematic features of signature inversion of $\pi 1/2^-[541] \otimes \nu i_{13/2}$ bands. However, it is noted that the pattern of level staggering of the $\pi 1/2^-[541] \otimes \nu 5/2^+[642]$ band in $^{166}$Lu reported in previous study [8,9] is quite different from those of neighboring odd-odd nuclei. To clarify the difference and extend the systematics of $\pi 1/2^-[541] \otimes \nu i_{13/2}$ bands, high-spin states of $^{166}$Lu are reinvestigated.

The present experiment was carried out at the HI-13 tandem accelerator of CIAE in Beijing. high-spin states of $^{166}$Lu were populated in the $^{152}$Sm($^{19}$F, 5n)$^{166}$Lu reaction at an incident energy of 97 MeV. A self-supporting $^{152}$Sm foil with 0.5mg/cm2 was used as target. Gamma-gamma coincidence was measured by using an array consisting of ten HpGe detectors, each of which was equipped with a BGO Compton suppression shield. These HpGe detectors were positioned at 38°, 90° and 144° with respect to the beam direction, respectively. A total of 127 million of two-fold events were collected. DCO ratios of some transitions were extracted from the coincidence data.

The level scheme of $^{166}$Lu established from the present work is shown in fig. 1, with the rotational bands labeled both alphabetically and according to their suggested configurations at low spin. The $E2$ decay sequences 1 through 6 (from left to right) had been reported in [8,9], while 7 through 9 are established in the present study. The assignment of $\gamma$-ray to $^{166}$Lu was mainly based on previous knowledge of level schemes of $^{166}$Lu [8], $^{165}$Lu [10], $^{166}$Yb [11], $^{167}$Lu [12] and $^{163}$Tm [13]. Due to the contamination of Pb X-rays in the present study, we were not able to confirm the placements of the linking transitions reported in [8,9] between the ground state and the levels belonging to band A and B. Therefore these linking transitions of [8,9] are not included in the present level scheme. The gated spectra of band A,B,C and E are shown in fig. 2.

Figure 3 presents the plot of quasiparticle alignment $i_{\rm pn}$ *versus* frequency for the five bands ($\alpha = 0$ branches only) observed in $^{166}$Lu. In this mass region, the normal alignment of $i_{13/2}$ neutrons occurs around a frequency of $\sim 0.26$ MeV. The absence of the first backbend corresponding to the normal alignment of $i_{13/2}$ neutrons in fig. 3 suggests that in the configurations of the five bands the neutron occupies $\nu i_{13/2}$ orbital. It is known, up to now, that bands based on orbitals $\pi 7/2^+[404]$, $\pi 9/2^-[514]$, $\pi 1/2^-[541]$, $\pi 1/2^+[411]$ and $\pi 5/2^+[402]$ are

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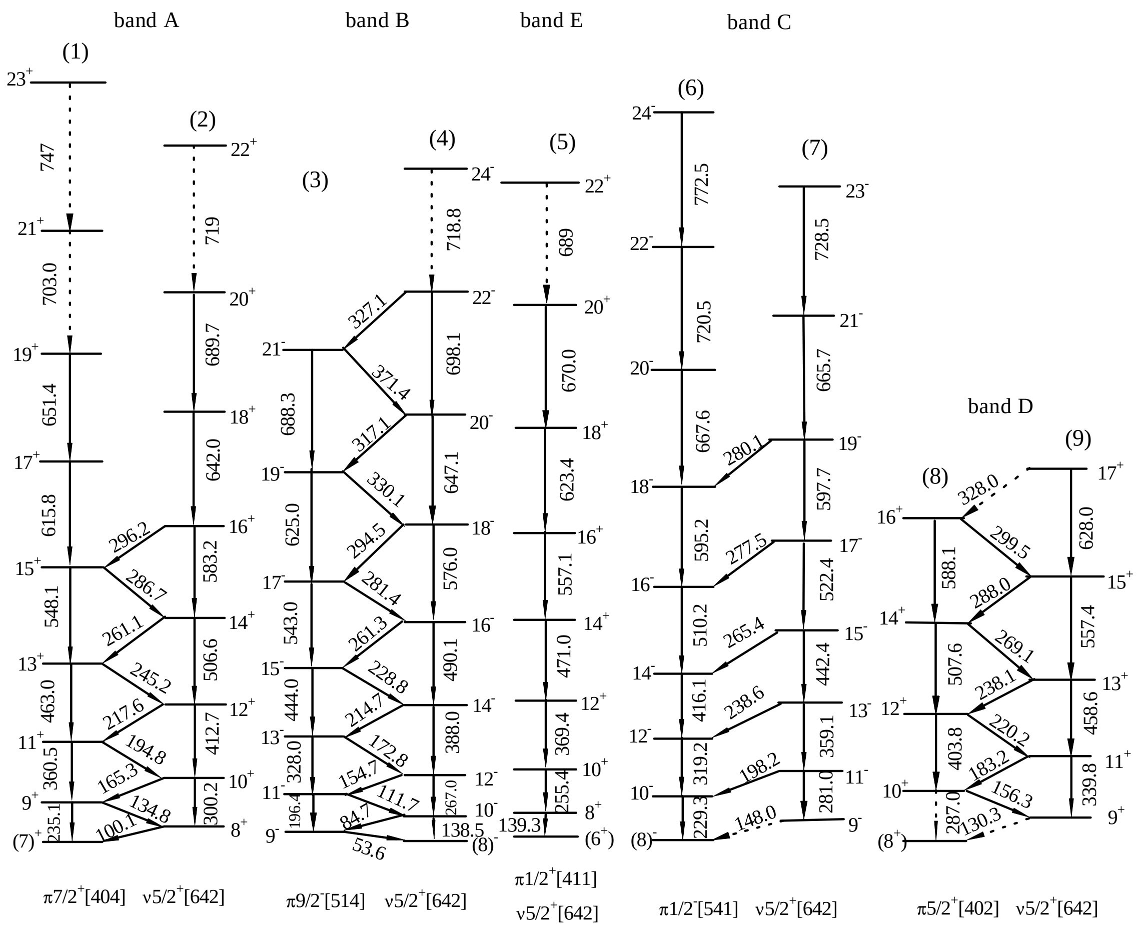


**Fig. 1.** Level scheme of $^{166}$Lu proposed in the present work. $(I)^{\pi}$ or $(I^{\pi})$ for the lowest observed state of a band indicate that the spin or both spin and parity of that band are assigned tentatively.

the only bands which had been observed in $^{165}$Lu [10] and $^{167}$Lu [12], and $\nu i_{13/2}[642]5/2^+$ band is the yrast band in $^{165}$Yb [11] and $^{167}$Hf [14]. Naturally, configurations obtained by combining $\nu 5/2^+[642]$ and above-mentioned proton orbitals are the most probable candidate configurations for bands observed in $^{166}$Lu. Bands A and B had been assigned to $\pi 7/2^+[404] \otimes \nu i_{13/2}$ and $9/2^-[514] \otimes \nu i_{13/2}$, respectively [8,9]. These assignments are in agreement with the present experimental data. Band based on configuration $\pi 1/2^-[541] \otimes \nu i_{13/2}$ (spin-parallel or G-M favored coupling) is characterized by large signature splitting, low-spin signature inversion, delayed BC crossing and small value of $B(M1)/B(E2)$ as observed in neighboring odd-odd nuclei [2–4]. Band C exhibits all these characteristics. Figure 3 shows that the BC crossing of band C is delayed relative to those of band A and B. The properties of large signature splitting and low-spin signature inversion are demonstrated in fig. 4. The average value of $B(M1)/B(E2)$ (for spins 13–17$\hbar$) is about $0.25\,\mu_N^2/e^2b^2$ which is very close the values of the $\pi 1/2^-[541] \otimes \nu i_{13/2}$ band in $^{162}$Tm [2],$^{164}$Tm [3] and $^{174}$Ta [4]. On the basis of above arguments, band C in fig. 1 is assigned to the configuration $\{\pi 1/2^-[541] \otimes \nu 5/2^+[642]\}$ $K = 2$.

Only one decay sequence is observed in band $E$ of fig. 1. With the above-mentioned probable candidates in mind, it is natural to assume that band $E$ is the decay sequence of the favored signature ($\alpha = 0$) of the semi-decoupled band $\{\pi 1/2^+[411] \otimes \nu 5/2^+[642]\}$ $K = 2$. This assignment is supported by the similarity of the level structure of band $E$ and the even-spin decay sequence ($\alpha = 0$) of $\pi 1/2^+[411] \otimes \nu 5/2^+[642]$ band with $K = 2$ in $^{162}$Tm [2] and $^{164}$Tm [3]. Band $D$ is a strongly coupled band and it is very weakly populated in the present study. This band is tentatively assigned to the last most probable candidate configuration $\{\pi 5/2^+[402] \otimes \nu 5/2^+[642]\}$ $K = 5$. This assignment is supported by the fact that the level structure of band $D$ is similar to that of the strongly coupled band $\{\pi 5/2^+[402] \otimes \nu 5/2^+[642]\}$ $K = 5$ in $^{162}$Tm [2].

Spin assignments are based on level energy systematics of similar bands observed in neighboring odd-odd nuclei and are further checked by the rule of alignment additivity. Spin values of levels are one unit ($\hbar$) higher than those given in [8] and [9] for band A and one unit ($\hbar$) higher than those given in [8] for band B.

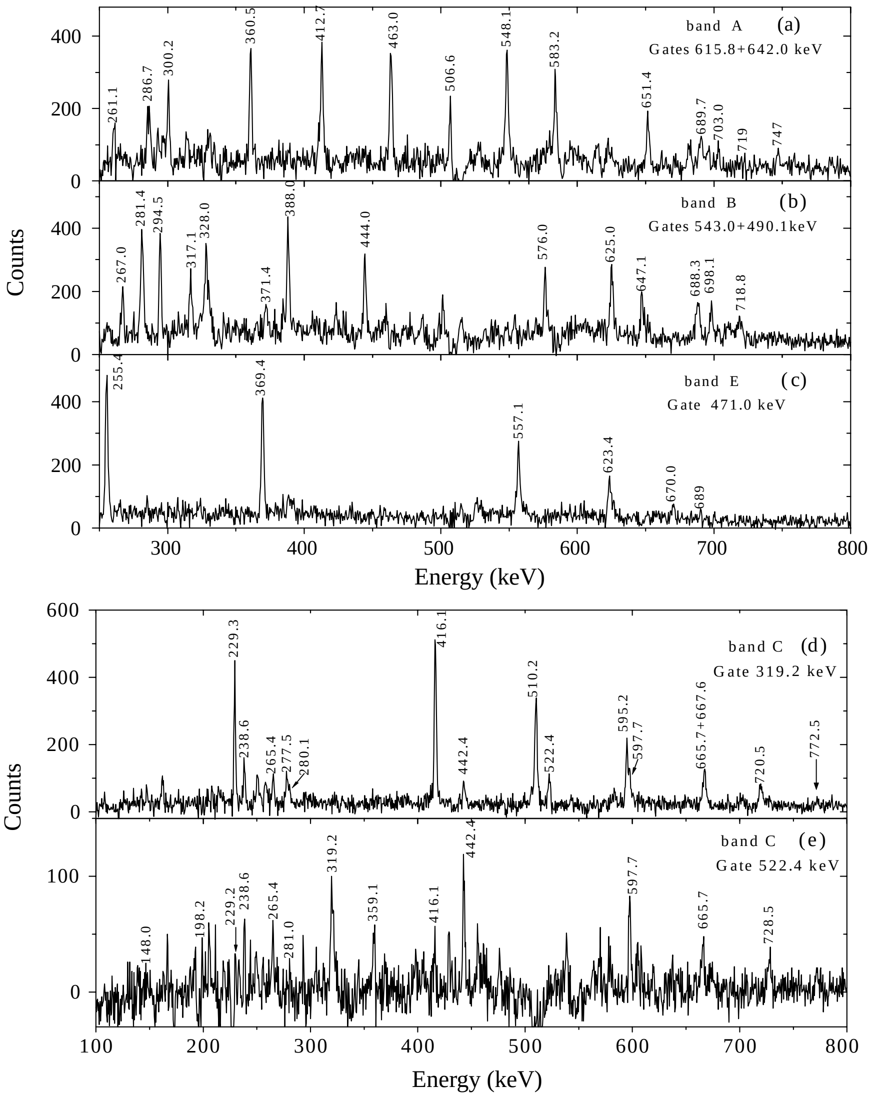


**Fig. 2.** Gamma-ray coincidence spectra of band A (a), band B (b), band C (d,e) and band E (c).

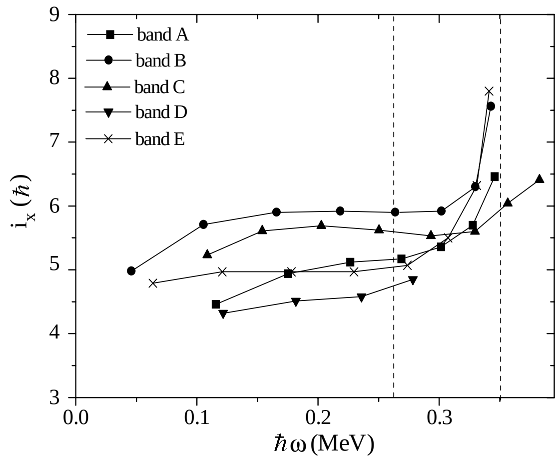


**Fig. 3.** Plots of alignment *versus* frequency for the five rotational bands assigned to $^{166}$Lu ($\alpha = 0$ branchs only). The reference parameters $J_0(\text{MeV}^{-1}\hbar^{-2})$ and $J_1(\text{MeV}^{-3}\hbar^{-4})$ are: 23.1, 150 for band A; 31.2, 104 for band B; 34, 69 for band C; 30, 71 for band D and 32, 60 for band E.

In order to reveal the systematic features of signature inversion of the $\pi h_{9/2}[541]1/2^- \otimes \nu i_{13/2}$ bands, the plots of $S(I) = E(I) - E(I-1) - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$ *versus* $I$ for known $\pi h_{9/2}[541]1/2^- \otimes \nu i_{13/2}$ bands in twelve odd-odd nuclei around $A = 170$ are presented in fig. 4. Figure 4 shows that signatures at low spin are inverted for all known $\pi h_{9/2}[541]1/2^- \otimes \nu i_{13/2}$ bands and the spin value at the inversion point increases with increasing $N$ and decreases with increasing $Z$.

In plotting fig. 4, spin values of $\pi h_{9/2}[541]1/2^- \otimes \nu i_{13/2}$ bands of $^{172}$Ta [15] and $^{178}$Re [16] have been increased by $3\hbar$ and $\hbar$, respectively. These spin changes are supported by arguments of level energy systematics and alignment additivity.

Triaxial shape with $\gamma > 0$ [17], Coriolis effect [18–20], band crossing and self-inversion [21] and p-n interaction [22] are able to cause signature inversion in odd-odd nuclei. The facts that low-spin signature inversion has only been observed in two-quasiparticle bands in odd-odd nuclei, the results of the systematic calculations for

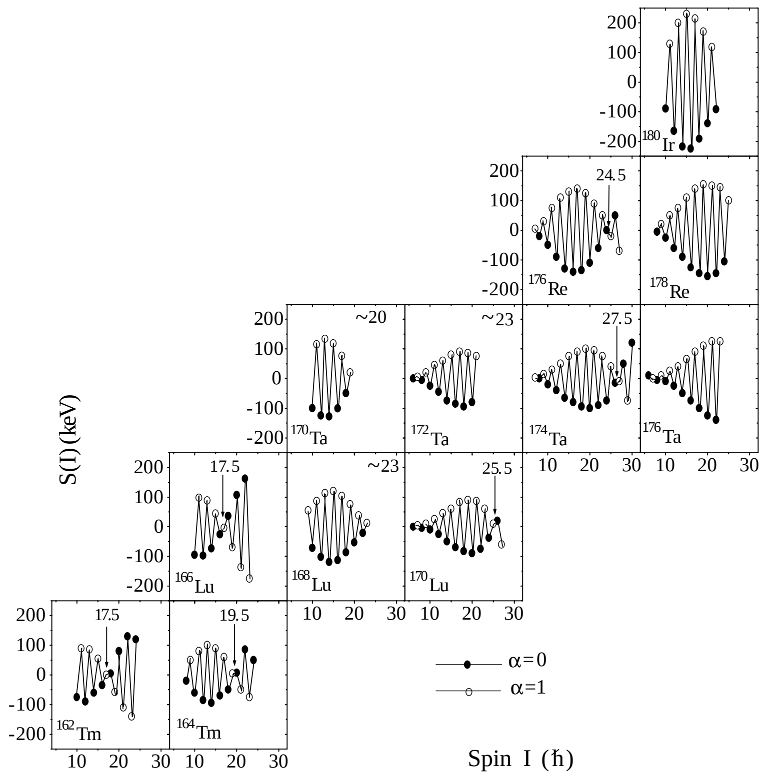


**Fig. 4.** Systematics of the signature splitting $S(I) = E(I) - E(I-1) - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$ *versus* $I$ of the $1/2^-[541] \otimes \nu i_{13/2}$ bands in odd-odd nuclei: $^{162}$Tm [1,2], $^{164}$Tm [3], $^{168}$Lu [24], $^{170}$Lu [5], $^{170}$Ta [25], $^{172}$Ta [15], $^{174}$Ta [4], $^{176}$Ta [6], $^{176}$Re [7], $^{178}$Re [16], $^{180}$Ir [26] and $^{166}$Lu (present work). The spin values given in [15] for $^{172}$Ta and [16] for $^{178}$Re are increased by $3\hbar$ and $\hbar$, respectively, according to the level energy systematics and alignment additivity rule.

$\pi h_{11/2} \otimes \nu h_{11/2}$ bands based on particle-rotor-model with the inclusion of p-n interaction [23,27] and the recent applications of p-n interaction to the $\pi 1/2^-[541] \otimes \nu i_{13/2}$ bands in $^{162}$Tm [1,2], $^{164}$Tm [3] and $^{174}$Ta [4] suggest that p-n interaction plays an important role in understanding the phenomenon of low-spin signature inversion in odd-odd nuclei. Systematic features of signature inversion of bands based on different configurations in odd-odd nuclei should be helpful in deciding the relative importance of the above-mentioned mechanisms. Firm spin assignment is crucial for the discussion of signature inversion. In fig. 4, the spins of the $\pi 1/2^-[541] \otimes \nu i_{13/2}$ bands in $^{166}$Lu (present work),$^{168}$Lu [24], $^{170}$Ta [25], $^{172}$Ta [15], $^{178}$Re [16], and $^{180}$Ir [26] were suggested on the basis of systematics. Therefore the systematic features reported in the present work should be considered as tentative and further experimental confirmation of the spins of the $\pi 1/2^-[541] \otimes \nu i_{13/2}$ bands of those nuclei is desirable.

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