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Short note

High-spin states of rotational bands built upon $\nu i_{13/2}$ in ^{166}Lu

C.S. Lee[1], J.H. Ha[2], J.H. Lee[1], J.Y. Huh[1], J.C. Kim[2], C.-B. Moon[3], S.J. Chae[3], T. Komatsubara[4], T. Shizuma[4], H. Kimura[4], K. Matsuura[4], K. Kato[4], Y. Sasaki[4], H. Ishiyama[4], and K. Furuno[4]

[1] Department of Physics, Chung-Ang University, Seoul 156-756, Republic of Korea
[2] Department of Physics, Seoul National University, Seoul 151-742, Republic of Korea
[3] Department of Physics, Hoseo University, Chung-Nam 337-795, Republic of Korea
[4] Institute of Physics and Tandem Accelerator Center, University of Tsukuba, Ibaraki 305, Japan

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Abstract. High-Spin states of odd-odd ^{166}Lu were populated using the ^{139}La(^{30}Si,3nγ)^{166}Lu at a beam energy of 120 MeV. Twelve new γ-rays were placed on top of the previously known two rotational bands built upon $\pi g_{7/2} \otimes \nu i_{13/2}$ and $\pi h_{11/2} \otimes \nu i_{13/2}$. Extending high-spin states up to 21^+ and 25^- for each band, we have observed the onset of band crossing near $\hbar\omega_c \approx 0.35$ MeV. The band crossing frequency of the yrast $\pi h_{11/2} \otimes \nu i_{13/2}$ band is consistent with the neutron BC band crossing observed in lighter odd-odd Lu isotopes.

PACS. 21.10.Re Collective levels – 23.20.En Angular Distribution and correlation measurements – 23.20.Lv Gamma transitions and level energy – 27.70.+q $150 \le A \le 189$

High-spin states in deformed odd-odd nuclei in the rare-earth region have revealed a number of intriguing phenomena. One of them has been signature inversion (anomalous signature splitting) [1] observed in the yrast band of $\pi h_{11/2}$ coupled to $\nu i_{13/2}$, while the other has been the anomalously high band crossing frequency for the neutron AB band crossing observed in the band of $\pi g_{7/2}$ or $\pi h_{11/2}$ coupled to $\nu h_{9/2}$ [2]. These two phenomena have been central themes in recent experimental studies on odd-odd isotopes of Eu, Tb, Ho, Tm, Lu and Ta in an effort to probe the role of a proton-neutron residual interaction underlying their mechanism. Among the odd-odd nuclei in this mass region have Lu isotopes received renewed attention in recent years—signature inversion observed in the yrast $\pi h_{11/2} \otimes \nu i_{13/2}$ band of $A = 160$, 162, 164 and 166 [3–5]; anomalous neutron AB crossing in the $\pi h_{11/2} \otimes \nu h_{9/2}$ band of ^{164}Lu [6,7]; the first superdeformed bands in ^{164}Lu [8]. Band crossing frequencies for the yrast $\pi h_{11/2} \otimes \nu i_{13/2}$ band in lighter isotopes such as ^{162}Lu [3] and ^{164}Lu [6–8] were identically ≈ 0.35 MeV. This high band crossing frequency is attributed to the occupied neutron in the $\nu i_{13/2}$ orbital, corresponding to the neutron BC crossing whose frequency is normally higher than the lowest AB crossing. Therefore, one can expect the same band crossing frequency for the $\pi h_{11/2} \otimes \nu i_{13/2}$ band if it is yrast in ^{166}Lu. Until now the frequency has been known to be ≥ 0.32 MeV [9] because ^{166}Lu has been lacking in spin states high enough to reach band crossing in contrast to the case of lighter Lu isotopes.

We populated high-spin states in ^{166}Lu through the ^{139}La(^{30}Si,3nγ)^{166}Lu reaction at a beam energy of 120 MeV. The beam was provided by the 12UD tandem accelerator and a Linac booster at the University of Tsukuba. Target current was ≈ 0.1 particle nA over the course of the experiment. Such a small current was due to transmission efficiency of the Linac booster as well as relatively low abundance of ^{30}Si (3.1%) in the natural Si used for a sputtering ion source. A ^{139}La self-supporting foil with areal density of 15 mg/cm^2 was used as target. We used a recently upgraded Tsukuba Ball consisting of ten BGO Compton-suppressed high-purity Ge detectors and one low-energy photon spectrometer. The time-to-digital converter range was set at 500 ns and about 29 million coincidence events were collected. The coincidence data were analyzed by the RADWARE code and the spin-parity assignment was made through extracting the ratios of directional correlation for oriented nuclei.

Gated spectra and level scheme of ^{166}Lu are shown in figs. 1 and 2, respectively. The new γ-ray transitions observed in the present work are the six high-lying lines of 320.0, 322.7, 330.0, 361.4, 704.2 and 736.2 keV in band A, the six high-lying lines of 326.3, 373.2, 690.2, 699.5, 719.5, 749.1 and 780.8 keV in band B, and the line of 281.1 keV linking band C and D. With these new γ-rays, we could

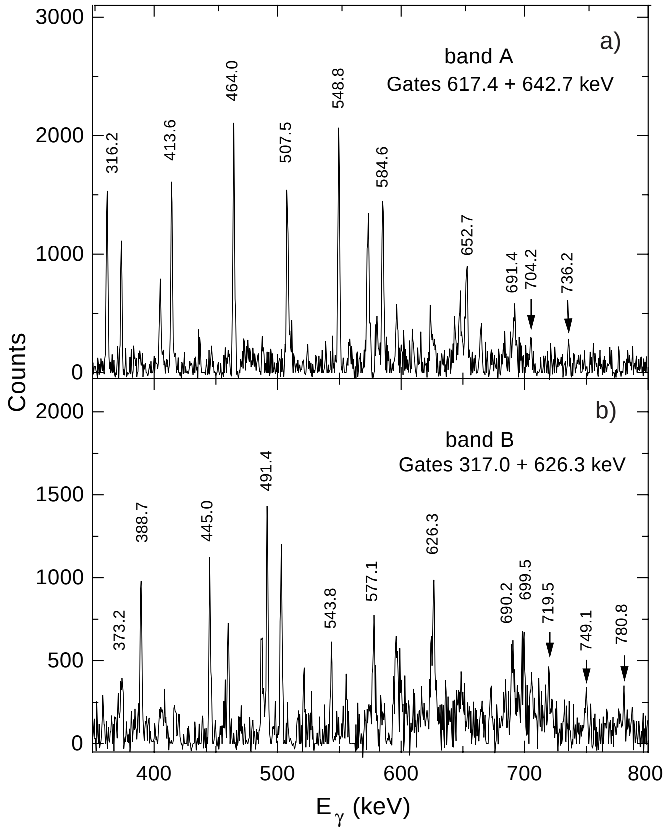

Fig. 1. Spectra gated by (a) 617.4 + 642.7 keV transitions in band A and (b) 317.0 + 626.3 keV transitions in band B.

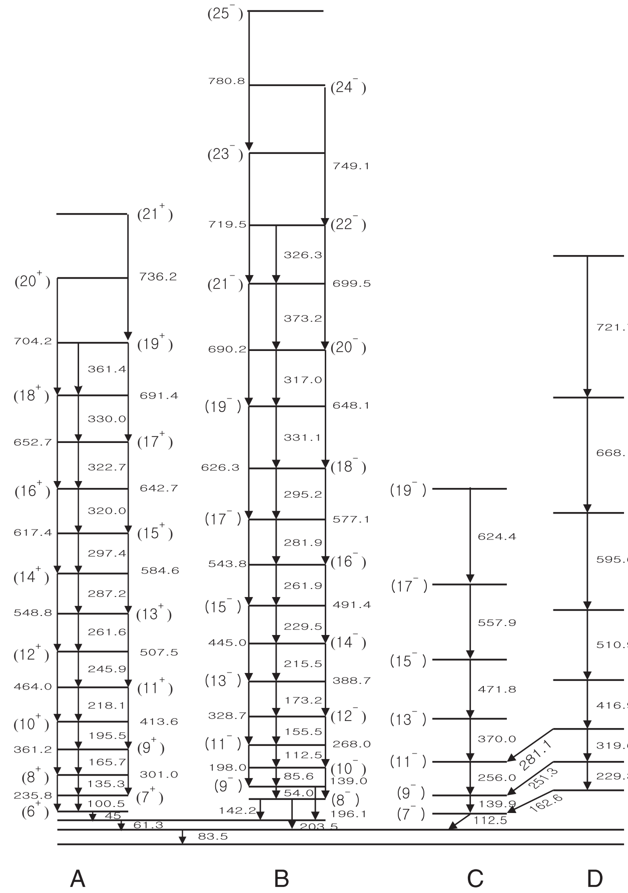

Fig. 2. Level scheme of ^{166}Lu.

extend high-spin states up to 21^+ and 25^- for band A and B, respectively. Furthermore, our coincidence data show that the 626.3-690.2-719.5 keV γ-ray sequence in band B should replace the previous 625.7-721 keV sequence missing the 690.2 keV line for the yrast band in ref. [5] and [9].

Band B was most strongly populated, thereby being yrast. Since all four bands A, B, C and D do not much differ in their excitation energy, they are likely to be built upon the same neutron configuration, *i.e.*, $\nu i_{13/2}$ in this mass region. According to a previous study on ^{166}Lu [9], the configurations for band A and B were $\pi g_{7/2} 7/2^+[404] \otimes \nu i_{13/2} 5/2^+[642]$ and $\pi h_{11/2} 9/2^-[514] \otimes \nu i_{13/2} 5/2^+[642]$, respectively. Band C and D were of the same intrinsic configuration, $\pi h_{9/2} 1/2^-[541] \otimes \nu i_{13/2} 5/2^+[642]$ and were shown to have the decoupled band structure due to the lowest $K = 1/2$ on the proton side.

The spin values in the yrast band B are shown to be larger by one unit as compared to the previous study [9]. The present spin assignment for band B agrees with other studies [5,10,11] which carefully examined the energy systematics as well as the alignment additivity rule for the yrast bands in odd-odd Lu isotopes. The spin assignment can be further justified in the light of the systematics of signature inversion [3] occurring in low-lying states of yrast bands in Lu isotopes with A = 160, 162, 164 and 166. With signature α being defined as $I = \alpha \bmod 2$, there are two signatures $\alpha = 0$ or 1 for odd-odd nuclei. Since the yrast band B is made of $\pi h_{11/2} \otimes \nu i_{13/2}$, the signature $\alpha = 0$ is favored, while $\alpha = 1$ is unfavored. In the case of normal signature splitting, an even-spin sequence with $\Delta I = 2$ should, therefore, form a favored band, thereby lying lower than an odd-spin sequence in the experimental Routhian. However, in the case of signature inversion, the even-spin sequence of the favored band ($\alpha = 0$) in the yrast band B lies higher than the odd-spin sequence of the unfavored band ($\alpha = 1$) below the inversion spin.

To better illustrate signature inversion, one can make a plot using a figure of merit ΔE *versus* spin I where the parameter ΔE is defined as $\Delta E = [E(I) - E(I-1)] - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$. As the result is shown in fig. 3, the even-spin sequence with the favored signature $\alpha = 0$ lies higher below the inversion spin $I_c = 16$ and then restores normal signature splitting with lying lower after the inversion spin, which confirms the spin assignment for band B to be correct as shown in fig. 2. It is also noted that the inversion spin decreases with increasing neutron number. For example, the inversion spin I_c decreases from a large value (not measured yet) down to 20, 18 and 16 as we go from ^{160}Lu to ^{162}Lu, ^{164}Lu and ^{166}Lu. Then no signature inversion has been re-

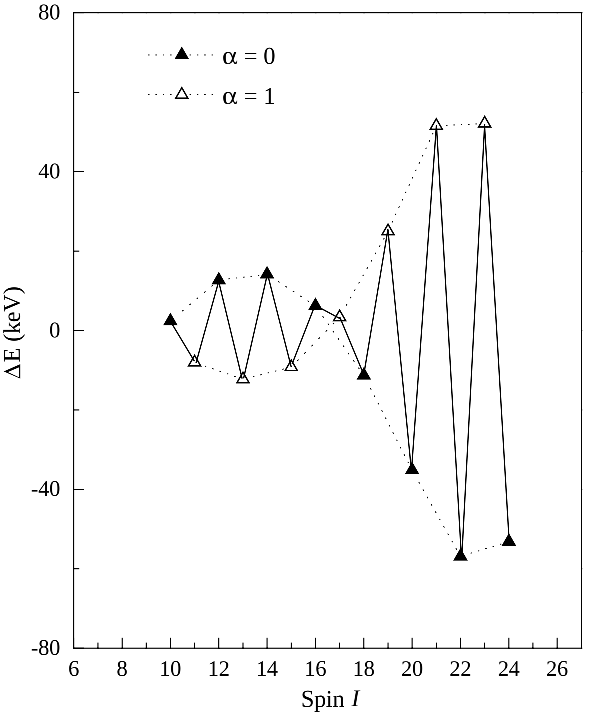

Fig. 3. Signature inversion plot using a parameter $\Delta E = [E(I) - E(I-1)] - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$ for the yrast band B in ^{166}Lu.

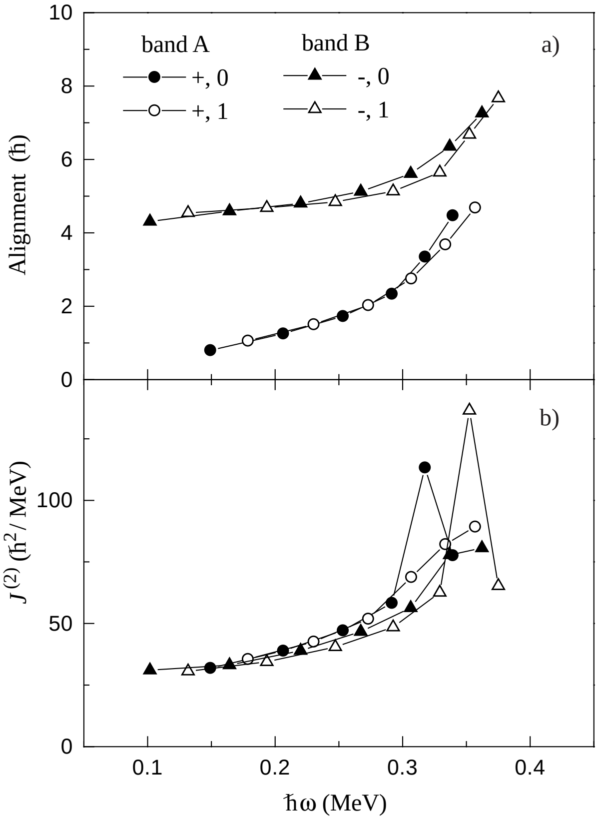

Fig. 4. (a) Alignment and (b) dynamic moment of inertia as a function of rotational frequency for band A and B in ^{166}Lu.

ported so far in heavier lutetium isotopes such ^{168}Lu and ^{170}Lu.

As the experimental alignment and the dynamic moment of inertia are shown as a function of rotational frequency in fig. 4, both bands A and B exhibit the onset of band crossing near $\hbar\omega_c \approx 0.35$ MeV. In plotting fig. 4, we used Harris parameters as $J_0 = 34\ \hbar^2\text{MeV}^{-1}$ and $J_1 = 38\ \hbar^4\text{MeV}^{-3}$. They were obtained by directly fitting the experimental values in neighboring nuclei without resorting to constant values used in a two-parameter fit [12]. We also confirmed these band crossing frequencies by extracting experimental Routhians for the two bands.

The band crossing frequency for band A is somewhat higher than 0.29 MeV of ^{164}Lu [3] while the one for band B is the same as the one for the yrast band of ^{162}Lu [3] and ^{164}Lu [6–8]. If one invokes the additivity rule [13] for band crossing frequencies using their known values in neighboring odd-A and even-even nuclei, one can estimate the band crossing frequency for the yrast band in ^{166}Lu as follows: $\hbar\omega_c(^{166}\text{Lu}) = \hbar\omega_c(^{165}\text{Lu}) + \hbar\omega_c(^{165}\text{Yb}) - \hbar\omega_c(^{164}\text{Yb}) = 0.280 + 0.360 - 0.285 = 0.355$ MeV, which is in good agreement with the observed value ≈ 0.35 MeV. This band crossing frequency of the yrast $\pi h_{11/2} \otimes \nu i_{13/2}$ band is consistent with the neutron BC band crossing observed in lighter odd-odd Lu isotopes as well as odd-N and even-Z nuclei in this mass region [3].

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