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Short Note

Signature inversion phenomena in odd-odd ^{182}Au

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Abstract. High-spin states in the odd-odd ^{182}Au nucleus have been investigated using the ^{152}Sm(^{35}Cl, 5nγ)^{182}Au reaction through X-γ and γ-γ-t coincidence measurements. Rotational bands based on the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ configurations have been identified. It is found that the two bands show characteristics of low-spin signature inversion. The observed signature inversion can be well reproduced by pairing-deformation self-consistent cranking Woods-Saxon calculations.

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

The low-spin signature inversion [1] has been systematically observed in the rotational bands of odd-odd nuclei. These bands are usually built on the $\pi g_{9/2} \otimes \nu g_{9/2}$, $\pi h_{11/2} \otimes \nu h_{11/2}$, $\pi h_{11/2} \otimes \nu i_{13/2}$, and $\pi h_{9/2} \otimes \nu i_{13/2}$ configurations. Several attempts have been made suggesting that the triaxiality [1], proton-neutron (p-n) interactions [2–4], band crossings [5], band mixing [6], quadrupole pairing [7], or the combined effects [8] could be possible reasons for the inversion phenomenon. It has been pointed out that the occurrence of signature inversion are generally related to the positions of the Fermi surfaces of nucleons (*i.e.*, particle numbers) [1,9] and the configurations of states [8]. Therefore, the observation of new signature-inversion bands in different mass regions and different configurations is important for a deeper understanding of the inversion phenomenon. In this paper, we report two newly identified rotational bands in the odd-odd nucleus ^{182}Au; both of them have anomalous signature splitting at low and medium spins. No high-spin data were available Prior to the present work. During the course of this investigation, Ibrahim *et al.* reported [10] the low-spin states in ^{182}Au populated by β^+/EC decay of ^{182}Hg, this information helps us assign the in-beam γ-rays to ^{182}Au.

The standard in-beam γ-ray spectroscopy experiment was performed at the Japan Atomic Energy Research Institute (JAERI) using the ^{152}Sm(^{35}Cl, 5nγ)^{182}Au reaction. The ^{35}Cl beam was provided by the JAERI tandem accelerator. The target of enriched ^{152}Sm metallic foil of 1 mg/cm^2 thickness was backed with a 5 mg/cm^2 Au layer in order to stop the recoil residuals. A γ-ray detector array was used including one HPGe LOAX for low-energy γ-ray detection and 11 HPGe's with BGO anti-Compton (AC) shields. These detectors were divided into 3 groups positioned at 32° (±148°), 58° (±122°), and 90° with respect to the beam direction so that the DCO ratios (directional correlations of γ-rays de-exciting the oriented states) could be deduced. All the detectors were calibrated using the standard ^{152}Eu and ^{133}Ba sources. A beam energy of 183 MeV was used for X-γ and γ-γ-t coincidence measurements according to the ALICE and CASCADE calculations, and a total of 3.5×10^8 γ-γ coincidence events was accumulated. These coincidence events were sorted into a symmetric and a non-symmetric (DCO sorting) matrix for off-line analysis.

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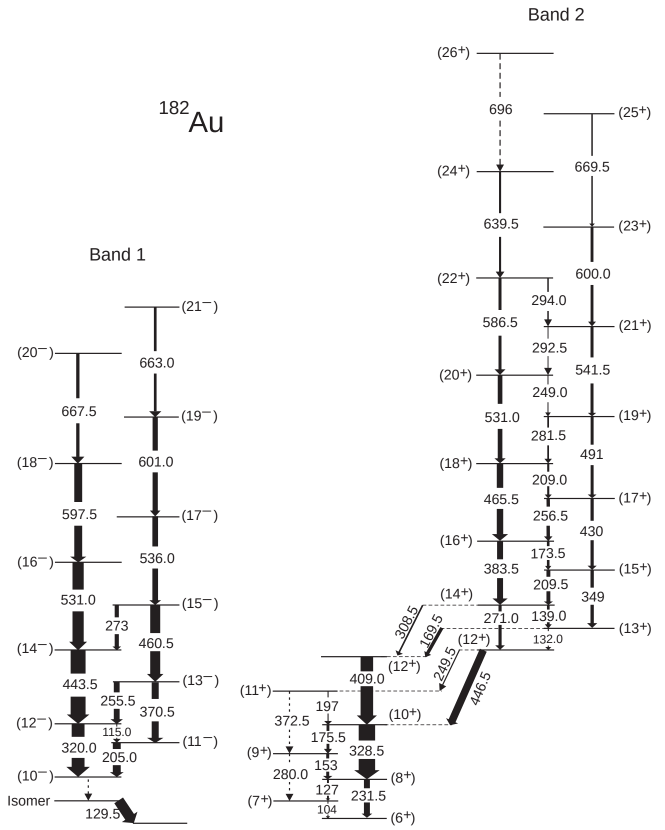

Fig. 1. Partial level scheme for ^{182}Au deduced from the present work.

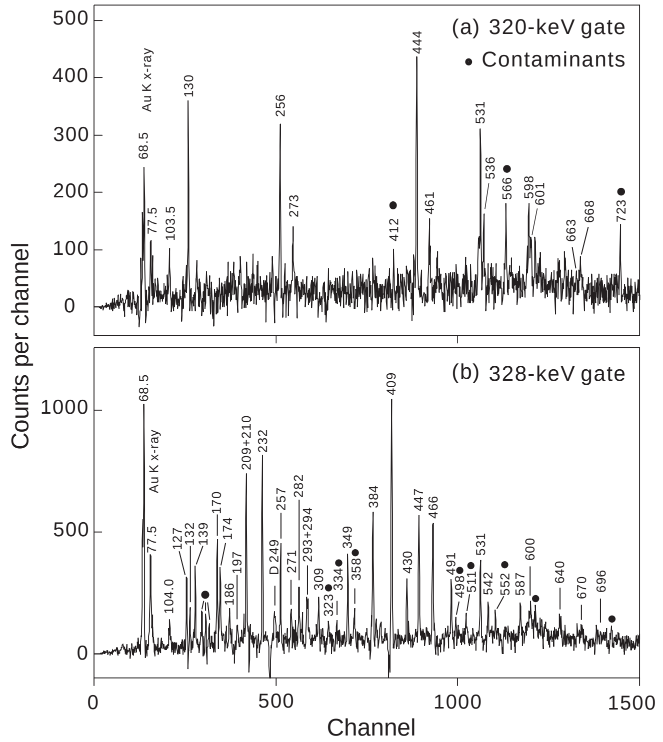

Fig. 2. Selected coincidence spectra for (a) band 1 and (b) band 2.

The in-beam γ-rays in this experiment were very complex, and we analyzed them very carefully. Apart from the most intense in-beam γ-rays due to Coulomb excitation of ^{152}Sm and ^{197}Au, the main contaminant γ-rays were from ^{181,183}Au [11], ^{182,181}Pt [12,13], and ^{179}Ir [14] corresponding to 6n, 4n, p4n, p5n, and α3n evaporation channels. Furthermore, γ-rays from other reaction products of both fission (Sr through Sn isotopes) and transfer or inelastic reactions were also significant. All these in-beam γ-rays together with the β-decay activities make the data analysis very complicated. In the total projected spectrum, the 129.5 keV, 320 keV, and 328.5 keV lines were less contaminated, and their relative intensities were found to be comparable with those of intense γ-rays from ^{182}Pt and ^{181}Au. These three γ-rays coincide strongly with Au K X-rays, indicating that they were emitted from an Au isotope. Referring to the well-established high-spin level schemes of ^{181,183}Au [11], the 129.5 keV, 320 keV, and 328.5 keV lines and the associated cascade transitions observed in this experiment were assigned to ^{182}Au. Very recently, Ibrahim *et al.* reported [10] the low-spin states in ^{182}Au populated by the β^+/EC decay of ^{182}Hg. The 129.5 keV line was assigned to de-excite an isomeric state ($T_{1/2} \leq 50$ ns) in ^{182}Au [10]. In our work, a cascade of γ-rays including the 320 keV line shows a delayed coincidence with 129.5 keV γ-rays, providing a definite evidence for the γ-ray assignment to ^{182}Au. A partial level scheme of ^{182}Au deduced from the present work is shown in fig. 1, where the γ-transition energies are within an uncertainty of 0.5 keV. The ordering of in-band γ-transitions is established on the basis of γ-γ coincidence relationships, γ-ray energy sums, and γ-ray relative intensities. The relative spins within a band have been suggested according to the analysis of DCO ratios. Selected coincidence spectra are displayed in fig. 2 showing the quality of the data. The absolute excitation energies of these bands are not known, therefore, the assignments of spins and configurations rely mainly on the level spacing systematics and the existing knowledge of band structures in neighboring odd-odd nuclei.

The irregular $\Delta I = 1$ transition energies in bands 1 and 2 of fig. 1 present a common feature of semi-decoupled bands in odd-odd nuclei [15]. For such a semi-decoupled 2-quasiparticle band, one quasiparticle occupies only the signature-favored state of an $\Omega = 1/2$ orbital. Another quasiparticle locates at the middle of a high-j shell and can occupy signature-favored and unfavored levels due to its small signature splitting. In the mass region of the present interest, the signature splittings of the Nilsson orbitals originating from $\pi h_{9/2}$ and $\pi i_{13/2}$ spherical parentage are very large, whereas the signature splittings in the $\nu i_{13/2}$ bands of neighboring odd-N nuclei are comparable with that in the two bands observed in ^{182}Au. Therefore, we propose the configurations $\pi h_{9/2}(\alpha_{\rm f} = \frac{1}{2}) \otimes \nu i_{13/2}(\alpha = \pm\frac{1}{2})$ for band 1 and $\pi i_{13/2}(\alpha_{\rm f} = \frac{1}{2}) \otimes \nu i_{13/2}(\alpha = \pm\frac{1}{2})$ for band 2. Such configuration assignments are further supported by the following considerations: 1) The $\pi h_{9/2}$ and $\pi i_{13/2}$ bands in ^{181,183}Au [11] and the $\nu i_{13/2}$ bands in ^{181}Pt [13] have been observed. These bands are intensely

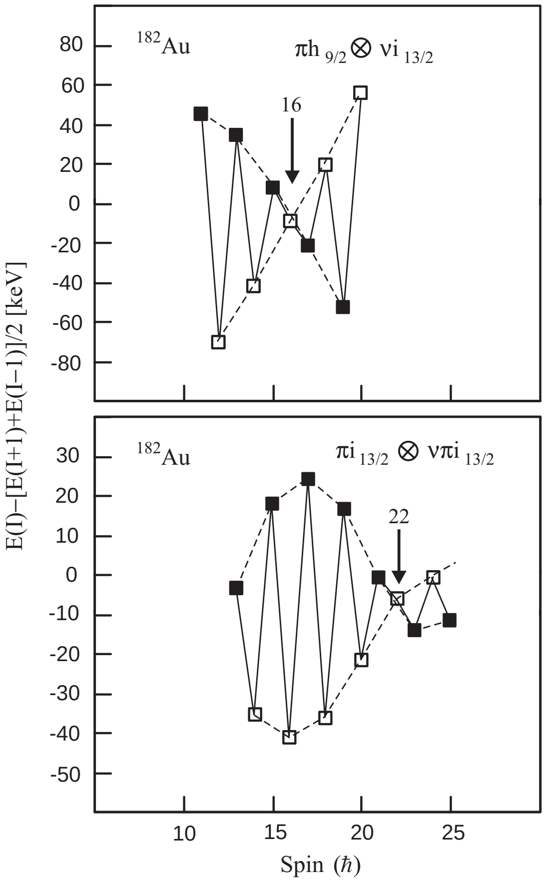

Fig. 3. Experimental signature splittings, $E(I) - [E(I+1) + E(I-1)]/2$ *vs.* I, for the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ bands observed in ^{182}Au. The filled symbols indicate $\Delta I = 2$ favored signature branch ($\alpha_{\mathrm{f}} = 1$), and the open symbols the unfavored one ($\alpha_{\mathrm{uf}} = 0$).

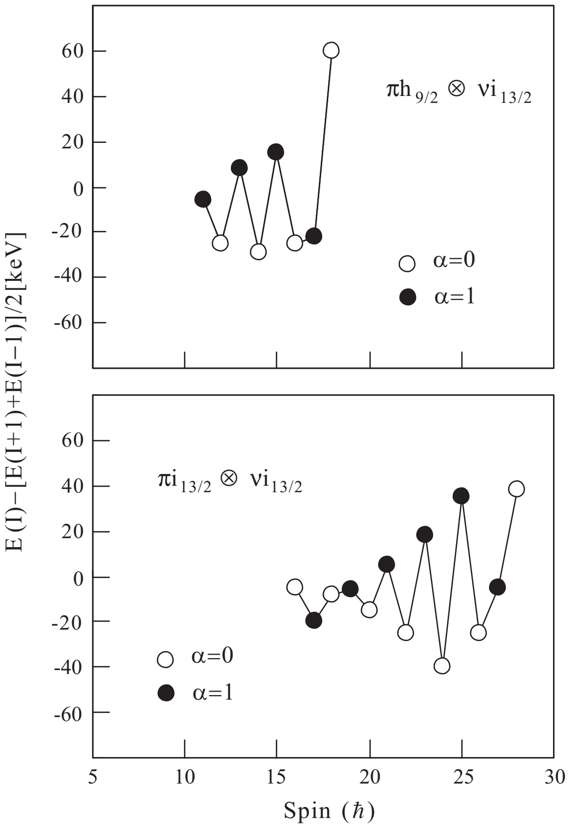

Fig. 4. Calculated signature splittings, $E(I) - [E(I+1) + E(I-1)]/2$ *vs.* I, for the $\pi h_{9/2} \otimes \nu i_{13/2}$ (top) and the $\pi i_{13/2} \otimes \nu i_{13/2}$ bands (bottom) in ^{182}Au.

populated by the heavy-ion–induced fusion-evaporation reactions. The bands built on the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ configurations in the odd-odd ^{182}Au are expected, *a priori*, to be strongly populated and easily observed in the reaction used here. 2) The $\frac{5}{2}^-$ levels of $\pi \frac{1}{2}^-[541]$ configuration were suggested to be the ground states in ^{181,183,185}Au, whereas the $\frac{13}{2}^+(\pi i_{13/2})$ band head locates 0.53 MeV higher than the $\pi h_{9/2}$ band member $\frac{9}{2}^-$ in ^{181}Au [11]. This difference in quasiproton excitation energies may lead to the stronger population for band 1 than that for band 2. 3) Band 1 de-excites (probably through several undetected low-energy γ-transitions) to the 129.5 keV isomeric state which was proposed to have the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration in ref. [10]. 4) The semi-decoupled band based on the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration has been identified in many odd-odd nuclei in this region (*e.g.*, in ^{180}Ir [16] and ^{184}Au [17]), and they exhibit very similar decay patterns, namely, the in-band $\Delta I = 1$ transitions from odd-spin states to the even-spin ones are much stronger than vice versa. 5) The signature splitting in band 2 is smaller than that in band 1 (see fig. 3). This feature has been observed in the related bands of neighboring ^{176,178}Ir [18]. It is also worth mentioning that the $\pi i_{13/2} \otimes \nu i_{13/2}$ bands have been identified recently in neighboring odd-odd ^{184,186}Au [17,19] and ^{176,178}Ir [18,20,21] nuclei. Particularly, the connections between the $\pi i_{13/2} \otimes \nu i_{13/2}$ and the $\pi 9/2^-[514] \otimes \nu \frac{5}{2}^-[512]$ bands have been established in ^{176,178}Ir [18,20,21], leading to a definite spin-parity assignment of one band relative to the other. With these information and the level spacing systematics in the two bands of $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ configurations, we propose the spin and parity for the two bands observed in ^{182}Au.

According to the configuration and spin-parity assignments discussed above, we find that the signature splitting in the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ bands is inverted at low and medium spins. To illustrate clearly the features of signature inversion, we compare the typical staggering curves $S(I) = E(I) - [E(I+1) + E(I-1)]/2$ *vs.* I in fig. 3. The similar staggering pattern is impressive, *i.e.*, the $\alpha_{\mathrm{f}}^{\mathrm{p\text{-}n}} = \alpha_{\mathrm{f}}^{\mathrm{p}} + \alpha_{\mathrm{f}}^{\mathrm{n}} = \frac{1}{2} + \frac{1}{2} = 1$ favored signature branch (odd-spin sequence) lies higher than the $\alpha_{\mathrm{uf}}^{\mathrm{p\text{-}n}} = \alpha_{\mathrm{f}}^{\mathrm{p}} + \alpha_{\mathrm{uf}}^{\mathrm{n}} = \frac{1}{2} - \frac{1}{2} = 0$ unfavored signature branch (even-spin sequence). The signature splitting reverts to the normal ordering at $I_{\mathrm{c}} = (16^-)$ and $I_{\mathrm{c}} = (22^+)$ for the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ bands, respectively, providing supplementary arguments for the spin and configuration assignments.

The low-spin signature inversion in the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands has been discussed in the framework of 2-quasiparticle plus rotor model in several recent publications [3,4]. It has been demonstrated that the proton-neutron residual interaction plays a key role for the low-spin signature inversion. The inversion phenomenon in the $\pi i_{13/2} \otimes \nu i_{13/2}$ bands may be understood, as proposed by Hojman *et al.* [20], in the same theoretical framework of the particle rotor model with p-n interaction. In this paper, we propose an alternative explanation based on cranked Woods-Saxon calculations [7]. The calculated results well support the present assignments of spins and configurations. For the observed $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ bands, the odd proton occupies the favored orbitals with the signature $\alpha_{\mathrm{f}}^{\mathrm{p}} = +1/2$, and the signature splitting is entirely due to the odd neutron. The neutron occupation of the favored orbital ($\alpha_{\mathrm{f}}^{\mathrm{n}} = +1/2$) leads to the favored branch with $\alpha_{\mathrm{f}}^{\mathrm{p\text{-}n}} = \alpha_{\mathrm{f}}^{\mathrm{p}} + \alpha_{\mathrm{f}}^{\mathrm{n}} = 1$, while the neutron unfavored orbital ($\alpha_{\mathrm{uf}}^{\mathrm{n}} = -1/2$) defines the unfavored branch with $\alpha_{\mathrm{uf}}^{\mathrm{p\text{-}n}} = 0$. The calculated staggering in energy is shown in fig. 4. It can be seen that the $\pi h_{9/2} \otimes \nu i_{13/2}$ band has a low-spin signature inversion and a signature crossing at $I \approx 17$. This is in good agreement with our observation. The inversion phenomenon in the $\pi i_{13/2} \otimes \nu i_{13/2}$ band is also reproduced by the theory although the inversion range ($18 \leq I \leq 26$) is shifted to higher spins in comparison with experiment. It has been pointed out (see, *e.g.*, [1,7,8]) that the γ deformation is one of the most important factors for the signature inversion. Our total Routhian surface calculations for the bands 1 and 2 show the small positive γ deformations ($\gamma \approx 4°$–$8°$) which changes slightly with spin I. With the obtained γ-values, we have calculated the quasiparticle Routhians and found that the involved neutron $i_{13/2}$ orbital appears in the signature inversion. The inversion range is related to the β_2 deformation. Due to the higher-j proton intruder orbital in the $\pi i_{13/2} \otimes \nu i_{13/2}$ configuration, band 2 has a larger quadrupole deformation of $\beta_2 \approx 0.26$ in contrast to $\beta_2 \approx 0.23$ for the $\pi h_{9/2} \otimes \nu i_{13/2}$ band. A larger β_2-value results in a delayed signature crossing in band 2 with respect to that in band 1. Both the experiment and calculations show the delay (see figs. 3 and 4). In energy, the involved $\pi h_{9/2}$ (*i.e.*, $1/2^-[541]$) orbital is the lowest at lower rotational frequencies. However, the increase of β_2 deformation pulls the $\pi i_{13/2}$ (*i.e.*, $1/2^+[660]$) orbital down and it becomes the lowest at higher rotational frequencies ($\hbar\omega \geq 0.17$ MeV approximately). This corresponds to the two low-lying signature-inversion bands observed in our experiment. It should be noted that the amplitude of anomalous signature splitting in band 2 is smaller than that in band 1 (see fig. 3). This experimental observation cannot be reproduced in the calculation (see fig. 4). The inconsistency between theory and experiment is not understood and needs further investigations.

In summary, two rotational bands with anomalous signature splitting have been identified in ^{182}Au. The cranked shell model reproduces the observed signature inversion. From our calculations, which include quadrupole pairing, we seem to find that the reasons for the signature inversion in the $A \sim 180$ region are similar to that in the $A \sim 130$ and $A \sim 160$ region. Small positive γ deformations are important to produce the signature inversion. Other factors, *e.g.*, p-n residual interaction, also enhance the signature inversion.

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