Eur. Phys. J. A **13**, 429–433 (2002)
DOI 10.1140/epja/iepja1353

THE EUROPEAN PHYSICAL JOURNAL A

Rotational bands and signature inversion phenomena in $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ structures in odd-odd ^{176}Ir

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Received: 14 December 2001 / Revised version: 18 January 2002
Communicated by D. Schwalm

Abstract. High-spin states in ^{176}Ir have been investigated via the ^{149}Sm(^{31}P,4nγ)^{176}Ir reaction through excitation functions, X-γ and γ-γ coincidence measurements. Four rotational bands have been identified for the first time and their configurations are suggested on the basis of the existing knowledge of band structures in odd-odd nuclei as well as the measured in-band $B(M1)/B(E2)$ ratios. Among the four bands observed, the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi i_{13/2} \otimes \nu i_{13/2}$ bands exhibit an anomalous signature splitting. The signature inversion point is observed in the former at $I_c = 18\hbar$ which is consistent with expectations; this signature inversion spin in the $\pi i_{13/2}\otimes\nu i_{13/2}$ band may be larger than $25\hbar$. The combined effects of Coriolis and p-n residual interactions involved in such an inversion phenomenon have been discussed qualitatively.

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

Signature inversion [1] is a very interesting phenomenon observed in a number of deformed odd-odd nuclei (see ref. [2] and references therein) and it has been attracting large experimental [3] and theoretical [4] interests. Up to date, the signature inversion has been systematically observed throughout the chart of nuclides in 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. Systematic analyses for the first three configurations have been done by Bermúdez and Cardona [5]. Analysis for the $\pi h_{9/2}\otimes\nu i_{13/2}$ structure shows that the critical spin I_c, at which the two $\Delta I = 2$ signature branches cross with each other, seems to decrease (increase) 2–3$\hbar$ while decreasing two neutrons (protons) for a chain of isotopes (isotones) [6]. If this regularity could be extended to a wide range of nuclei, one may expect to observe such an inversion spin around $I_c \sim 18\hbar$ in ^{176}Ir. On the other hand, such signature inversion bands systematically investigated correspond to the high-j spherical parentage, it is thus a natural assumption that the $\pi i_{13/2}\otimes\nu i_{13/2}$ bands of high-j parentage may present a similar inversion phenomenon; the $\pi i_{13/2}(\frac{1}{2}^+[660])$ orbital is involved instead of the $\pi h_{9/2}(\frac{1}{2}^-[541])$ in the $\pi h_{9/2}\otimes\nu i_{13/2}$ structure [7]. With these points in mind, great efforts have been devoted recently to the studies of in-beam γ-ray spectroscopy in odd-odd ^{176,178}Ir and ^{182}Au. We concentrated on the observation of critical spin I_c in the $\pi h_{9/2}\otimes\nu i_{13/2}$ band; this could be regarded as an indirect evidence of signature inversion in spite of the uncertainties in spin assignment. Meanwhile, much attention has been paid to establish the interband transitions from the expected $\pi i_{13/2}\otimes\nu i_{13/2}$ structure to a low-lying 2-quasiparticle band. We have noticed the fact that the $\nu i_{13/2}$ bands are yrast in the neighboring odd-N nuclei, and the excitation energy of the $\pi i_{13/2}$ band member $\frac{13}{2}^+$ decreases from 0.807 MeV in ^{177}Ir to 0.66 MeV in ^{175}Ir [8]. Thus, the $\pi i_{13/2}\otimes\nu i_{13/2}$ band in ^{176}Ir may locate at lower excitations with respect to the same band in ^{178}Ir, making it easier to observe the $\pi i_{13/2}\otimes\nu i_{13/2}$ band in ^{176}Ir. Prior to this work, no high-spin data on ^{176}Ir were available in the literature [9]. Bosch *et al.* proposed [10] the spin and parity of 5^+ for the ground state of ^{176}Ir according to the intense β^+/EC feeding to the 6^+ rotational state in ^{176}Os. Preliminary results of this research subject have been reported in refs. [6,11,12]. During the course

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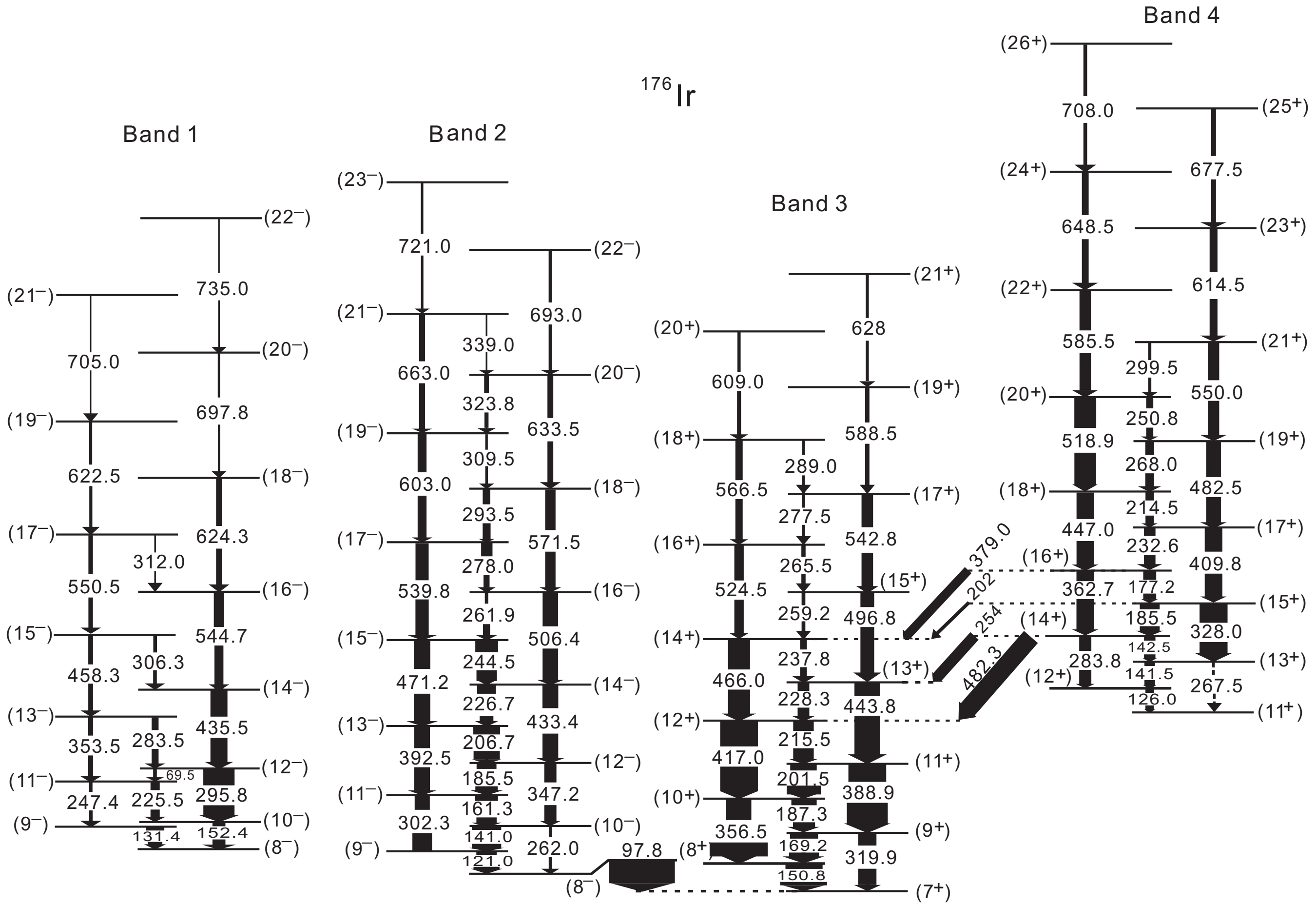

Fig. 1. Partial level scheme of ^{176}Ir deduced from the present work.

of this investigation, Hojman *et al.* reported the observation of signature inversion in the $\pi i_{13/2}\otimes\nu i_{13/2}$ band in ^{178}Ir [13].

The experiment was performed at the Japan Atomic Energy Research Institute (JAERI). The ^{149}Sm(^{31}P, 4nγ)^{176}Ir reaction was induced by a ^{31}P beam provided by the JAERI tandem accelerator. The target was an enriched ^{149}Sm metallic powder of 2.1 mg/cm^2 thickness evaporated on to a 5.5 mg/cm^2 Pb backing layer. A γ-ray detector array [14] was used comprising 11 HPGe's and one LOAX with BGO anti-Compton shields. The detectors were calibrated with ^{60}Co, ^{133}Ba, and ^{152}Eu standard sources; typical energy resolution was about 2.0–2.5 keV at FWHM for the 1332.5 keV line. In order to identify the in-beam γ-rays belonging to ^{176}Ir, we measured an excitation function by varying the ^{31}P beam from 145 MeV to 160 MeV with 5 MeV energy steps. The γ spectrum in this experiment was very complex; the photon peaks were often doublets or contaminated by the γ-rays from other reaction channels, and therefore we used coincidence mode in the excitation function measurements. At each beam energy, about 5–10 $\times 10^6$ γ-γ coincidence events were accumulated and sorted on-line into a $4k\times 4k$ matrix. The Ir K X-ray gated γ-ray spectra were projected and analyzed with cares during the experiment; the intensities of known γ-rays from ^{177}Ir/^{175}Ir decrease/increase apparently with increasing the beam energy, whereas numerous unknown γ-rays were found to have comparable intensities as those from ^{177}Ir and ^{175}Ir at beam energies of 145 MeV through 155 MeV. These unknown γ-rays were considered to be emanated most probably from ^{176}Ir, and finally a beam energy of 155 MeV was used for γ-γ coincidence measurements. About 350 million coincidence events were accumulated and sorted into $4k\times 4k$ matrices for off-line analysis. The relatively intense γ-rays were from the fusion-evaporation residues of ^{175,176,177}Ir, ^{175,176}Os, and ^{173}Re corresponding to 5n, 4n, 3n, 4np, 3np, and α3n evaporation channels, respectively. Fortunately, the detailed high-spin level schemes for ^{175,177}Ir,^{175,176}Os and ^{173}Re are available. These known information on ^{175,177}Ir,^{175,176}Os and ^{173}Re, and the measurements of excitation functions and Ir K X-γ coincidences helped us assign new rotational bands in ^{176}Ir.

The partial level scheme of ^{176}Ir deduced from the present work is shown in fig. 1. A selected single-gate coincidence spectrum and a sum-gate spectrum are displayed in fig. 2, showing the quality of the data. The γ-transition energies in the level scheme are within an uncertainty of 0.5 keV, and the ordering of the transitions within the bands is established on the basis of γ-γ coin-

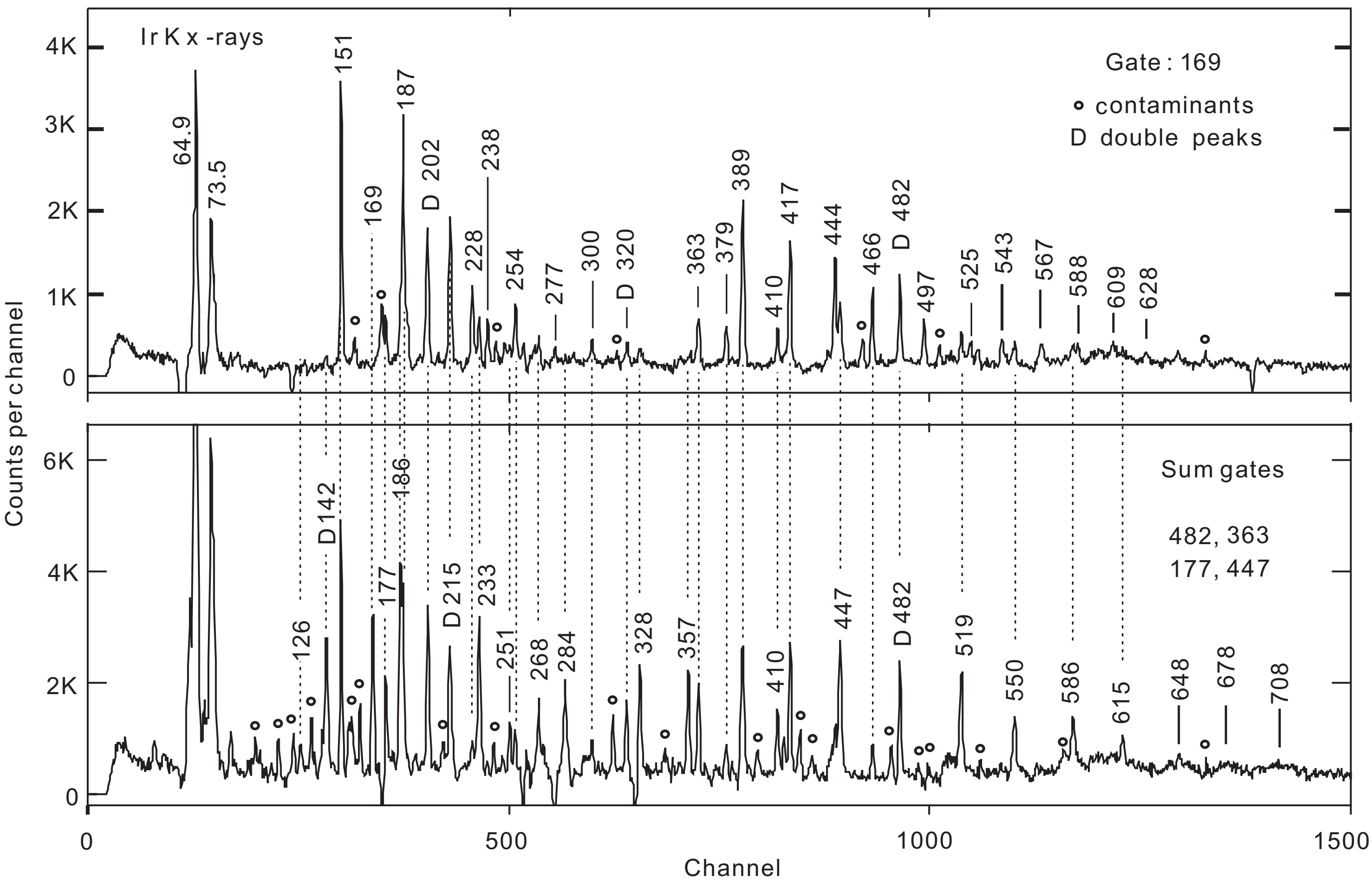

Fig. 2. Selected coincidence spectra for bands 3 and 4. The interband transitions (254, 379, and 482.3 keV lines) can be seen clearly in the upper panel of the figure.

cidence relationships, γ-ray energy sums and γ-ray relative intensities. No linking transitions have been observed from band 1 to bands 2, 3, and 4. The 97.8 keV line deexcites the (8^-) band head of band 2, and its DCO ratio is measured to be 0.66(10) corresponding to a stretched $\Delta I = 1$ dipole transition (the DCO ratios are close to unity for the stretched $\Delta I = 2$ quadrupole transitions for the detector array used here). The total internal conversion coefficient for the 97.8 keV transition was extracted to be $\alpha_T = 0.80(15)$ based on the arguement of intensity balance between the 121 keV and 97.8 keV lines in the 141 keV gated spectrum (theoretical value of α_T(121 keV; $M1$)= 3.684 was used in the calculation). This experimental conversion coefficient is close to the theoretical one of α_T(97.8 keV; $E1$)= 0.43, thus, we tentatively placed the 97.8 keV γ-ray to feed to the (7^+) level of band 3; no other interband transition between band 2 and band 3 could be identified. Band 3 and band 4 are connected through several interband transitions (one can see clearly the 254, 379, and 482.3 keV lines in the upper panel of fig. 2). The connection between the two bands has been established as shown in fig. 1, which fix unambiguously the spin and parity of one band relative to the other and thus facilitates their configuration assignments.

According to the classification of coupling scheme for odd-odd nuclei proposed by Kreiner *et al.* [15], and considering the fact that the $\pi 1/2^-[541]$, $\pi 9/2^-[514]$ and $\pi 1/2^+[660]$ bands in ^{175}Ir [8] and the $\nu 1/2^-[521]$, $\nu 5/2^-[512]$ and $\nu 7/2^+[633]$ bands in ^{175}Os [16] are strongly populated in the heavy-ion–induced fusion-evaporation reactions, we propose the configurations of $\pi h_{9/2}(1/2^-[541])\otimes\nu i_{13/2}(7/2^+[633])$, $\pi h_{11/2}(9/2^-[514])\otimes\nu i_{13/2}(7/2^+[633])$, $\pi h_{11/2}(9/2^-[514]) \otimes \nu 5/2^-[512]$, and $\pi i_{13/2}(1/2^+[660]) \otimes \nu i_{13/2}(7/2^+[633])$ for bands 1, 2, 3, and 4, respectively. Indeed, the $\pi h_{9/2}\otimes\nu i_{13/2}$ and $\pi h_{11/2}\otimes\nu i_{13/2}$ bands have been identified in many odd-odd nuclei in this region, and they exhibit very similar level spacings and decay patterns (*e.g.*, in ^{176}Re [3] and ^{178}Ir [6]). Therefore the band head spins and parities are proposed to be $I_0^\pi = (8^-)$ for band 1 and $I_0^\pi = \Omega_p + \Omega_n = (8^-)$ for band 2 which are consistent with systematics. Band 3 have an effective $K_{\rm eff} = (2-X)/(X-1) = 7.2$ (X is the energy ratio of first two in-band $\Delta I = 1$ transitions) close to the projection quantum number $K = \Omega_p + \Omega_n = 9/2 + 5/2 = 7$. This high value corresponds to a case in which both proton and neutron orbitals are weakly affected by the Coriolis interaction, resulting in $K_{\rm eff} \approx K = \Omega_p + \Omega_n = 7$ [17]. Consequently, the spin and parity for the lowest level of band 3 have been assigned to be $I_0^\pi = K^\pi = 7^+$. It should be noted that the $\pi h_{11/2}\otimes\nu 5/2^-[512]$ band has been identified in ^{178}Ir [11,13] which shows similar level spacings as band 3 in ^{176}Ir. Based on the spin and parity assignments

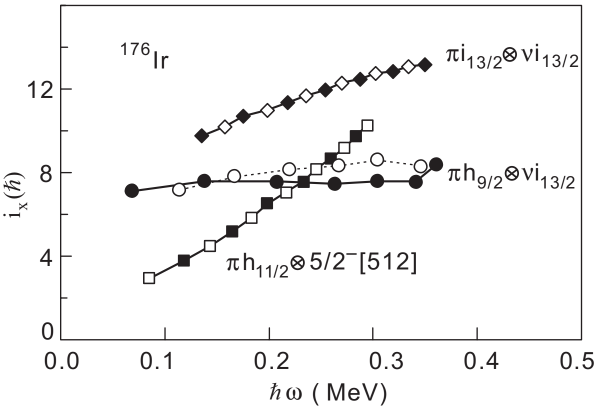

Fig. 3. Plot of quasiparticle alignments i_x *vs.* $\hbar\omega$. The common Harris parameters ($J_0 = 21$ MeV $^{-1}\hbar^2$, $J_1 = 110$ MeV$^{-3}\hbar^4$) are used for all the bands. Band 2, showing similar pattern as band 3, is not presented in this figure.

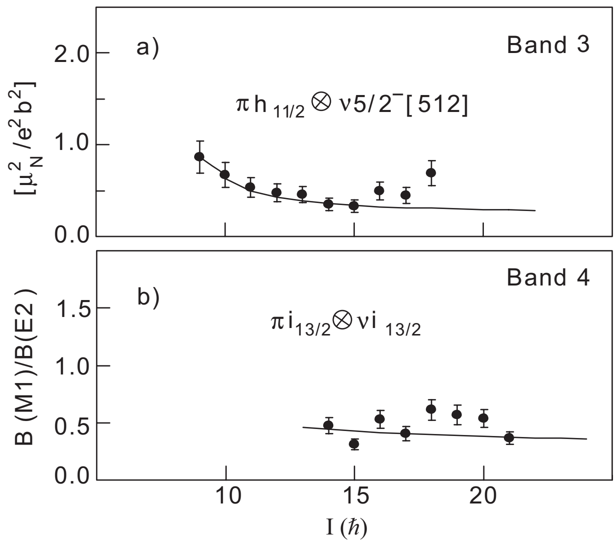

Fig. 4. Experimental $B(M1)/B(E2)$ ratios for bands 3 and 4 together with the geometric model calculations [3] under the assumptions of proposed configurations indicated on the panel. Common parameters $g_R = Z/A = 0.438$ and $Q_0 = 7.0$ eb are used. Other parameters (i_n, g_{Ω_n}, $\langle K_\mathrm{n}\rangle$, i_p, g_{Ω_p}, $\langle K_\mathrm{p}\rangle$, $\langle K_\mathrm{p\text{-}n}\rangle$) are used as (1.0, −0.31, 5/2, 1.0, 1.29, 9/2, 7) for the $\pi h_{11/2}\otimes\nu 5/2^-[512]$ configuration, and (4.0, −0.25, 7/2, 6.0, 1.124, 1/2, 3.5) for the $\pi i_{13/2}\otimes\nu i_{13/2}$ configuration, respectively.

for band 3 and the observed linking transitions between band 3 and band 4, the spin and parity for band 4 can be fixed as shown in fig. 1.

Figure 3 presents a plot of quasiparticle alignments i_x *versus* rotational frequency $\hbar\omega$. In this plot, a common reference ($J_0 = 21$ MeV $^{-1}$ $\hbar^2$,$J_1 = 110$ MeV^{-3} $\hbar^4$) has been used in order that the alignment for band 1 is roughly constant. As is clear from this figure, large alignment for band 4 strongly suggests that the high-j orbitals both for proton and neutron have been involved. The alignment in the $\pi h_{9/2}\otimes\nu i_{13/2}$ band is roughly $i_x(\omega)\sim 7.5\hbar$, only the $\pi i_{13/2}\otimes\nu i_{13/2}$ two-quasiparticle band can have such alignment as high as $\sim 10\hbar$; the $i_{13/2}$ proton contributes more

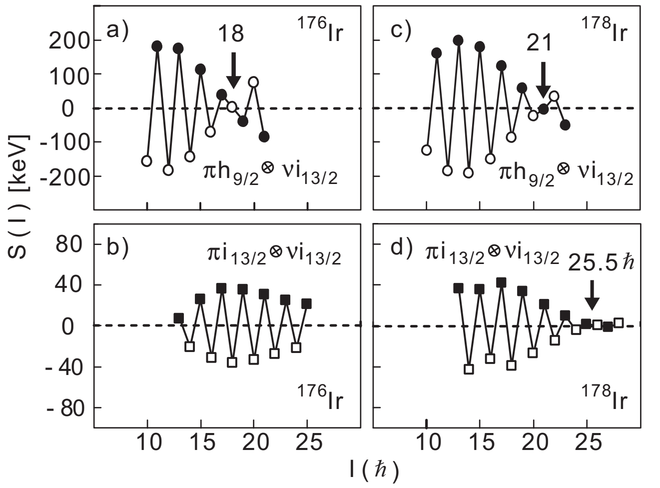

Fig. 5. Plot of signature splittings $S(I)$ *vs.* I for the $\pi h_{9/2}\otimes\nu i_{13/2}$ (upper panel) and $\pi_{13/2}\otimes\nu i_{13/2}$ (lower panel) bands in both ^{176}Ir (present work) and ^{178}Ir [11,13]. The arrows indicate the inversion spin.

than $6\hbar$ [8], whilst the rest originates from the $i_{13/2}$ neutron [16]. In fact, this band has been identified in ^{178}Ir [11, 13] and ^{182}Au [12] which show a structure very similar to band 4 in ^{176}Ir. Figure 4 presents the experimental $B(M1)/B(E2)$ ratios for bands 3 and 4 together with the geometrical model calculations [3]. It is clear from this figure that the experimental $B(M1)/B(E2)$ ratios can be well reproduced under the assumption of the proposed configurations.

According to the configuration and spin-parity assignments, it is now interesting to point out 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 of odd-odd ^{176}Ir is inverted at low and medium spins. To illustrate further the features of signature inversion, we compare the typical staggering curves $S(I) = E(I)-E(I-1)-\frac{1}{2}[E(I+1)-E(I)+E(I-1)-E(I-2)]$ *vs.* I in fig. 5 for the $\pi h_{9/2}\otimes\nu i_{13/2}$ and $\pi i_{13/2}\otimes\nu i_{13/2}$ bands in both ^{176}Ir and ^{178}Ir. 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); this is the so-called low-spin signature inversion [1]. On the other hand, the signature splitting reverts to the normal ordering at $I_\mathrm{c} = (18^-)$ for the $\pi h_{9/2}\otimes\nu i_{13/2}$ band in ^{176}Ir. This critical spin is $3\hbar$ lower than that in ^{178}Ir which is consistent with systematic expectations [6]. For the $\pi i_{13/2}\otimes\nu i_{13/2}$ band in ^{176}Ir, the critical inversion spin has not been reached in this work, indicating that the critical inversion spin I_c should be larger than $25\hbar$.

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 (*e.g.*, refs. [3,7] and references therein); it has been demonstrated that the particle-hole component of proton-neutron residual interaction plays a key role for the low-spin signature inversion. The inversion phenomena in the

$\pi i_{13/2} \otimes \nu i_{13/2}$ bands may be understood, as proposed by Hojman *et al.* [13], in the same theoretical framework of the Particle Rotor Model with p-n interaction. In fact, the signature splitting (or level staggering) in both bands is determined by two important factors, *i.e.*, the Coriolis and p-n residual interactions. The Coriolis force favors a normal signature splitting, namely, the odd-spin sequence is lower in energy than the even-spin levels, whereas the inclusion of p-n residual interaction will lead to an inverted signature splitting; this has been studied many years ago by Kreiner in the case of oblate odd-odd Tl isotopes [18]. The competition between the Coriolis and p-n residual interactions results in the level staggering pattern as shown in fig. 5; the signature splitting is inverted at low and medium spins (signature inversion) when the p-n residual interaction dominates, and the normal signature splitting is restored at higher spins when Coriolis interaction dominates. Thus the critical inversion spin I_c should be related to the combined effects of Coriolis and p-n residual interactions. The inversion spins in the $\pi i_{13/2} \otimes \nu i_{13/2}$ bands are observed to be larger than that in the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands as clearly demonstrated in fig. 5; this may be understood, at least qualitatively, by considering the two points: 1) Both quasi-proton and quasi-neutron occupy the same high-j orbitals in the $\pi i_{13/2} \otimes \nu i_{13/2}$ structures, thus the residual p-n interaction could be stronger than that in the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands. The strong residual p-n interaction tends to keep the inverted signature splitting up to high spins. 2) The $\pi i_{13/2}(\frac{1}{2}^+[660])$ proton drives the nucleus towards a larger quadrupole deformation, this will reduce the amplitute of normal signature splitting caused by the Coriolis force. As a result, the restoration to the normal signature splitting in the $\pi i_{13/2} \otimes \nu i_{13/2}$ bands is retarded with respect to the case in the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands. The inversion spin I_c for the $\pi h_{9/2} \otimes \nu i_{13/2}$ band in ^{176}Ir is $3\hbar$ lower than that in the same band of ^{178}Ir; this could be interpreted probably due to the lowering of the neutron Fermi surface and the reduced deformation of the core [19]; both will enhance the normal signature splitting caused by the Coriolis interaction and lead to an early restoration to the normal signature splitting. We are not able to understand the non-observation of such inversion spin in the $\pi i_{13/2} \otimes \nu i_{13/2}$ band of ^{176}Ir up to $I^\pi = (25^+)\hbar$, this is certainly in need of further investigations.

In conclusion, an in-beam γ-spectroscopy experiment has been performed leading to the observation of four rotational bands in odd-odd ^{176}Ir. The quasiparticle configurations and the level spin assignments for each band have been proposed on the basis of several considerations, *i.e.*, quasiparticle alignments, signature splitting, in-band $B(M1)/B(E2)$ ratios, and level spacing systematics, as well as the knowledge in neighboring nuclei. The interband connection from the $\pi i_{13/2} \otimes \nu i_{13/2}$ structure to the proposed $\pi h_{11/2} \otimes \nu \frac{5}{2}^-[512]$ band has been established leading to the signature inversion for the $\pi i_{13/2} \otimes \nu i_{13/2}$ band at low and medium spins. The signature inversion in the $\pi h_{9/2} \otimes \nu i_{13/2}$ band has been confirmed by the observation of signature crossing at $I \sim 18\hbar$ which is consistent with systematic expectations. The patterns of signature splitting in the two bands of both ^{176}Ir and ^{178}Ir are discussed, qualitatively, on the basis of the combined effects of Coriolis and p-n residual interactions. A deeper understanding on the inversion phenomena in both the $\pi h_{9/2} \otimes \nu i_{13/2}$ and the $\pi i_{13/2} \otimes \nu i_{13/2}$ structures, and on the different features presented in ^{176}Ir and ^{178}Ir is in need of further investigations; this is however beyond the scope of this paper. We would like to emphasize that the observation of such inversion phenomena in both ^{176}Ir and ^{178}Ir provides an interesting test ground for different theoretical interpretations.

The authors wish to thank the staffs in the JAERI tandem accelerator for providing ^{31}P beam and their hospitality during experiment. This work is partially supported by the National Natural Sciences Foundation of China (grant No. 10025525) and the Major State Basic Research Development Program of China (Contract No. G2000077400).

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