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Short note

Signature inversion in $\pi \mathrm{i}_{13/2} \otimes \nu \mathrm{i}_{13/2}$ structure in ^{178}Ir

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Abstract. High-spin states in ^{178}Ir were investigated by means of in-beam γ-ray spectroscopy techniques using the multidetector array GASP. Excited states of ^{178}Ir were populated through the ^{159}Tb(^{24}Mg, 5n) fusion-evaporation reaction at $E(^{24}\mathrm{Mg}) = 131$–141 MeV. Several rotational bands were observed. Among them, the $\pi i_{13/2} \otimes \nu i_{13/2}$ structure has been identified up to spin 36 $\hbar$. This band exhibits an anomalous signature splitting and a signature inversion around spin 25 $\hbar$.

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

Recently, spins of $\pi h_{9/2} \otimes \nu i_{13/2}$ bands have been established relative to other bands in ^{162,164}Tm [1], ^{172,174}Ta [2,1], and ^{176}Re [3]. With these spin assignments the favored states have even spins ($\alpha = 0$) up to high-spin values where a change of phase is produced. This is contrary to the expected favored signature in odd-odd nuclei ($\alpha^{\mathrm{f}}_{\text{p-n}}$) corresponding to the coupling between the favored signature of both proton ($\alpha^{\mathrm{f}}_{\mathrm{p}}$) and neutron ($\alpha^{\mathrm{f}}_{\mathrm{n}}$) orbitals, which for the $\pi h_{9/2} \otimes \nu i_{13/2}$ band corresponds to $\alpha^{\mathrm{f}}_{\text{p-n}} = \alpha^{\mathrm{f}}_{\mathrm{p}} + \alpha^{\mathrm{f}}_{\mathrm{n}} = 1/2 + 1/2 = 1$ (odd-spin values). The occurrence of this phenomenon has been found in bands of high-j parentage throughout the chart of nuclides, concerning 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. Among other explanations [4,5], a residual proton-neutron interaction in the framework of the Particle Rotor Model has been proposed [1,3,6]. Using this interaction, good agreement was obtained for the $\pi h_{9/2}$ ($1/2^-[541]$) $\otimes \nu i_{13/2}$ ($5/2^+[642]$,$7/2^+[633]$) structures [1,3], for the phase of the staggering and for the inversion point. Since the effect of the p-n interaction depends on the particle and hole character of the participating quasiparticles, a similar analysis can be performed for the $\pi i_{13/2}$ ($1/2^+[660]$) $\otimes \nu i_{13/2}$ ($7/2^+[633]$) structure. Proton $\pi i_{13/2}$ ($1/2^+[660]$) bands are strongly populated in ^{177,179}Ir [7,8] and the same occurs for neutron $\nu i_{13/2}$ bands in ^{177,179}Os [9]. In this context we have performed an experiment to search for high-spin states in ^{178}Ir. Previous to this work, only little information about low-spin states in ^{178}Ir was known from decay studies [10]. During the course of the present investigation some results about in-beam studies and signature inversion in the $\pi h_{11/2} \otimes \nu i_{13/2}$ and $\pi h_{9/2} \otimes \nu i_{13/2}$ structures became available [11].

High-spin states in ^{178}Ir were populated through the ^{159}Tb(^{24}Mg, 5n) fusion-evaporation reaction at $E(^{24}\mathrm{Mg}) = 131$, 133, 136 and 141 MeV. The target consisted of three self-supported 380 μg/cm^2 stacked Tb foils. The beam was provided by the Tandem XTU accelerator of Legnaro and γ-rays emitted by the evaporation residues were detected using the GASP array [12], which consisted of 40 Compton suppressed large volume Ge detectors and a multiplicity filter of 80 bismuth germanate (BGO) elements, providing the sum-energy and γ-ray multiplicity used to select the different reaction channels. Events were collected when at least three suppressed Ge and four inner multiplicity filter detectors were fired. With this condition a total of $\approx 1.7 \times 10^9$ events were recorded. We

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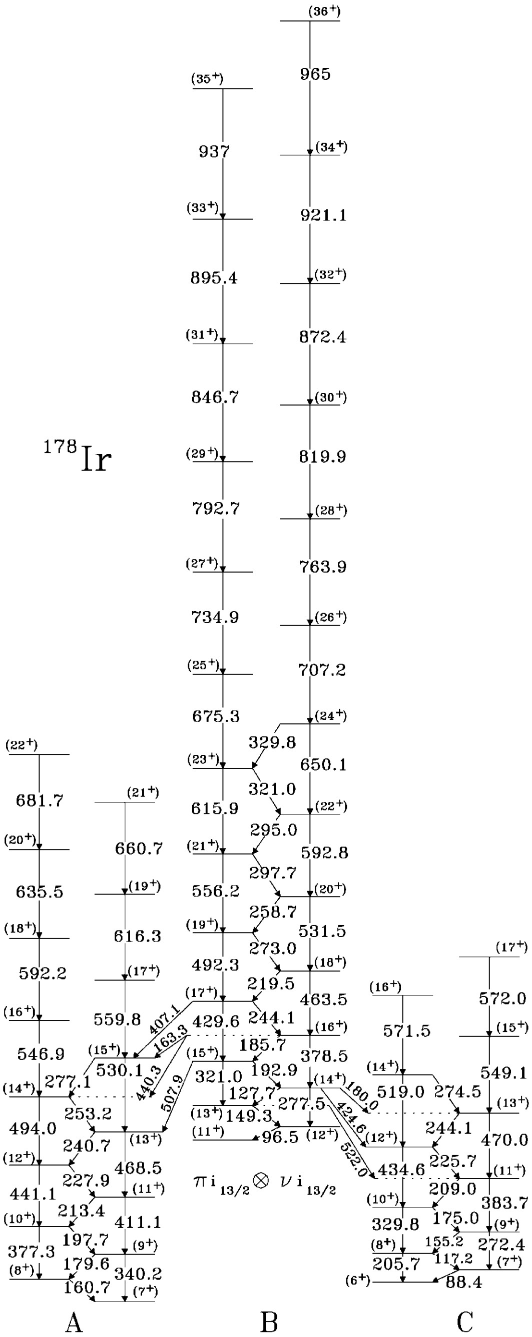

Fig. 1. Partial level scheme of ^{178}Ir.

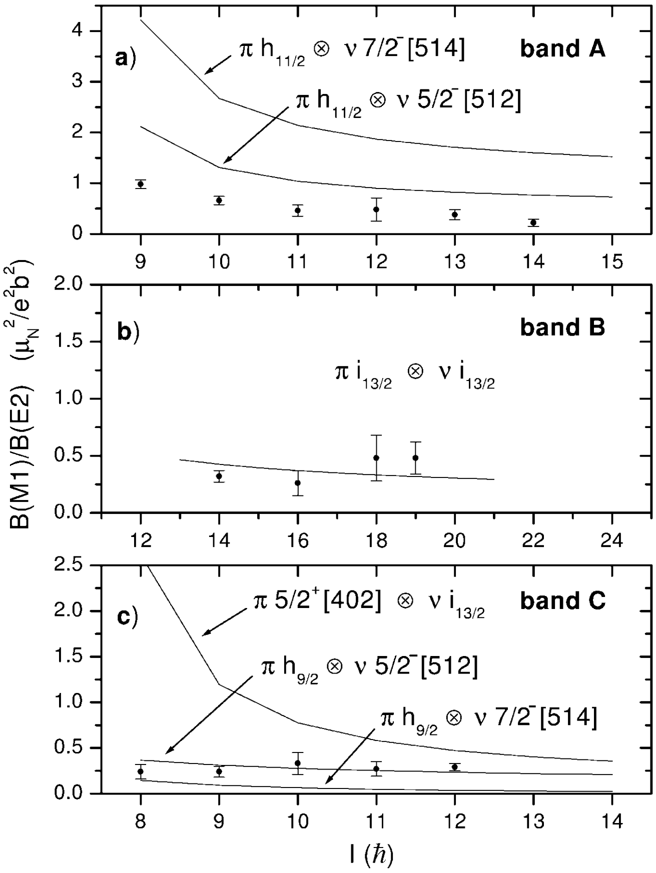

Fig. 2. Experimental and calculated $B(M1)/B(E2)$ ratios for the bands in ^{178}Ir, reported in the present work. For the $\pi h_{11/2} \otimes \nu 7/2^-[514]$ configuration, in a), spins must be increased by $1\hbar$.

constructed fully symmetrized E_γ-E_γ-E_γ cubes, E_γ-E_γ-multiplicity cubes, and angular correlation matrices for different time, multiplicity, sum-energy, beam energy and detector position conditions.

Several rotational bands have been assigned to ^{178}Ir on the basis of excitation functions, multiplicity distributions (well separated for channels differing in one evaporated neutron), and coincidences with Ir X-rays. Among these bands, two correspond to those reported in ref. [11]. Figure 1 shows a partial level scheme displaying only the bands of interest in the present work. The bands reported by Zhang *et al.* [11] are not included in fig. 1.

Band A exhibits an effective projection quantum number [13] $K_{\rm eff} = 7.5$. This high value corresponds to a case in which both proton and neutron orbitals are weakly affected by the Coriolis interaction, resulting in $K_{\rm eff} \approx K = \Omega_{\rm p} + \Omega_{\rm n}$. Two configurations, constructed from the proton and neutron orbitals lying close to the ground state in neighboring odd nuclei: $\pi h_{11/2}(9/2^-[514]) \otimes \nu 5/2^-[512]$ ($K^\pi = 7^+$) and $\pi h_{11/2}$ $(9/2^-[514]) \otimes \nu 7/2^-[514]$ ($K^\pi = 8^+$), have a K value close to $K_{\rm eff}$ and satisfy the above condition. Theoretical estimates of the $B(M1)/B(E2)$ ratios [2,14] can be compared in fig. 2a) with the experimental values, resulting in a better agreement for the $\pi h_{11/2}$ $\otimes\, \nu 5/2^-[512]$ configuration, which is assigned to band A. With this assignment band A has a positive parity and a bandhead spin $I = 7$.

The transitions linking the three bands fix the positive parity of bands B and C. In the case of the 180.0 keV linking transition, the assumed $M1+E2$ character is based on intensity balances. For band C, we extract a $K_{\rm eff} = 2.1$, which is too small except for a compressed band. This compression is due to the presence of a high-j, low-Ω orbital in its structure. The configurations satisfying these

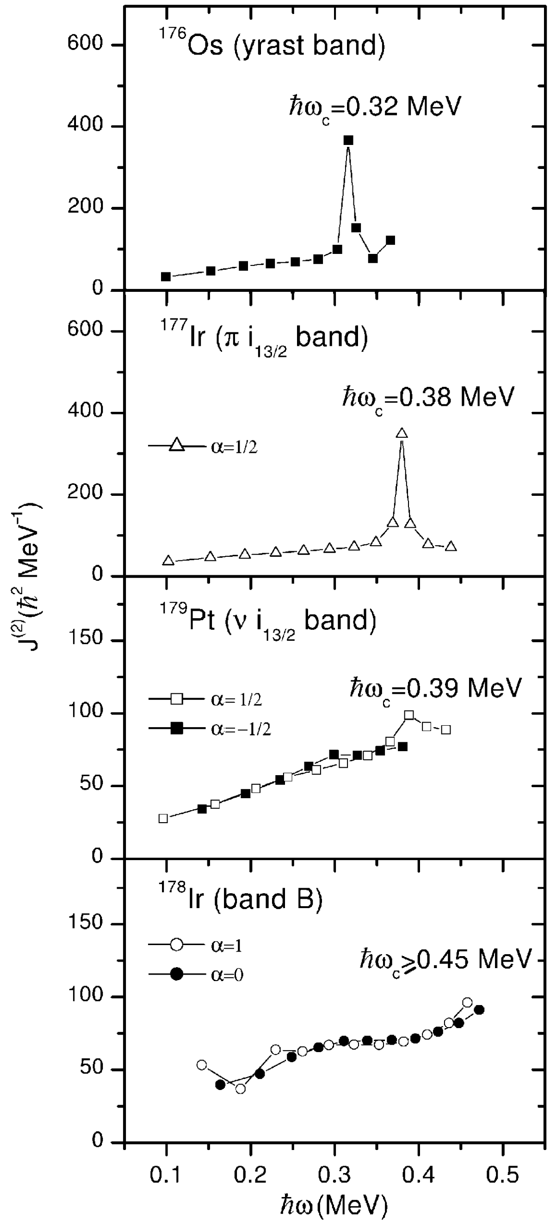

Fig. 3. Experimental dynamical moments of inertia as a function of the rotational frequency corresponding to the yrast band in ^{176}Os, $\pi i_{13/2}$ band in ^{177}Ir, $\nu i_{13/2}$ band in ^{179}Pt, and to band B in ^{178}Ir.

conditions and not assigned to other bands in the nucleus are: $\pi 5/2^+[402] \otimes \nu i_{13/2}$, $\pi h_{9/2} \otimes \nu 5/2^-[512]$, and $\pi h_{9/2} \otimes \nu 7/2^-[514]$. In fig. 2c) we observe a very good agreement between experimental and calculated $B(M1)/B(E2)$ ratios for the second configuration, which is assigned to band C. We note that a similar band has been observed in ^{180}Ir [15], where a $I^\pi = 6^+$ for the bandhead was unambiguously fixed and assigned to the same structure.

As mentioned before, band B has a positive parity and their spins are established relative to band A. The assignment of the $\pi i_{13/2} \otimes \nu i_{13/2}$ structure to this band is supported by several features. Calculated and experimental $B(M1)/B(E2)$ ratios are in very good agreement, see fig. 2b). The extracted alignment for this band, $i \approx 8.5\hbar$, is compatible with the sum of those extracted from the $\pi i_{13/2}$ and $\nu i_{13/2}$ bands in neighboring odd nuclei, $i_\mathrm{p}+i_\mathrm{n} \approx 5\hbar+4\hbar = 9\hbar$. In addition, we plot in fig. 3 the experimental dynamical moments of inertia as a function of the rotational frequency corresponding to the yrast band in ^{176}Os [16], $\pi i_{13/2}$ band in ^{177}Ir [7], $\nu i_{13/2}$ band in ^{179}Pt [17], and to band B in ^{178}Ir. The first band shows a band-crossing at $\hbar\omega_\mathrm{c} = 0.32$ MeV, corresponding to the energy needed to break an $i_{13/2}$ neutron pair. The delay in the crossing frequency, with respect to this value, observed in the $\pi i_{13/2}$ band in ^{177}Ir ($\delta\hbar\omega_\mathrm{c} = \hbar\omega_\mathrm{c}(^{177}\mathrm{Ir}) - \hbar\omega_\mathrm{c}(^{176}\mathrm{Os}) = 0.38\,\mathrm{MeV} - 0.32$ MeV $= 0.06$ MeV) can be explained in terms of a deformation driving effect induced by the $\pi i_{13/2}$ orbital [7]. On the other hand, the delay in the crossing frequency observed in the $\nu i_{13/2}$ band in ^{179}Pt ($\delta\hbar\omega_\mathrm{c} = 0.39$ MeV $- 0.32$ MeV $= 0.07$ MeV) is explained as a blocking effect. ^{179}Pt has been used instead of its isotone ^{177}Os because there are not data to determine the band-crossing frequency for the $\nu i_{13/2}$ band in this nucleus. For band B in ^{178}Ir, the delay in the band-crossing, $\delta\hbar\omega_\mathrm{c} \geq 0.45$ MeV $- 0.32$ MeV $= 0.13$ MeV is compatible with the sum of the delays in the neighboring odd-mass nuclei, 0.06 MeV + 0.07 MeV = 0.13 MeV, reflecting both effects, in agreement with the assigned structure. Finally, in-band $\Delta I = 1$ transitions have DCO ratios ≈ 0.5 (as an example, for the 185.7 keV transition we obtain DCO = 0.49(8)), which are consistent, in the GASP geometry [2], with $\Delta I = 1, \delta \leq 0$ transitions, as expected for this structure.

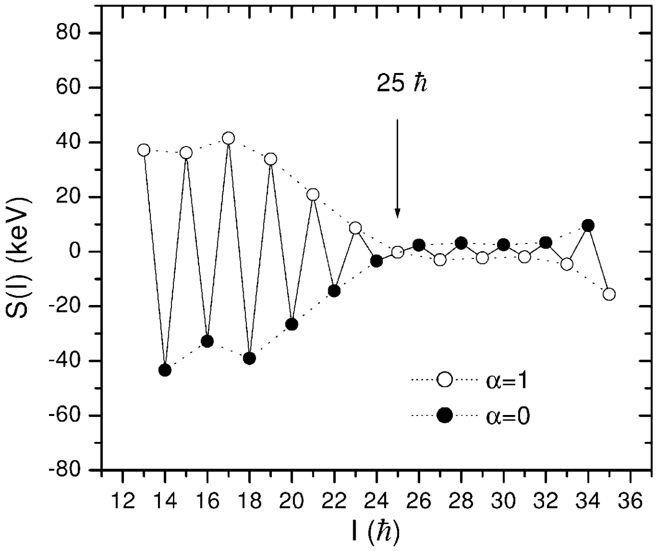

Fig. 4. Variation of the energy difference $S(I) = E(I) - E(I-1) - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$ between levels of band B in ^{178}Ir as a function of the angular momentum. The signature inversion point is indicated with an arrow.

For band B we plot, in fig. 4, the variation of the energy difference $S(I) = E(I) - E(I-1) - [E(I+1) -$

$E(I) + E(I-1) - E(I-2)]/2$ as a function of the spin. Here we can see that below $I = 25\hbar$, where a change of phase occurs, even-spin ($\alpha = 0$) states are anomalously favored, and beyond this spin value odd-spin ($\alpha = 1$) states become normally favored. This behavior, similar to the $\pi h_{9/2} \otimes \nu i_{13/2}$ case, can be understood in the framework of the Particle Rotor Model with p-n interaction. For the $\pi i_{13/2} \otimes \nu i_{13/2}$ configuration the proton-particle - neutron-hole matrix elements of the residual zero-range interaction have similar values for the $J = 5 - 12$ states, while the value for $J = 13$ is strongly repulsive, so the $J = 13$ component is practically excluded from the spectrum of intrinsic excitations. In this context, the valence nucleons couple to an intrinsic angular momentum $J \leq 12$. For $I \geq 13$, even-spin states with I and odd-spin states with $I - 1$ have mainly the same components, $J = 12$ and $R = I - 12$ (R= even is the core angular momentum) and consequently similar rotational energies. Then, even-spin states become favored if compared with the normal rotational sequence $E(I) \propto I(I+1)$. When the rotational energy required to go from one state to the next one starts to become comparable to the intrinsic (p-n interaction) energy required to maximally align the odd proton and neutron to $J = 13$, this value become available for the intrinsic excitations and the change of phase occurs. In this case, one returns to a regime dominated by the Coriolis interaction and the phase of the staggering will become the "normal" one (*i.e.* the odd-spin sequence will become favored).

As pointed out before signature inversion in the $\pi h_{11/2} \otimes \nu i_{13/2}$ and $\pi h_{9/2} \otimes \nu i_{13/2}$ structures in ^{178}Ir has been reported by Zhang *et al.* [11]. The authors show a systematic analysis of the inversion point as a function of the proton and neutron numbers, for the last mentioned structure. A detailed discussion of signature inversion in these bands is left for a more comprehensive publication.

To conclude, we report in this work three new rotational bands in ^{178}Ir, whose configurations are assigned from rotational model arguments. Among these bands that one corresponding to the $\pi i_{13/2} \otimes \nu i_{13/2}$ structure exhibits anomalously favored $\alpha = 0$ states below $I = 25\hbar$ where a change of phase occurs. This phenomenon is interpreted in the framework of the Particle Rotor Model with residual proton-neutron interaction.

References

1. R.A. Bark *et al.*, Phys. Lett. B **406**, 193 (1997).
2. D. Hojman *et al.*, Phys. Rev. C **61**, 064322 (2000).
3. M.A. Cardona *et al.*, Phys. Rev. C **59**, 1298 (1999).
4. J.A. Pinston *et al.*, Phys. Lett. B **137**, 47 (1984), and references therein.
5. I. Hamamoto, Phys. Lett. B **235**, 221 (1990).
6. N. Tajima, Nucl. Phys. A **572**, 365 (1994).
7. R.A. Bark *et al.*, Phys. Rev. C **52**, R450 (1995).
8. H.-Q. Jin *et al.*, Phys. Rev. C **53**, 2106 (1996).
9. G.D. Dracoulis *et al.*, Nucl. Phys. A **401**, 490 (1983).
10. E. Browne, Nucl. Data Sheets **72**, 221 (1994).
11. Y.H. Zhang *et al.*, Eur. Phys. J. A **8**, 439 (2000).
12. D. Bazzacco, *Proceedings of the International Conference on Nuclear Structure at High Angular Momentum, Ottawa, 1992*, edited by J. Wadington, D. Ward, Vol. **2** (AECL 10613) p. 376.
13. D. Hojman *et al.*, Phys. Rev. C **45**, 90 (1992).
14. F. Dönau, S. Frauendorf, *Proceedings of the Conference on High Angular Momentum Properties of Nuclei, Oak Ridge, USA, 1982*, edited by N. Johnson (Harwood Academic, Chur, 1982) p. 143.
15. Y.H. Zhang *et al.*, Eur. Phys. J. A **5**, 345 (1999).
16. G.D. Dracoulis *et al.*, Nucl. Phys. A **383**, 119 (1982).
17. C. Baglin, Nucl. Data Sheets **72**, 617 (1994).