Eur. Phys. J. A **8**, 439–442 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Short note

Observation of signature inversion in odd-odd ^{178}Ir

Y.H. Zhang[1,a], T. Hayakawa[2], M. Oshima[2], Y. Toh[2], J. Katakura[2], Y. Hatsukawa[2], M. Matsuda[2], N. Shinohara[2], T. Ishii[2], H. Kusakari[3], M. Sugawara[4], and T. Komatsubara[5]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, P.R.China
[2] Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan
[3] Chiba University, Inage-ku, Chiba 263-8512, Japan
[4] Chiba Institute of Technology, Narashino, Chiba 275-0023, Japan
[5] Institute of Physics and Tandem Accelerator Center, University of Tsukuba, Ibaraki 305-0006, Japan

Received: 23 March 2000 / Revised version: 5 July 2000
Communicated by D. Schwalm

Abstract. High spin states in ^{178}Ir have been studied via the ^{152}Sm(^{31}P,5nγ)^{178}Ir reaction through excitation functions, X-γ and γ-γ-t coincidence measurements. According to the band structure characteristics and the measured intraband $B(M1)/B(E2)$ ratios, two rotational bands are identified and assigned to be associated with the $\pi h_{9/2}\otimes\nu i_{13/2}$ and $\pi h_{11/2}\otimes\nu i_{13/2}$ configurations, respectively. Both bands show the signature inversion feature.

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

For the one-quasiparticle bands in an odd-mass deformed nucleus, the energy levels are usually classified according to the parity (π) and signature (α) quantum numbers. The two $\Delta I = 2$ stretched $E2$ transition sequences are usually split because of (mainly) the Coriolis and centrifugal interactions. Thus the lower-lying levels correspond to the favored signature defined as $\alpha_{\rm f} = 1/2(-1)^{j-1/2}$, and the higher-lying ones to the unfavored signature of $\alpha_{\rm uf} = 1/2(-1)^{j+1/2}$, where j is the angular momentum of the quasiparticle in the specific orbit. For the two-quasiparticle bands in an odd-odd nucleus, the levels with $\alpha_{\rm f}^{\rm n-p} = \alpha_{\rm f}^{\rm p} + \alpha_{\rm f}^{\rm n}$ are expected to be lower in energy than the levels with unfavored signature of $\alpha_{\rm uf}^{\rm n-p} = \alpha_{\rm f}^{\rm p} + \alpha_{\rm uf}^{\rm n}$ or $\alpha_{\rm uf}^{\rm n-p} = \alpha_{\rm uf}^{\rm p} + \alpha_{\rm f}^{\rm n}$. However, this rule is broken in a number of $\pi h_{11/2}\otimes\nu i_{13/2}$ bands in the lighter Eu, Ho, Tm, Lu, and Ta nuclei at low rotational frequencies (see ref. [1] and references therein); the levels with $\alpha_{\rm uf}^{\rm n-p} = \alpha_{\rm uf}^{\rm p} + \alpha_{\rm f}^{\rm n} = 1/2 + 1/2 = 1$ are lower in energy than those with $\alpha_{\rm f}^{\rm n-p} = \alpha_{\rm f}^{\rm p} + \alpha_{\rm f}^{\rm n} = -1/2 + 1/2 = 0$ at low spins. At a certain spin, the two $\Delta I = 2$ sequences get crossed, and signature splitting recovers to be normal. This phenomenon is called signature inversion [2] and has been attracting a large theoretical and experimental interest. Recently the signature inversion has been observed in the $\pi h_{9/2}\otimes\nu i_{13/2}$ bands of ^{162,164}Tm, ^{174}Ta [3] and ^{176}Re [4]. These observations result in a re-evaluation of spins for a number of rotational bands in this mass region [1, 4]. The present work is a contribution to the subject cited above. However, due to the well-known experimental difficulties, the connections of rotational bands to the ground state or to the low-lying levels with known spins cannot be established in most cases. Therefore we concentrate in this work on the observation of signature crossing at higher or moderate spins. This might be an indirect evidence of signature inversion. No high spin data in ^{178}Ir were available previously, and little information is known from the decay studies of ^{182}Au [5] .

The experiment was performed in the Japan Atomic Energy Research Institute (JAERI) using the ^{152}Sm(^{31}P,5nγ)^{178}Ir reaction. The ^{31}P beam was provided by the JAERI tandem accelerator. The target is an enriched ^{152}Sm metallic foil of 1 mg/cm^2 thickness with a 5 mg/cm^2 Au backing. The excitation function was measured using a ^{31}P beam from 150 MeV to 170 MeV with 5 MeV energy steps. The beam energy of 160 MeV was used during X-γ and γ-γ coincidence measurements. A total of 3×10^8 γ-γ coincidence events was accumulated using 11 HPGe's with BGO anti-Compton (AC) shields. The details of the experiment and data analysis have been described in our previous publication [6].

The partial level scheme of ^{178}Ir 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 the transitions in the two bands is established on

[a] e-mail: zzzhao@ns.lzb.ac.cn

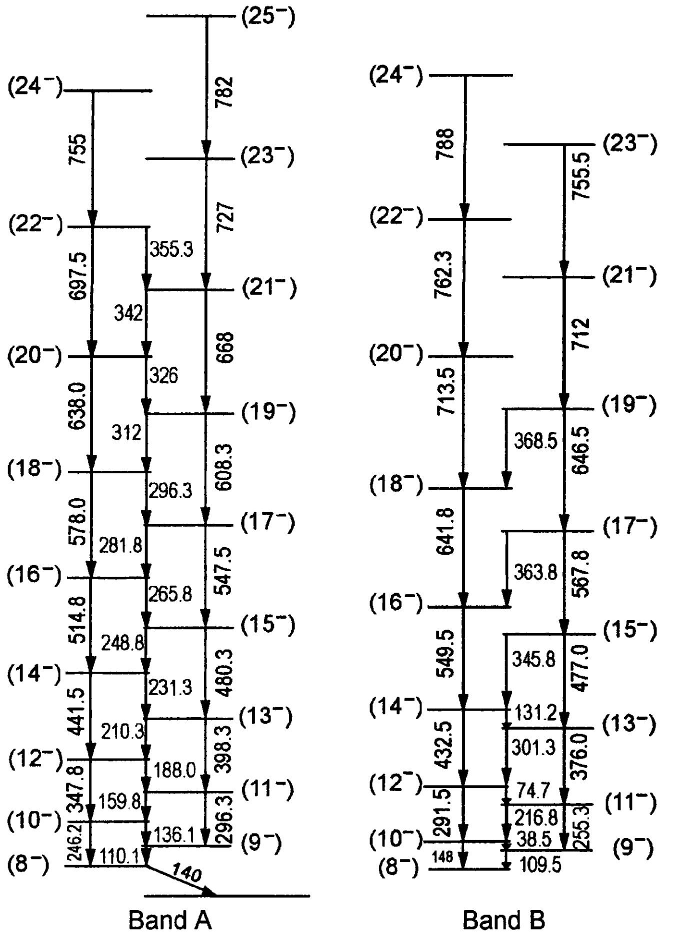

Fig. 1. Partial level scheme of ^{178}Ir deduced from the present work.

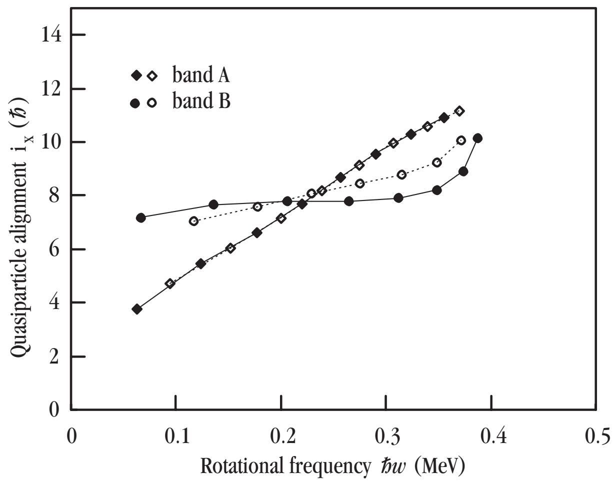

Fig. 2. Quasiparticle alignments, $i_x(\omega)$ as a function of rotational frequency, $\hbar\omega$. The common Harris parameters $J_0 = 21.5$ MeV$^{-1}\hbar^2$, $J_1 = 80$ MeV$^{-3}\hbar^4$ are used.

the basis of the γ-γ coincidence relationship, γ-ray energy sums and γ-ray relative intensities. Figure 2 presents the quasiparticle alignments, $i_x(\omega)$, as a function of rotational frequency ($\hbar\omega$). The same reference with common Harris parameters $J_0 = 21.5$ MeV$^{-1}\hbar^2$, $J_1 = 80$MeV$^{-3}\hbar^4$ is used in this plot in order that the alignments of the yrast band in ^{178}Os [7] keep roughly constant values after the first bandcrossing.

Band A is considered most likely to be associated with the $\pi 9/2^-[514](\alpha = \pm 1/2) \otimes \nu 7/2^+[633](\alpha = 1/2)$ quasiparticle configuration. The configuration assignment is supported by the following considerations: 1) The proton $h_{11/2}$-$9/2^-[514]$ band and the neutron $i_{13/2}$-$7/2^+[633]$ band have been observed to be intensely populated by the heavy-ion induced fusion-evaporation reactions in the neighboring ^{177,179}Ir [8,9] and ^{177}Os [10] nuclei, respectively. Thus the band with $\pi 9/2^-[514] \otimes \nu i_{13/2}$ coupling in the odd-odd ^{178}Ir is expected, *a priori*, to be strongly populated and easily observed in the reaction used here. Indeed the band with the same quasiparticle configuration has been observed in its lower-Z isotone ^{176}Re [4]. 2) As shown in fig. 2, no sudden backbend or upbend is observed up to $\hbar\omega \sim 0.35$ MeV indicating the involvement of an $i_{13/2}$ quasi-neutron. Instead, this band shows a gradual increase of alignment very similar to that in the $\pi 9/2^-[514]$ band of ^{177,179}Ir [8,9]. 3) An average g_K factor of 0.58(5) is deduced from the measured intra-band $M1/E2$ branching ratios. This gyromagnetic ratio is in good agreement with the theoretically predicted value $g_K = (\Omega_p g_{\Omega_p} + \Omega_n g_{\Omega_n})/K = 0.61$ under the assumption of $\pi 9/2^-[514] \otimes \nu 7/2^+[633]$ ($K^\pi = 8^-$) configuration. 4) The intra-band $B(M1)/B(E2)$ ratios have been extracted from the measured branching ratios and plotted in fig. 3. In this figure we compare the results with the theoretical calculations using the formulae of Bohr-Mottelson [11] under the assumptions of two possible configurations of $\pi 9/2^-[514] \otimes \nu 7/2^+[633](K^\pi = 8^-)$ and $\pi 5/2^+[402] \otimes \nu 7/2^+[633](K^\pi = 6^+)$, respectively. As is clear in this figure, the calculations are in favor of the first assumption. The lowest level of this band is proposed to be the band head with $I^\pi = K^\pi = 9/2^- + 7/2^+ = 8^-$.

In order to illustrate the level staggering pattern in band A, the quantity $S(I) = E(I) - E(I-1) - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$ is plotted as a function of spins in fig. 4 together with the data of the similar band in ^{176}Re [4] for comparison. For the adopted spin values shown in fig. 1, it is found that the levels with odd spin ($\alpha_{\rm uf} = 1$) are energetically favored at lower spins and the states with even spin ($\alpha_{\rm f} = 0$) turn out to be favored beyond the signature crossing point around 16 $\hbar$ in both nuclei. This is expected for the $\pi h_{11/2} \otimes \nu i_{13/2}$ structure. Previous studies of odd-odd nuclei in the light rare-earth region have established a consistent pattern of the energy signature dependence, and different mechanisms have been proposed to interpret this signature inversion phenomenon using several theoretical approaches (see references quoted in [1]). We would like to address that the signature inversion presents in a wider nuclear regime than previously predicted [2] and the particular shell filling seems not to be a strict restriction to the presence of this phenomenon.

Band B is the most strongly populated band in this experiment and can be regarded as the semidecoupled band

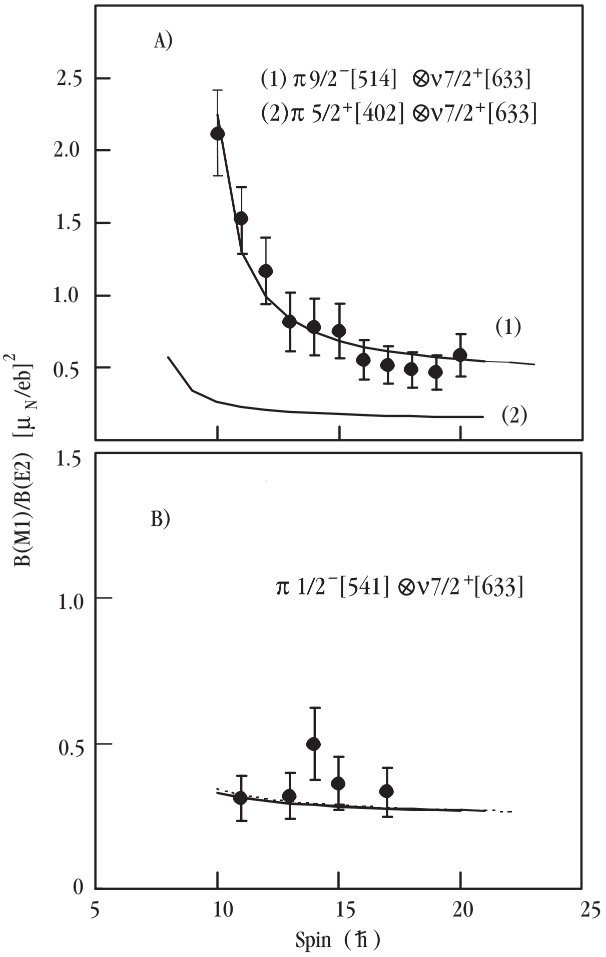

Fig. 3. Experimental $B(M1)/B(E2)$ ratios and theoretical calculations using the formulae of Bohr-Mottelson [11] for the possible configurations. Common parameters $g_R = 0.30$, $Q_0 = 6.0$ b are used and $g_K = 0.58$, $K = 8$ $\hbar$ for the $\pi 9/2^-[514] \otimes \nu 7/2^+[633]$ configuration; $g_K = 0.51$, $K = 6$ $\hbar$ for the $\pi 5/2^+[402] \otimes \nu 7/2^+[633]$ configuration; $g_K = -0.12$, $K = 4$ $\hbar$ for the $\pi 1/2^-[541] \otimes \nu 7/2^+[633]$ configuration. The dashed line in fig. 3(b) is the calculations using the geometric model of Dönau and Frauendorf [12] extended to the odd-odd nuclei [4] with the parameters of $i_{\rm p} = 3.8\hbar$, $i_{\rm n} = 3.6\hbar$, $g_K(p) = 0.85$, $g_K(n) = -0.25$, $\langle K_n \rangle = 3.5\hbar$, $\langle K_p \rangle = 0.5\hbar$, and $\langle K_{\rm np} \rangle = 4\hbar$, respectively.

based on the $\pi 1/2^-[541](\alpha = 1/2) \otimes \nu i_{13/2}(\alpha = \pm 1/2)$ configuration. This assignment is supported by the pronounced level staggering and a large band crossing frequency of $\hbar\omega_{\rm c} > 0.35$ MeV as shown in figs. 1 and 2. These two typical features have been observed and confirmed in a number of $\pi h_{9/2} \otimes \nu i_{13/2}$ semidecoupled bands in this mass region [13]. Furthermore, the $B(M1)/B(E2)$ values deduced from the measured branching ratios are scattering around 0.33 $(\mu_N/eb)^2$ which can be well reproduced from the rotational model and the geometric model of Donau and Frauendorf [12] extended to the odd-odd nuclei [4] (see fig. 3(b)). The spin assignment for this band is proposed on the basis of the systematics of level spacings in the similar bands of $N = 101$ odd-odd [3,4] isotones and the neighboring ^{180}Ir [6].

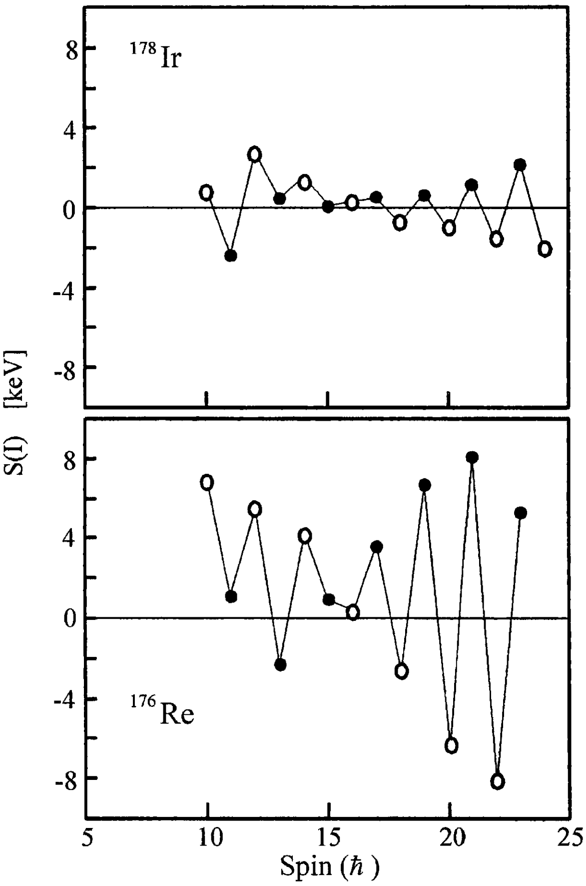

Fig. 4. Plot of level staggering for band A in ^{178}Ir and for the similar band in its isotone ^{176}Re [4].

We plot the energy staggering defined as $E(I) - E(I-1)$ versus spin in fig. 5 for band B in ^{178}Ir and for the similar bands in some neighboring odd-odd nuclei. The similarity in the staggering pattern is impressive. The signature splitting is inverted at lower spins for all the semidecoupled bands shown in this figure; the odd-spin levels with favored signature ($\alpha_{\rm f}^{\rm n-p} = \alpha_{\rm f}^{\rm p} + \alpha_{\rm f}^{\rm n} = 1/2 + 1/2 = 1$) are lying higher than the even-spin levels with unfavored signature ($\alpha_{\rm uf}^{\rm n-p} = \alpha_{\rm f}^{\rm p} + \alpha_{\rm uf}^{\rm n} = 1/2 - 1/2 = 0$). The signature splitting reverts (or tend to revert) to the normal ordering at a certain high-spin value. As cited in the first paragraph, the spin assignment based on the spectroscopic methods is rather difficult for most of the semidecoupled bands observed in this mass region, therefore the observation of the crossing point becomes very important and could be regarded as an indirect evidence of low-spin signature inversion. In ^{178}Ir, this signature crossing point is observed at $I = (21)\hbar$. Finally from the careful inspection of fig. 5, the statement can be made that the crossing spin decreases 2–3 $\hbar$ while decreasing two neutrons for a chain of isotopes, and it decreases 2–3 $\hbar$ while increasing two protons for a chain of isotones.

To summarize, two rotational bands in odd-odd ^{178}Ir have been newly identified and assigned to the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi h_{11/2} \otimes \nu i_{13/2}$ quasiparticle configurations, respectively. The low spin signature inversion in both bands

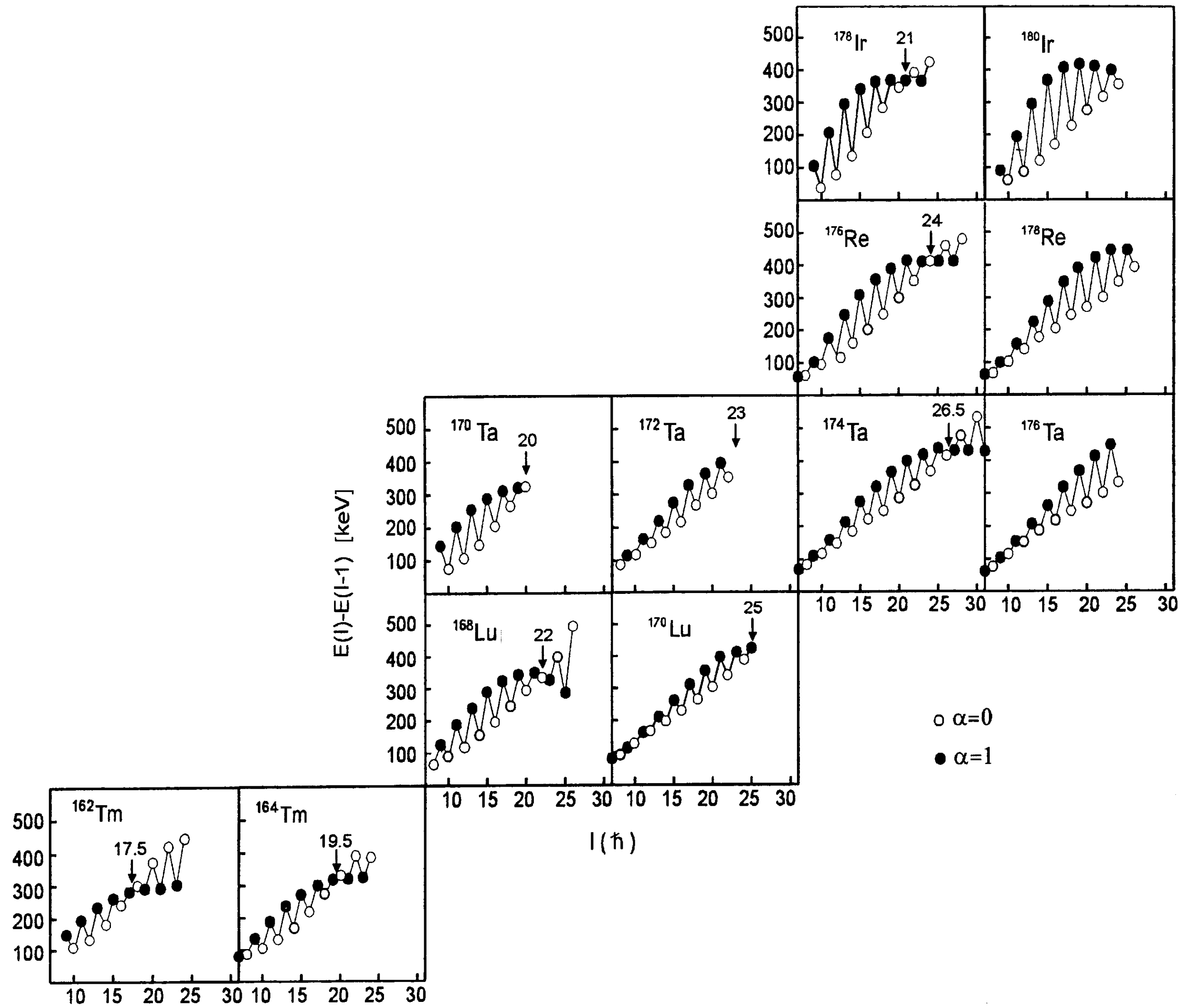

Fig. 5. Plot of level staggering for band B in ^{178}Ir and the semidecoupled bands in its neighboring odd-odd nuclei. The data are from refs. [1] and [4] and references therein.

has been confirmed due to the observation of signature crossing at a certain spin value.

The authors wish to thank the staffs in the JAERI tandem accelerator for providing the ^{31}P beam. This work was supported by the Japan STA Scientist Exchange Program (grant No. 1998-21) and the National Natural Sciences Foundation of China (grant No. 19605008).

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