Observation of High-j Two-Quasiparticle Bands in Odd–Odd ^{174}Re *

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High spin states in ^{174}Re have been investigated via the ^{152}Sm (^{27}Al, $5n\gamma$) ^{174}Re reaction. Gamma-ray excitation functions, x-γ and γ-γ coincidences have been measured. Two rotational bands built on the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi h_{11/2} \otimes \nu i_{13/2}$ configurations have been identified and extended up to high-spin states. The relative spin and parity of the band levels have been unambiguously fixed due to observations of several inter-band transitions. Both the bands show the low-spin signature inversion, which is consistent with systematic expectations for the high-j two-quasiparticle bands in the $A = 170$ mass region.

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In deformed odd–odd nuclei of the $A = 170$ mass region, the yrast or near-yrast levels correspond usually to the intrinsic excitations with quasiparticles occupying the $\pi h_{11/2}$, $\pi h_{9/2}$, and $\nu i_{13/2}$ high-j orbitals, respectively. Among the two-quasiparticle (2-qp) bands at low excitation energy, high-j bands have attracted special attention in the last two decades. A typical feature in such high-j bands is the so-called low-spin signature inversion which has been systematically observed in the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi h_{11/2} \otimes \nu i_{13/2}$ two-quasiparticle (2-qp) bands. Although several mechanisms have been introduced to explain the inversion phenomenon,[1] the proton–neutron (p–n) interaction is now considered to be the most important reason for such a phenomenon (see Refs. [2-4] and references therein). In the past few years, efforts have been made in our group to study the band structures of prolate-deformed odd–odd nuclei at the upper end of rear-earth region.[5] As for the odd–odd ^{174}Re nucleus, the high-spin data are scarce. The level scheme accepted in Ref. [6] deviates evidently from the systematics, and it could not be confirmed in the recent work using the ^{159}Tb(^{20}Ne, $5n\gamma$) ^{174}Re reaction.[7] With this in mind, we performed an in-beam γ-spectroscopy experiment to study the high-spin states of ^{174}Re using the ^{152}Sm(^{27}Al, $5n\gamma$) ^{174}Re reaction. This reaction system is expected to populate favourably the high-j 2-qp bands in ^{174}Re involving the $\pi 9/2^-[514]$, $\pi 1/2^-[541]$, and $\nu 7/2^+[633]$ Nilsson orbitals from the $\pi h_{11/2}$, $\pi h_{9/2}$, and $\nu i_{13/2}$ high-j spherical parentages, respectively.

The experiment was carried out in the Japan Atomic Energy Research Institute (JAERI) using the ^{152}Sm(^{27}Al, $5n\gamma$)^{174}Re reaction. The ^{27}Al beam was provided by the JAERI tandem accelerator and impinged on an enriched ^{152}Sm metallic foil of 2.0 mg/cm^2 thickness with a 10 mg/cm^2 Pb backing. The γ-ray detection array consisted of 13 large volume HPGe's with BGO anti-Compton shields. γ-ray excitation functions were measured at 125-, 132-, and 140-MeV beam energies, thus the in-beam γ-rays belonging to ^{174}Re could be identified by comparing their relative yields at different beam energies. It was found that the γ rays from ^{174}Re are predominant at 140-MeV beam energy, therefore γ-γ coincidence measurement was performed at this beam energy. A total of 2×10^8 γ-γ coincidence events were accumulated in this experiment and sorted into a symmetric E_γ-E_γ matrix of 4096×4096 size for the off-line analysis. To determine the multipolarities of emitted γ rays, the coincidence events were sorted into an asymmetric matrix with one γ ray detected in one of the 6 detectors at 47° or 147°, and the other one detected in one of the 7 detectors close to 90° with respect to the beam direction. From this matrix, the DCO ratios of γ rays have been analysed giving information on their multipole order.

From detailed analyses on the γ-ray excitation functions, coincidence relationships, energy sums, relative intensities, and DCO ratios, five rotational bands have been identified belonging to ^{174}Re, among which three bands reported in Ref. [7] have been confirmed and extended down to lower- and up to higher-spin states. For the interests of the present investigation

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and for ease of discussion, we present here a partial level scheme in Fig. 1 to show the high-j 2-qp bands built on the $\pi h_{11/2}\otimes\nu i_{13/2}$ (band 1) and $\pi h_{9/2}\otimes\nu i_{13/2}$ (band 2) configurations. It is most important that the present work has established spectroscopic connection between the two bands due to a number of inter-band transitions observed. This is caused by the accidental degeneracy of energy levels of same spin and parity. The linking transitions, such as the 260.8- and 507.4-keV γ rays, can be clearly observed in the 217.5-keV gated spectrum of Fig. 2. The 115.5- and 93.2-keV γ rays are assigned as out-of-band transitions considering the γ-ray intensity balance; the placement of the 115.5-keV line can be easily evaluated and assigned from an inspection on Fig. 2.

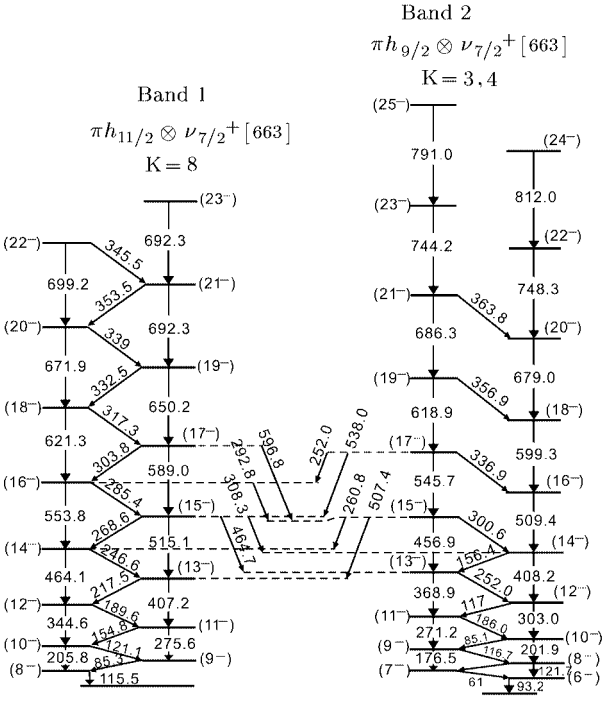


Fig. 1. Partial level scheme of ^{174}Re deduced from the present work.

It has been known that the heavy-ion-induced fusion-evaporation reactions populate favourably the bands at or near the yrast line, which correspond usually to the high-j bands. The $\pi h_{9/2}(1/2^-[541])$ and $\pi h_{11/2}(9/2^-[514])$ bands in ^{173,175}Re [8,9] and the $\nu i_{13/2}$ bands in adjacent odd-N nuclei are all intensely populated and observed, it is expected that the 2-qp bands built on the $\pi h_{11/2}(9/2^-[514])\otimes\nu i_{13/2}$ and $\pi h_{9/2}(1/2^-[541])\otimes\nu i_{13/2}$ high-j configurations, *a prior*, should be favourably populated as well in the (HI, xn) reaction used here and easy to observe in the present experiment. Indeed, such high-j 2-qp bands have been observed in a number of neighbouring odd–odd Ta, Re, and Ir isotopes.[2,10,11] Correspondingly we have assigned the $\pi h_{11/2}(9/2^-[514])\otimes\nu i_{13/2}$ and $\pi h_{9/2}(1/2^-[541])\otimes\nu i_{13/2}$ configurations to band 1 and band 2, respectively, thus giving negative parity to both bands. This assignment is also supported by comparing the level and transition properties of similar bands in the adjacent odd–odd nuclei. For example, the $\pi h_{11/2}(9/2^-[514])\otimes\nu i_{13/2}$ bands in this region are known to have small signature splitting associated with the $\pi h_{11/2}(9/2^-[514])$ proton and intense in-band $\Delta I = 1$ transitions due to its high-K and large-g_K characters. These features are clearly demonstrated in Fig. 2, from which one can see that the $\Delta I = 1$ transition energy increases with spin *regularly* indicating a small signature splitting, and the $\Delta I = 1$ transitions are more intense than the corresponding $\Delta I = 2$ ones. In contrast with the $\pi h_{11/2}(9/2^-[514])\otimes\nu i_{13/2}$ bands, the so-called $\pi h_{9/2}(1/2^-[541])\otimes\nu i_{13/2}$ semidecoupled bands have large signature splitting, which is exhibited as irregular $\Delta I = 1$ transitions. This is really the case for band 2 as shown in Fig. 1, in which *irregular* $\Delta I = 1$ transition energy is evident. Accepting the configuration assignments cited above, we have assigned the level spins for band 1 according to the level spacing systematics,[12] and the spins for band 2 can be determined via the linking transitions. It is worth noting that band 2 fits well into the level spacing systematics of the $\pi h_{9/2}(1/2^-[541])\otimes\nu i_{13/2}$ bands[5] in this region, providing in turn a self-consistent argument for our spin and parity assignments for both bands.

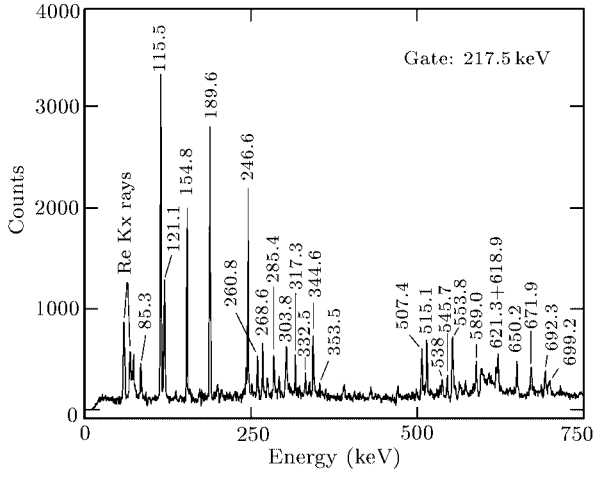


Fig. 2. Coincidence spectrum gated by the 217.5-keV transition in band 1.

The aligned angular momentum i_x versus rotational frequency $\hbar\omega$ are presented in Fig. 3 for the two bands in ^{174}Re. The ground-state-band (gsb) of ^{172}W[16] is also given in this figure for comparison. A reference with Harris parameters $J_0 = 29.6\hbar^2\mathrm{MeV}^{-1}$, $J_1 = 69.3\ \hbar^4\mathrm{MeV}^{-3}$ for ^{174}Re and $J_0 = 21\ \hbar^2\mathrm{MeV}^{-1}$, $J_1 = 85\ \hbar^4\mathrm{MeV}^{-3}$ for ^{172}W has been subtracted in order that the unfavoured signature branch of band 2 in ^{174}Re/(gsb of ^{172}W) has a constant alignment

before/after the first band crossing. As is obviously shown in Fig. 3, the first band crossing (or backbend) in the gsb of ^{172}W occurs below $\hbar\omega = 0.30$ MeV, while the band crossing is evidently delayed in band 1 of ^{174}Re, and no band crossing is observed in band 2 up to $\hbar\omega \sim 0.4$ MeV. On the other hand, band 2 has an initial alignment of $\sim 2\hbar$ higher than band 1. These properties can be understood in the framework of cranked shell model.[17] The band crossing in the gsb of ^{172}W is due to the alignment of a pair of $i_{13/2}$ neutrons, the so-called neutron AB crossing below $\hbar\omega = 0.30$ MeV. This AB crossing is blocked by an $i_{13/2}$ quasi-neutron in band 1; only the neutron BC and AD crossings may be observed at higher frequency. As for band 2 with the $\pi h_{9/2}(1/2^-[541])$ orbital occupied, the quasiproton with particle character drives the nucleus to a larger quadrupole deformation.[13] This shape driving effect and the proton-neutron residual interactions[14,18] lead to an extra delay of crossing frequency for band 2 with respect to band 1. As the initial alignments for the $\pi h_{9/2}(1/2^-[541])$ bands are usually higher that in the $\pi h_{11/2}(9/2^-[514])$ bands, it is thus reasonable to have higher initial alignments in band 2 than that in band 1.

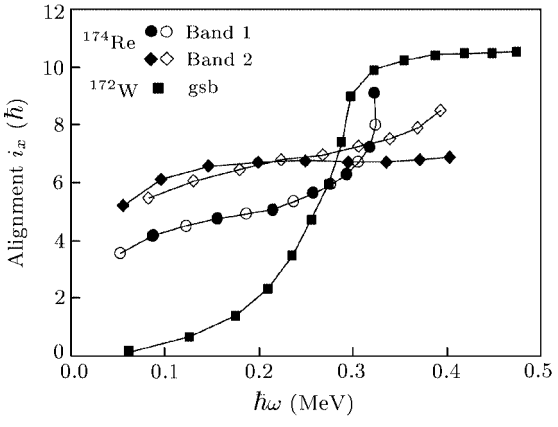


Fig. 3. Plot of quasiparticle alignments i_x as a function of rotational frequency $\hbar\omega$.

We have analysed the features of signature splitting for bands 1 and 2. The typical level staggering curves of $S(I) = E(I) - E(I-1) - \frac{1}{2}[E(I+1) - E(I) + E(I-1) - E(I-2)]$ versus spin I are plotted in Figs. 4 and 5 together with the similar bands in the odd–odd neighbours. The (15^-) levels are corrected by 2 keV considering the level interaction effect. In such a plot, the points (associated with levels of I) that have negative values are energetically favoured over those with positive ones. The expected favoured signatures are 0 and 1 for bands 1 and band 2, corresponding to the even and odd spin sequences, respectively. It can be seen in this figure that, it is the unfavoured-signature branches that are favoured energetically at low and medium spins rather than the expected favoured ones. Such behaviour has been referred to as the low-spin signature inversion. With increasing angular momentum, the inverted signature splitting becomes decreasing, and the two signature branches cross with each other at the high spins beyond which normal signature splitting is observed. The low-spin signature inversion

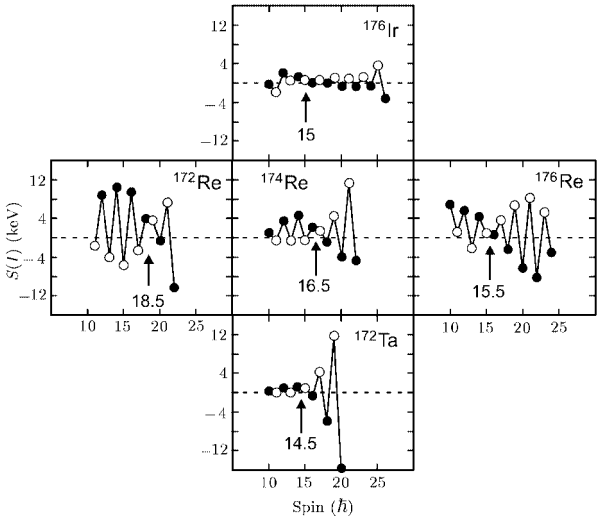


Fig. 4. Behaviour of signature splitting $S(I)$ versus I for band 1 and the $\pi h_{11/2} \otimes i_{13/2}$ bands in adjacent odd–odd nuclei. The arrow indicates the signature inversion spin.

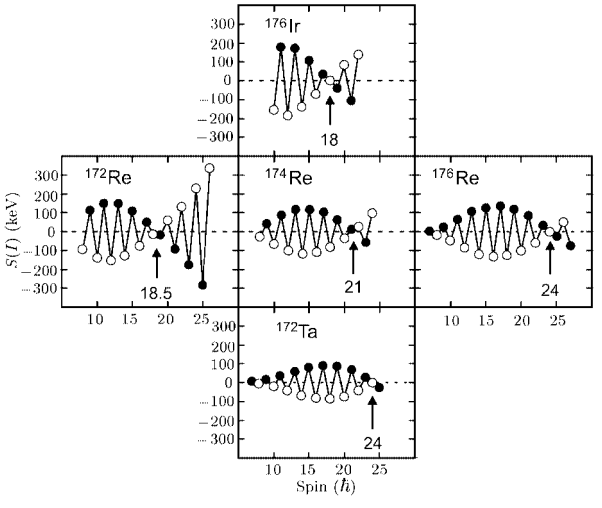


Fig. 5. Plot of signature splitting $S(I)$ vs I for band 1 and the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands in adjacent odd–odd nuclei. The arrow indicates the signature inversion spin.

in ^{174}Re fits well into systematics as shown in Figs. 4 and 5, providing supplementary argument for our configuration and spin-and-parity assignments for the two bands observed in ^{174}Re.

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 cited in Ref. [1]). The calculations in the framework of two-quasiparticle plus rotor model including p-n residual interactions have provided satisfactory explanations to both the signature inversion and the refined properties in quasiparticle alignments as well.[3] The reader is referred to Ref. [3] for details.

In conclusion, the high-spin band structures in odd–odd ^{174}Re have been investigated and the reported results in our previous work have been confirmed. Two high-j bands built on the $\pi h_{9/2} \otimes \nu i_{13/2}$ and $\pi h_{11/2} \otimes \nu i_{13/2}$ configurations have been identified and extended down to lower- and up to higher-spin states. The two bands are connected with each other via several linking transitions due to accidental degeneracy of energy levels of the same spin and parity. This result leads to a self-consistent spin-and-parity assignments and provides a new example of low-spin signature inversion. The inversion phenomena in both high-j bands of ^{174}Re, level spacing systematics, and the pattern in quasiparticle alignments are consistent with systematic expectations.

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