High-spin structure of odd-odd ^{172}Re

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A significant extension of the level scheme for the odd-odd nucleus ^{172}Re was accomplished through the use of the Gammasphere spectrometer. States up to a tentative spin assignment of 39 were observed and two new structures were identified. Configuration assignments are proposed based on alignment properties and observed band crossings.

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Odd-odd nuclei often display a broad sample of nuclear structure phenomena. However, they are usually not as well studied as their odd-A or even-even neighbors owing to the complexities resulting from the coupling of the odd quasiproton to the odd quasineutron. There are, however, noteworthy exceptions. An expansive level scheme of doubly-odd ^{170}Ta was established in Ref. [1], with over 400 transitions placed in 11 rotational bands, and the phenomenon of signature inversion in the $A \approx 170$ region was addressed. In addition, Ref. [2] discusses the results of ^{170}Re and the influence of residual interactions in this region. The present work focuses on the nearby isotope ^{172}Re, where the level scheme was significantly extended. The previously known bands have been established to higher spins and two new structures have been identified.

High-spin states in ^{172}Re were populated in the $3n$ channel of the ^{55}Mn + ^{120}Sn reaction and the γ rays were detected with the Gammasphere array [3]. The experimental details and analysis procedures are presented in Ref. [4]. Many of the new transitions were too weak to perform reliable angular correlation measurements. Therefore, it has been assumed that normal rotational characteristics persist to the highest observed spins such that the long decay sequences consist of $E2$ transitions.

Similar to the situation in many odd-odd systems, the ground-state spin and parity of ^{172}Re have not yet been firmly established. Two isomers have been observed, one with a 15(3) s half-life and another with a 55(5) s one. In an evaluation [5], tentative spin assignments of $(5\hbar)$ and $(2\hbar)$, respectively, have been proposed based on the β-decay feeding characteristics into ^{172}W. The only previous high-spin measurement on ^{172}Re was reported by Zhang *et al.* [6], and three rotational structures were identified based on the observed coincidence with rhenium x rays and the measured excitation function.

Figure 1 displays the new level scheme for ^{172}Re resulting from the current data. The two presumed negative-parity structures have now been connected together, and all the presumed positive-parity sequences are also linked. However, no transitions were found between the negative- and positive-parity states and, as a result, the relative excitation energies of the bands are not known at this time. The spins and parities are listed as tentative for all levels since the ground-state quantum numbers are not known.

The semi-decoupled structure labeled band 1 in Fig. 1 was previously observed up to (27^-) [6]. Zhang *et al.* proposed the $\pi h_{9/2}\nu i_{13/2}$ configuration for this structure and based their spin assignment on the known systematics of $\pi h_{9/2}\nu i_{13/2}$ bands found in heavier rhenium odd-odd isotopes. These spin values have been adopted in Fig. 1. Figures 2(a) and 2(b) provide the high-energy portions of spectra that allowed for the extension of this band up to (39^-). These coincidence spectra were generated in a hypercube by summing over a large number of gates requiring γ rays in coincidence with three in-band transitions. In addition to the extension of this

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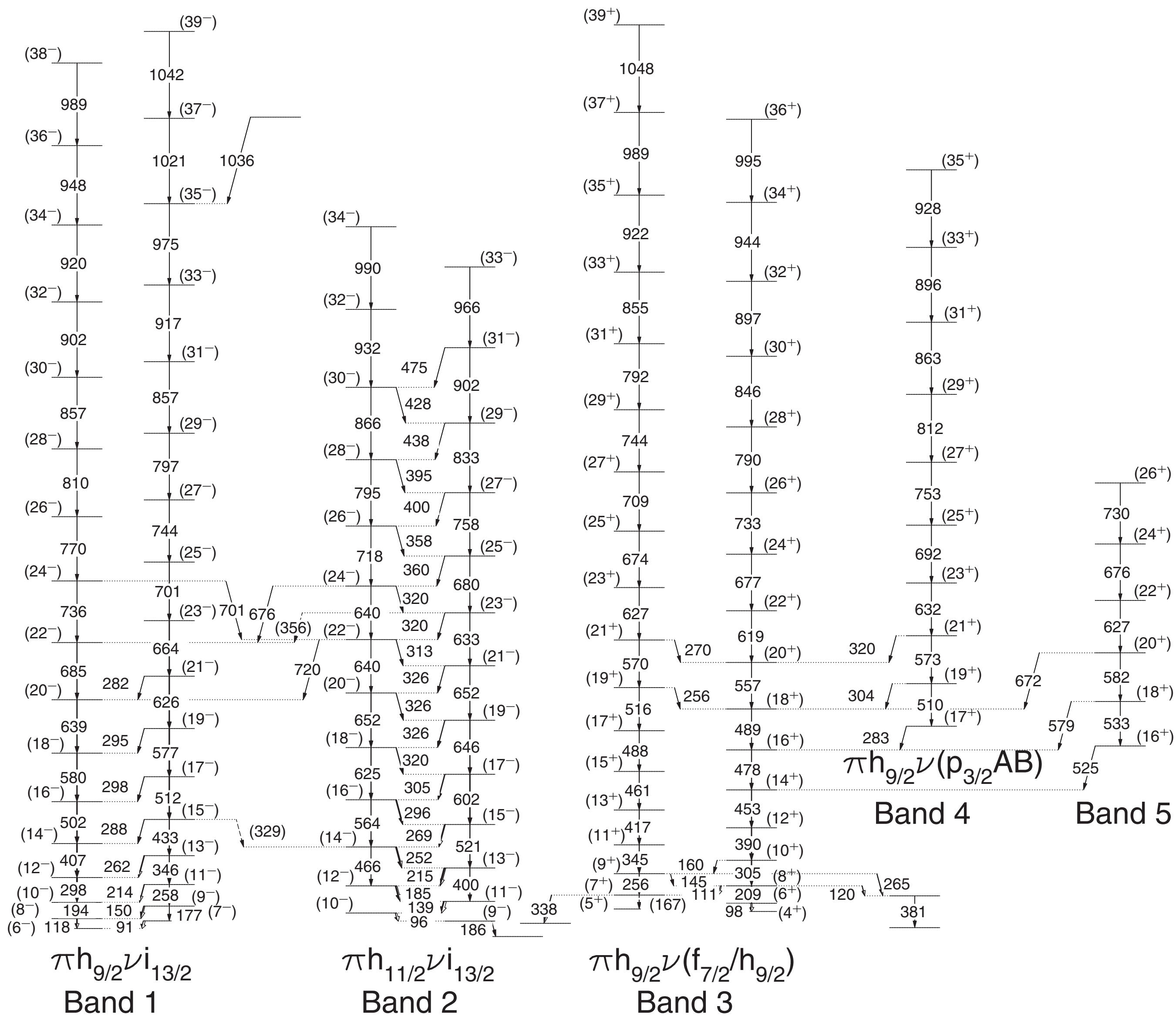

FIG. 1. Proposed level scheme for ^{172}Re. All spins and parities must be considered tentative as the ground-state quantum numbers are not yet firmly established.

band, an interaction was found between this sequence and band 2, as seen in Fig. 1. Several linking transitions were established as a result of the (22^-) levels being nearly degenerate and only separated by 35 keV. Assuming that the 676-, 701-, and 720-keV linking transitions are of $E2$ character, this interaction fixes the relative spin assignments of these two structures and requires that they be of the same parity.

Zhang *et al.* [6] assigned the $\pi h_{9/2}\nu i_{13/2}$ configuration to band 1 based on the energy splitting characteristics between its two signatures (signature splitting), its initial alignment, as well as the good agreement between experimental and theoretical $B(M1)/B(E2)$ ratios. Figure 3(a) presents the alignment of the $\pi h_{9/2}\nu i_{13/2}$ band, and several crossings are now observed. For reference, the alignment of the favored signature ($\alpha = +1/2$) from the $\nu i_{13/2}$ band in ^{171}W [7,8] is also plotted in the figure. The crossing found at 0.31 MeV in the $\nu i_{13/2}$ sequence is commonly referred to as the BC alignment which results from the second and third lowest $i_{13/2}$ quasineutrons aligning their spin with the rotation axis. In the odd-spin signature partner of the ^{172}Re band 1 [solid triangles in Fig. 3(a)], this crossing is delayed to a frequency of 0.34 MeV. It is likely that the $h_{9/2}$ odd quasiproton drives the nucleus to a slightly larger deformation, which in turn results in this delay in the crossing frequency. This quasiproton is well known for creating delayed crossings, as reported in Ref. [9]. The even-spin signature of band 1 [open triangles in Fig. 3(a)] displays a similar crossing at a higher frequency of 0.38 MeV. This is slightly higher than the frequency at which the unfavored signature of the $\nu i_{13/2}$ band in ^{171}W exhibits the AD crossing (alignment of the first and fourth lowest $i_{13/2}$ quasineutrons). Therefore, it is proposed that the first crossing observed in the even-spin signature of band 1

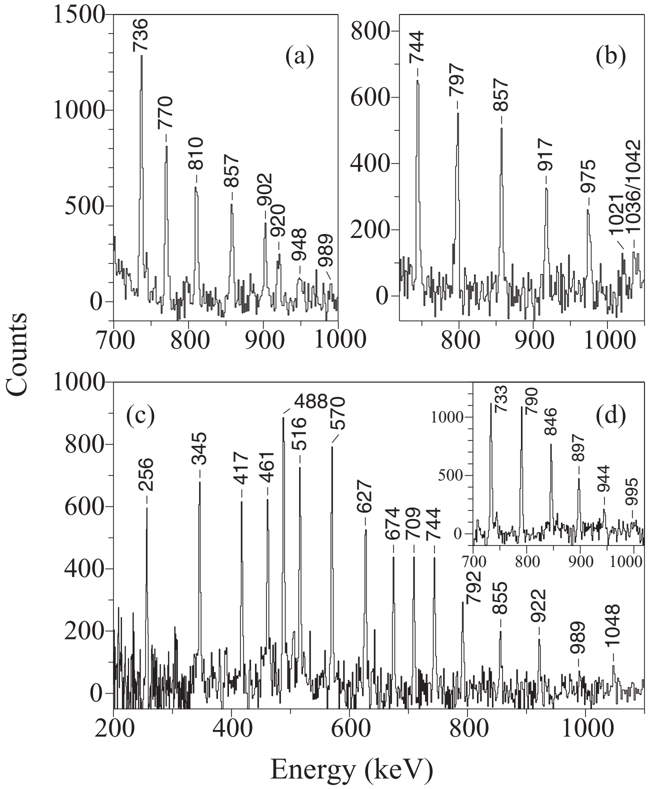

FIG. 2. Panels (a) and (b) display the extensions of the even- and odd-spin signatures, respectively, of band 1 in ^{172}Re. The spectra of all the panels in this figure result from summing gates where γ rays are in coincidence with three in-band transitions. (c) Summed spectrum for the new sequence assigned as the odd-spin signature of band 3. (d) Spectrum displaying the extension of the even-spin sequence of band 3.

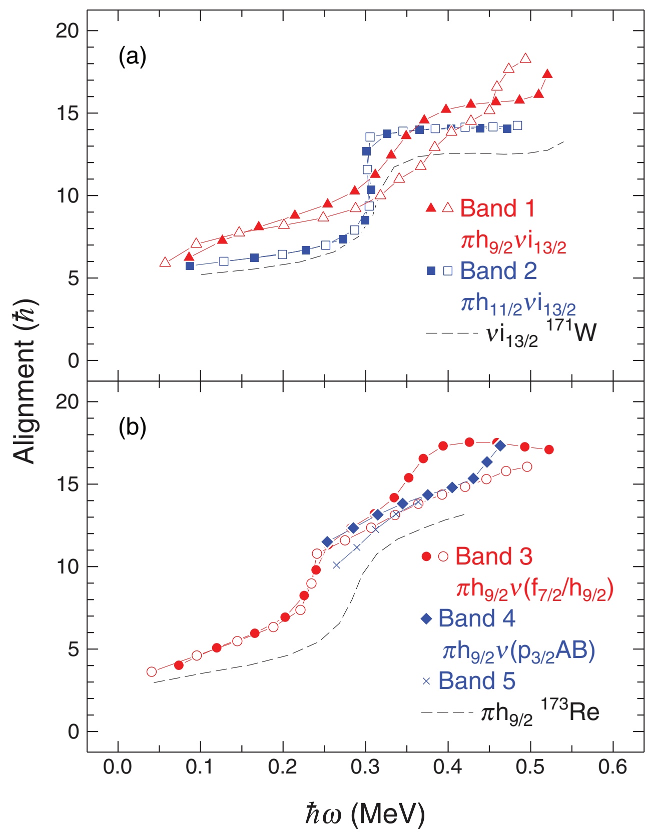

FIG. 3. (Color online) Alignments of the bands in ^{172}Re plotted versus the rotational frequency $\hbar\omega$, where Harris parameters of $\mathcal{J}_0 = 23\ \hbar^2/\mathrm{MeV}$ and $\mathcal{J}_1 = 65\ \hbar^4/\mathrm{MeV}^3$ were used. Filled (empty) symbols denote the odd- (even) spin sequences. Several bands from the neighboring odd-A nuclei are also displayed as indicated.

corresponds to the same AD crossing, again delayed slightly by the occupation of the $\pi h_{9/2}$ orbital. With these crossing assignments, it is clear that the $\pi h_{9/2}\nu i_{13/2}$ band in ^{172}Re is based on the favored signature of the $h_{9/2}$ quasiproton coupling to both signatures of the $i_{13/2}$ quasineutron. The higher-frequency crossings (near 0.5 MeV) are likely the result of $h_{11/2}$ quasiproton alignment; however, it is not clear at this time why this would occur at different frequencies in the two signature partners.

The strongly coupled band 2 sequence (Fig. 1) was previously observed up to spin (23^-) and assigned to the $\pi h_{11/2}\nu i_{13/2}$ configuration [6]. Once again, Zhang *et al.* used systematics to assign the spin values. As stated above, the interaction between this band and the $\pi h_{9/2}\nu i_{13/2}$ structure fixes the relative spins of these two bands, and this agrees with the previous assignment. The configuration assignment was based mainly on the good agreement between experimental and theoretical $B(M1)/B(E2)$ ratios [6]. The present data extend the structure from (23^-) to (34^-).

The alignment for band 2 is also found in Fig. 3(a), where it exhibits nearly the same initial alignment as the ^{171}W $\nu i_{13/2}$ sequence. This observation is consistent with the configuration assignment as the high-K, $h_{11/2}$ quasiproton is associated with little alignment. The crossing observed at 0.30 MeV is assigned to the BC alignment as it occurs at approximately the same frequency as in the $\nu i_{13/2}$ sequence. Since both signatures display the BC crossing, it is clear that band 2 involves both signatures of the $h_{11/2}$ quasiproton coupled to the $i_{13/2}$ quasineutron favored signature. No other crossing is found through the observed frequency range, suggesting further that the crossings observed at high frequency in the $\pi h_{9/2}\nu i_{13/2}$ band are indeed based on $h_{11/2}$ quasiprotons aligning, as such proton crossings would be Pauli blocked in the $\pi h_{11/2}\nu i_{13/2}$ band.

The even-spin sequence of band 3 was identified in Ref. [6] and was thought to correspond to the doubly-decoupled $\pi h_{9/2}\nu p_{3/2}$ structure. However, in the present work this structure was found to be coupled to a new sequence of transitions that constitute the odd-spin signature of band 3. A spectrum for the new sequence is given in Fig. 2(c), while the extension of the previously known structure is found in Fig. 2(d). As seen in Fig. 1, only a few weak dipole transitions connect the signatures of band 3, but the alignment plot of these sequences in Fig. 3(b) clearly indicates that the two belong to the same initial intrinsic structure.

A new configuration for band 3 must be considered in light of the fact that a signature partner was found. Inspection of Fig. 3(b) indicates that the band has a crossing at 0.24 MeV;

i.e., well below the BC crossing frequency. In fact, the AB crossing is found at 0.25 MeV in the ground-state band of ^{170}W [8,10]; therefore, the crossing in band 3 is assigned as the AB interaction as well. With this assignment, an $i_{13/2}$ quasineutron is not likely involved in the initial band 3 configuration. After elimination of the $p_{3/2}$ and $i_{13/2}$ quasineutrons, the mixed $f_{7/2}/h_{9/2}$ orbitals appear to be the most suitable option. It is then reasonable to couple the mixed quasineutron with the $h_{9/2}$ quasiproton as the latter quasiparticle is known to compress the energy level spacings at the lowest spins, as seen in bands 1 and 3. Therefore, band 3 is assigned the $\pi h_{9/2}\nu(f_{7/2}/h_{9/2})$ configuration. The spins of the previously identified sequence were raised by one unit in order to systematically fit with the spin assignments in the $\pi h_{9/2}\nu h_{9/2}$ band of the ^{170}Ta isotone [1]. As seen in Fig. 3(b), the alignment of this band is slightly higher than that observed in the $\pi h_{9/2}$ structure of ^{171}Re [4], and this is consistent with the $\pi h_{9/2}\nu(f_{7/2}/h_{9/2})$ configuration assignment, as $\sim 1\ \hbar$ of alignment is typically associated with the $f_{7/2}/h_{9/2}$ quasineutron.

Although the $f_{7/2}/h_{9/2}$ quasineutron must be involved in the configuration of band 3, an issue remains regarding the lack of dipole transitions between signature partners which is notably different from the observed ones in the $\pi h_{9/2}\nu(f_{7/2}/h_{9/2})$ band of ^{174}Re$_{99}$ [11]. This is likely due to a change in the Nilsson orbital that dominates in the wave function of the $f_{7/2}/h_{9/2}$ quasineutron. In $N = 99$ nuclei, such as ^{173}W [12] and ^{175}Os [13], the $f_{7/2}/h_{9/2}[512]5/2$ orbital is occupied and strong dipole transitions appear between signatures. In contrast, at $N = 97$, the ^{171}W [7,8] and ^{173}Os [14] nuclei display bands based on the $f_{7/2}/h_{9/2}[523]5/2$ orbital with weak dipole transitions between partner sequences. Thus, the $\pi h_{9/2}\nu(f_{7/2}/h_{9/2})$ structure in ^{172}Re$_{97}$ would also be expected to exhibit weak dipole transitions and have its quasineutron based on the [523]5/2 orbital.

A second crossing is observed in the odd-spin signature of band 3 near 0.33 MeV [filled circles in Fig. 3(b)]; i.e., near the BC crossing frequency observed in the $\pi h_{9/2}\nu i_{13/2}$ band. However, this crossing should be blocked due to the AB alignment occuring at 0.24 MeV in band 3. Cranked shell model calculations (see Fig. 9 in Ref. [4]) do not predict any other neutron or proton crossing near this frequency. Therefore, this may correspond to an unpaired crossing with another band. Similar alignment gains were observed in three positive-parity bands of ^{170}Ta [1] and were suggested to result from a possible interaction with the $\pi i_{13/2}\nu i_{13/2}$ sequence.

As seen in Fig. 1, bands 4 and 5 feed into the $\pi h_{9/2}\nu(f_{7/2}/h_{9/2})$ structure near spin (16^+). A normalized angular-correlation ratio (see Ref. [4] for details) of $R_{\mathrm{ang}} = 0.6(1)$ is consistent with the 283-keV line linking bands 4 and 3 being of dipole character. Thus, the lowest observed state has been assigned spin (17). The alignments of this band and of the odd-spin signature of the $\pi h_{9/2}\nu(f_{7/2}/h_{9/2})$ sequence are very similar [see Fig. 3(b)]; therefore, it is likely that band 4 is observed following the AB crossing and that the $h_{9/2}$ quasiproton is involved in its configuration. Since band 4 appears to be doubly decoupled and the $\nu p_{3/2}[521]1/2$ quasineutron is near the Fermi surface, band 4 is assigned the $\pi h_{9/2}\nu(p_{3/2}AB)$ configuration. However, this assignment must be considered tentative until further spectroscopic information becomes available. The alignment gain near 0.45 MeV is likely the result of the $h_{11/2}$ quasiproton crossing, similar to that seen in the even-spin sequence of band 1.

The 525- and 533-keV transitions in band 5 were previously observed in Ref. [6], and the sequence was extended to higher spin as seen in Fig. 1. The angular-correlation ratio, $R_{\mathrm{ang}} = 0.95(6)$, of the 525-keV line indicates that it has an $E2$ nature, leading to the spin assignment of Fig. 1. This band [Fig. 3(b)] displays nearly the same amount of alignment as the $\pi h_{9/2}\nu(f_{7/2}/h_{9/2})$ sequence following the AB crossing, suggesting that it is likely a four-quasiparticle structure. It could possibly be the unfavored signature of the $\pi h_{9/2}\nu(p_{3/2}AB)$ band; however, one would expect that this signature would lie higher in energy, relative to the favored one, as both the $h_{9/2}$ quasiproton and $p_{3/2}$ quasineutron exhibit large amounts of signature splitting. At this time, it is not possible to propose a configuration for this structure.

In summary, over 80 new transitions were added to the doubly-odd ^{172}Re level scheme. Two sequences were extended to a spin near (40), and the observed crossings aided in assigning configurations to four of the five observed structures. One of the previously known bands was given a new assignment based on the observation of its signature partner. Additional experimental work is required to determine the relative excitation energies of the structures, and provide further confirmation of the proposed assignments.

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