Configuration changes and hindered decays in four- and six-quasiparticle isomers in ^{178}Ta

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A six-quasiparticle isomer with $K^{\pi}=21^{-}$, a half-life of 290(12) ms, and the $\pi^3\nu^3$ configuration has been identified in the odd-odd nucleus ^{178}Ta, at an excitation energy of 2902 keV. The rotational bands built on the known $K^{\pi}=15^{-}$ isomer and on the newly found 16^{+} four-quasiparticle and 22^{+} six-quasiparticle states, have also been identified, allowing characterization of the configurations. The 15^{-} band is predominantly of $\pi\nu^3$ character with a $\pi^3\nu$ admixture. When the mixing is taken into account the excitation energies of the main yrast multi-quasiparticle states can be reproduced. The multi-quasiparticle states observed are related essentially through the addition of the two-quasiparticle component ν^2 [6^{+}] or π^2 [6^{+}]. Depending on whether the transition between the states involves the change ν^2 [6^{+}] $\rightarrow$ [0] or π^2 [6^{+}] $\rightarrow$ [0], the *E*2 hindrance factors for decays between the six- and four-quasiparticle states are relatively large or small. This dependence mimics the pattern observed in the two-quasiparticle core transitions and, because the 15^{-} isomer is mainly $\pi\nu^3$, the magnitude sequence is inverted compared to that observed in ^{176}Ta. [S0556-2813(96)50508-X]

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Axially symmetric deformed nuclei can build angular momentum by collective rotation, or by coupling of the individual angular momenta of unpaired nucleons, or by a combination of both. Around $A\sim180$, where nucleonic orbits with large projections Ω of the intrinsic spin on the symmetry axis are close to both the neutron and proton Fermi surfaces, these two modes compete to form the yrast line. In favorable situations, no one mechanism dominates and both collective (band) structures and intrinsic states can be observed and characterized, as was demonstrated in a recent study of ^{177}Ta [1] and ^{179}W [2]. In these cases the yrast line is formed by a combination of multi-quasiparticle states with high values of $K=\Sigma_i\Omega_i$, and their associated rotational band members.

When large K changes are involved and the depopulating transitions have low energy, high multipolarity or both, the intrinsic states may have substantial lifetimes, thus enabling delayed coincidence techniques and unambiguous placement of states and transitions through temporal ordering. However, in some cases the half-lives may be so long ($\geqslant10$ μs) as to be outside the range usually considered for delayed coincidence measurements.

In this Rapid Communication we report the discovery of a very long-lived six-quasiparticle $K^{\pi}=21^{-}$ isomer, as well as other yrast multi-quasiparticle states and associated collective structures in the odd-odd nucleus ^{178}Ta. The properties of the rotational band that we associate with the previously known four-quasiparticle 15^{-} isomer [3], suggest a predominantly $\pi\nu^3$ configuration. Although both 15^{-} and 21^{-} isomers are very long lived, indicating the persistence of the K quantum number, there turns out to be a configuration dependence in the underlying $E2$ hindrance factors that occurs within ^{178}Ta, between the set of similar isomers in the odd-odd tantalum neighbors and in decays from the 6^{+} core states in ^{174}Hf, ^{176}Hf, and ^{178}Hf isotopes.

High-spin states in ^{178}Ta were populated in the (^{7}Li,5n) reaction with pulsed beams from the ANU 14UD pelletron accelerator, incident on a 4.6 mg cm^{-2} enriched ^{176}Yb target, using beam energies between 30 and 60 MeV. In the γ-γ coincidence measurements, pairs of γ rays detected within ±856 ns of each other, and their associated times, were recorded event by event. In one case, chopped beams with a separation of 0.5 ms were used, and only γ rays in the out-of-beam region were collected. In two separate measurements, the beam was pulsed to give ~1 ns wide pulses, 1712 ns apart and all coincidence events were collected. Beam energies of 45 and 51 MeV were used to favor population of ^{179}Ta in the former case, and ^{178}Ta in the latter case. γ rays were detected with the CAESAR array, comprising six Compton suppressed detectors, together with one LEPS detector. The experimental details and methods of analysis are similar to those described recently [1,2].

To measure the lifetime of a high-lying isomer that was apparently very long, further γ-time measurements with a range of beam pulse width/separation were explored. Times were measured in a resettable ADC clock, to avoid some of the rate and time-range limitations introduced when time-to-amplitude converters are used. The definitive lifetime measurements were carried out with a 107 ms/1819 ms combination. Finally conversion electron measurements were carried out with a superconducting electron spectrometer [6] with the beam pulsed and the momentum and time regimes selected to match the decay of the long-lived isomer. Total conversion coefficients were also deduced from intensity balances and the results were considered, together with the excitation function data and where appropriate, the apparent band structure, to make spin and parity assignments.

Assignment to tantalum was made on the basis of coincidences between the main γ rays and characteristic x rays. Transitions from the neighboring isotopes (predominantly ^{179}Ta, where long isomers are known [4]) were distinguished by the measured excitation functions and by comparing relative yields in coincidence data at 45 and 51 MeV. [Additional confirmation was obtained from the studies of ^{180}Ta [5], using the ^{176}Yb(^{11}B,αxn) reaction, where there was a

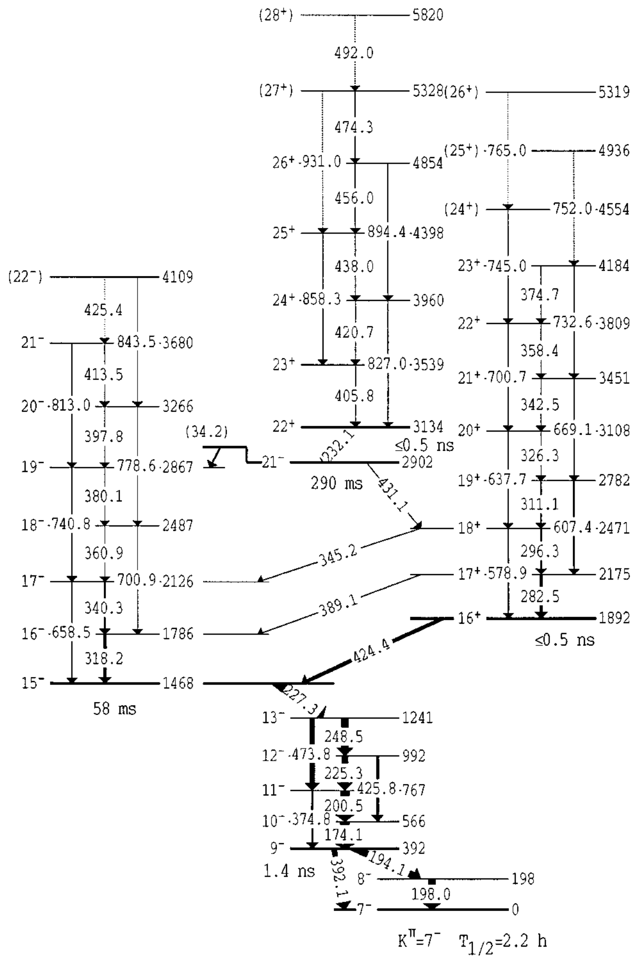

FIG. 1. Partial level scheme of ^{178}Ta.

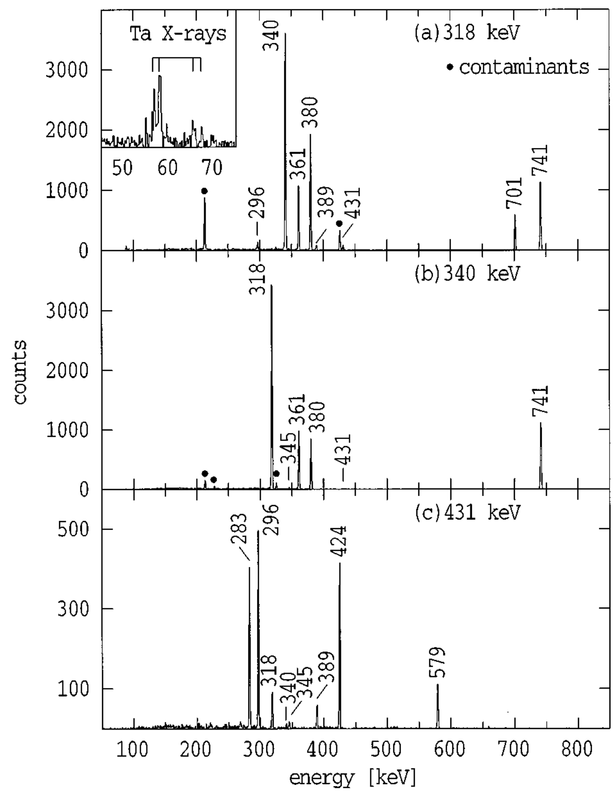

FIG. 2. γ-ray coincidence spectra projecting the events in prompt (± 20 ns) coincidence, in the out-of-beam region. The inset was obtained by summing the gates on the 318, 340, and 380 keV transitions projecting the events in the LEPS detector.

detectable yield of ^{179}Ta, but not of ^{178}Ta.]

The level scheme developed for ^{178}Ta showing the main multi-quasiparticle states is given in Fig. 1. A key feature is the isomeric state at 2902 keV, which decays ~86% by an unobserved 34.2 keV transition to the 19^- member of the 15^- band, and ~14% by a 431.1 keV transition to the 18^+ member of a new 16^+ band. The 15^- intrinsic state was known [3], but its associated rotational band was not. In Fig. 2(a) and Fig. 2(b), out-of-beam coincidence γ-ray spectra with gates on the first two cascade transitions assigned in the 15^- band are shown. The transitions in these spectra form a single rotational band with relatively strong crossover transitions, apparently isolated from known structures in ^{178}Ta. In Fig. 2(c) a spectrum with a gate on the 431 keV transition is shown, establishing a path through a second band, with several connections to the first.

As indicated in Fig. 1, this whole structure is placed between two isomers at 2902 keV and 1468 keV. The 34.2 keV transition was not seen directly but the delayed intensity balance at the 19^- level at 2867 keV and our detection efficiency for low energy transitions gives a limit for its total conversion coefficient of $\alpha_T > 11$, thus eliminating an $E1$ multipolarity ($\alpha_T = 1.3$) and favoring $M1$ ($\alpha_T = 17.9$) or $E2$ ($\alpha_T = 510$). The absence of a transition to the 18^- level at 2487 keV argues against a 20^- assignment to the 2902 state, which would be the case if the 34.2 keV transition were an $M1$. Thus the 34.2 keV transition most likely has $E2$ (or higher) multipolarity and therefore the 2902 keV level must have $I^\pi = 21^-$ (or higher). The second decay path is via the 431.1 keV transition to the 18^+ member of the 16^+ band. Its measured K- and L-shell conversion coefficients of $\alpha_K = 0.056(7)$ and $\alpha_L = 0.033(4)$ and K/L ratio of 1.7(2) compared to theoretical expectations [7] are only consistent with $E3$ multipolarity ($\alpha_K = 0.058$, $\alpha_L = 0.032$), therefore favoring $I^\pi = 21^-$ for the 2902 keV isomer. Another intrinsic state with an associated rotational band was placed above the 21^- isomer. (This set of transitions was isolated from other structures, was in prompt coincidence with the beam pulses, in coincidence with tantalum x rays and has an excitation function that places it high in ^{178}Ta.) The total conversion coefficient of 0.08(5) deduced from intensity balances for the 232.1 keV connecting transition, when compared to the theoretical values of $\alpha_T = 0.042$ for $E1$, $\alpha_T = 0.184$ for $E2$, and $\alpha_T = 0.423$ for $M1$ multipolarities [7] establishes $E1$ character, and hence $I^\pi = 22^+$ for the 3134 keV state.

The half-life of the 21^- isomer was obtained from the analysis of the γ-time measurements. Separate time spectra constructed by summing gates on transitions in the independent decay paths through the 15^- and 16^+ bands are shown in Fig. 3(a) and Fig. 3(b). Both time spectra were fitted independently and the values obtained for the lifetime are consistent with each other, implying the decay of a single isomer, with a half-life of 290(12) ms. However, the time spectrum for the 227 keV transition [Fig. 3(c)], which depopulates the 15^- bandhead (see Fig. 1) shows evidence for

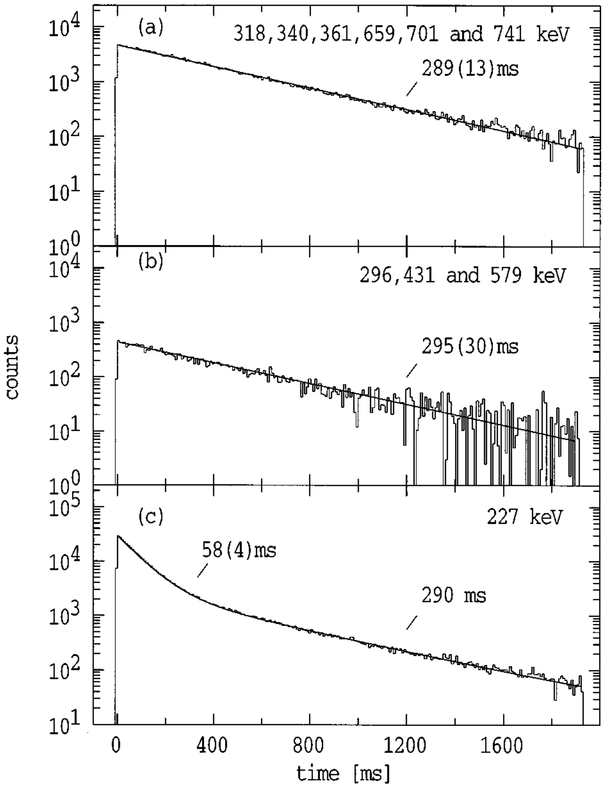

FIG. 3. Background subtracted time spectra. The solid lines in frame (a) and (b) show fits with a single isomer that yield the the half-lives indicated. The solid line in frame (c) shows a fit with two isomers in sequence, one with the half-life fixed at 290 ms, the other yielding a half-life of 58(4) ms for the 15^- isomer.

two isomers. One is attributable to the 15^- isomer [3], but the longer component reflects the half-life of the 21^- isomer, establishing unambiguously its placement in ^{178}Ta, despite the fact that the long lifetime of the intermediate 15^- isomer precludes measurement of delayed coincidences.

Configuration assignments to the observed multi-quasiparticle structures were made on the basis of observed spins and parities, and the in-band decay properties from which the $(g_K\text{-}g_R)/Q_0$ values were deduced. They were also supported by the degree of rotational alignment that allows some distinction to be made between the number (or absence) of $i_{13/2}$ neutrons or $h_{9/2}$ protons in the configuration [2], although there are differences attributable to the reduction of pairing, which are discussed elsewhere [8]. The experimental g_K factors, deduced from the in-band cascade/crossover branching ratios are compared in Table I with the expected values computed using Nilsson model wave functions and additivity. Since all proposed configurations contain an $9/2^+$ [624] ($i_{13/2}$) quasineutron that could differ from the Nilsson value because of Coriolis mixing [2], where possible, empirical values for the recurring components, such as the $\pi\nu$ [9^-] configuration, have also been used.

The 15^- isomer had been suggested previously [3] to arise from the four-quasiparticle $\pi^3\nu$ [15^-] configuration, obtained by coupling the $\pi\nu$ [9^-] state to a π^2 [6^+] configuration. However, the properties of the rotational band established in the present work favor the alternative $\pi\nu^3$ [15^-] configuration formed from the $\pi\nu$ [9^-] state coupled to a ν^2 [6^+] configuration. [Note that the strong 700.9 and 740.8 keV crossover transitions evident in Fig. 2(a) and Fig. 2(b) are indicative of a small g_K.] At the same time, the experimental g_K value is somewhat larger than the predicted values, which could indicate mixing between the alternative configurations. If the g_K factors of the unperturbed configurations given in the last column of Table I are compared with experiment, the admixtures in the 15^- band can be estimated as 26(11)% ($\pi^3\nu$) and 74(11)% ($\pi\nu^3$).

The 16^+ state can be viewed as a $9/2^-$ [514] quasiproton coupled to the ν^3 [$23/2^-$] configuration observed at 1832 keV in ^{179}W [2]. Both intrinsic states exhibit a fast *E1* decay, via a 200.3 keV $23/2^- \rightarrow 21/2^+$ ($T_{1/2} < 0.5$ ns) transition in ^{179}W, and via a 424.4 keV $16^+ \rightarrow 15^-$ ($T_{1/2} < 0.5$ ns) transition in ^{178}Ta, consistent with the same change of orbitals. The bands also have similar degrees of rotational alignment. In addition, the measured g_K for the 16^+ band is in good agreement with the empirical value (last column of Table I) for the $\pi\nu^3$ [16^+] configuration.

TABLE I. Proposed configurations and g_K factors for multi-quasiparticle states in ^{178}Ta.

K^π	Configuration [a] π	ν	g_K Exp[b]	Nilsson[c]	empirical[d]
9^-	$9/2^-$	**9/2$^+$**	0.59(5)	0.53	0.59(5)
15^-	$9/2^-$	$[5/2^-, 7/2^-]_{6^+}$, **9/2$^+$**	0.46(5)	0.32	0.36(3)
15^-	$[5/2^+, 7/2^+]_{6^+}$, $9/2^-$	**9/2$^+$**		0.72	0.76(6)
16^+	$9/2^-$	$7/2^-$, **7/2$^+$**, **9/2$^+$**	0.40(4)	0.30	0.41(4)[e]
21^-	$[5/2^+, 7/2^+]_{6^+}$, $9/2^-$	$[5/2^-, 7/2^-]_{6^+}$, **9/2$^+$**		0.50	0.58(5)
22^+	$[5/2^+, 7/2^+]_{6^+}$, $9/2^-$	$7/2^-$, **7/2$^+$**, **9/2$^+$**	0.55(8)	0.50	0.58(5)[e]

[a]Neutrons (ν): **7/2$^+$**:$7/2^+$ [633]; **9/2$^+$**:$9/2^+$ [624]; $5/2^-$:$5/2^-$ [512]; $7/2^-$:$7/2^-$ [514]. Protons (π): $9/2^-$: $9/2^-$ [514]; $7/2^+$:$7/2^+$ [404]; $5/2^+$:$5/2^+$ [402].

[b]Assuming $g_R=0.30$ and positive sign for $(g_K\text{-}g_R)/Q_0$. $Q_0=6.5(6)$ e b [11].

[c]Calculated values using Nilsson model wave functions, $g_s=0.7g_s^{\text{free}}$ and deformations of $\varepsilon_2=0.245$ and $\varepsilon_4=0.047$.

[d]Empirical values calculated using the experimental value for the $\pi\nu$ [9^-] band and the Nilsson model values for the remaining orbitals, unless otherwise stated.

[e]An empirical value of $g_K=0.08$ for the $7/2^+$ [633] ($i_{13/2}$) quasineutron is assumed [2].

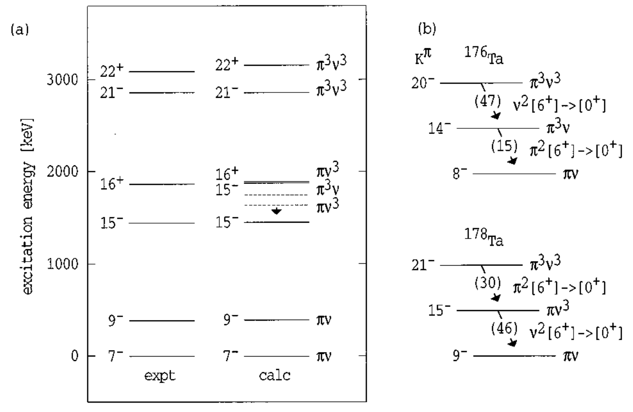

FIG. 4. (a) Experimental and calculated multi-quasiparticle states in ^{178}Ta. The dashed lines show the 15^- states before mixing; (b) Transitions between four and six-quasiparticle isomers in ^{176}Ta and ^{178}Ta. Reduced *E2* hindrances are given in parentheses and configuration changes are indicated. The reduced hindrance factors for the 14^- and 20^- isomers in ^{176}Ta are from Ref. [12]. (The value for the 20^- isomer is larger than the value of 37 given in Ref. [1] because of the additional decay branches identified in Ref. [12].)

Because of their high spins and considering the available orbitals close to proton and neutron Fermi surfaces, the 21^- and the 22^+ intrinsic states must be formed from six-quasiparticles. The configuration of the 21^- isomer is suggested to be π^2 $[6^+]$ coupled to $\pi\nu^3$ $[15^-]$, although its associated rotational band has not been observed. Examination of the branching ratios within the rotational band based on the 22^+ state gives g_K=0.55(8), consistent with it being formed by coupling the π^2 $[6^+]$ and $\pi\nu^3$ $[16^+]$ configurations. Furthermore, the fast decay via the 232.1 keV $22^+ \rightarrow 21^-$ transition ($T_{1/2}$<0.5 ns) corresponds again with the $16^+ \rightarrow 15^-$ and $23/2^- \rightarrow 21/2^+$ (in ^{179}W) decays discussed above.

In Fig. 4(a) the observed excitation energies of the bandheads are compared with the values given by multi-quasiparticle calculations, similar to those performed in Refs. [1,2,9] but with the refinement that the pairing correlations are treated using the Lipkin-Nogami approach. These calculations include the effect of blocking and estimates of the residual nucleon-nucleon interactions [9]. All 64 states in the N=4, 5, and 6 oscillator shells were included, with fixed pairing force strengths of G_π=0.117 MeV and G_ν=0.101 MeV. The single-particle energies were taken from the Nilsson model, but with the states close to the Fermi surface adjusted to reproduce approximately the experimental one-quasiparticle energies in neighboring odd-*A* nuclei. As can be seen in Fig. 4(a) the calculated energies of the lowest predicted yrast states are in remarkable, and what must be partly fortuitous, agreement. More importantly they show a one-to-one correspondence with the sequence of observed states. The next, high-*K*, six-quasiparticle states predicted to be low in energy are a pair with $K^\pi = 24^+$ and 25^- obtained from the 21^- and 22^+ states by substitution of an $11/2^-$ [505] proton for the $5/2^+$ [402] proton in their configurations. These, however, are predicted to lie more than 1 MeV higher and would not compete with the yrast states formed by the 22^+ band.

The calculated 21^- state, from the $\pi^3\nu^3$ configuration, can be associated with the long-lived isomer at 2902 keV. It is formed by coupling of the $\pi\nu$ $[9^-]$ state to *both* π^2 $[6^+]$ and ν^2 $[6^+]$ configurations. As can be seen in Fig. 4(a) the calculations reproduce well the excitation energies of the $\pi\nu$ $[9^-]$ state (base of the level scheme), as well as those of the $\pi^3\nu^3$ $[21^-]$ isomer (upper part of scheme), but initially not that of the intermediate 15^- isomer, predicted [dashed line in Fig. 4(a)] as being ~180 keV higher than observed. However the two 15^- configurations, which differ by the presence of either a π^2 $[6^+]$ or a ν^2 $[6^+]$ component are expected to mix, as do the 6^+ states in the ^{176}Hf core [10]. (Note that this ambiguity does not arise for the 21^- state, since *both* 6^+ components are present.) Taking the calculated excitation energies of 1636 keV and 1743 keV for the $\pi\nu^3$ $[15^-]$ and $\pi^3\nu$ $[15^-]$ states respectively, and a matrix element of 208 keV, estimated from the mixing between the π^2 $[6^+]$ and ν^2 $[6^+]$ states in ^{176}Hf [10], a depression of ~160 keV in the energy of the lower 15^- state would be expected, giving its predicted energy as 1475 keV, in excellent agreement with experiment. The corresponding mixed amplitudes obtained for the lower of the 15^- states are 38% ($\pi^3\nu$) and 62% ($\pi\nu^3$), in reasonable agreement with the estimates drawn from the analysis of the g_K values.

The very long-lived nature of the 15^- and 21^- isomers arises partly because both depopulating $E2$ transitions have K forbiddenness, $\nu = \Delta K - \lambda = 4$. However, while the much longer lifetime of the 21^- isomer can be attributed to the low energy (34.2 keV) of the $21^- \rightarrow 19^-$ transition compared to that of 227.3 keV for the $15^- \rightarrow 13^-$ transition, when the energy factor is removed, the decay from the 21^- state is found to be *less* inhibited than that from the 15^-. The reduced hindrance factors per degree of K forbiddenness, defined as $f_\nu = (T^\gamma_{1/2}/T^W_{1/2})^{1/\nu}$, where $T^\gamma_{1/2}$ is the partial γ-ray half-life, and $T^W_{1/2}$ is the Weisskopf estimate, are f_ν=30 for the 34.2 keV transition and f_ν=46 for the 227.3 keV transition. Recently Dracoulis *et al.* [5] pointed out that the large difference between reduced hindrance factors for $E2$ decays from the four-quasiparticle (14^- and 15^-) isomers in ^{176}Ta, ^{178}Ta, and ^{180}Ta closely followed the corresponding $E2$ decays from the two-quasiparticle (6^+) core states in ^{174}Hf, ^{176}Hf, and ^{178}Hf and depended on whether the 6^+ state was formed from the π^2 or ν^2 configuration. Such a correlation extends to the six-quasiparticle states, as summarized in Fig. 4(b). The crucial factor is apparently that the intervening 14^- and 15^- states change in character, being mainly $\pi^3\nu$ in ^{176}Ta and mainly $\pi\nu^3$ in ^{178}Ta. As a result, the sequence of configuration changes of ν^2 $[6^+] \rightarrow$ $[0^+]$, π^2 $[6^+] \rightarrow$ $[0^+]$ that occurs in ^{176}Ta is inverted in ^{178}Ta, and so are the corresponding hindrance factors. The magnitudes do not match as closely as in the decay of the lower spin states [5] but the pattern persists.

Taking the admixtures identified, it is not possible to explain the hindrances quantitatively but the pattern of a consistent sensitivity to configuration emphasizes the need for incorporation of the configuration effects into the calculation of K forbidden transitions. The other ingredients that have to be considered are the possibility of γ tunnelling [13,14], which provides an upper limit to the hindrance and also the possible correlation with the proximity of the states to the yrast line [15]. The last effect may be partly related to the energy depression by mixing with specific states (such as between the 6^+ core), which then results in their isolation from other states that can mix.

In summary, a very long-lived six-quasiparticle isomer has been unambiguously assigned to ^{178}Ta. Its decays reveal rotational bands based on the 15^- isomer and also a 16^+ intrinsic state, allowing their configurations to be established. The configuration change that occurs through the π^2 $[6^+]$ and ν^2 $[6^+]$ core changes is reflected in differences in $E2$ hindrance values that occur in a consistent fashion within multi-quasiparticle states in ^{178}Ta and in neighboring isotopes.

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