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Three-quasiparticle isomer in ^{173}Ta and the excitation energy dependence of K-forbidden transition rates

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Using the ^{168}Er(^{10}B,5n) reaction at a beam energy of 68 MeV, new data have been obtained for the population and decay of a $T_{1/2} = 148$ ns, $K^{\pi} = 21/2^{-}$ three-quasiparticle isomer at 1717 keV in ^{173}Ta. Revised decay energies and intensities have been determined, together with newly observed members of a rotational band associated with the isomer. By comparison with other isomers in the $A \approx 180$ deformed region, the ^{173}Ta isomer properties help to specify the key degrees of freedom that determine K-forbidden transition rates. In particular, when all three quasiparticles are of the same nucleon type, there is a strong dependence of the $E2$ reduced hindrance factor on the isomer excitation energy.

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I. INTRODUCTION

High-K isomers, with half-lives ranging from nanoseconds to years, can provide sensitive access to weakly populated excited-state structures in deformed nuclei [1–5]. The K quantum number represents the angular momentum projection on the nuclear symmetry axis, and transitions that violate the K-selection rule, i.e., those with multipole order $\lambda < \Delta K$, probe the symmetry-breaking mechanisms. Despite the large body of data on these "K-forbidden" transitions [3], the understanding of the corresponding transition rates remains poor. Nevertheless, the systematic variation of hindrance factors has the potential to provide critical predictive power [2,5,6], which may be helpful in the study of exotic nuclei.

The present work focuses on $^{173}_{73}$Ta$_{100}$, which is close to the neutron-deficient limit of the well known $A \approx 180$ region of K isomerism. No multi-quasiparticle isomers, i.e., those involving pair-breaking excitations, are known in the lighter tantalum isotopes. Therefore, this could be a good case for understanding the erosion and eventual loss of the integrity of the K quantum number. In ^{173}Ta, a three-quasiparticle, $K^{\pi} = (21/2^{-})$ isomer has previously been reported, from high-resolution germanium-detector γ-ray measurements following the ^{165}Ho(^{12}C,4n) and ^{175}Lu(α,6n) fusion-evaporation reactions, but only an approximate half-life of $T_{1/2} \approx 100$ ns was determined [7]. Subsequent relatively high-statistics studies using the ^{159}Tb(^{18}O,4n) and ^{160}Gd(^{19}F,6n) reactions [8,9] did not confirm the existence of this isomer. However, support for the isomer came from measurements of its electric quadrupole moment [10] and its magnetic dipole moment [11], both using low-resolution sodium iodide detectors in conjunction with the ^{165}Ho(^{12}C,4n) reaction, and a half-life of 132(3) ns was reported [11]. Nevertheless, significant problems remained regarding the data interpretation, and further measurements seemed to be warranted. The present work provides definitive data together with a consistent interpretation.

II. EXPERIMENTAL METHOD

A beam of 68 MeV ^{10}B, from the ANU 14UD tandem accelerator, was incident on a 5 mg/cm^2, self-supporting highly enriched (98%) ^{168}Er target foil at 70 degrees to the beam axis. This reaction optimizes the population of states with spins similar to that of the reported isomer. The beam consisted of nanosecond pulses separated by 1.7 μs, and the target was sufficiently thick to stop the recoiling fusion-evaporation reaction products. The main yield was from the ^{168}Er(^{10}B,5n)^{173}Ta reaction. Deexcitation γ rays were recorded with the CAESAR array, consisting of nine Compton-suppressed n-type high-purity germanium (HPGe) detectors, and two unsuppressed planar Ge detectors. The latter gave improved performance at low γ-ray energies. Additional details of the setup are given in Refs. [12,13].

III. EXPERIMENTAL RESULTS

The initial focus of the present measurements was on the detection of γ-ray transitions between beam pulses, i.e., those associated with the decay of isomeric states. Figures 1 and 2 show these "delayed" transitions assigned to ^{173}Ta, and the corresponding level structure, deduced on the basis of γ-γ coincidence relationships. Also shown in the level scheme are transitions that feed the isomer, observed by prompt-delayed coincidence gating on transitions that follow the isomeric decay. Three γ-ray spectra are shown in Fig. 2, illustrating transitions associated with the observed isomer feeding and decay.

Most of the delayed γ rays are seen to be the same as those known [7] to belong to the $9/2^{-}$[514] rotational band of ^{173}Ta. In accordance with the work of Carlsson *et al.* [9], the band head is placed at 173 keV. As well as the lower-spin $9/2^{-}$[514]

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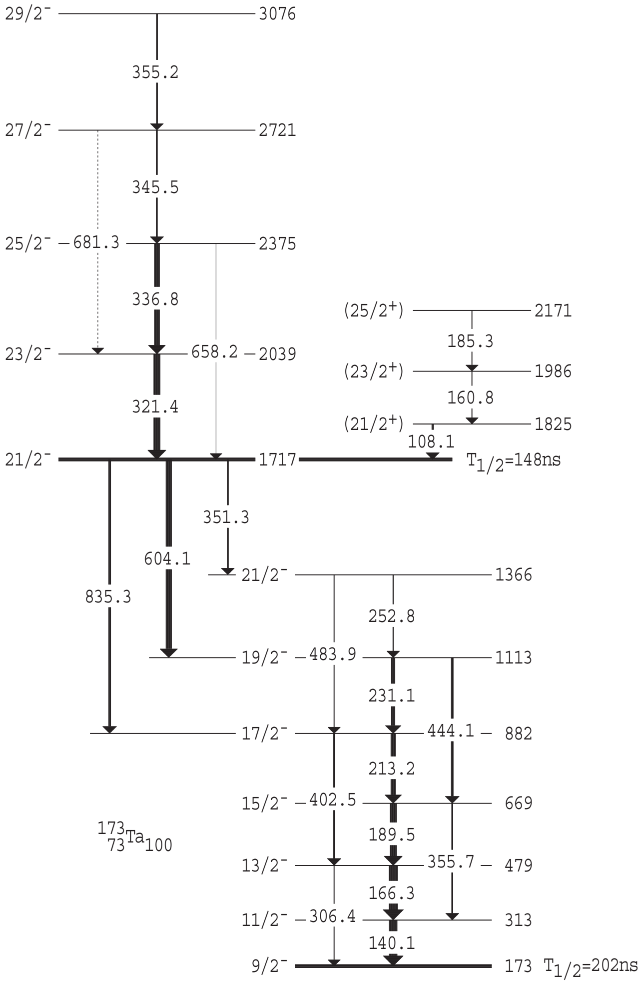

FIG. 1. Partial level scheme for ^{173}Ta above the $9/2^-$ bandhead at 173 keV, showing transitions related to the $K^\pi = 21/2^-$ three-quasiparticle isomer.

band members, additional delayed transitions are observed at 351, 604, and 835 keV, feeding into the $I^\pi = 21/2^-$, $19/2^-$ and $17/2^-$ levels, respectively. These are interpreted as depopulating a $K^\pi = 21/2^-$ isomer at 1717 keV (with the usual assumption that the K value is equal to the spin of the band head). The half-life is measured to be 148(9) ns, as illustrated in Fig. 3. (Note that the $9/2^-$ isomer at 173 keV is measured in the present work, see Fig. 3, to have a half-life of 202(6) ns, which compares well with 225(15) ns from Kurniawan *et al.* [14].)

The $I = 21/2$ isomer spin assignment is based on the assumption that the lower intensity of the highest-energy depopulating transition (835 keV) indicates $\lambda = 2$, while the 351 and 604 keV transitions have $\lambda = 1$. Furthermore, since the 835 keV transition is not of very low relative intensity, its Weisskopf hindrance factor strongly favors $E2$ character, rather than $M2$ (see also Sec. IV), hence negative parity for the isomeric state.

It is notable that André *et al.* [7] reported an isomer depopulated by 356, 609, and 840 keV transitions, each 5 keV higher in energy than those presently observed. The spectra shown by André *et al.* do not allow this difference to be understood, but it is clearly beyond the expected energy uncertainties. Moreover, they estimated a half-life of about 100 ns, but they reported that their statistics were too poor to obtain an accurate value. We conclude that André *et al.* indeed had good evidence for the same isomer, but that the directly depopulating transitions were too low in intensity for reliable identification in their relatively low-statistics experiment.

It is at first sight surprising that Carlsson *et al.* [9] did not identify the isomer, despite high statistics and the use of both thin (935 μ/cm^2) and thick (3.0 mg/cm^2) targets, the latter with a 5.8 mg/cm^2 backing of ^{208}Pb. We suggest that their heavier beam (^{19}F) led to less population of the very non-yrast isomer, and, perhaps more significantly, the use of a DC beam gave less than optimal isomer sensitivity.

It is also notable that, from a g-factor measurement, Thakur *et al.* [11] reported a half-life of 132(3) ns, in reasonable agreement with our value of 148(9) ns. However, their use of NaI detectors, combined with their assumption of incorrect γ-ray energies from André *et al.*, could render their analysis unreliable. We will return later to their g-factor results.

In addition to the 1717 keV isomer itself, in the present work feeding transitions have also been identified, as illustrated in Figs. 1 and 2, time correlated with the depopulating isomeric transitions. Most of these can be placed in a single rotational sequence (see Fig. 1) while the γ-ray coincidence relationships require a 108 keV transition to be separately feeding the isomer.

IV. DISCUSSION

In the assignment of quasiparticle configurations to rotational bands, it is common practice (see, for example, Ref. [15]) to use in-band γ-ray branching ratios to obtain values of $|(g_K - g_R)|/Q_0$, where g_K is the intrinsic configuration g factor, g_R is the rotational g factor, and Q_0 is the intrinsic quadrupole moment. For the $K^\pi = 9/2^-$ band, Carlsson *et al.* [9] use $g_R = 0.40$ and $Q_0 = 7.0$ eb. With those values we find, using their branching ratios and $(g_K - g_R) > 0$, that $g_K = 1.17(6)$, assuming an uncertainty of ± 0.05 in the g_R value [15,16]. This "experimental" value of $g_K = 1.17(6)$ can be compared with the "theoretical" estimate for the Nilsson $9/2^-[514]$ configuration in the strong-coupling approximation ($Kg_K = \Lambda g_\Lambda + \Sigma g_\Sigma$, where Λ and Σ are the Nilsson orbital and intrinsic asymptotic quantum numbers, respectively). It is assumed that $g_\Lambda = 1$ and $g_\Sigma = 5.59$ for protons (and 0 and -3.83 for neutrons, respectively) and that there is an additional g_Σ quenching factor of 0.6 to account for the nuclear medium. Hence, the Nilsson model predicts $g_K = 1.26$ for the $9/2^-[514]$ configuration, which is in satisfactory accord with the experimental value of 1.17(6). [The alternative sign of $(g_K - g_R)$ gives $g_K = -0.37(6)$ which is unphysical, in the sense that no one-proton configuration could generate such a small value.]

We note that Thakur *et al.* [11] obtained $g_K = 0.665(43)$ using time-differential perturbed angular distributions for the bandhead decay γ rays, disagreeing with both the experimental and theoretical values just discussed. However, we consider that the use of NaI detectors renders their results unreliable.

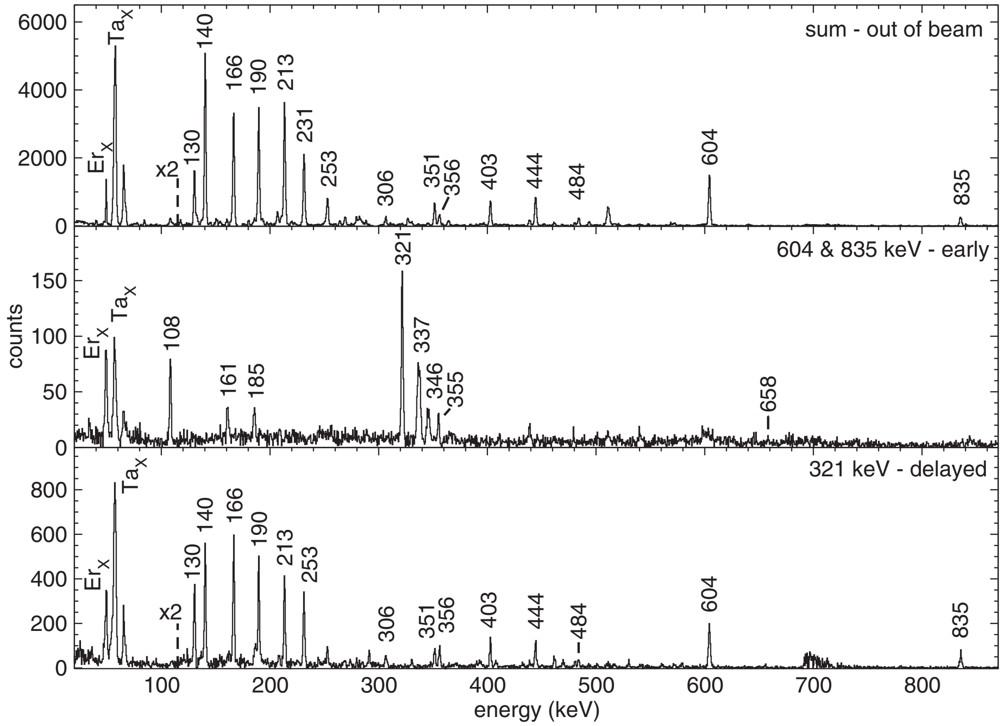

FIG. 2. Examples of coincidence γ-ray spectra decaying from and feeding into the ^{173}Ta isomer at 1717 keV. The top panel shows the sum of coincidence gates on selected out-of-beam transitions (i.e., between the beam bursts). The bottom panel looks very similar, though with lower statistics. It is from a single gate on the 321 keV transition above the isomer, with a time-difference requirement, so that only "delayed" transitions below the isomer are seen. The middle panel is from two gates below the isomer, with a time-difference condition that selects "early" transitions that feed the isomer.

Also, in a separate study (again with NaI detectors) Thakur *et al.* [10] measured spectroscopic quadrupole moments, implying $Q_0 = 5.35(8)$ eb for the $9/2^-$ bandhead, and 8.30(12) eb for the $21/2^-$ bandhead.

We now address the configuration of the $K^\pi = 21/2^-$ isomer and its rotational band, using the γ-ray branching from the $25/2^-$ band member: $I_\gamma(658\ \text{keV})/I_\gamma(337\ \text{keV}) = 0.065(18)$. With the same assumptions of $g_R = 0.40$ and $Q_0 = 7$ eb, we obtain $g_K = 1.25(12)$. [The alternative sign of $(g_K - g_R)$ gives $g_K = -0.45(12)$, which is again unphysical.] Further, to gain insight into the possible multi-quasiparticle configurations, we have performed Nilsson + BCS calculations using the model of Jain *et al.* [17], which includes blocking effects. The most energetically favored (closest to yrast) calculated three-quasiparticle configuration has the three-proton structure $\{\pi 9/2^-[514] \otimes \pi 7/2^+[404] \otimes \pi 5/2^+[402]\}$ with $K^\pi = 21/2^-$, matching the K^π value of the experimental state. With deformation parameters $\epsilon_2 = 0.26$, $\epsilon_4 = 0.04$, and pairing strengths $G_\nu = 21/A$ MeV, $G_\pi = 24/A$ MeV, which are appropriate for the region [17,18], the calculated excitation energy of 1694 keV is close to the measured energy of 1717 keV. For this configuration, the Nilsson model g-factor calculation gives $g_K = 1.11$, in satisfactory agreement with the experimental value of 1.25(12). However, there is again disagreement with Thakur *et al.* [11], who reported $g_K = 0.63(1)$ and hypothesised configuration mixing to explain their low value. In particular, they suggest a 61% component of the $\{\pi 7/2^+[404] \otimes \nu 7/2^-[514] \otimes \nu 7/2^+[633]\}$ configuration, but (i) the $7/2^-[514]$ neutron is well above the $N = 100$ Fermi surface, and (ii) this configuration would be expected to give additional rotation alignment from the $i_{13/2}$, $7/2^+[633]$ neutron, such as is observed in ^{173}Hf [19] and ^{175}Ta [20]. In fact, the alignment of the isomer band is small, consistent with the above three-proton structure.

In the multi-quasiparticle calculations, there is also a $\{\pi 9/2^-[514] \otimes \nu 7/2^+[633] \otimes \nu 5/2^-[512]\}$, $K^\pi = 21/2^+$ configuration 113 keV higher in energy, with a theoretical value of $g_K = 0.32$. This configuration can be ruled out for the isomer on the basis of its parity, alignment, and g_K value. However, its properties match very well the structure that feeds into the isomer through the 108 keV transition, as shown in Fig. 1. From the transition intensity balance, allowing for electron conversion, the γ-ray strength of the 108 keV transition indicates $E1$ character ($\alpha_{\text{tot}} < 0.32$, compared to the theoretical $E1$ value of 0.30 [21], assuming $M1$ character for the 161 keV transition, with $\alpha_{\text{tot}} = 1.13$) hence positive parity for the 1825 keV level. The relatively low energy of the probable band members (161 and 185 keV) indicates additional alignment, which can be understood as coming from the $i_{13/2}$, $7/2^+[633]$ neutron. Nevertheless, we only give tentative spin and parity assignments for this structure due to the low transition intensities and the absence of identified $E2$ crossover transitions. It should also be noted that ^{175}Ta [20] has $K^\pi = 21/2^-$ and $21/2^+$ rotational bands which are very

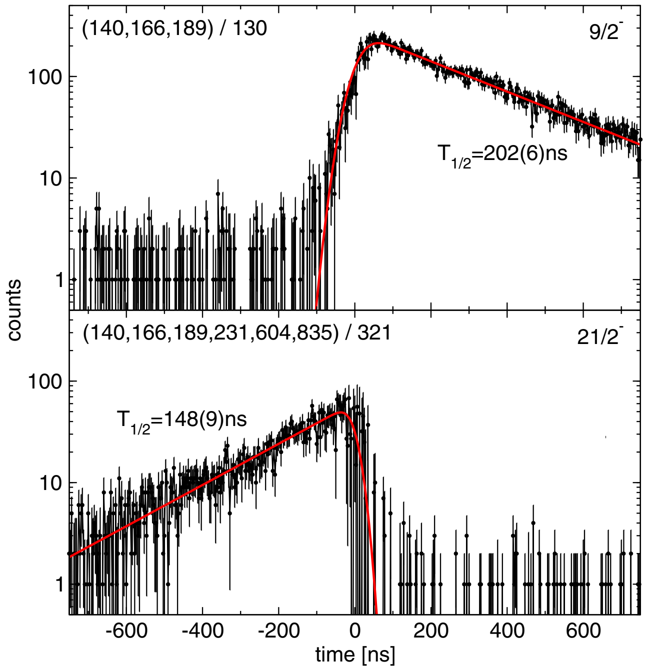

FIG. 3. Time-difference decay curves for two isomers in ^{173}Ta. The upper panel is for the $K^\pi = 9/2^-$ isomer, while the lower panel is for the $K^\pi = 21/2^-$ isomer. The specific gating energies either side of each isomer are indicated, together with the measured half-lives.

similar to those in ^{173}Ta (though more strongly populated on account of lower excitation energies) and with corresponding configuration assignments.

Having achieved a consistent analysis of the experimental data in comparison with Nilsson model calculations, we are now in a position to discuss the isomer decay rate, or, more specifically, the reduced hindrance (f_ν) values for the decay transitions. Here, $f_\nu = (T^\gamma_{1/2}/T^W_{1/2})^{1/\nu}$, where $T^\gamma_{1/2}$ is the partial γ-ray half-life, $T^W_{1/2}$ is the Weisskopf single-particle estimate, and ν is the degree of forbiddenness ($\nu = \Delta K - \lambda$). The reduced hindrance thus includes the influence of transition energy and multipole character, as well as the degree of K forbiddenness, so that variations in f_ν should be due to other degrees of freedom.

In the present study, three K-forbidden transitions are observed from the $K^\pi = 21/2^-$ isomer of ^{173}Ta. Their properties are given in Table I. For the interpretation presented below, the reduced hindrance of the 835 keV, $E2$ ($\nu = 4$) transition, $f_\nu = 12.5$, is the most important, though the $M1$ behavior is at least qualitatively consistent. We also note that a positive-parity assignment for the isomer would imply $M2$ character for the 835 keV transition, with $f_\nu = 4$. This is unreasonably low, especially in comparison with the then-implied $E1$, f_ν values of 45 and 48, for the 351 and 604 keV transitions, respectively, thus supporting the earlier negative-parity assignment for the isomer.

TABLE I. Properties of K-forbidden transitions from the $K^\pi = 21/2^-$, 148(9) ns isomer in ^{173}Ta. Theoretical conversion coefficients are from Kibédi *et al.* [21].

E_γ (keV)	λ	$I^{\rm rel}_\gamma$	$\alpha_{\rm tot}$	$T^\gamma_{1/2}$ (μs)	ν	f_ν
351.3(2)	$M1$	27(2)	0.132	0.98(10)	5	18.1(4)
604.1(2)	$M1$	100(5)	0.032	0.27(2)	5	19.3(3)
835.3(2)	$E2$	45(4)	0.006	0.59(6)	4	12.5(4)

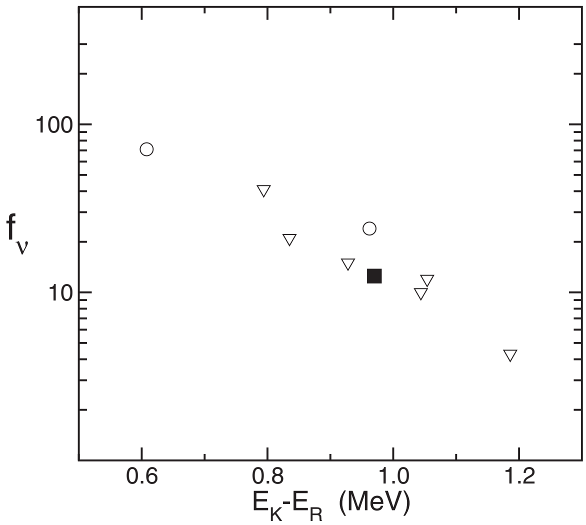

FIG. 4. Reduced hindrance, f_ν, shown as a function of excitation energy relative to a rigid rotor of A atomic mass units, for $E2$ decays with $\nu \geqslant 4$, from three-quasiparticle isomers in the deformed $A \approx 180$ region. Numerical values are given in Table II. The triangles and square are for isomer configurations with three nucleons of the same type (3π or 3ν) and the circles correspond to isomers in ^{181}W and ^{185}Ta, where there is no consensus regarding the configuration [6,27,28]. The new data point for ^{173}Ta is represented by the filled square, with $f_\nu = 12.5$ and $E_K - E_R = 970$ keV. The rigid-rotor moment-of-inertia reference is chosen as 85 $\hbar^2$MeV^{-1} for $A = 178$, scaling as $A^{5/3}$. The uncertainties in the f_ν values are typically smaller than the data points.

The systematic variation of decay rates from three-quasiparticle isomers in the $A \approx 180$ region has been discussed recently by Walker *et al.* [6]. They showed that, when all three quasiparticles are of the same nucleon type, reduced hindrance factors for $E2$ decays display a strong inverse dependence on excitation energy relative to a rigid rotor of appropriate mass. Higher energies result in lower hindrance factors. Figure 4 illustrates this behavior and now includes the new value for the ^{173}Ta, $K^\pi = 21/2^-$ isomer. The data are compiled in Table II. Note that the values for the ^{177}Ta and ^{179}Ta, $K^\pi = 21/2^-$ isomers are omitted, due to complex mixing effects involving one-proton–two-neutron configurations [3,22,23]. It is seen that the new data point for ^{173}Ta (filled square in Fig. 4) is consistent with the earlier analysis [6], thus lending support to the significance of this correlation. A similar correlation had been demonstrated previously for four- and five-quasiparticle isomers [24], later extended to higher quasiparticle numbers [4,5,25]. It can be interpreted [24] as a statistical K-mixing effect which depends on the nuclear level density. As the isomers become embedded in regions of higher level density, mixing increases with states of the same spin and parity but different K values; i.e., K mixing increases. We infer from

TABLE II. Reduced hindrance values for $E2$ decays from three-quasiparticle isomers, with $\nu \geqslant 4$ and with all three quasiparticles of the same nucleon type (though see footnote [a]).

Nuclide	K^{π}	E_K (keV)	$E_K - E_R$ (keV)	E_{γ} (keV)	$T_{1/2}$	$T_{1/2}^{\gamma}$	ν	f_{ν}	Ref.
^{173}Ta	$21/2^-$	1717	970	835	148 ns	580 ns	4	13	
^{175}Ta	$21/2^-$	1568	837	710	2 μs	10 μs	4	21	[20]
^{177}Ta	$17/2^+$	1523	1044	890	6 ns	125 ns	4	10	[22]
^{181}Ta	$21/2^-$	1485	794	711	25 μs	150 μs	4	41	[26]
^{185}Ta[a]	$21/2^-$	1274	608	280	12 ms	120 ms	4	71	[27]
^{179}W	$21/2^+$	1632	928	884	390 ns	920 ns	4	15	[15]
^{181}W[a]	$21/2^+$	1653	962	1054	200 ns	2.2 μs	4	24	[28]
^{183}W	$19/2^-$	1746	1186	556	13 ns	60 ns	4	4.3	[29]
^{181}Os	$21/2^+$	1744	1053	1213	7 ns	62 ns	4	12	[30]

[a] There is no consensus regarding the ^{175}Ta and ^{181}W configurations [6,27,28].

Fig. 4 that once the isomer energy exceeds that of a rigid rotor of the same spin by more than ≈ 1.3 MeV, K hindrance has drastically decreased and K isomers with significant (>1 ns) half-lives may cease to exist. This proposition is, of course, open to further experimental tests.

In summary, the odd-Z nuclide ^{173}Ta has been studied by pulsed-beam γ-ray spectroscopy techniques, and a three-quasiparticle, $T_{1/2} = 148$ ns isomer has been established. The newly determined isomer properties are seen to be in accord with recently proposed systematic behavior, demonstrating a strong correlation between increasing isomer excitation energy and decreasing reduced hindrance.

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