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Structure of neutron-rich tungsten nuclei and evidence for a 10^- isomer in ^{190}W

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Isomers in the neutron-rich nucleus ^{190}W have been characterized. A 10^- state from the $9/2^-[505] \otimes 11/2^+[615]$ two-neutron configuration with a 240-μs lifetime decays via a K-allowed, 97-keV, $M2$ transition to an 8^+ state with a 160-ns lifetime from the $9/2^-[505] \otimes 7/2^-[503]$ neutron configuration. New states have also been identified in ^{188}W, including a $K^\pi = 8^-$, 158-ns isomer from the $9/2^-[614] \otimes 7/2^+[404]$ two-proton configuration. The K hindrance is observed to decrease with increasing neutron number, consistent with a trend toward increasing triaxial softness.

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The properties of long-lived states in nuclei have been reviewed in Refs. [1,2], with a particular focus on the K isomers found in deformed nuclei with axial symmetry. These occur when an excited state can decay only via transitions that have a change in K (the projection of the nuclear angular momentum on the symmetry axis) greater than the transition multipolarity λ. Such hindered transitions can be classified according to the shortfall in λ compared to ΔK, termed the forbiddenness and defined by $\nu = |\Delta K| - \lambda$. It is found empirically that the strengths of K-forbidden transitions typically decrease by a factor of 50–100 or more per unit of forbiddenness [3]. This leads to the concept of a reduced hindrance $f_\nu = F^{1/\nu}$ (with F being the hindrance compared to the Weisskopf single-particle estimate) that typically ranges from 30 to 200 in nuclei where K is well conserved.

Even in well-deformed nuclei with axial symmetry, transitions with low reduced hindrances can arise from various forms of K mixing, such as chance degeneracies with isolated collective states [4–7], Coriolis effects [4], or mixing with random states in regions of high level density [8]. Tunneling through the potential barrier in the triaxial degree of freedom has also been proposed to explain low hindrance values [9,10]. The authors of Ref. [2] predict the presence of K isomers in neutron-rich $A \approx 190$ nuclei, but they note that proximity to the edge of the well-deformed region may mean that they are γ-soft (see, for example, Ref. [11]), implying nonconservation of K and lower hindrances.

Tungsten isotopes near the neutron midshell are well studied, with K isomers identified in a range of nuclei [12,13]. Less is known about the neutron-rich isotopes that are difficult to access, with only two isomers observed in the heaviest stable isotope, ^{186}W [14]. The higher lying of these is long-lived ($\tau > 1$ ms), but its spin and parity are unknown. The strongest branch from the lower-lying 7^-, 26-μs isomer has $f_\nu = 10$, a rather low value that may indicate γ softness. In ^{188}W, the first even-even nucleus beyond stability, only limited information is available for moderate spin states [15], and no isomers had been identified previously.

The discovery of a long-lived isomer in ^{190}W [16], produced in a fragmentation reaction, resulted in considerable interest [17–19], both because of the properties of the isomer and the unusual sequence of yrast states populated in its decay. The energies of the 2^+ and 4^+ yrast states have since been confirmed in β-decay studies [20], together with the tentative assignment of a low-lying 2_2^+ state that was interpreted as evidence for increased γ softness [20]. However, the isomeric state itself has not yet been identified. The original speculation [16] was that it might have the same configuration as the $K^\pi = 10^-$ isomers known in the even-even osmium isotopes [21,22]. These states have long lifetimes ($\tau > 1$ s) but decay via transitions with small reduced hindrances ($f_\nu < 10$), an indication of possible triaxiality. The anomalous $E(4^+)/E(2^+)$ ratio observed in the ground-state band of ^{190}W has also prompted an interpretation involving shape coexistence [17], with the long-lived state perhaps being a shape isomer [18].

In the present work, nuclei located beyond the heaviest stable tungsten isotope (^{186}W) were accessed with multinucleon transfer and deep-inelastic reactions, with the dual aims of investigating K-hindered decays and resolving the existing ambiguities for ^{190}W. Pulsed beams of 840-MeV ^{136}Xe ions from the ATLAS accelerator at Argonne National Laboratory were used to bombard enriched targets of 6 mg/cm^2 ^{186}W and 20 mg/cm^2 ^{192}Os, with 25 and 6 mg/cm^2 gold backings, respectively. The emitted γ rays were observed with Gammasphere. In the main measurement (with 99 detectors operational), triple- and higher-fold coincidence events were collected with 1/825-ns pulsing. For the determination of long isomer lifetimes, chopping regimes from the microsecond-to-second range were employed, and double- and

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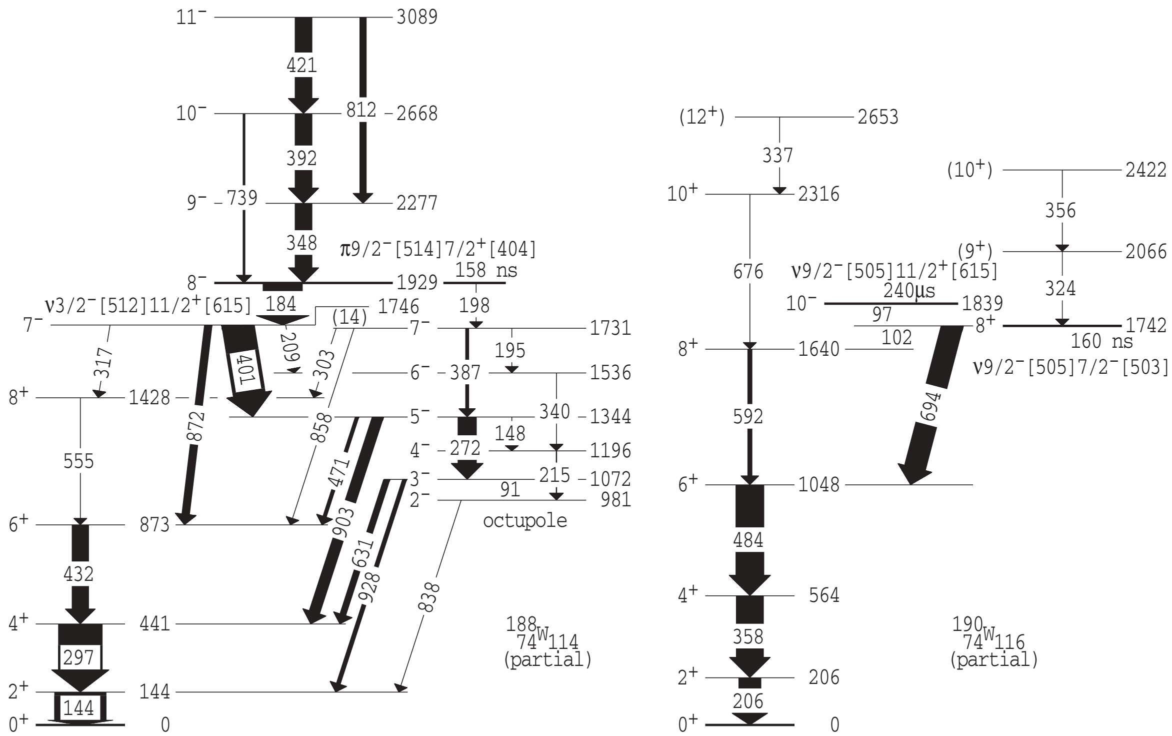

FIG. 1. Partial level schemes for ^{188}W and ^{190}W showing states associated with the new isomers.

higher-fold coincidence events were collected only in the beam-off period. The event time within the beam-off period was recorded with a microsecond clock. In the analysis, γ-ray coincidence events were incremented into a "Blue" database [23] from which various types of coincidence histograms could be projected, with arbitrarily complex gates on γ-ray energies and times.

Figure 1 provides partial level schemes for ^{188}W and ^{190}W deduced from the present data, focusing on the new isomeric states and their main decay paths. (Full-level schemes will be published elsewhere [24].) Each nucleus was populated in both target bombardments, providing an independent check on the assignments. However, the highest yield of ^{188}W was obtained with the ^{186}W target (addition of two neutrons), whereas the highest yield of ^{190}W was obtained with the ^{192}Os target (two-proton removal).

Evidence for a new isomer at 1929 keV in ^{188}W can be seen in the out-of-beam coincidence spectrum in Fig. 2(a) that shows the known low-spin transitions in ^{188}W [15], together with new γ rays at 184 and 401 keV (see also Ref. [20]) that comprise the main decay path from the isomer toward the known octupole band. A lifetime curve for the isomer is given in Fig. 3(a). The octupole band is extended to a 7^- state at 1731 keV and a second 7^- level is identified, close in energy at 1746 keV, with a very similar decay pattern. The total conversion coefficient for the 184-keV transition was deduced from a delayed intensity balance. The value of 0.77(6), when compared to calculated values of 0.078 for $E1$, 0.85 for $M1$, 0.41 for $E2$, and 4.63 for $M2$ multipolarity, establishes $M1$ character and an 8^- assignment for the 1929-keV state.

Previous studies of ^{190}W [16] identified transitions in the ground-state band that were fed by a higher-lying isomer with $30\ \mu s < \tau < 3$ ms. More recent work by the same collaboration [25] suggested an isomer lifetime of $\tau = 152(32)\ \mu s$ and a rearrangement of the previous level scheme above the 6^+ level was proposed, including (assumed) direct observation of the isomeric state. A substantially different level scheme is established here (Fig. 1), with a cascade of two isomers feeding the ground-state band.

The coincidence spectra in Figs. 2(b) and 2(c) confirm and extend the ground-state band in ^{190}W and identify a new state at 1742 keV with 102- and 694-keV decay branches. [The 228- and 436-keV γ rays seen in Fig. 2(b) are observed to be delayed, and they appear to feed above the 6^+ level. There are also indications of a higher-lying isomer with a lifetime of ~400 ns. Neither of these features is shown in Fig. 1.] The intensity balance for the 102-keV γ ray gives a total conversion coefficient of 4.3(13), to be compared with expected values of 0.36 for $E1$, 4.50 for $M1$, 3.62 for $E2$, and 40 for $M2$ multipolarity. This implies that the 102-keV transition is either $M1$ or $E2$. Together with the observation that the 102- and 694-keV γ rays are not likely to have the same multipolarity, since their measured branching ratio shows only a moderate favoring of the higher energy transition (see Table I), this leads to an 8^+ assignment for the 1742-keV state. (Alternative 6^+, 7^+, 9^+, or 10^+ assignments would result in one branch being much more strongly favored, contrary to the measured intensity ratio.)

Figure 3(b) gives the intensity of γ rays from the ground-state band as a function of time in the out-of-beam region, as obtained from the 1/825-ns pulsed beam measurement. The spectrum can be reproduced by a two-component fit (solid curve) with short and long lifetimes. Figure 2(d) shows the γ rays detected in the beam pulse that also precede the decay of

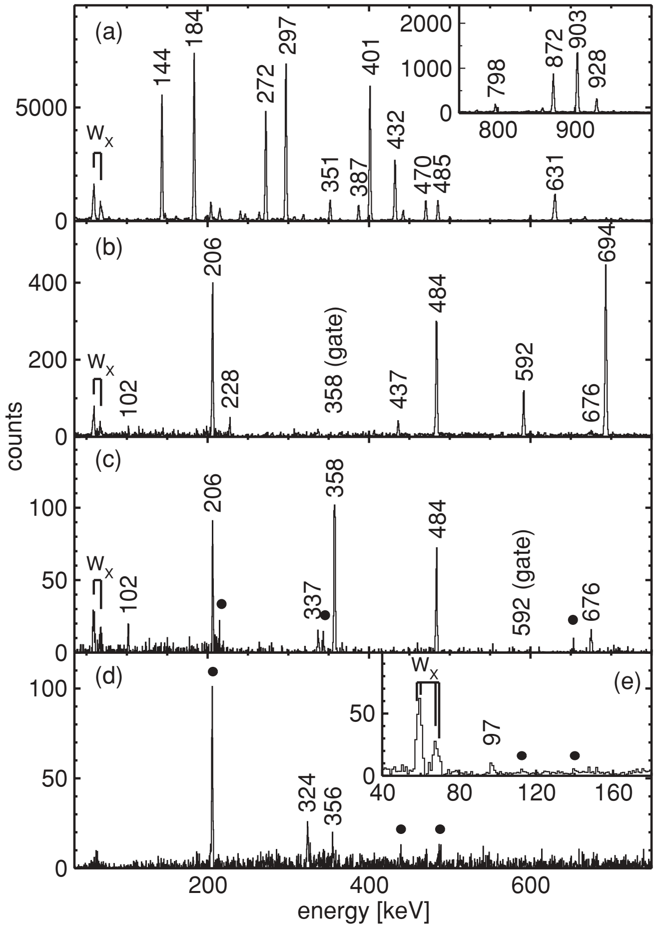

FIG. 2. Coincidence spectra with various gating conditions: (a) sum of 42 double-gated, out-of-beam spectra showing transitions below the 8^- isomer in ^{188}W; (b) sum of 358-206- and 358-484-keV double-gated spectra, showing the ground-state band in ^{190}W; (c) sum of 206-592-, 358-592-, and 484-592-keV double-gated spectra chosen to enhance both ground-state band transitions in ^{190}W above 8^+ as well as the 102-keV decay from the 8^+ isomer; (d) in-beam and (e) out-of-beam spectra gated on six clean pairs of γ rays below the 8^+ isomer in ^{190}W, projecting γ rays emitted 30–800 ns earlier in time. Filled circles denote contaminants.

the 1742-keV state, revealing a 324-356-keV cascade feeding the 8^+ isomer. The measured time difference between these γ rays and those from the ground-state band is used to deduce a lifetime of 160(24) ns for the isomer [see Fig. 3(c)]. The 324-356-keV cascade that is placed on the 8^+, 1742-keV state is only observed in-beam, with no indication of delayed feeding. The intensity of the ground-state band transitions as a function of time in the out-of-beam region for data collected with a 40/400-μs beam chopping ratio is shown in Fig. 3(d). The deduced lifetime of 240(8) μs for the long-lived isomer can be compared with the less precise value of 152(32) μs reported in Ref. [25].

The decay from the 240-μs isomer was isolated by selecting γ rays that precede the 8^+, 160-ns isomer but are still emitted in the out-of-beam region. Figure 2(e) shows a sum of six out-of-beam spectra with these constraints. Only the 97-keV line and characteristic tungsten x rays occur in all of the individual spectra. (Lines marked as contaminants are only seen in some of the gates.) Since there is only a single transition present in the spectrum, the observed x-ray yield can be used to deduce a conversion coefficient for the 97-keV transition. The value obtained of $\alpha_T = 33(13)$ is to be compared with expected values of 0.406 for $E1$, 5.18 for $M1$, 4.41 for $E2$, 48.1 for $M2$, or 103.7 for $E3$, leading to an $M2$ assignment. This defines a 10^-, 240(8)-μs isomer at 1839 keV in ^{190}W.

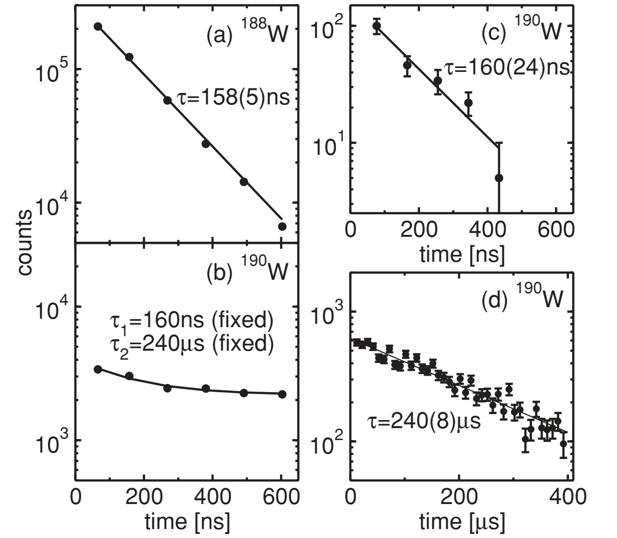

FIG. 3. Time curves in ^{188}W and ^{190}W: (a) and (b) intensity of γ-ray coincidence events in the two ground-state bands, measured in the 825 ns between beam pulses; (c) intensity of the 324- and 356-keV γ rays that lie above the 1742-keV isomer in ^{190}W, measured in spectra requiring that they are detected prior to transitions in the ground-state band; (d) intensity of γ-γ coincidences in the ground-state band of ^{190}W measured in the 400-μs out-of-beam region.

Configuration assignments for the intrinsic states can, in principle, be guided by the results of multiquasiparticle calculations. However, the accuracy of such calculations for nuclei in this region is compromised by the rapid changes in deformation predicted with neutron number [26] and by the fact that there is comparatively little firm information on intrinsic (one-quasiparticle) state energies. Nevertheless, we have performed calculations for ^{186}W, ^{188}W, and ^{190}W, taking single-particle energies from the Nilsson model with predicted deformations from Ref. [26], using the Lipkin-Nogami formalism for nuclear pairing with strengths $G_\nu = 18$ MeV$/A$ and $G_\pi = 20.8$ MeV$/A$, and correcting for empirical residual interactions. The calculations follow the methods of Ref. [27], but without adjustment of the single-particle levels. These should indicate general trends, if not precise excitation energies.

Figure 4 shows large shifts in the relative energies of the lowest-lying states in neighboring nuclei, demonstrating the potential danger of making assignments based on systematics in this region. The most rapid changes occur in configurations that involve the strongly sloping $9/2^-[505]$ and $11/2^+[615]$ neutron orbitals, while the shifts are amplified by the decreasing deformation with increasing neutron number. Note that the energy of the 10^- state in ^{190}W (which involves both of these

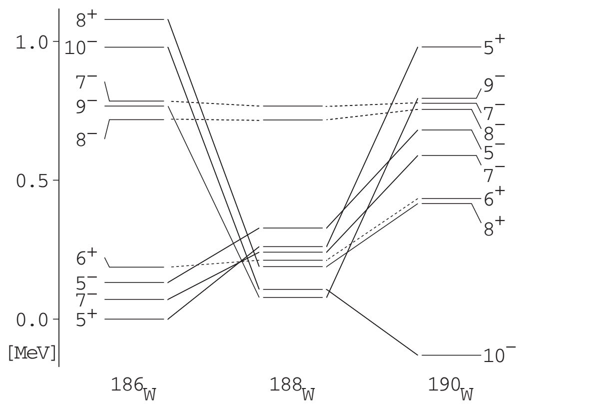

FIG. 4. Calculated selected two-particle states in ^{186}W, ^{188}W, and ^{190}W relative to the 5^+ state in ^{186}W. The solid (dashed) lines connect states with the same two-neutron (two-proton) configuration.

orbitals) is artificially low in these indicative calculations. Multiquasiparticle calculations have also been performed by other authors for ^{188}W [15] and ^{190}W [16,18,25], two of which [16,18] include γ deformation. Although the calculations show significant differences, the present experimental observations constrain the configuration assignments.

The 7^- state at 1746 keV in ^{188}W probably has the same configuration as the 7^-, 26-μs state observed in ^{186}W at 1517 keV [14]. (The absence of a long lifetime for the 7^- state in ^{188}W is discussed further in the following.) Both $\pi 9/2^-[514] \otimes 5/2^+[402]$ and $\nu 3/2^-[512] \otimes 11/2^+[615]$ configurations were suggested for this state in ^{186}W [14]. Indirect evidence that the two-neutron configuration is the correct assignment was presented in Ref. [28], although this has been questioned recently [29]. For ^{188}W, the multiquasiparticle calculations of Ref. [15] predict a $\nu 3/2^-[512] \otimes 11/2^+[615]$, 7^- state at 1544 keV in reasonable proximity to the observed state at 1746 keV. The only calculated low-lying state that could correspond to the 8^- experimental level at 1929 keV is from the $\pi 9/2^-[514] \otimes 7/2^+[404]$ configuration, predicted to lie much higher at 2486 keV in Ref. [15], but lying lower in energy (1787 keV) in the present calculations (Fig. 4). This assignment is supported by the measured cascade to crossover branching ratios in its rotational band. These give a large value of $|g_K - g_R| = 0.76(4)$ (assuming $g_R = 0.3$ and $Q_0 = 6.5$ eb estimated from the moment of inertia of the ground-state band), in good agreement with the value of 0.70 expected from the Nilsson model.

In ^{190}W, a state with $K^\pi = 10^-$ from the $\nu 9/2^-[505] \otimes 11/2^+[615]$ configuration is expected to lie low in energy (see Fig. 4). Other calculations for ^{190}W [16,18,25] predict 10^- states at energies ranging from just over 2 MeV [16] to as low as 1633 keV [18], approximately consistent with the observed energy of 1839 keV. Both of these calculations predict the 10^- state to have $\gamma \approx 0^\circ$, albeit with some degree of γ softness. The most recent calculation [25] (limited to axial symmetry) also predicts a low-lying 8^+ state from the $\nu 9/2^-[505] \otimes 7/2^-[503]$ configuration at 1775 keV (after allowing for the residual interaction), in agreement with the observed 8^+ state at 1742 keV. However, the Nilsson model predicts $g_K - g_R \approx 0$ for this configuration so that the

TABLE I. Measured transition strengths for isomeric transitions in ^{188}W and ^{190}W.

E_γ (keV)	I_γ relative	$\sigma\lambda$	α_T	$B(\sigma\lambda)$ (W.u.)	ν	f_ν
^{188}W; 1929 keV; $\tau = 158(5)$ ns; $K^\pi = 8^-$						
184	100(2)	$M1$	0.848	$1.72(8) \times 10^{-5}$	0	
198	1.9(7)	$M1$	0.692	$2.6(10) \times 10^{-7}$	5	21(2)
^{190}W; 1742 keV; $\tau = 160(24)$ ns; $K^\pi = 8^+$						
102	4.8(11)	$M1$	4.50	$7(2) \times 10^{-6}$	7	5.4(2)
694	100(2)	$E2$	0.0097	$3.9(6) \times 10^{-4}$	6	3.7(1)
^{190}W; 1839 keV, $\tau = 240(8)$ μs; $K^\pi = 10^-$						
97	100	$M2$	48.1	$1.34(5) \times 10^{-2}$	0	

crossover $E2$ transitions are expected to dominate. Thus either the assignment is questionable or the 324- and 356-keV γ rays are not cascade transitions within the 8^+ band, given as well that their energies are lower than expected.

Transition strengths are presented in Table I. The 184-keV, $8^- \to 7^-$ transition in ^{188}W is K-allowed, but hindered at 10^{-5} W.u. (Weisskopf units), consistent with the proposed two-proton to two-neutron configuration change. Although the 198-keV, $8^- \to 7^-$ transition is nominally fivefold K-forbidden, its reduced hindrance of 21 is low. This can be explained by mixing between the close-lying 7^- states, a test of which [4,7] is that the branching ratio of the 209- and 401-keV transitions from the 1746-keV state should reflect the same collective and single-particle properties as are obtained from the cascade to crossover intensity ratios within the octupole band. The value of $|\frac{g_K - g_R}{Q_0}|$ measured for the 2^- band is 0.028(3), in good agreement with the implied value of $|\frac{g_K - g_R}{Q_0}| = 0.022(9)$ obtained from the 209/401-keV branching ratio. This mixing means that the 198-keV transition proceeds via a K-allowed admixture, and it also explains the short lifetime for the 1746-keV level compared to that of the 26-μs, 7^- state in ^{186}W with the same configuration. Using the methods described, for example, in Refs. [4,5,7], and assuming that the 198-keV transition only occurs due to a $K = 7$ component in the wave function of the 1731-keV state, a 1.5% admixture of the $K^\pi = 7^-$ state into the mixed 1731-keV state can be deduced. The interaction strength between the levels can then be calculated from the expression $|V| = \alpha\beta\Delta E$, where the separation of the mixed-state energies ΔE is known and $\alpha = 0.1222$ and $\beta = 0.9925$ are the mixed-wave-function amplitudes. The deduced interaction of $|V| = 1.7$ keV agrees with the expectations for $\Delta K = 5$, as cataloged recently in Fig. 4 of Ref. [4].

In ^{190}W, the 102- and 694-keV transitions from the 8^+ isomer have low reduced hindrances of 5.4 and 3.7, respectively, with no obvious explanation in terms of K mixing with specific states. The long lifetime for the 1839-keV, 10^- state in ^{190}W is not due to a K-forbidden decay. In fact, the 97-keV transition is a K-allowed, $M2$ decay, corresponding to the $11/2^+[615] \to 7/2^-[503]$ single-neutron transition. The $11/2^+[615]$ state originates from the $i_{13/2}$ spherical shell and the Nilsson calculation used for the multiquasiparticle calculation above predicts the $7/2^-[503]$ state to be 90% $f_{7/2}$, 8% $h_{9/2}$, and 2% $h_{11/2}$. An $M2$ decay from $i_{13/2}$ to $f_{7/2}$ is j forbidden, whereas $i_{13/2} \rightarrow h_{9/2}$ and $i_{13/2} \rightarrow h_{11/2}$ transitions are allowed. These considerations can explain the measured $M2$ decay strength without invoking additional hindrance. The 10^- state in ^{190}W is therefore an "yrast trap" rather than a K isomer.

In summary, the present measurements have identified new isomers in the neutron-rich tungsten isotopes ^{188}W and ^{190}W and characterized their decay. The previous experimental ambiguities in ^{190}W have been resolved, with the available evidence concerning the long-lived isomer now supporting a 10^- assignment. Its decay proceeds via a K-allowed, $M2$ transition. The low reduced hindrances observed for other decays such as those from the 8^+ state in ^{190}W are consistent with expectations for increasing γ softness in neutron-rich tungsten isotopes.

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