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High-K isomers in neutron-rich hafnium nuclei at and beyond the stability line

R. D'Alarcao, P. Chowdhury, and E. H. Seabury
Department of Physics, University of Massachusetts, Lowell, Massachusetts 01854

P. M. Walker and C. Wheldon
Department of Physics, University of Surrey, Guildford GU2 5XH, United Kingdom

I. Ahmad, M. P. Carpenter, G. Hackman, R. V. F. Janssens, T. L. Khoo, C. J. Lister, D. Nisius, P. Reiter, D. Seweryniak, and I. Wiedenhoever
Argonne National Laboratory, Argonne, Illinois 60439

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Pulsed ^{238}U and ^{208}Pb beams have been used to populate multi-quasiparticle high-K isomers in neutron-rich hafnium isotopes at and beyond the line of β-stability, via inelastic excitation and transfer. Spectroscopic properties and configuration assignments of several new high-K isomers are compared with earlier theoretical predictions. A striking example of the robustness of the K quantum number is demonstrated by the observed competition between $E1$ and $E3$ decay modes in ^{180}Hf, the heaviest stable isotope of the element. [S0556-2813(99)50503-7]

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The conditions under which K, the projection of the aligned nucleonic spins on the symmetry axis in deformed nuclei [1], is a good quantum number remain a topic of much current interest. On the one hand, there are striking examples of K conservation at high spins, such as the $K^\pi=16^+$ isomer in ^{178}Hf, with $t_{1/2}=31$ yr [2]. On the other, experiments with the new generation of detector arrays have isolated multi-quasiparticle (multi-qp) K isomers in the $A\approx180$ region with unexpectedly fast decay rates, suggesting a severe breakdown of K-selection rules [3,4]. Clearly, a systematic study of the properties of K isomers as a function of different parameters, such as the number of quasiparticles in the isomeric configuration, the spin and excitation energy of the isomers, and the magnitude of the K quantum number are needed, preferably over a wide range of N/Z ratios, from the most neutron-deficient to the most neutron-rich nuclei.

The Hf($Z=72$) isotopic chain is rich in K isomers, due to a robust axial symmetry and the availability of multiple high-Ω orbitals near the Fermi surface. High-K isomers have long been predicted in isotopes heavier than ^{180}Hf [5], the heaviest stable Hf isotope. Experimental information to date on neutron-rich Hf nuclei, however, has been limited, primarily because fusion reactions with stable beam-target combinations are unable to populate neutron-rich nuclei beyond the line of β stability. Recent advances with inelastic and transfer reactions in populating high spins in target- and projectile-like fragments [6–10] have motivated our current investigation of high-K isomers in the $A\approx180$ region using these techniques. Our pilot experiment, with pulsed ^{238}U beams on the heaviest stable isotopes of Lu($Z=71$), Ta($Z=73$), and W($Z=74$), was very successful in populating new multi-qp isomers in the target nuclei [10]. This article presents the results of our follow-up experiments with Hf($Z=72$) targets, where inelastic excitation and transfer mechanisms were used to populate several new 4-qp K isomers in a ^{180}Hf target, as well as other new K isomers in neutron-rich Hf nuclei. Prior to our present study, only very long-lived 2-qp 8^- isomers were known in the even-even ^{180,182,184}Hf nuclei, the first two from β-decay studies [2], and the last one from a recent experiment using a transfer reaction [11].

In our primary experiment, thick targets of isotopically enriched ^{180}Hf (~40 mg/cm^2) and natural Hf (~6 mg/cm^2, which contains 25% ^{180}Hf), each backed by enough ^{208}Pb to

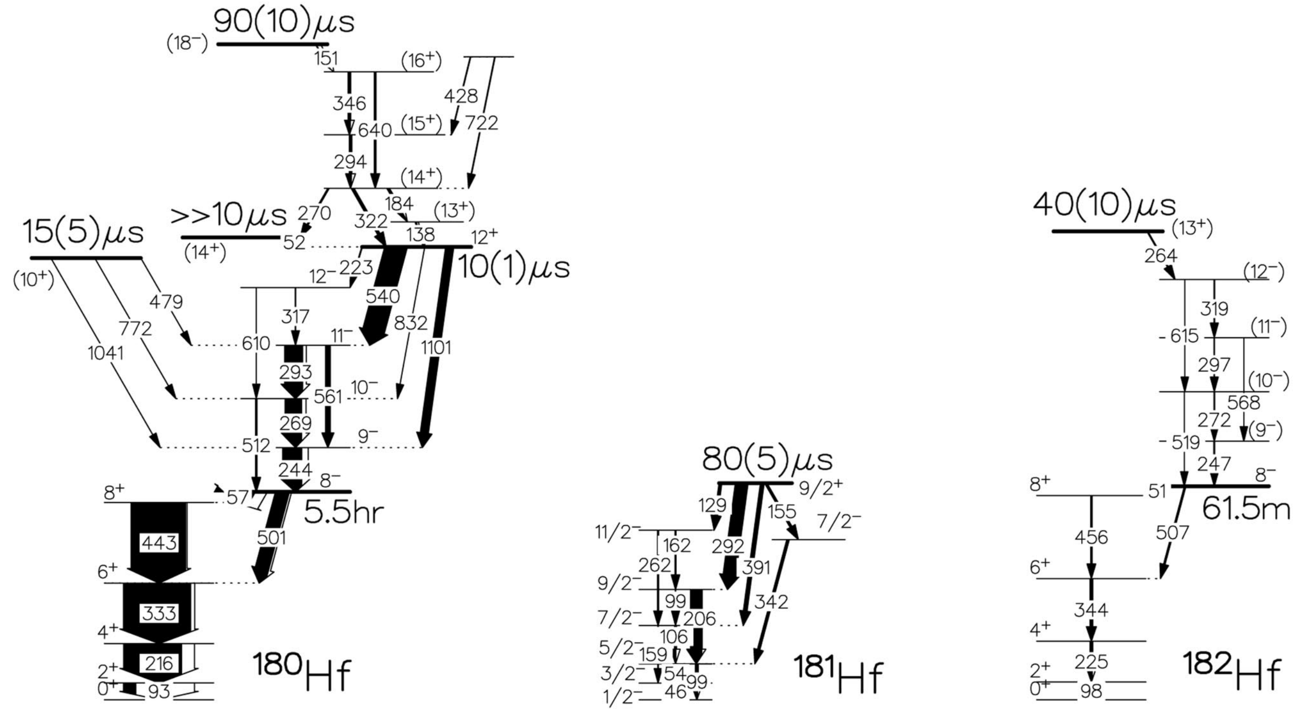

FIG. 1. Decay scheme of new high-K isomers in ^{180,181,182}Hf. New data from the present work include all states above the 8^- isomers in ^{180,182}Hf, and above $J=7/2$ in ^{181}Hf. Note that the energy scale for ^{181}Hf is expanded by a factor of 2.

stop the beam at the target position, were bombarded with pulsed ^{238}U beams of 1.6 GeV ($\approx$15% above the Coulomb barrier) provided by the ATLAS facility at Argonne National Laboratory. The beam, which has a natural separation of 82.5 ns between nanosecond pulses, was switched on and off by a sweeper in three different time periods of 1.65, 165, and 1650 μs, with an on/off ratio of 1/4. Only delayed γ rays were recorded in the beam-off periods by the Argonne-Notre Dame BGO array of 12 Compton-suppressed Ge detectors with a master trigger of at least one Ge firing in the beam-off interval. Isomer decay schemes were constructed from γ-γ coincidence events recorded in all three time ranges. The time between the master trigger and the sweeper was also recorded for each event, and used to measure the half-lives of individual γ rays. In addition to this primary experiment, the results were clarified and extended by more recent data obtained in conjunction with tests of the Gammasphere array [12] operated with the beam sweeper at ATLAS, where a 1.3 GeV ^{208}Pb beam was incident on the ^{180}Hf target for a few hours. The Pb beam was swept in intervals of 20 μs on and 25 μs off, with data collected as before during the beam-off periods. The decay schemes of ^{180}Hf, ^{181}Hf, and ^{182}Hf nuclei deduced from the present experiment are shown in Fig. 1. Representative γ-γ coincidence data and time spectra are presented in Figs. 2 and 3, respectively. All the rotational band structures observed in this study are populated from higher-lying isomers, since only delayed γ rays were recorded. A total of six *new* isomers are observed in the three nuclei, of which four involve four quasiparticles. Three of the four are assigned to ^{180}Hf and one to ^{182}Hf. New properties of these isomers in the even-even ^{180,182}Hf nuclei are summarized in Table I, and discussed in detail below.

The most intensely populated new isomer in this study decays with a half-life of 10 ± 1 μs to a previously unobserved, regularly spaced rotational band, with the transitions in the band coincident with Hf x rays [Fig. 2(b)]. When the ^{nat}Hf target is replaced by the ^{180}Hf target, the γ rays in this rotational band are the strongest ones that persist in the spectrum (other than the ground-state band members of ^{180}Hf populated in the decay of the known 2-qp 8^- isomer, $t_{1/2}=5.5$ h). Although coincidence events are not measurable across the 5.5 h half-life, the most logical placement of the new band is on top of the 8^- isomer. The transitions in the band, which are almost certainly of $M1$ and $E2$ character, in line with the properties of strongly coupled bands in axially deformed nuclei, adhere well to the systematics of rotational

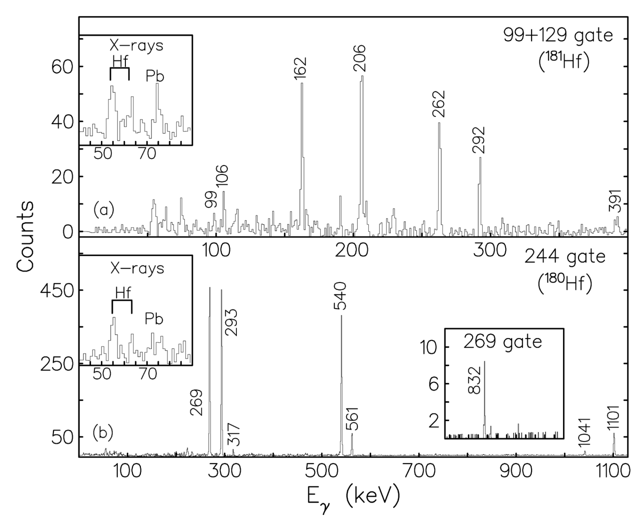

FIG. 2. Gamma-ray spectra gated on (a) the 99 and 129 keV transitions from the decay of the $9/2^+$ isomer in ^{181}Hf, and (b) the 244 keV transition from the decay of the 12^+ isomer in ^{180}Hf. The inset in (b) is an expanded view of the 269 keV gate which cleanly shows the weak 832 keV branch from the isomer.

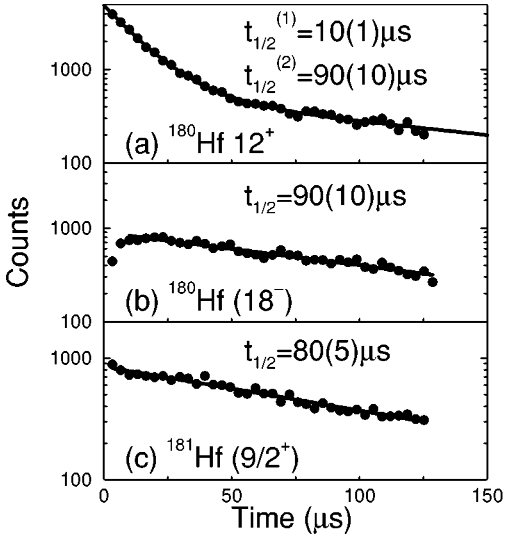

FIG. 3. Time spectra for (a) the 540 and 1101 keV γ rays below the 12^+ isomer in ^{180}Hf with a two-component half-life fit (see text), (b) the 640 and 346 keV γ rays above the 12^+ isomer in ^{180}Hf (isolating the longer feeding component) and (c) the 205 keV γ ray depopulating the $9/2^+$ isomer in ^{181}Hf. All spectra shown are from a beam-sweep interval of 165 μs. Points close to the arbitrary $t=0$ origin following the prompt veto may not be very reliable for low statistics, as in (b) and (c).

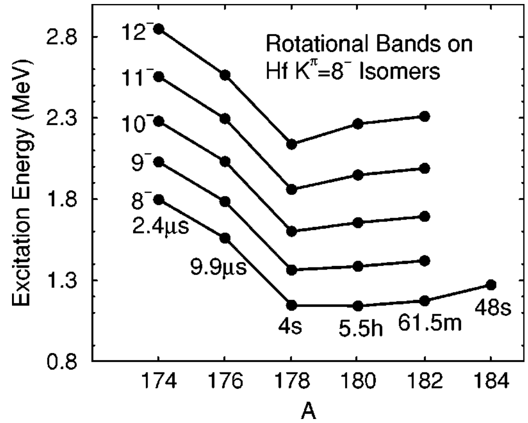

FIG. 4. Systematics of rotational band structures built on 2-quasiproton 8^- isomers in even-even Hf nuclei.

band structures built on 2-quasiproton 8^- states in even-even Hf nuclei (Fig. 4). In addition, the $|(g_K-g_R)/Q_0|$ values deduced from the measured $M1/E2$ branching ratios in this rotational band are in excellent agreement with the constant value expected from a $\pi7/2^+[404]\otimes\pi9/2^-[514]$ configuration assignment for the 8^- bandhead (see Table I). In fact, the measured branching ratios provide the first evidence for the configuration and for the $K=8$ assignment to the previously known 8^- isomer.

Four decay branches are observed from the new isomer to the 9^-, 10^-, 11^-, and 12^- members of the rotational band built on the 2-quasiproton 8^- isomer, with strong branches to the 11^-(75%) and the 9^-(23%) states. This observation limits the spin of the isomer to either 11 or 12. The significantly weaker (1%) decay branch to the 10^- state argues against a $J=11$ assignment for the isomer. Under the normal assumption that competition between $M2$ and $E3$ multipolarities are more probable than between $E2$ and $M3$ multipolarities, the spin-parity assignment for the isomer that is consistent with the observed decay pattern is 12^+. This associates the two strong 540-keV and 1101-keV decay transitions with $E1$ and $E3$ character, respectively, and the weaker

TABLE I. New properties of 2- and 4-qp isomers in ^{180}Hf and ^{182}Hf measured in this work.

Nucleus	K^π $t_{1/2}$	Configuration assignment	E (keV) expt[calc][d]	$\|(g_K-g_R)/Q_0\|$[a] expt[calc]	E_γ[b] (keV)	$t^{\gamma}_{1/2}$ (partial)	ΔK	f_ν[c]
^{180}Hf (2-qp)	8^- 5.5 h[e]	$\pi7/2^+$ [404] $\otimes\pi9/2^-$ [514]	1143[e] [1128]	0.106(6) [0.103]				
^{180}Hf (2-qp)	(10^+) 15(5) μs	$\nu9/2^+$ [624] $\otimes\nu11/2^+$ [615]	2427 [2387]					
^{180}Hf (4-qp)	12^+ 10(1) μs	$\pi^2 8^-\otimes\nu9/2^+$ [624] $\otimes\nu1/2^-$ [510]	2487 [2487]		540($E1$) 1101($E3$)	16 μs 44 μs	4 4	107 136
^{180}Hf (4-qp)	(14^+) $\geqslant$10 μs	$\pi^2 8^-\otimes\nu9/2^+$ [624] $\otimes\nu3/2^-$ [512]	2539 [2854]		52($E2$)	$\geqslant$10 μs	2	
^{180}Hf (4-qp)	(18^-) 90(10) μs	$\pi^2 8^-\otimes\nu9/2^+$ [624] $\otimes\nu11/2^+$ [615]	3600 [3514]		151($M2$)	90 μs	4	
^{182}Hf (2-qp)	8^- 61.5 min[e]	$\pi7/2^+$ [404] $\otimes\pi9/2^-$ [514]	1174[e] [1073]	0.11(3) [0.103]				
^{182}Hf (4-qp)	(13^+) 40(10) μs	$\pi^2 8^-\otimes\nu11/2^+$ [615] $\otimes\nu1/2^-$ [510]	2573 [2429]		264($E1$)	40 μs	5	24

[a]Derived from $M1/E2$ branching ratios in rotational bands built on the isomer. Values typical for this region, $g_R=0.28$ and $Q_0=7$ e b, have been used for the comparison with calculations.
[b]Only the most intense decays (with multipolarity assignments) are included.
[c]Reduced hindrance. A 10^{-4} retardation is factored into the $E1$ Weisskopf estimates (see text).
[d]Using the method of Ref. [13] (see text).
[e]Measured in earlier work [2].

832-keV intermediate branch with $M2$ character. The 12^+ assignment is also strengthened by a comparison with estimates of multi-qp excitation energies from blocked-BCS–type calculations [13] for a 12^+ state with a $\pi^2 8^- \otimes \nu^2 4^-$ configuration (see Table I), though the precision of the agreement to within a keV is purely fortuitous.

The competition of a multipolarity $\lambda=3$ transition with a $\lambda=1$ transition is a classic example of K-selection rules, and highlights the robustness of the K quantum number in this case. Transitions between states with different K values are forbidden to first order if $\Delta K > \lambda$. Such forbidden transitions are observed due to higher order corrections from small admixtures of other K components in the wave functions of the initial and final states. The degree of forbiddenness is defined as $\nu = \Delta K - \lambda$, and the reduced hindrance (or hindrance factor per degree of K forbiddenness) as $f_\nu = [t_{1/2}^{\mathrm{exp}}/t_{1/2}^{W}]^{1/\nu}$, where $t_{1/2}^{\mathrm{exp}}$ is the experimentally measured partial half-life of the γ-ray transition, and $t_{1/2}^{W}$ is the Weisskopf single-particle estimate of the half-life. Since the $K=12$ isomer decays to a $K=8$ band, $\Delta K=4$, which results in values of $\nu=3$ for the $E1$ and $\nu=1$ for the $E3$ transition. The $E3$ transition is thus less K hindered than the $E1$ decay and able to compete. With the decay branching ratios and measured half-life for the 12^+ isomer, $f_\nu=136$ for the $E3$ branch, and 107 for the $E1$ transition (using a 10^{-4} retardation that is typically factored into the $E1$ Weisskopf estimate for comparison with other multipolarities). The reduced hindrance for the $E3$ transition is consistent with those observed in other Hf nuclei for 3- and 4-qp isomers. This clean example bolsters the scant experimental systematics of K hindrances for $E3$ transitions in this mass region.

In addition to the 10 μs primary half-life, all the transitions observed in the decay of the 12^+ isomer show a longer half-life component (Fig. 3), which establishes that this isomeric state is being fed by a higher-lying isomer (or isomers). A two-lifetime fit incorporating this feeding scenario yields a $t_{1/2} \approx 100\ \mu$s for this longer component. Based on the data from our primary experiment, it was difficult to isolate clean candidate feeder γ rays for the 12^+ isomer. The more recent data from Gammasphere (GS) helped clarify and strengthen this part of the level scheme, since weak coincidence relationships were observable across the 10 μs isomer, due to the wider ($\approx 1\ \mu$s) overlap criterion in the GS trigger electronics. A γ-γ-γ coincidence cube of out-of-beam delayed γ rays from the GS data set was used to analyze double-gated spectra. This proved to be crucial, as a significant fraction of the new γ rays were found to be energy doublets with stronger transitions in the same nucleus. The new group of γ rays thus isolated was then analyzable in our original data with U beams. Contaminant-free γ rays feeding the 12^+ isomer have a measured half-life $t_{1/2}=90\pm 10\ \mu$s, and the $\approx 10\%$ measured intensity in these feeding transitions is consistent with the intensity of the longer half-life component observed for the decay γ rays of the 12^+ isomer.

The GS data set also reveals the presence of a third new isomer, with $t_{1/2}=15\pm 5\ \mu$s, in ^{180}Hf at an excitation energy of 2427 keV. The decay pattern to the rotational states built on the 8^- bandhead points to a tentative (10^+) assignment, which also agrees within 40 keV with theoretical predictions for the 2-quasineutron configuration $\nu 9/2^+[624] \otimes \nu 11/2^+[615]$. The low population intensity, which is expected from the non-yrast character of the isomer (772 keV above the yrast 10^- state), does not provide sufficient statistics for a precise half-life measurement.

The analysis of the γ rays feeding the 10 μs isomer, through intensity balances and a comparison with theoretical predictions, leads to tentative spin-parity assignments for this part of the level scheme. For example, the conversion coefficient for the 151-keV γ ray depopulating the isomer is measured from intensity balance to be 9 ± 6, which constrains the multipolarity to either a $M2$ or an $E3$. The $M2$ assignment, based on the general rule of choosing the lowest reasonable multipole, leads to a tentative 18^- assignment for the 90 μs isomer, with a proposed configuration of $\pi^2 8^- \otimes \nu^2 10^+$ from comparison with calculations (see Table I). This assignment is further strengthened by the observation of the $\nu^2 10^+$ isomer as described above. The measured excitation energies of the constituent 2-qp states add up to within 30 keV of the observed (18^-) isomer. A 4-qp yrast 18^- isomer with this configuration has long been predicted in this nucleus [5].

The triples coincidence data from GS also isolated a new isomeric state located 52 keV above the 12^+ isomer, presumably with $t_{1/2} \gg 10\ \mu$s, since no coincidences are observable *across* this isomer, even with the $\approx 1\ \mu$s overlap criterion in the GS trigger electronics. No direct 52-keV transition would be observable in the GS experiment, as γ rays below ≈ 100 keV were severely attenuated by absorbers that were in place in front of the Ge detectors in this unoptimized test run. A 52-keV transition would also be extremely difficult to observe in our primary experiment with U beams, due to the presence of strong 55-keV Hf x-ray peaks in the spectra. However, such a 52-keV transition would be from an isomeric initial state to an isomeric final state, i.e., it would be a cascade with multiplicity 1. In our U beam data, a spectrum obtained by dividing a spectrum of multiplicity ≥ 1 by one of multiplicity ≥ 2 shows a strong peak at 52 keV, together with peaks at other well-known multiplicity-1 transitions, such as the 1461-keV radioactivity line in ^{40}K. Theoretical calculations [14] predict a 12^- and a 14^+ level as the two primary candidates for the next higher isomer above the 12^+ isomer. The long half-life of the 52-keV transition eliminates a 12^- assignment, since no K hindrance would be present for the $E1$ transition in that case. A 14^+ assignment would make the 52-keV γ ray a K-allowed $E2$ transition, with a half-life consistent with the systematics of highly converted K-allowed $E2$ transitions in this mass region, such as a 97-keV transition in ^{176}Hf from a $K=22$ isomer with $t_{1/2}=43\ \mu$s [2], and an 86-keV transition in ^{177}Ta from a $K=49/2$ isomer with $t_{1/2}=133\ \mu$s [15]. A tentative spin-parity of 14^+ is, therefore, proposed for this isomer.

In addition to the multiple isomers populated in the target nucleus, new isomers were observed in the neutron-rich Hf nuclei via neutron transfer. A new 1-qp isomer, with $t_{1/2}=80\pm 5\ \mu$s is placed in ^{181}Hf at an excitation energy of 594 keV, from direct coincidence relationships with γ rays in the rotational band built on the $1/2^-[510]$ orbital, which was extended from the highest spin previously known [2] of $J=7/2$ to $J=11/2$ in this work. The intensities of the decay branches from the isomer to the 7/2, 9/2, and 11/2 members of this band limit the isomer spin assignment to either 9/2 or 11/2. A $9/2^+$ assignment agrees with a previous tentative assignment of a $\nu 9/2^+[624]$ configuration to a state observed in (t,p) reactions [16] at an excitation energy of 600 ± 5 keV. A $J=11/2$ value would require a negative parity assignment in order to account for the intensity distribution in the observed decay branches, and the only possible negative-parity quasineutron orbital of $11/2^{-}[505]$ is expected to be located at a much higher excitation energy from systematics.

There is also evidence for the population of a new 4-qp isomer in the neutron-rich ^{182}Hf nucleus via two-neutron transfer. The isomer, with $t_{1/2}=40\pm 10\,\mu$s, decays to a strongly coupled rotational cascade, which we again infer to consist of $M1$ and $E2$ transitions. The energy of each of the four $M1$ transitions in this cascade is exactly 3 keV greater than the corresponding transitions in the strong band placed on top of the 8^- isomeric level in ^{180}Hf. The intensities of these new transitions are a factor of 30 lower than the corresponding transitions in the 8^- band of ^{180}Hf, and are too weak for unambiguous identification via x rays. The same intensity ratio of 30 is observed between the γ rays which *depopulate* the known 2-qp 8^- isomers in ^{182}Hf and ^{180}Hf nuclei. Based on the above evidence, the rotational band is placed on top of the known 8^- isomer in ^{182}Hf. The $|(g_K-g_R)/Q_0|$ values deduced from the measured $M1/E2$ branching ratios are in excellent agreement with the constant value expected from the same 2-quasiproton assignment to the 8^- bandhead as in ^{180}Hf (see Table I). The energy systematics of rotational band structures built on 2-qp 8^- isomers in even-even Hf nuclei are shown in Fig. 4. Again, the measured branching ratios provide the first evidence for the configuration and for the $K=8$ assignment to the previously known 8^- isomer in ^{182}Hf [2]. A tentative spin-parity assignment of 13^+ to the isomer from the decay pattern agrees well with theoretical calculations for a $\pi^2 8^- \otimes \nu^2 5^-$ configuration (see Table I). The single decay branch observed from the isomer is consistent with an $E1$ multipolarity assignment for this 264-keV transition. The measured half-life then leads to a reduced hindrance of $f_\nu=24$, again factoring in a typical 10^{-4} retardation into the $E1$ Weisskopf estimate, as described above. This makes the (13^+) level in ^{182}Hf the first 4-qp K isomer in the $A\approx 180$ region observed in a neutron-rich nucleus beyond the line of β-stability. It is worth noting that the known 2-qp 8^- isomer in ^{184}Hf [11] is also observed in the GS data via four-neutron transfer, with approximately a factor of 50 lower counts than the two-neutron transfer channel, as seen in double-gated spectra of analogous transitions.

The observed excitation energies of the 2- and 4-qp isomers are compared in Table I to predictions, where the energies are calculated with the blocked BCS method [13], without explicit inclusion of residual interactions. The effective pairing strengths of $G(n)=21$/nucleon MeV and $G(p)=22$/nucleon MeV give realistic estimates for like-nucleon spin-singlet couplings (with favored residual interactions) but spin-triplet energies may be underestimated. It is interesting to note that almost all the new isomers observed are favored configurations. This like-nucleon spin-singlet coupling is especially evident in the 4-qp isomers involving the $\nu 1/2^{-}[510]$ orbital in both ^{180}Hf and ^{182}Hf, where the two quasineutrons couple to $K_{max}-1$, in order to take advantage of the spin-singlet configuration. The $K_{\max}=13$ configuration had seemed to be the lower state in ^{180}Hf in earlier calculations [14], where only $K_{\max}$ couplings had been calculated. We now observe the $K=12$ level instead as the isomer. Using the empirical values of the residual interactions from the same reference [14], the $K=12$ state is lowered by ≈ 200 keV compared to the $K_{\max}=13$ configuration, thus providing a consistent understanding of the experimental data.

In summary, we have populated and measured spectroscopic properties of 4-qp K isomers in neutron-rich nuclei at and beyond the line of β stability in the $A\approx 180$ region, using inelastic excitations and transfer mechanisms. Configuration and K assignments have been proposed for previously observed 2-qp isomers, based on $M1/E2$ branching ratios measured in rotational bands observed in the present work to feed these 2-qp states. A classic example of the robustness of the K quantum number is demonstrated by competing $E1$ and $E3$ transitions from a 4-qp isomer in ^{180}Hf. These techniques can be extended to study multi-qp yrast isomers in neutron-rich nuclei at higher angular momenta by using the highest efficiency arrays currently available, such as GS and Euroball.

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