

**Yrast three-quasiparticle  $K$  isomers in neutron-rich  $^{181}\text{Hf}$** 

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New high- $K$  orbitals have been identified in the neutron-rich  $^{181}\text{Hf}$  nucleus via one-neutron transfer from a pulsed  $^{238}\text{U}$  beam onto a stable  $^{180}\text{Hf}$  target. Yrast three-quasiparticle high- $K$  isomers, with half-lives as long as 1.5 ms, have been populated. The decay scheme of  $^{181}\text{Hf}$  has been extended to  $(25/2^-)$ . Blocked BCS calculations, including residual interactions, compare well with the experimental results.

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**I. INTRODUCTION**

Long-lived isomeric states in nuclei are unique laboratories for studying the detailed properties of nuclear wave functions. From an experimental standpoint, transitions de-exciting long-lived isomers provide clean information on wave-function admixtures, since a better signal-to-noise ratio is achieved if short-lived excitations are allowed to decay away. From a theoretical perspective, a long-lived isomeric state is a manifestation of underlying symmetries of the nuclear wave function.  $K$  isomers (where  $K$  is the projection of the total angular momentum of a deformed nucleus onto its axis of symmetry) form a special subset that showcases the competition and rich dynamics between collective and single-particle excitations in a deformed system. In this work,  $K$  isomers are used to locate and follow the evolution of individual Nilsson states and their couplings in a previously unexplored neutron-rich region of the nuclear chart and provide a groundwork for future exploration of rotational excitations built on these new isomers.

High- $K$  configurations at low excitation energy abound in the  $A \approx 180$  region of the nuclear chart, where deformed nuclei with axial symmetry have valence nucleons in Nilsson orbitals with large angular momentum projections on the symmetry axis. The Hf ( $Z=72$ ) isotopes offer an especially robust platform for a systematic study of high- $K$  physics, with rigid axial deformations persisting over a wide range of spin and isospin. While yrast high- $K$  isomers have long been predicted [1,2] to dominate the excitation spectrum of neutron-rich ( $A > 180$ ) Hf nuclei, recent calculations [3] suggest oblate rotation as a collective mode at high spins. Limi-

tations of standard fusion-evaporation techniques for populating neutron-rich nuclei effectively imposed a delay of half a century between the observation of the first isomer in  $^{180}\text{Hf}$  (the heaviest stable isotope) [4] and the first isomer in  $^{181}\text{Hf}$  [5]. The recent availability of energetic heavy-ion beams has made it possible to produce high-spin states in the neutron-rich Hf nuclei by inelastic excitation and transfer reactions. Our earlier work [5,6] documented the population and decay of a one-quasiparticle (1qp)  $9/2^+$  isomer with a half-life of 80  $\mu\text{s}$  in  $^{181}\text{Hf}$ . We report here on new results from a more sensitive experiment with improved analysis techniques which extend the level scheme to 3qp isomers.

**II. EXPERIMENTAL DETAILS**

Excitations in  $^{181}\text{Hf}$  nuclei were studied at the ATLAS facility at Argonne National Laboratory via the transfer of one neutron from a beam of  $^{238}\text{U}$  at 1585 MeV incident on a thick (40  $\text{mg}/\text{cm}^2$ ) enriched  $^{180}\text{Hf}$  target backed by Pb (50  $\text{mg}/\text{cm}^2$ ). The  $\gamma$  and x rays emitted by reaction products stopped in the target were detected by 98 Compton-suppressed coaxial Ge and three planar LEPS detectors in the Gammasphere array. An electrostatic deflector was used to sweep the beam on and off. The primary experiment was performed using a beam-sweeping cycle of 8.25  $\mu\text{s}$  on and 16.5  $\mu\text{s}$  off, with a secondary data set using a 2 ms on and 4 ms off cycle. Data acquisition was triggered by the first  $\gamma$  ray detected in the “beam-off” period, and data events were recorded from all detectors firing within a time interval of  $\approx 800$  ns following each trigger. An “in-beam” data set with no beam sweeping was also collected for a short time.

**III. RESULTS**

The level scheme of  $^{181}\text{Hf}$  deduced in the present work is shown in Fig. 1, where all levels and transitions above the  $9/2^+$  isomer are new. An “early-delayed”  $\gamma$ - $\gamma$  correlation

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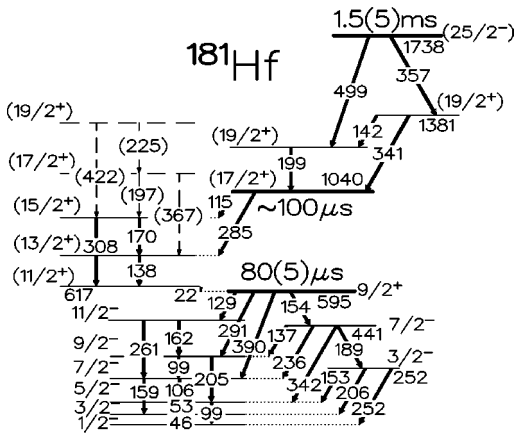


FIG. 1. Level scheme of  $^{181}\text{Hf}$  obtained from the present work. All transition and level energies are given in keV. Tentative transitions denoted by dashed lines were observed only in the “in-beam” data set (see text for details).

matrix was created by selecting only  $\gamma$  rays separated by  $>150$  ns in the same event (see Fig. 2). This suppresses the dominant “background” of “prompt”  $\gamma$ - $\gamma$  coincidence events and, given the overlap window of  $\approx 800$  ns in the Gammasphere electronics, retains only delayed coincidence relationships that occur in a 150–800 ns time window across isomers with any half-life, albeit with decreasing efficiency for increasing half-lives. A “delayed” gate on a known 390-keV transition depopulating the 80- $\mu\text{s}$   $9/2^+$  state shows five previously unobserved “early” transitions (with energies of 115, 138, 170, 285, and 308 keV), feeding the isomer (Fig. 2). By analyzing single- and double-gated spectra from  $\gamma$ - $\gamma$  coincidence matrices and  $\gamma$ - $\gamma$ - $\gamma$  cubes generated with open ( $\approx 800$  ns) time windows (Fig. 3), the coin-

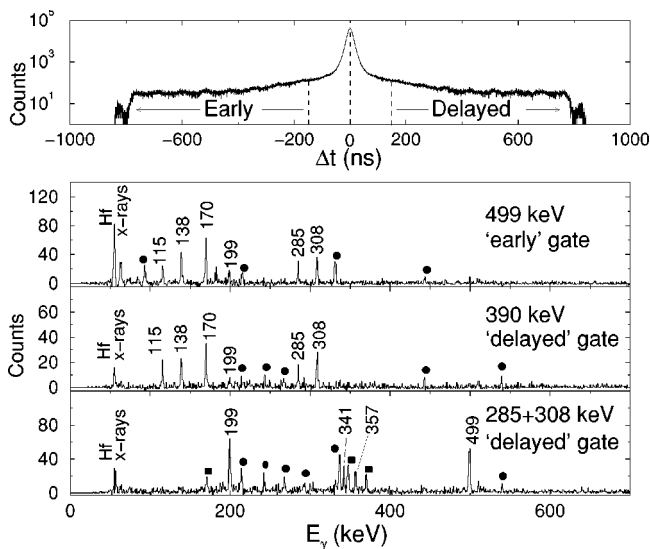


FIG. 2. Representative “early-delayed” coincidence spectra. The top panel shows a spectrum of the time difference between any two  $\gamma$  rays in an event and the gating regions used to generate an “early-delayed”  $\gamma$ - $\gamma$  correlation matrix. The peaks marked with symbols are known contaminants from  $^{180}\text{Hf}$  (solid circles) and  $^{179}\text{Hf}$  (solid squares).

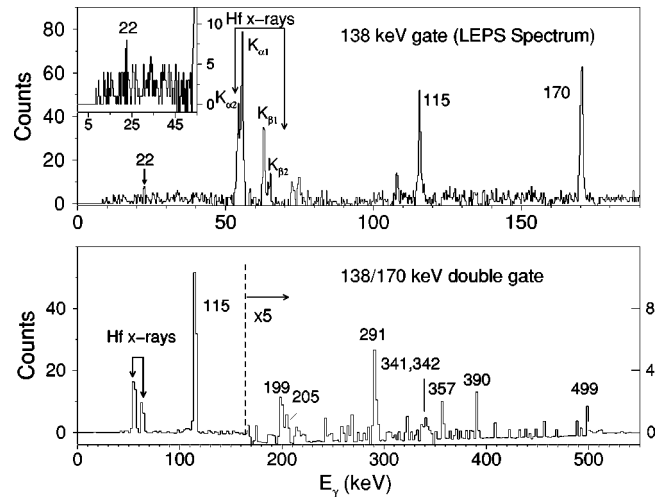


FIG. 3. (Bottom) Double-gated spectrum for the decay transitions of the intermediate isomer feeding the 80- $\mu\text{s}$  isomer. Extremely weak but clean coincidence relationships are observed with decay transitions of the 80- $\mu\text{s}$  isomer, and comparable coincident intensities are observed with transitions feeding the intermediate isomer (see text). (Top) LEPS spectrum in coincidence with a single 138-keV gate in the coaxial Ge detectors, highlighting the well-resolved Hf (and Pb) x rays and the 22-keV transition (see inset and text).

idence and intensity relations among the new transitions were used to place them as a rotational band fed from a second isomer. By further gating on the transitions of this rotational band as “delayed,” additional “early”  $\gamma$  rays were observed to populate this state from a third, higher-lying, isomeric level (Fig. 2). An “early” gate on one of the new  $\gamma$  rays (499 keV) clearly shows the intermediate rotational band (Fig. 2). The in-beam data allowed a tentative extension of this band (Fig. 1). All delayed transitions placed in the level scheme were also observed to be in coincidence with hafnium x rays.

Half-lives of the new isomers were deduced from  $\gamma$ - $\gamma$  matrices created for various time slices (in both the  $\mu\text{s}$  and ms beam-sweeping cycles). To correct for distortions of the recorded time spectra between the trigger and the beam sweeper, the  $\gamma$ - $\gamma$  intensities obtained from these matrices were normalized to those of the decay  $\gamma$  rays from the  $t_{1/2} = 5.5$  h isomer in  $^{180}\text{Hf}$ , before being fit to exponential decay functions. The procedure was checked with known half-lives ranging from 10  $\mu\text{s}$  [5] to 210  $\mu\text{s}$  [7] in neighboring nuclei. Since the half-lives of both new isomers were found to be significantly greater than a few  $\mu\text{s}$ , the analysis was concentrated on the data set with beam sweeping in the ms range, which, unfortunately, had considerably lower statistics. Figure 4 shows the normalized intensity for the 199–499-keV combination from the decay of the upper, 1738-keV isomer, where a possible two-lifetime behavior is observed. A half-life of 1.5(5) ms was obtained from a least-squares fit to the early part of the time spectrum. The essentially flat latter part suggests feeding from even higher-lying isomers with longer half-lives. The half-life of the 1040-keV isomeric state was difficult to extract, since the time spectrum is dominated by the feeding from the upper long-lived

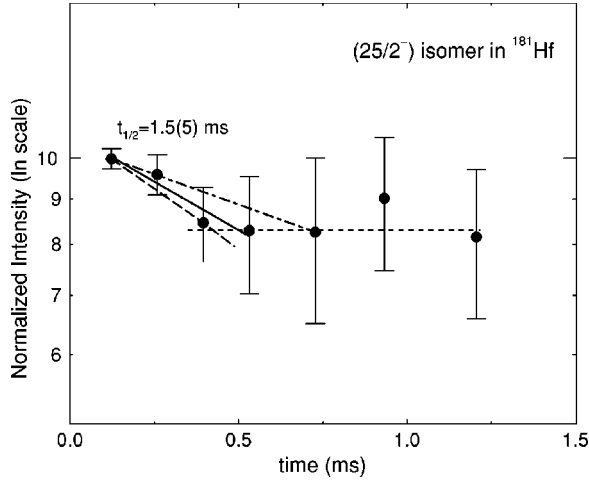


FIG. 4. Lifetime of the  $(25/2^-)$  isomer fitted to normalized intensities of the 199-keV  $\gamma$  ray in 499-keV coincidence gates. Multiple  $\gamma$ - $\gamma$  matrices were created by slicing the beam sweeper versus trigger time parameter. The solid line is a single-exponential fit to the first four data points, with the neighboring lines denoting the extent of the error bars quoted for the fit. The horizontal dashed line (drawn arbitrarily to guide the eye) suggests possible long-lived feeding from a higher isomer (see text for details).

level with  $t_{1/2} = 1.5$  ms. An estimate of the half-life can be made from the observed intensities of  $\gamma$  rays seen across the intermediate isomer in double-gated spectra from the delayed  $\gamma$ - $\gamma$ - $\gamma$  cube (cf. 138/170 gate in Fig. 3), compared with intensities of  $\gamma$  rays observed across the lower isomeric state with a measured  $t_{1/2} = 80$   $\mu$ s. Comparable intensities suggest a half-life of the order of 100  $\mu$ s. Fits to the normalized intensity ratios of double-gated time spectra as described above were attempted for the early part of the decay in the ms time range. Fitted values to the low-statistics data fluctuate in the 100–400  $\mu$ s time range. Earlier preliminary reports of this work [8] had severely underestimated the half-life of this isomer. Table I lists the properties of states and  $\gamma$  rays observed in the decay of new 3qp isomers in  $^{181}\text{Hf}$ .

#### IV. DISCUSSION

The primary focus of this experiment was on the decay spectroscopy of long-lived isomers, with very little data on prompt  $\gamma$  rays or on the decay of short-lived levels. The long half-lives of the isomers preclude any angular distribution analysis, since spin alignments are washed out. Our assignments of  $\gamma$ -ray multiplicities and level spins and parities, therefore, rely on intensity balances, branching ratios, and single-particle half-life estimates, as well as comparisons with expected quasiparticle excitation energies near the yrast line. The quantum numbers  $J^\pi$  for the ground state of  $^{181}\text{Hf}$  are  $1/2^-$ , with the valence neutron occupying the  $\nu[510]1/2^-$  orbital. As far as 1qp states are concerned, we had established, in our previous work [5], the  $\nu[624]9/2^+$  state at an excitation energy of 595 keV. This level was found to decay primarily to a rotational band built on the  $1/2^-$  orbital, which we had extended to  $11/2^-$ . We had also observed a 154-keV decay branch to a 441-keV state which in turn decayed via a 342-keV transition to the  $5/2^-$  member of the  $1/2^-$  rotational band. Our earlier tentative assignment of  $7/2^-$  for the 441-keV level was confirmed in the present work through the observation of two new decay branches of 236 and 137 keV to the  $7/2^-$  and  $9/2^-$  members of the  $1/2^-$  rotational band. Another new 189-keV decay branch from this level was observed to populate the known  $\nu[512]3/2^-$  state at an excitation energy of 252 keV. A previous tentative configuration assignment for the 441-keV  $7/2^-$  state as a member of the  $\nu[512]3/2^-$  band [9] seems tenuous, as no decays are observed to any intermediate  $5/2^-$  state. A tentative configuration assignment of  $\nu[503]7/2^-$  for the 441-keV level seems more reasonable and is consistent with energy systematics in neighboring nuclei.

High- $K$  configurations expected to lie especially low in this nucleus are those associated with the  $\nu[624]9/2^+$  and the  $\nu[615]11/2^+$  levels for neutrons and with the  $\pi[514]9/2^-$  and the  $\pi[404]7/2^+$  states for the protons. The well-known  $\pi^2(8^-)$  combination, which is observed throughout the even-even Hf isotopic chain, lies at an exci-

TABLE I. Properties of states and  $\gamma$  rays observed in the decay of new 3qp isomers in  $^{181}\text{Hf}$ .

$E_x^{isomer}$ (keV)	$J_{isomer}^\pi$	$E_\gamma$ (keV)	$E_x$ (keV)	$I_\gamma^a$	$J_i^\pi$	$J_f^\pi$	$E_\lambda/M_\lambda$	$\alpha_{tot}$
1040	$(17/2^+)$	22.1	617	$4.6 \pm 1.5$	$(11/2^+)$	$9/2^+$	$M1$	59.8
		115.3	1040	$61 \pm 3$	$(17/2^+)$	$(15/2^+)$	$M1$	2.76
		138.4	755	$83 \pm 5$	$(13/2^+)$	$(11/2^+)$	$M1$	1.64
		169.5	925	$100 \pm 3$	$(15/2^+)$	$(13/2^+)$	$M1$	0.91
		284.9	1040	$37 \pm 2$	$(17/2^+)$	$(13/2^+)$	$E2$	0.09
		308.1	925	$52 \pm 3$	$(15/2^+)$	$(11/2^+)$	$E2$	0.07
1738	$(25/2^-)$	142.4	1381	$1.2 \pm 0.3$	$(19/2^+)$	$(19/2^+)$	$M1$	1.51
		199.3	1239	$69 \pm 2$	$(19/2^+)$	$(17/2^+)$	$M1$	0.59
		341.4	1381	$15 \pm 2$	$(19/2^+)$	$(17/2^+)$	$M1$	0.14
		357.0	1738	$19 \pm 2$	$(25/2^-)$	$(19/2^+)$	$E3$	0.18
		499.2	1738	$100 \pm 3$	$(25/2^-)$	$(19/2^+)$	$E3$	0.06

<sup>a</sup>Intensities are separately normalized to the strongest  $\gamma$  ray in the decay of each of the two new isomers. The two normalizations are estimated to be within 10% of each other.

tation energy of  $\approx 1$  MeV in the neighboring  $^{180}\text{Hf}$  and  $^{182}\text{Hf}$  nuclei [5]. Our earlier placement of the  $\nu[624]9/2^+$  state at an excitation energy of 595 keV agreed with transfer reaction results of Burke *et al.* [10], who had reported the observation of a level at  $600 \pm 5$  keV using a  $^{179}\text{Hf}(t,p)^{181}\text{Hf}$  reaction. While no direct evidence for the  $\nu[615]11/2^+$  state had been found in our previous work [5], Burke *et al.* had proposed a  $11/2^+$  assignment to a level lying  $22 \pm 3$  keV above the  $9/2^+$  state. These authors argued that, due to the Coriolis mixing with the  $11/2^+$  rotational state of the  $9/2^+$  band, the intrinsic  $\nu[615]11/2^+$  level is pushed down in energy. Their Coriolis-mixing calculations had provided a consistent fit to five observed states, which included the  $9/2^+$ ,  $11/2^+$ , and  $13/2^+$  members of the  $\nu[624]9/2^+$  band and the  $11/2^+$  and  $13/2^+$  members of the  $\nu[615]11/2^+$  sequence. Their measured level energies lead to an energy difference of  $142 \pm 3$  keV between the  $13/2^+$  and  $11/2^+$  members of the  $\nu[615]11/2^+$  band and a difference of  $204 \pm 3$  keV between the  $11/2^+$  and  $9/2^+$  members of the  $\nu[624]9/2^+$  band. The lowest band transition of 138 keV in our work is in good agreement with their  $13/2^+ \rightarrow 11/2^+$  energy difference for the sequence based on the  $11/2^+$  bandhead. Multipolarity assignments of  $M1$  to the 138-, 170-, and 115-keV transitions and  $E2$  to the 308- and 285-keV  $\gamma$  rays satisfy intensity balance requirements. The large electron conversion coefficient of 60 for a 22-keV  $M1$  transition leaves very little intensity in the  $\gamma$  branch for a  $11/2^+ \rightarrow 9/2^+$  transition. While the efficiency of the coaxial detectors in our experimental setup was too small for the detection of any  $\gamma$  ray below  $\approx 50$  keV, the LEPS detectors were ideally suited for this purpose. Although the statistics accumulated with just three LEPS detectors was relatively poor, a discernible peak at 22 keV was observed in the LEPS spectrum in coincidence with a 138-keV transition observed in the coaxial Ge detectors (see Fig. 3). The counts in the peak satisfy the intensity balance with a total conversion coefficient  $\alpha_{tot} = 60 \pm 20$ , which is in excellent agreement with an  $M1$  assignment [ $\alpha_{tot}(M1) = 60$ ,  $\alpha_{tot}(E1) = 4.3$ ,  $\alpha_{tot}(M2) = 9700$ ,  $\alpha_{tot}(E2) = 4200$ ]. As discussed below, additional experimental information and comparisons with theoretical expectations lead to the level scheme presented in Fig. 1, with the new rotational band placed on a  $\nu[615]11/2^+$  bandhead at 617 keV, which decays via a  $K$ -allowed, 22-keV  $M1$  transition to the  $\nu[624]9/2^+$  state at 595 keV.

While the systematics of the  $\nu[624]9/2^+$  state is well documented in the lighter odd- $A$  Hf isotopes, data on the  $\nu[615]11/2^+$  level are lacking, since the orbital is only expected to approach the Fermi level for neutron-rich Hf isotopes. This  $11/2^+$  level is observed, however, in the higher- $Z$  isotones of W, Os, and Pt [9,11]. The systematic trend of excitation energies for the  $\nu[624]9/2^+$  and  $\nu[615]11/2^+$  levels in the  $N=109$  isotones is shown in Fig. 5, highlighting their close proximity in  $^{181}\text{Hf}$ . The  $M1$  transition energies of 138 keV and 170 keV (with a 308-keV  $E2$  crossover transition) in the rotational band are consistent with the systematics of rotational bands built on  $11/2^+$  bandheads in the region [9,11], considering the energy perturbations expected

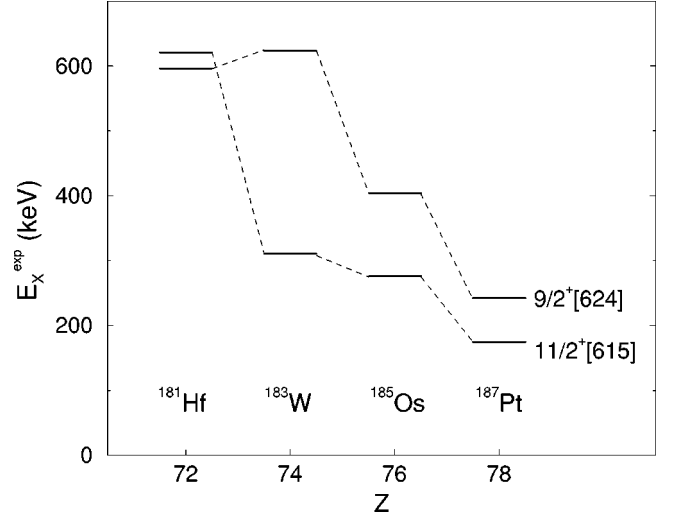


FIG. 5. Systematics of the experimental excitation energies of  $\nu[624]9/2^+$  and  $\nu[615]11/2^+$  orbitals in the  $N=109$  isotones.

from the strong mixing between the  $\nu[624]9/2^+$  and  $\nu[615]11/2^+$  orbitals. It should be noted that the levels suggested by Burke *et al.* [10] that comprise the nonyrast excitations above the  $9/2^+$  bandhead do not seem to be populated with any observable strength from the decay of higher-lying isomers in our data.

Typically,  $|(g_K - g_R)/Q_0|$  values extracted from the  $M1/E2$   $\gamma$ -branching ratios in high- $K$  bands provide a solid experimental observable for use in configuration assignments. Unfortunately, in the present case, Coriolis effects complicate the analysis in two ways. First, the strong Coriolis mixing of the wave functions of the two configurations, arising from the closeness in their excitation energies, dilutes the definition of the  $K$  quantum number. Furthermore, the individual  $\nu[624]9/2^+$  and  $\nu[615]11/2^+$  orbitals are strongly influenced by Coriolis alignment effects, and theoretical  $g_K$  values have to be modified to include alignment contributions in order to compare with experiment. Effective  $g_K$  factors, which include alignment contributions, can be calculated for 1qp bands using the formula [12]

$$g_K^{eff} - g_R = (g_K - g_R) \left( 1 - \frac{i_j}{\sqrt{I^2 - K^2}} \right), \quad (4.1)$$

where  $i_j$  is the aligned angular momentum. With an  $i_j$  value of  $\approx 1\hbar$  and typical values for this region of  $g_R = 0.28$ ,  $Q_0$  of 7.0 e b, and a quenching factor of 0.6 for the spin  $g$  factor, the effective  $|(g_K - g_R)/Q_0|$  value, using  $K = 11/2$ , is calculated to be 0.056. Reasonable variations in the chosen parameters can change this number by  $\approx 10\%$ . Measurable intensities are available only from the bottom fragment of the band populated through the decay of higher-lying isomers. Consequently, only a single  $|(g_K - g_R)/Q_0|$  value could be extracted from the  $M1/E2$  intensity ratio of the 170-keV and 308-keV  $\gamma$ -ray branches depopulating the  $J^\pi = 15/2^+$  rotational state. The extracted values are 0.040(4) and 0.072(6) for  $K$  values of 11/2 and 9/2, respectively. Coriolis mixing would return a value in between these two extremes. An

estimate of the amount of mixing can be made along the lines of Burke *et al.* [10]. The unperturbed energies for the rotational states of the  $9/2^+$  band are calculated using the transition energies of the corresponding band observed in  $^{179}\text{Hf}$ , where the  $\nu[615]11/2^+$  state is located at a much higher excitation energy and no appreciable mixing can occur. The analysis leads to a  $\approx 50/50$  admixture of the  $K=9/2$  and  $K=11/2$  components in the observed  $11/2^+$  bandhead, which translates to a  $|(g_K - g_R)/Q_0|$  value of 0.056(5) extracted from the  $M1/E2$  intensity ratio, consistent with the effective value calculated above. (Using  $K=9/2$  changes the calculated effective value from 0.056 to 0.058.) Our new data on 3qp isomers and their decays lend additional support for a  $11/2^+$  bandhead assignment.

Low-lying 3qp excitations in the odd- $A$  Hf nuclei are typically seen to involve the  $\pi^2(8^-)$  state coupled to quasineutron states. The lowest 3qp excitation expected in  $^{181}\text{Hf}$  is a  $17/2^+$  state, which corresponds to the  $\pi^2(8^-)$  configuration coupled to the  $1/2^-$  quasineutron ground state. A possible antialigned coupling of the neutron spin, leading to a  $15/2^+$  state, is expected to lie  $\approx 200$  keV higher due to residual interactions. The  $17/2^+$  state would very likely be a  $K$  isomer, since the levels expected immediately below correspond to rotational excitations built on the 1qp  $K=9/2$  or  $K=11/2$  states. A  $J^\pi$  assignment of  $(17/2^+)$  for the 1040-keV isomer fits well with the observed decay pattern that feeds the rotational band built on the  $11/2^+$  bandhead. For the 1738-keV isomer, the ms half-life and conversion coefficients necessary for satisfying intensity balances leads to multipolarity assignments of  $E3$  for both the 499-keV and 357-keV transitions (84% and 16% decay branches, respectively) and  $M1$  for the 199-keV and 341-keV transitions. This leads to a tentative  $J^\pi$  assignment of  $(25/2^-)$  for the 1738-keV isomer. Expected 3qp excitations above the  $17/2^+$  state are the  $\pi^2(8^-)$  configuration coupled to the neutron  $3/2^-$ ,  $7/2^-$ ,  $9/2^+$ , and  $11/2^+$  states, leading to  $19/2^+$ ,  $23/2^+$ ,  $25/2^-$ , and  $27/2^-$  levels, respectively. The partial half-life of  $9 \pm 3$  ms for the 357-keV decay branch of the 1738-keV isomer to the  $(19/2^+)$  state at 1381 keV is consistent with a  $K$ -allowed  $E3$  decay to an intrinsic  $K=19/2$  state. The Weisskopf estimate for the half-life of such an  $E3$  transition is 0.9 ms, while half-lives for other multiplicities differ by at least two orders of magnitude. The 142-keV transition connecting the two states with tentative spin-parity assignments of  $(19/2^+)$  is very weak. The  $\gamma$ -ray energy of 199 keV is consistent with that expected for the first  $M1$  transition of a rotational band built on a  $17/2^+$  bandhead (cf. energies of 185 keV and 210 keV for analogous transitions in  $^{179}\text{Hf}$  [13]). The 499-keV  $\gamma$  ray would then be a  $K$ -hindered decay with  $\Delta K=4$  and a degree of forbiddenness,  $\nu=\Delta K-\lambda$ , of 1, where  $\lambda$  is the transition multipolarity. A possible  $M2$  decay to a yet-to-be-located  $21/2^+$  state of the  $17/2^+$  rotational band, while energetically allowed, was not observed. This scenario would be analogous, for example, to the  $\Delta K=4$  decay of a  $12^+$  isomer in  $^{180}\text{Hf}$  to the rotational members of a  $K=8$  band, where the  $E3$   $\gamma$ -decay path (with  $\nu=1$ ) competes with the  $E1$  branch (with  $\nu=3$ ), and is a factor of 30 stronger than the  $M2$  path (with  $\nu=2$ ). The

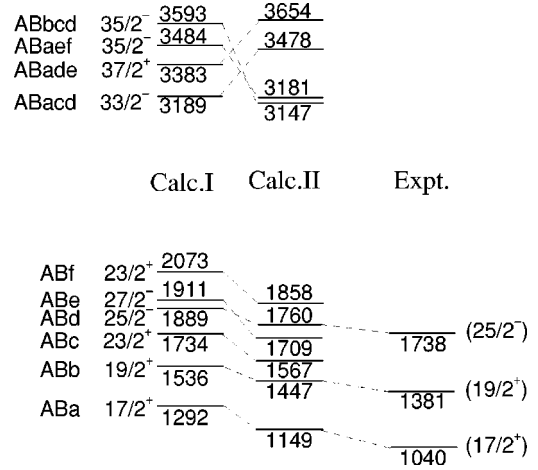


FIG. 6. Experimentally observed excitation energies of low-lying 3qp states in  $^{181}\text{Hf}$  compared with theoretical calculations (which include low-lying 5qp states). Calc. I and II refer to blocked BCS calculations without and with residual interactions, respectively (see text). The single-particle orbitals are A,  $\pi[514]9/2^-$ ; B,  $\pi[404]7/2^+$ ; a,  $\nu[510]1/2^-$ ; b,  $\nu[512]3/2^-$ ; c,  $\nu[503]7/2^-$ ; d,  $\nu[624]9/2^+$ ; e,  $\nu[615]11/2^+$ ; and f,  $\nu[514]7/2^-$ .

absence of an  $E1$  branch in our case could be explained if the rotational  $23/2^+$  state were located just above the  $(25/2^-)$  isomer. The reduced hindrance  $f_\nu = (t_{\text{expt}}^\gamma / t_{1/2}^W)^\nu$  (where  $t_{\text{expt}}^\gamma$  is the partial  $\gamma$ -ray half-life and  $t_{1/2}^W$  is the corresponding Weisskopf single-particle estimate) for the  $E3$  decay is  $22 \pm 7$ . This is consistent with an observed range of 10–150 for  $K$ -hindered  $E3$  transitions in this region [5,9,13]. The level scheme indicates that both the new 3qp isomers are yrast isomers.

Blocked BCS calculations of the type described in Ref. [14] were performed for  $^{181}\text{Hf}$ , and effective residual interactions were calculated by summing the nucleon-nucleon interactions of all possible 2qp combinations [15,16]. The calculated energy levels with and without residual interactions are presented in Fig. 6. In these calculations, the single-particle orbitals have been matched to  $^{181}\text{Hf}$  (neutrons) and  $^{181}\text{Ta}$  (protons). Monopole pairing strengths of 22.0 MeV/nucleon (neutrons) and 23.0 MeV/nucleon (protons) were used. The good agreement with calculations for the energies of the new 3qp isomers provides further support for our spin-parity assignments. In these calculations, residual interactions are seen to push the  $27/2^-$  state just below the  $25/2^-$  level. This  $27/2^-$  state is not observed in our out-of-beam data, which suggests that the  $27/2^-$  state probably lies above the  $(25/2^-)$  isomer and decays via a  $K$ -allowed transition to the  $(25/2^-)$  isomer. Close proximity between the two states is expected, given that the constituent one-quasineutron orbitals, which couple with the same two-quasiproton configuration to form these states, lie only 22 keV apart. Predictions for the lowest-lying 5qp states are also presented in Fig. 6. Residual interactions seem to favor two possible  $35/2^-$   $3\nu-2\pi$  states as the lowest 5qp levels at around 3.1 MeV. The experimental evidence for long-lived feeding of the  $(25/2^-)$  isomer suggests that such states at higher angular momenta are possibly being populated.

## V. CONCLUSION

In conclusion, the “out-of-beam” experiments presented here have been successful in identifying high- $K$  configurations and long-lived isomers in the neutron-rich  $^{181}\text{Hf}$  nucleus. We have observed 3qp  $K$  isomers in neutron-rich  $^{181}\text{Hf}$ , with tentative  $J^\pi$  assignments of  $(17/2^+)$  and  $(25/2^-)$ , populated by one-neutron transfer from  $^{238}\text{U}$  beams. Using Gammasphere, they were identified with “early-delayed” coincidence techniques across isomers with half-lives as long as  $\approx 100 \mu\text{s}$ . The observation of a rotational band built on a  $\nu[615]11/2^+$  orbital in odd- $A$  Hf nuclei and its close proximity to the  $\nu[624]9/2^+$  orbital provides a rich arena for extending into the neutron-rich region the study of strong Coriolis mixing and alignment effects on

high- $K$  orbitals. Blocked BCS calculations with residual interactions are in good agreement with the observed 3qp states. These results provide the foundation for experiments planned in the near future to study the collective rotational structures built on these multiquasiparticle excitations. These complementary data are essential for a comprehensive discussion of the evolution of properties such as deformation and pairing strength with increasing neutron number beyond the line of  $\beta$  stability.

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