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K-isomers in Hf nuclei at and beyond the neutron-rich edge of β-stability

P. Chowdhury[a], R. D'Alarcao[a], E.H. Seabury[a], P.M. Walker[b], C. Wheldon[b], I. Ahmad[c], M.P. Carpenter[c], G. Hackman[c], R.V.F. Janssens[c], T.L. Khoo[c], D. Nisius[c] and P. Reiter[c]

[a]Department of Physics, University of Massachusetts, Lowell, MA 01854, USA

[b]Department of Physics, University of Surrey, Guildford GU2 5XH, UK

[c]Argonne National Laboratory, Argonne, IL 60439, USA

New high-K isomers are populated in ^{180,181,182}Hf nuclei via inelastic excitation and transfer reactions, using pulsed ^{238}U beams on Hf targets. The new data explore K-hindrances for different multipolarities and the role of residual spin-spin interactions for multi-quasiparticle (qp) configurations at the neutron-rich edge of the β-stability line. The mapping of 4-qp K-isomers in the A≈180 region is extended into neutron-rich territory.

1. MOTIVATION AND EXPERIMENT

One of the more potent arenas where the K quantum number can be studied up to high angular momenta is the A≈180 region, where both neutrons and protons can occupy high-Ω orbitals simultaneously. The Hf nuclei, in particular, provide textbook examples of multi-qp K-isomers, such as the 6-qp $K^\pi = 22^-$ isomer in ^{176}Hf ($t_{1/2} = 43\mu$s) and the classic 4-qp $K^\pi = 16^+$ isomer ($t_{1/2} = 31$ years) [1]. Long-standing predictions [2] of high-K isomers in A≥180 Hf nuclei (where ^{180}Hf is the heaviest stable isotope), however, have remained untested for almost two decades, since fusion reactions with stable beams and targets are ineffective for producing neutron-rich nuclei at high spins. Recent progress in experimental techniques using inelastic excitation and transfer reactions with heavy beams [3] has motivated our current exploration of the neutron-rich Hf isotopes [4].

Prior information on K-isomers in the A≥180 even-Hf nuclei was restricted to long-lived 2-qp 8^- states, known from β-decay studies in ^{180,182}Hf [1] and a recent transfer reaction study in ^{184}Hf [5]. In our study, a 1.6 GeV ^{238}U beam, provided by the ATLAS facility at Argonne National Laboratory, was incident on thick Pb-backed targets of natural Hf as well as isotopically enriched ^{180}Hf. A sweeper was used to switch the beam micropulses (82.5 ns separation) off and on in three different time periods (1.65, 165 and 1650 μs), with an on:off ratio of 1:4. The γ rays were detected only in the beam-off intervals by the 12 CSG detectors of the Argonne-Notre Dame BGO array. For each γ ray in an event, the energy as well as the time with respect to the master trigger (first Ge detector firing in the beam-off interval) was recorded. In addition, an electronic TAC, started by the beam-sweeper pulse and stopped by the master trigger, was used to tag each event. Time spectra for individual γ rays from this TAC were used to measure half-lives. Decay schemes of isomers were deduced from γ-γ coincidences.

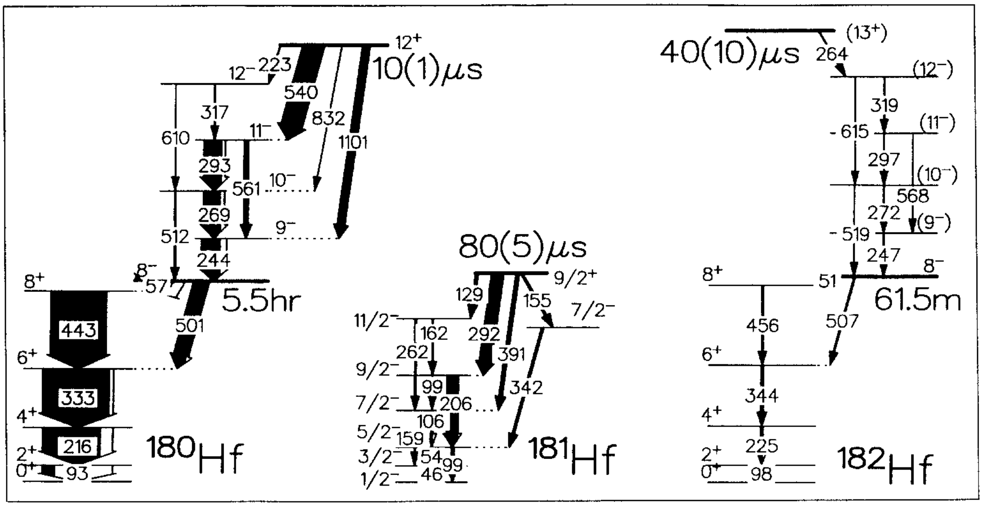

Figure 1. Decay scheme of new high-K isomers in ^{180,181,182}Hf. New data from the present work include all states above the 8^- isomers in ^{180,182}Hf, and above J=7/2 in ^{181}Hf. Note that the energy scale for ^{181}Hf is expanded by a factor of 2.

2. RESULTS AND DISCUSSION

Multiple new isomers were populated in this study with half-lives of the order of a few μs. The most strongly populated isomer, with a measured half-life of $10\pm1\mu$s, is placed in ^{180}Hf and assigned a K^π of 12^+ (Fig.1). The isomer decays to a new strongly-coupled rotational band. The transitions in the decay are coincident with Hf X-rays, and are the strongest new peaks that are present in the spectra of both the ^{nat}Hf and ^{180}Hf targets. The rotational band is most likely built on the known 8^- isomer, based on the energy systematics of bands built on two-quasiproton 8^- isomers in even-A Hf nuclei. Coincidences are not measurable across the 5.5 hr half-life of the 8^- state. However, with the normal assumption of M1 and E2 multipolarities for the band transitions, the M1/E2 branching ratios provide an estimate of the quantity $|(g_K - g_R)/Q_0|$. This ratio is expected to be a constant for a rotational band built on an intrinsic configuration. With values of g_R=0.28 and Q_0=7 eb which are typical for this region, the expected $|(g_K - g_R)/Q_0|$ ratio for the $\pi 7/2^+[404]\otimes\pi 9/2^-[514]$ two-quasiproton 8^- bandhead is 0.103, and the ratio obtained from the measured M1/E2 branching ratios is 0.106(6). This agreement provides additional support for the placement of the new rotational band atop the 8^- bandhead. The spin-parity assignment and decay of the new isomer is discussed later in the paper.

New isomers were also populated in the neutron-rich A>180 Hf nuclei through neutron transfer from the projectile to the target. A new isomer with a half-life of 80 ± 5 μs is placed in ^{181}Hf at an excitation energy of 594 keV, with a tentative K^π assignment of $9/2^+$ based on the measured decay scheme. This agrees with a previous $\nu 9/2^+[624]$

configuration assignment to a state observed at an excitation energy of 600±5 keV in (t,p) reactions [6]. Another new isomer, with a half-life of 40±10 μs, decays to a new rotational band very similar to the one placed on top of the 8^- isomer in ^{180}Hf. The four dipole transitions in the band each have energies exactly 3 keV larger than the analogous transitions in ^{180}Hf. The intensity of the new band is a factor of 30 lower compared to the band in ^{180}Hf. This same factor of 30 is observed when we compare the intensities of the ground-state-band transitions populated in the decay of the 2-qp 8^- isomers in ^{180}Hf and ^{182}Hf. Following the same prescription described above for ^{180}Hf, the $|(g_K - g_R)/Q_0|$ ratio obtained for this band is 0.11(3), again consistent with a $\pi 7/2^+[404] \otimes \pi 9/2^-[514]$ two-quasiproton assignment for the 8^- bandhead. Based on these observations, the new band is placed on top of the previously known 8^- isomer in ^{182}Hf.

The placement of the new rotational bands on top of the 8^- isomers in the ^{180,182}Hf nuclei leads to spin assignments for the new isomers themselves. The isomer in ^{180}Hf exhibits four decay branches to the 9^-, 10^-, 11^- and 12^- members of the rotational band built on the 2-quasiproton 8^- isomer. Intensity analysis of the decay pattern, where the two strong branches are to the 11^-(75%) and the 9^-(23%) states, leads to a K^π assignment of 12^+ for the isomer. The assignment is further strengthened by comparison with estimates of multi-qp excitation energies from blocked-BCS type calculations [7] for a 4-qp 12^+ state with a $\pi^2 8^- \otimes \nu 9/2^+[624] \otimes \nu 1/2^-[510]$ configuration, as discussed later (see Fig.3).

The two strong decay branches from the 12^+ isomeric state are thus of E1 and E3 character, and provide an excellent demonstration of hindrances associated with the K quantum number. A transition of multipolarity λ is forbidden to first order if $|\Delta K|$ between the initial and final state is greater than λ. In practice, such transitions occur via higher order corrections, and are hindered by large factors, which are typically of magnitude 10^2 for each order of K-forbiddenness [8], which is defined as $\nu = |\Delta K| - \lambda$. Ordinarily, the single-particle estimate for the partial half-life of an E3 decay branch is orders of magnitude longer than an E1 branch. In this case, however, since ΔK=4 for a K=12 isomer decaying to a K=8 band, we have ν=1 for an E3 and ν=3 for an E1 branch. The larger K-hindrance for the E1 transition thus allows the E3 to compete effectively.

The single decay branch observed from the new isomer placed in ^{182}Hf is consistent with a tentative spin-parity assignment of (13^+). Comparison with calculations point towards a $\pi^2 8^- \otimes \nu^2 5^-$ configuration, where the $\nu^2 5^-$ is the coupling of the $\nu 11/2^+[615]$ to the $\nu 1/2^-[510]$ orbital. This extends the systematics of 4-qp K-isomers in the A≈180 region beyond the neutron-rich edge of the β-stability line (Fig.2).

The measured excitation energies of the isomers are compared with predictions from blocked-BCS type calculations [7] in Fig.3. While residual interactions are not included explicitly in these calculations, the pairing strengths are chosen to provide realistic estimates of the energies for "favored" couplings of like-nucleon spin-singlet configurations. The new 4-qp isomers in both ^{180}Hf and ^{182}Hf demonstrate the affinity for such "favored" couplings rather pointedly with the common presence of the $\nu 1/2^-[510]$ orbital. The two quasi-neutrons prefer to couple to $K_{max}-1$ rather than to K_{max}, in order to take advantage of the spin-singlet configuration. In earlier calculations [9], where only K_{max} couplings had been calculated, the K_{max}=13 coupling had been predicted to be the lower state in ^{180}Hf for that particular configuration. The K=12 level now appears as the isomer. Using

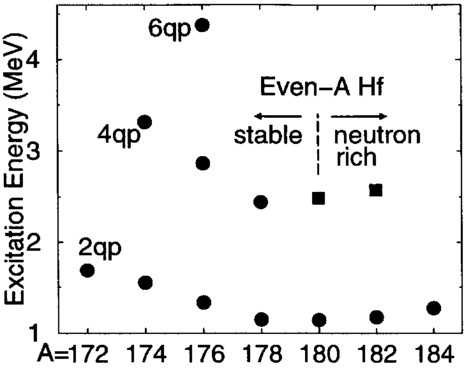

Figure 2. Systematics of the lowest 2-, 4- and 6-qp isomers observed in even-A Hf nuclei. Squares denote present work.

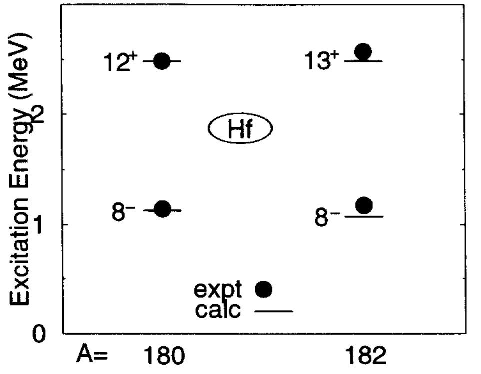

Figure 3. Comparison of excitation energies of 2- and 4-qp isomers in ^{180,182}Hf nuclei with predictions (see text).

the empirical values of the residual interactions from the same reference [9], we estimate the K=12 state to be lowered by ≈200 keV compared to the K_{max}=13 configuration.

3. SUMMARY

We have populated and measured spectroscopic properties of multi-qp K-isomers in neutron-rich ^{180,181,182}Hf nuclei, using inelastic excitations and transfer reactions. 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. The K quantum number is found to be robust and residual spin-spin interactions important for multi-qp isomeric configurations at the neutron-rich edge of the β-stability line. This work was supported by US DOE contracts DE-FG02-94ER40848 and W-31-109-ENG38, and by the UK ESPRC.

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