Inelastic excitation of new high-spin yrast isomers in ^{180}Ta

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For the first time, six-quasiparticle isomers have been observed in the meta-stable nucleus $^{180}_{73}\mathrm{Ta}_{107}$. Two new high-spin isomers were populated following deep-inelastic reactions with a pulsed $^{238}_{92}$U beam incident on a thick $^{180}_{72}$Hf target. Out-of-beam γ-ray events were collected using the Gammasphere germanium detector array. In addition to the known four-quasiparticle isomers, yrast $K^{\pi}=(22^{-})$ and $K\geqslant 23$ six-quasiparticle isomers have been observed with microsecond half-lives. These are the highest-spin isomers observed using the technique of deep-inelastic excitation. The assignments are compared to predictions made by BCS and Lipkin-Nogami multiquasiparticle calculations.

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The structure and excitations of the rare isotope ^{180}Ta are of considerable current interest, for example Refs. [1–3], arising from its unique status as the only isotope to occur naturally in an isomeric state. The 1^{+} ground-state has a half-life of only 8 hours, whereas an excited 9^{-} state lying at 75 keV, has a lifetime of $>10^{15}$ years. The direct decay of this isomer is highly hindered due to a combination of its low excitation energy and high spin, relative to the ground state. Several studies have attempted to explain the production and survival of this spin-trap isomer in stellar environments, most recently Ref. [1].

This odd-odd nucleus with 73 protons and 107 neutrons lies in a region of the nuclear chart where large prolate deformations are energetically favored. This leads to partial conservation of the angular momentum projection K on the nuclear symmetry axis [4]. The decay of these intrinsic states to the competing collective rotational levels is hindered, providing a sensitive probe of the underlying structure of the nucleus.

Previous experiments to study the yrast structure of ^{180}Ta have used light heavy-ion projectiles, namely, $^{11}_{5}$B and $^{7}_{3}$Li on targets of ^{176}Yb [2,3]. Several new isomers have been observed using these partial fusion and fusion-evaporation reactions, including a 31 μs $K^{\pi}=15^{-}$ four-quasiparticle state [5]. However, this technique is limited to $\sim 20\,\hbar$ of angular momentum. Recently, experiments using deep-inelastic reactions [6–8] have enabled states with spins up to $\sim 30\,\hbar$ to be reached [9] and K isomers have been populated in neutron-rich nuclei that cannot be accessed using fusion-evaporation reactions with stable beams and targets [10–12]. The first isomers at spins $>20\,\hbar$, using this method of transfer and inelastic excitation are now reported.

A 1.6 GeV pulsed $^{238}_{92}$U beam provided by the ATLAS accelerator facility at Argonne National Laboratory was used to bombard a thick target (≈ 40 mg cm^{-2}) of $^{180}_{72}$Hf, backed by $\geqslant 50$ mg cm^{-2} of $^{\mathrm{nat}}$Pb. The beam energy was chosen to be 15% above the Coulomb barrier, consistent with Refs. [11,12]. The target was enriched to 98.2% in ^{180}Hf, the heaviest stable isotope, to favor the population of neutron-rich products. The natural pulsing period of the beam is 82.5 ns, and this was swept on two longer time ranges with ON/OFF conditions of 8.25 μs/16.5 μs and 2 ms/4 ms (corresponding to 100/200 and 24 250/48 500 beam bursts, respectively). All of the recoils were stopped at the target position at the focus of the Gammasphere array, comprised of 98 γ-ray Compton-suppressed germanium detectors and 3 Compton-suppressed planar x-ray germanium detectors. The trigger condition required at least one germanium detector to fire in the beam-off period. These delayed events were sorted into γ-γ, γ-x-ray and γ-time matrices and a γ-γ-γ cube, allowing level schemes and half-lives to be deduced from coincidence relations. A wide variety of targetlike isomers have been observed from $^{171}_{69}$Tm up to $^{189}_{77}$Ir, together with a large number of nuclei from the fission of uranium. The most intense out-of-beam decays are those from the inelastically excited isomers in the ^{180}Hf target [12], but the one-proton transfer channels to tantalum nuclei are also strongly populated.

A new isomer was observed in ^{180}Ta, feeding the known states in the $K^{\pi}=19^{-}$ band based on the 2899 keV level [2,3] via transitions with energies of 492 and 370 keV. The level scheme is shown in Fig. 1. From the coincidence spectrum gated by the 365 keV transition [Fig. 2 (top)] it can be seen that the new 492 keV γ ray is much weaker than the 370 keV and subsequent decays (≈ 25% of the γ-ray intensity). A probable explanation for the difference in coincidence intensity is the presence of an intermediate half-life. The time window for γ-ray coincidences to be in the same event remains open for 800 ns. A half-life of 2.0 ± 0.5 μs for

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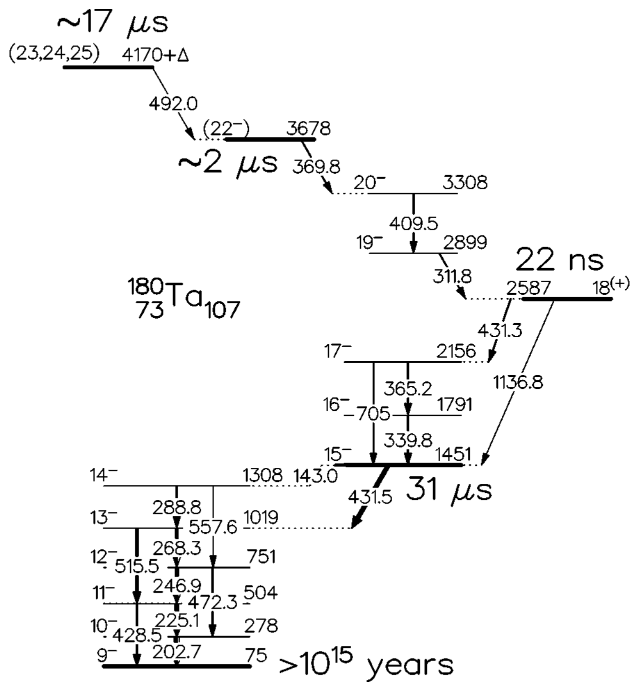

FIG. 1. Decay scheme for the new six-quasiparticle isomers in ^{180}Ta observed in the present work. The spins and parities for states below the (22^-) 3678 keV level are taken from Refs. [2,3].

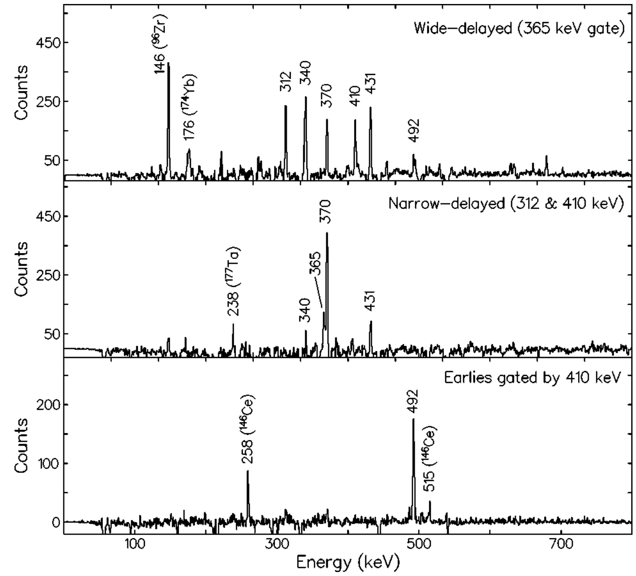

FIG. 2. The top panel shows delayed γ rays gated by the 365 keV transition in ^{180}Ta with an 800 ns coincidence window. The middle panel shows the ''logical and'' of two delayed spectra, obtained from single gates on the 312 and 410 keV transitions with a narrow ± 10 ns coincidence condition. (A ''logical and'' compares the counts per channel in two individual spectra, and displays the smaller of the two per channel [13]. This helps to reduce contaminant γ rays.) The 492 keV decay is no longer present and the intensity of the transitions below the 22 ns isomer is reduced. The bottom spectrum shows the ''early'' transitions which precede the 410 keV γ ray by between 40 and 800 ns. Known contaminant γ rays are labeled by their energy and associated nuclide.

the 3678 keV level would allow $\approx 25\%$ of the coincidences to fall inside of the 800 ns window. This half-life is confirmed by the absence of the 492 keV transition when the coincidence window is reduced to 20 ns [Fig. 2 (middle)]. (The transitions below the 22 ns isomer also have reduced intensity in this spectrum.) The 492 keV transition can be cleanly observed by gating on the 410 keV γ ray and projecting the coincidence events observed between 40 and 800 ns earlier, as shown in Fig. 2 (bottom).

All of the γ rays below the 4170 keV level are contaminated [see, for example, Fig. 2 (top)] precluding a half-life measurement using the γ-time matrix. In addition the time spectra for the 16.5 μs range are distorted, perhaps as a result of the high in-beam rate. Therefore, eight γ-γ matrices gated by 1.5 μs time intervals (with 1.6 μs separating the centroids), for times >2 μs, were constructed. The peak areas for the transitions above the 31 μs isomer, obtained from spectra gated by the 365, 410, and 431 keV decays, were plotted as a function of time, negating the problem of contaminants. To correct for the distortion, the resulting spectrum was divided by a normalized half-life curve corresponding to a long-lived product $\geqslant 100$ μs). (This technique reliably reproduced known half-lives, for example, the 10 ± 1 μs isomer in ^{180}Hf [12] was measured here to be 9.6 μs.) The result is shown in Fig. 3 yielding a lifetime of $t_{1/2} = 17 \pm 5$ μs. The large uncertainty arises from the presence of the ≈ 2 μs half-life component for the 3678 keV level and a sensitivity to the profile used to correct for the distortion.

No 779 keV decay was observed from the 3678 keV state to the $K^\pi = 19^-$ bandhead, but an upper limit can be obtained for the partial γ-ray half-life from the maximum intensity of this transition. This yields $t_{1/2}^{\gamma} > 10$ μs for the unobserved 779 keV transition. Comparisons with the Weisskopf single-particle estimate show that such a half-life is only consistent with $\lambda \geqslant 3$ transitions (within a generous margin of 10^3) suggesting a spin $I \geqslant 22$ for the 3678 keV state. From intensity balancing with the 410 keV $M1$ transition, the total electron conversion coefficient for the 370 keV decay is $\alpha_T(\mathrm{exp}) = 0.09 \pm 0.08$. This is consistent with electric quadrupole $[\alpha_T(E2) = 0.04]$ and electric octupole assignments $[\alpha_T(E3) = 0.16]$, considering only those multipolarities that lead to a spin greater than 21 $\hbar$ for the ≈ 2 μs isomer. ($M2$, $M3$, and higher multipoles are ruled out by this analysis.) Therefore, the most likely spin and parity assignments for the 3678 keV state are $K^\pi = 22^-$ and 23^+. Examining the Weisskopf units (W.u.) for the 370 keV decay favors the $E2$ assignment, as an $E3$ multipole would imply ~ 300 W.u., which is exceptionally fast for a noncollective K-forbidden transition. Thus, the preferred tentative assignment for the 3678 keV level is $K^\pi = (22^-)$.

There are two possible scenarios for the 492 keV transition observed above the ≈ 2 μs isomer. Firstly, it could be the direct decay from the isomeric state, consistent with $\lambda \leqslant 3$ transitions. Alternatively, the 4170 keV level could be the

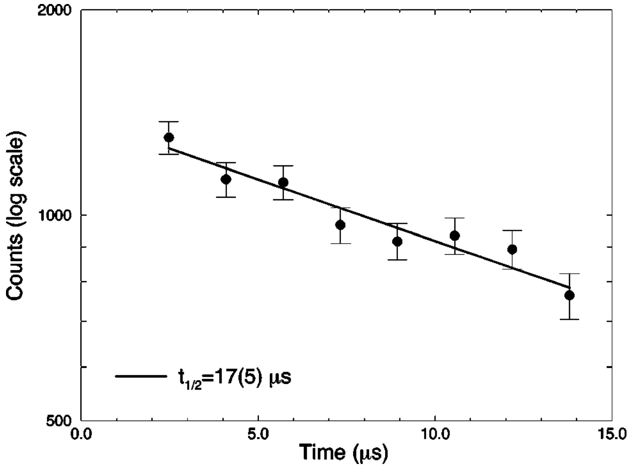

FIG. 3. Peak areas for the transitions above the 31 μs isomer in ^{180}Ta, plotted as a function of time. The intensities were obtained from spectra gated by the 365, 409, and 431 keV decays (see text for details). The solid line through the data represents a one-component fit with the half-life shown.

first excited member of the rotational band associated with the $K^{\pi}=22^{-}$ state, which could be fed by a low-energy (unobserved) transition from the ≈ 17 μs isomer, represented by the offset $\triangle < 60$ keV in Fig. 1. Such a decay would be compatible with $\lambda \leqslant 2$. In both of these situations the transition rate favors a quadrupole assignment by comparison with Weisskopf estimates. The most likely spin assignment for the ≈ 17 μs isomer is 23, 24, or 25 $\hbar$.

In addition to the first observation of the 3678 and 4170 $+\triangle$ keV isomeric states, a new 1137 keV *K*-allowed transition, with a branching ratio of 7%, has been observed from the 22 ns isomer to the 31 μs isomer. This is shown in Fig. 4. The 2587 keV $I=18$ level has previously been assigned a tentative positive parity [2,3]. The absence of a competing quadrupole decay to the 1791 $I^{\pi}=16^{-}$ state favors an $E3$ multipolarity for the 1137 keV transition, supporting a positive parity assignment for the 22 ns isomer.

Predictions for the excitation energies, spin and parity assignments for low-lying six-quasiparticle isomers have been made using Lipkin-Nogami [2] and BCS calculations [3] (see Fig. 5), at deformations of $\varepsilon_2=0.237$, $\varepsilon_4=0.056$ and $\varepsilon_2=0.242$, $\varepsilon_4=0.087$, respectively. These calculations both predict yrast $K^{\pi}=24^{+}$ and $K^{\pi}=22^{-}$ six-quasiparticle states with configurations $\nu\{\frac{11}{2}^{+}[615], \frac{9}{2}^{+}[624], \frac{7}{2}^{-}[514]\}$

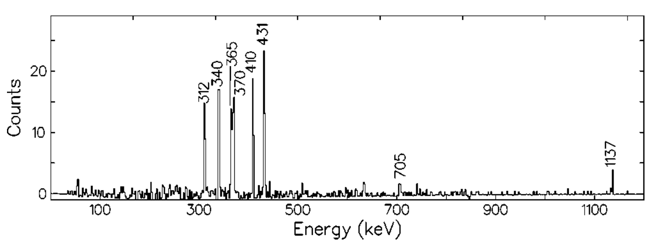

FIG. 4. Gamma-ray spectrum produced from summing the spectra double gated by the 492 keV decay with the 312, 370, and 410 keV transitions. The 1137 keV transition can be clearly seen.

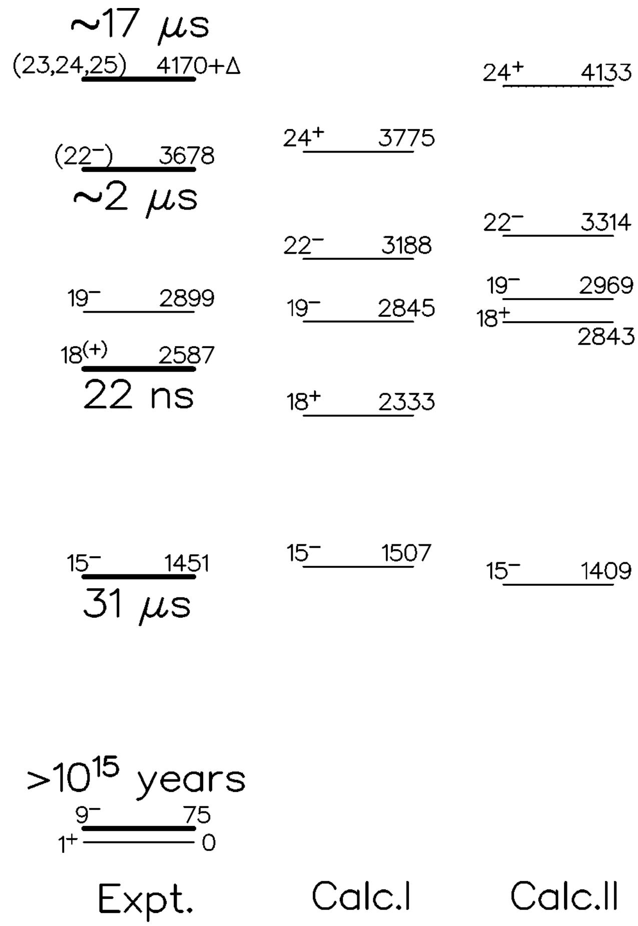

FIG. 5. Observed (Expt.) and calculated intrinsic four- and six-quasiparticle states in ^{180}Ta. The energies of Calc. I are taken from Ref. [2] and Calc. II are taken from Ref. [3]. Residual nucleon-nucleon interactions are included in the energies of both calculations. See text for details.

$\otimes\pi\{\frac{9}{2}^{-}[514], \frac{7}{2}^{+}[404], \frac{5}{2}^{+}[402]\}$ and $\nu\{\frac{9}{2}^{+}[624], \frac{7}{2}^{-}[514], \frac{7}{2}^{-}[503]\}\otimes\pi\{\frac{9}{2}^{-}[514], \frac{7}{2}^{+}[404], \frac{5}{2}^{+}[402]\}$, respectively. The predicted energies are $E^{24^{+}}=3775$ keV and $E^{22^{-}}=3188$ keV from Ref. [2] and $E^{24^{+}}=4133$ keV and $E^{22^{-}}=3314$ keV from Ref. [3]. (Note that these energies include residual nucleon-nucleon interactions.) These calculated states have the most favored residual interactions possible as given by the Gallagher-Moszkowski coupling rules [14], which result in a lowering of the energies with respect to unfavored configurations. Saitoh *et al.* [3] point out that these energies are ''only accurate to within ± 400 keV but that it is reasonable to assume that this $K^{\pi}=22^{-}$ level lies below the 21^{-} level of the 19^{-} band'' at 3737 keV. As no low-lying spin 23 $\hbar$ states are predicted it is likely that the ≈ 2 μs isomer is the calculated 22^{-} intrinsic level, which *does* lie below the 21^{-} member of the $K^{\pi}=19^{-}$ band. The $K^{\pi}=(22^{-})$ state qualifies as an *yrast trap*, as it lies below all of the $I=21$ levels, forcing it to decay by a $\lambda > 1$ transition. The energy of the ≈ 17 μs state observed at $4170+\triangle$ keV is in good agreement with the predicted $K^{\pi}=24^{+}$ level. [There are no low-lying $K = 25$ states predicted and a $K^{\pi} = 26^{-}$ state (discussed later) is calculated to be 1029 keV higher than the $K^{\pi} = 24^{+}$ state [2].]

Dracoulis *et al.* [2] have calculated the energies of the most favored eight-quasiparticle states. The lowest of these is a $K^{\pi} = 26^{-}$ level with the configuration $\nu\{\frac{9}{2}^{+}[624], \frac{7}{2}^{-}[514], \frac{7}{2}^{-}[503], \frac{5}{2}^{-}[512], \frac{3}{2}^{-}[512]\} \otimes \pi\{\frac{9}{2}^{-}[514], \frac{7}{2}^{+}[404], \frac{5}{2}^{+}[402]\}$, predicted at 4804 keV, including residual interactions. No candidates for transitions from this possible isomer to the $4170 + \triangle$ keV state have been identified in the present study, but this together with higher states provide a challenging objective for future studies.

In summary, two new high-spin six-quasiparticle yrast isomers have been populated in the nucleus ^{180}Ta, using deep inelastic reactions with a ^{238}U beam. These are the highest spin and highest seniority K isomers yet identified with deep inelastic reactions. The excitation energies of the new intrinsic states are found to be in good agreement with predictions of multiquasiparticle calculations, and configuration assignments have been made.

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