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Harvesting new isomers in neutron-rich hafnium nuclei

P. Chowdhury[a], I. Shestakova[a], R. D'Alarcao[a], C.J. Pearson[b], Z. Podolyak[b], P.M. Walker[b], C. Wheldon[b], D.M. Cullen[c], I. Ahmad[d], M.P. Carpenter[d], R.V.F. Janssens[d], T.L. Khoo[d], F.G. Kondev[d], C.J. Lister[d], D. Seweryniak[d] and I. Wiedenhoever[d]

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

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

[c]Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK

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

New multi-quasiparticle K-isomers have been investigated in neutron-rich hafnium nuclei via inelastic and transfer reactions with a pulsed ^{238}U beam on a ^{180}Hf target. The emphasis of this presentation is on the specific techniques of isolating and characterizing isomers with $\geq\mu$s half-lives and low cross-sections in the transfer channels using the Gammasphere array.

1. THE PHYSICS

Quantum numbers associated with special symmetries of the nuclear wave-function invite investigation regarding their limits of validity. One that has received considerable attention now for a number of years is K, the quantum number associated with axial symmetry in deformed nuclei, and defined as the projection of the total angular momentum of the nucleus onto the symmetry axis [1]. Conservation of K leads to selection rules for transitions involving changes in K, which in turn lead to decay hindrances resulting in isomers. The primary parameters that typically define the "phase space" in systematic studies of nuclear structure are excitation energies, angular momenta, and N/Z ratios. In the process of investigating the nature and limits of K as a function of these parameters, this particularly robust quantum number allows us to probe issues such as the quenching of pairing correlations, the evolution of residual n-p interactions, or the breakdown of axial symmetry.

The chain of stable Hf (Z=72) isotopes in the A≈180 region provide particularly striking examples of K-isomerism [2], with prolate deformed shapes and low-lying orbitals for both protons and neutrons geared towards generating high-K states. While neutron-rich A≥180 Hf nuclei have long been predicted to be a fertile landscape for high-spin multi-quasiparticle K-isomers [3], they have remained unexplored for two decades due to the inability of fusion-evaporation reactions with stable beam-target combinations to

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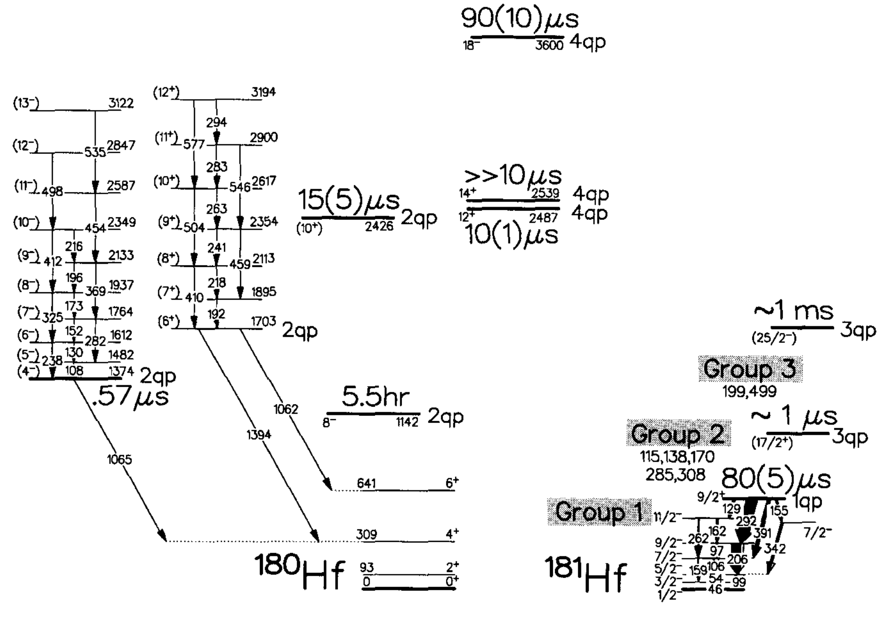

Figure 1. Schematic illustrations of isomers, multi-quasiparticle bandheads and γ-bursts in ^{180,181}Hf nuclei. For a detailed level scheme of the isomer decays in ^{180}Hf, see Ref. 4.

access this particular region. Our recent work using inelastic and transfer reactions with very heavy beams have made significant inroads into this terrain, and is revealing a rich harvest of isomers with $t_{1/2} \geq \mu$s [4,5]. Recent theoretical calculations have also raised the intriguing possibility of oblate rotational states becoming yrast at high spins in these nuclei [6]. This talk describes our continuing studies of multi-quasiparticle excitations in neutron-rich hafnium nuclei, detailing, in particular, the analysis techniques.

2. THE TECHNIQUES

In our most recent experiment, a 1.6 GeV ^{238}U beam from the ATLAS accelerator at Argonne was incident on a thick target of enriched ^{180}Hf, the most neutron-rich stable isotope. The beam was swept at two different time intervals 8.25 μs ON/16.5 μs OFF and 2ms ON/4ms OFF. Data were collected primarily in the beam-off intervals. A short period of prompt data was also collected. The γ-rays were detected by the Gammasphere (GS) array comprising of 98 HPGe and 3 LEPS detectors at the time.

In earlier experiments, we had identified three new four-quasiparticle (4-qp) isomers in ^{180}Hf via strong inelastic excitation up to a spin of 18$\hbar$ [4]. The present experiment has allowed the identification of new rotational bands built on the constituent 2-qp states in ^{180}Hf (Fig. 1), which are the building blocks of the 4-qp isomers, and provide excellent support for our earlier configuration assignments [4]. A systematic investigation of the

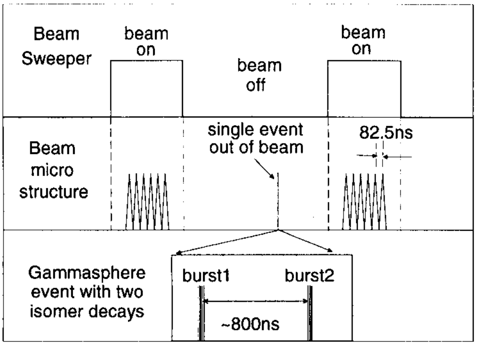

Figure 2. GS event logic that allows the correlation of γ-rays across μs isomers.

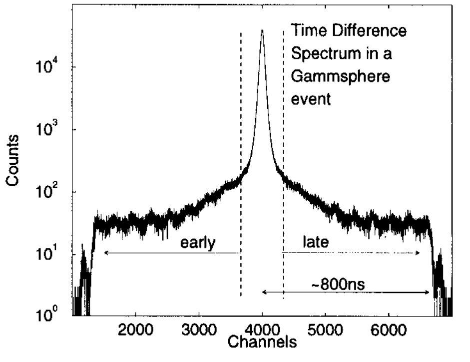

Figure 3. The time difference spectrum of pairs of γ-rays in a single GS event.

neutron transfer channels leading to neutron-rich hafnium nuclei is now in progress.

The out-of-beam data were sorted in a variety of ways to take advantage of time correlations that provide crucial signal enhancement and noise reduction in pulsed-beam studies. The various time correlation techniques possible with standard GS electronics and event formats are discussed in more detail below.

A single event in GS is defined by a coincidence window of $\approx$800 ns, which can be effectively used to correlate two bursts of γ-rays (Fig. 2), the first associated with the population of an isomer, and the second with the decay of the same isomer. Gating on a histogram of the time difference Δt between any two γ-rays in an event (Fig. 3) allows one to cleanly correlate an "early" populating burst with a "late" decay burst, both of which are caught in the time window of a single GS event. The statistics in such coincidence spectra across isomers depend both on the half-life and the population intensity of the isomer. Fig. 4 shows the quality of such spectra correlating γ-rays across an isomer with $t_{1/2} \approx 80\mu s$ in ^{181}Hf, with an estimated population cross-section of a few millibarns (see also Fig. 1 for the group definitions of γ-rays in the ^{181}Hf level schematic).

Once new feeding γ-rays are isolated, a delayed γ-γ-γ cube can be used to generate and inspect virtually background-free double-gated spectra (Fig. 5). These methods can be used sequentially to bootstrap up to isomers at higher spins. Given the high efficiency and granularity of GS, a "brute force" double-gated coincidence spectrum from a delayed γ-γ-γ cube is also capable of showing coincidences across μs isomers (Fig. 6). The time-difference spectra can also be used to order γ-rays in a cascade if the intermediate states have electronically measurable half-lives greater than a few ns (Fig. 7). This is especially helpful in delayed spectroscopy, since, in contrast to standard prompt spectroscopy of rotational cascades, there are no intensity variations, and sometimes no monotonic energy changes, to help decide the ordering. A γ-γ-Δt cube (modified from a RADWARE cube) is being tested at the present time. This allows quick generation of a Δt spectrum for any pair of γ-rays.

Measuring the mass and charge of the isomeric residue with a recoil separator is the

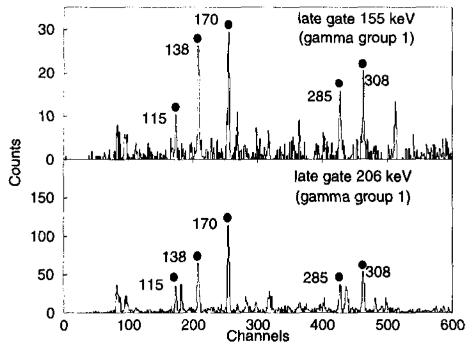

Figure 4. "Early" Group 2 γ-rays (filled circles) in ^{181}Hf coincident with "late" Group 1 transitions from the 1-qp isomer decay.

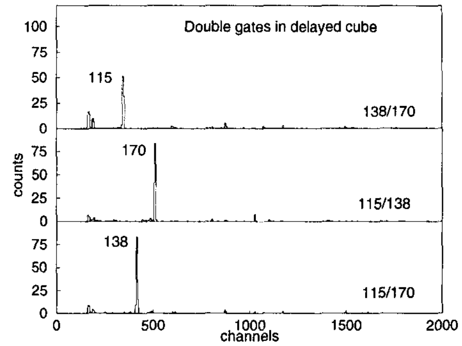

Figure 5. Double gates on Group 2 γ-rays in ^{181}Hf highlighting the excellent signal-to-noise characteristics.

foolproof method for assigning a cascade from a long-lived isomer to a particular nuclide. In the absence of that, reasonable mass identification is achievable in inelastic and transfer channels through cross-coincidences between target-like and projectile-like fragments. This, however, is possible only in prompt spectroscopy. Therefore, the method can only be applied to cascades that have both prompt and delayed feeding. This method allowed us to corroborate our earlier placement [4] of the rotational bands on top of long-lived 8^- isomeric states in ^{180,182}Hf (Fig. 8), although the "nearly-identical" bands in ^{236,238}U provided an additional challenge (see Ref. 4 for the appropriate Hf level schemes). Reasonable Z-identification can be achieved through X-γ coincidences. Since only three LEPS

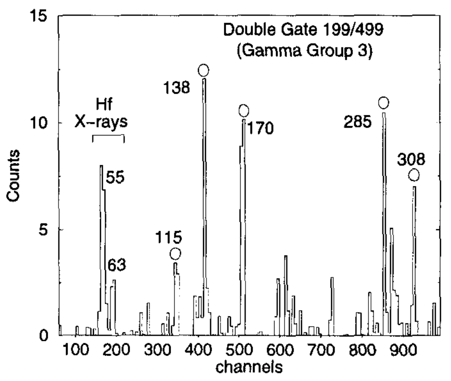

Figure 6. "Brute force" double-gated spectrum showing coincidences across the $\approx$1 μs isomer in ^{181}Hf.

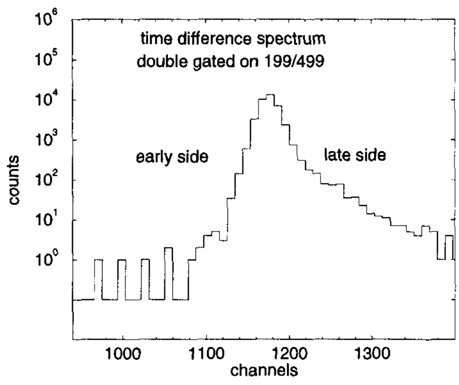

Figure 7. Δt spectrum showing an intermediate half-life that allows ordering of the γ-rays.

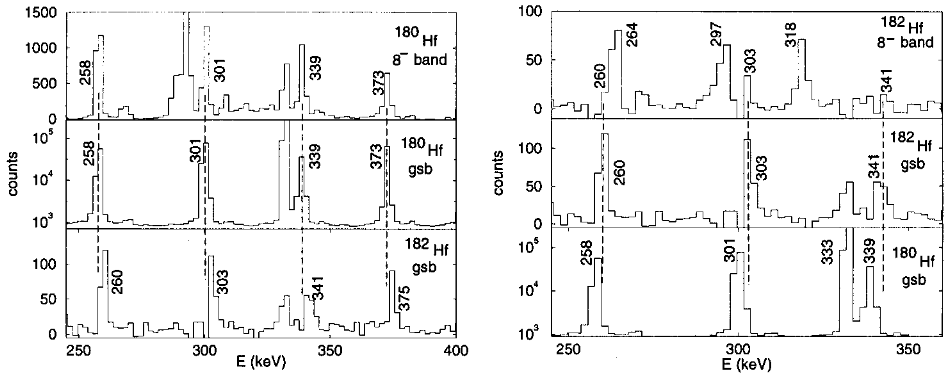

Figure 8. Cross-coincidences of target-like with projectile-like fragments. ^{180}Hf transitions are in coincidence with ^{238}U γ-rays (258-301-339-373 keV), while ^{182}Hf transitions are in coincidence with ^{236}U γ-rays (260-303-341-375 keV).

detectors were available in the experiment, the statistics were insufficient for using them effectively for any but the most strongly populated cascades. The X-rays detected in the HPGe detectors, however, were usable for a number of cascades (Fig. 9), although the efficiency of the detectors drop drastically at low energies with the slow-risetime-reject mode set for timing signals in GS electronics. The proposed option that would allow an user the choice of switching to a constant-fraction mode would improve this situation considerably.

3. THE CURRENT STATUS

The analysis of the full data set with the neutron-rich transfer channels is still in progress. While the spin-parity assignments of the new isomers in ^{181}Hf are tentative at the present time, there is strong evidence that these are 3-qp isomers formed by coupling the 2-quasiproton 8^- states in ^{180}Hf to the [510]$1/2^-$ neutron orbital for the lower ($\approx$ 1μs) and the [624]$9/2^+$ neutron orbital for the higher ($\approx$ 1ms) isomer, respectively. If the present spin-parities indicated hold up to the final scrutiny, these 3-qp isomers would definitely be yrast states. The intermediate states also seem to be of intrinsic character rather than rotational excitations. This would make the yrast line of ^{181}Hf overwhelmingly dominated by intrinsic excitations.

The more neutron-rich Hf nuclei, therefore, seem to be living up to their promise of long-lived yrast isomers. Populating and detecting them, however, is a significant challenge with our present combination of reaction mechanisms, arrays, and analysis techniques. For example, we do populate the known 2-quasiproton 8^- state in ^{184}Hf [7] with sufficient statistics to observe its decay in a double-gated spectrum of a delayed γ-γ-γ cube (Fig. 10). The cross-sections, however, drop sharply for the transfer channels leading to more neutron-rich isotopes of Hf, and it is unlikely that we will be able to observe 4-qp states in ^{184}Hf in this data.

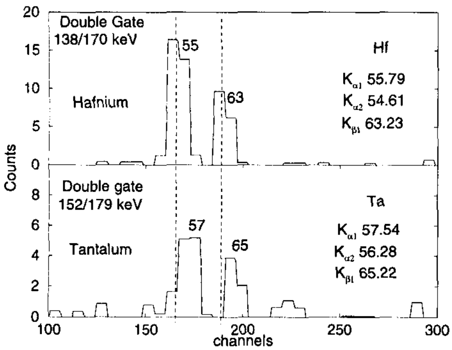

Figure 9. X-γ coincidence spectra using HPGe detectors used to distinguish between cascades in Hf and Ta.

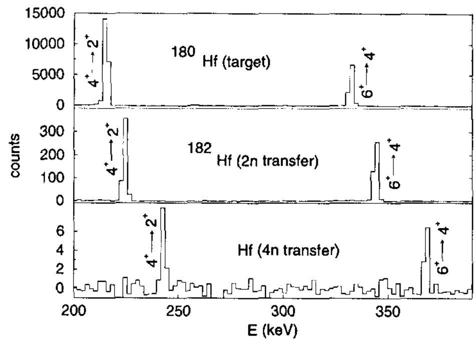

Figure 10. Double-gated spectra in the ground state bands of ^{180,182,184}Hf populated in the decay of the 8^- isomers.

A rare isotope accelerator, with neutron-rich beams and a return to fusion-evaporation reactions, would allow us to populate high spins easily in the 180<A<190 region, and provide a giant leap in knowledge for this region of the nuclear chart.

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