

Microscopy of femtoscale structures

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Abstract. Advances in experimental techniques are discussed for the study of long-lived isomers using gammasphere. Spectroscopy of neutron-rich nuclei in the $A \approx 180$ region is made possible for the first time via neutron transfer from heavy beams, and long-predicted high- K isomers are observed.

Keywords. K -isomers; delayed γ - γ - Δt ; neutron-rich Hf; multi-quasiparticle states.

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1. Prologue

Nuclear spectroscopy has come a long way in the last two decades of the past millenium. The success has been due, in no small part, to the rapid progress in gamma-ray detection devices. Complex multi-detector arrays, in varied shape and form, have been, and are being, assembled in different parts of the globe. The femtoscale structures called atomic nuclei, that are so close to our hearts, are yielding new secrets under the analysing power of these sophisticated and elegant microscopes. Hand in hand with advances in hardware, there has been a parallel explosion in data analysis techniques, riding on the waves of the computer revolution. The physics goals that we set ourselves, however, always tend to push the limits of our experimental capabilities. We are in the business of searching for needles in haystacks, and as we learn how to search better, the needles invariably get smaller, and the haystacks bigger. In this talk, I will present a biased overview of my personal searches of needles in haystacks, with one of the most powerful microscopes for γ -ray spectroscopy that I been involved with, both in planning and using.

2. The microscope

Gammasphere, a national gamma-ray facility in the U.S. funded by the Department of Energy, was proposed in 1988, and was commissioned in 1995 at the 88" cyclotron in Lawrence Berkeley National Laboratory [1]. After an extremely successful stint at Berkeley, it moved to the ATLAS accelerator facility at Argonne National Laboratory in 1997, to mount a focused campaign to take strategic advantage of three major capabilities, energetic heavy beams, pristine timing and coupling to the fragment mass analyser. It was

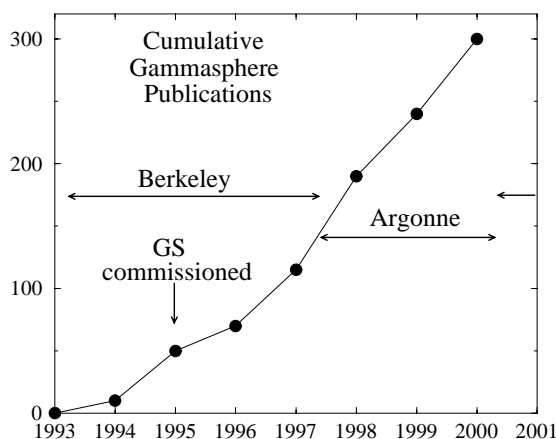


Figure 1. Cumulative publications in refereed journals using gammasphere.

moved again to Berkeley in 2000. Figure 1 shows the cumulative publications (in refereed journals) from gammasphere research plotted as a function of time. Needless to say, the facility has more than lived up to its promise. With 110 Compton-suppressed Ge detectors, a host of auxiliary detection devices and a versatile data acquisition system, the experimenter has a smorgasbord of choices in analysing the complex multi-parameter data. Some of the features incorporated in the instrument have, in fact, yet to be tested for their true potential. This talk will provide a glimpse of results achieved with gammasphere at ATLAS with energetic heavy beams and beam pulsing.

3. Hang-ups and half-lives

The interplay of single-particle and collective degrees of freedom is a dominant theme in nuclear structure studies. K -isomers, where K denotes the projection of the total angular momentum of a nucleus onto its symmetry axis, provide a special laboratory for studying this interplay. Axial symmetry of a deformed nucleus leads to an approximate conservation of the K quantum number, and, consequently, to K -selection rules for gamma-decays. Specifically, a decay is forbidden, to first order, if the change in K , ΔK , exceeds the multipolarity, λ , of the transition. These forbidden transitions do occur through higher order corrections, and are, therefore, hindered. The hindrances scale logarithmically with the degree of forbiddenness, $\nu = \Delta K - \lambda$, typically increasing by two orders of magnitude for every degree of K -forbiddenness. Decays with large ΔK , therefore, are seen to have long half-lives. One of the more famous examples is a $K = 16$ isomer in ^{178}Hf , which decays to a $K = 8$ rotational band with a half-life of 31 years. While the decay of a K -isomer depends on the details of the single-particle wave-functions and their admixtures, the typical feeding of a K -isomer is through a rotational band built on the isomer. Detailed analyses of both decay and feeding properties of these isomers are essential for understanding the physics of the K quantum number.

The $A \approx 180$ region is extremely fertile for the study of high- K physics. On one hand, nuclei in this region possess stable, axially-symmetric, prolate shapes, ideal for collective

rotation to be a dominant mode. On the other hand, the fermi levels for both neutrons and protons are close to orbitals with large projections, Ω , on the symmetry axis, which allows high- K (where $K = \Sigma\Omega$) non-collective nucleonic excitations to compete effectively. Nuclei with $71 \leq Z \leq 76$ have been extensively studied in this context, and a wide body of data now exist on high- K isomers. The parameters that are typically varied in a systematic study of high- K physics are excitation energy and spin of the isomers (which approximately scale with number of quasiparticles) and N/Z ratios. Enormous progress is being made on all these fronts with the help of instruments such as gammasphere. With increasing spin and excitation energy, a general tendency of decreasing half-life is expected for high- K isomers, since we expect an increasing overlap of the wave-functions for the multi-nucleon configurations of the initial and final states in a K -hindered decay. Increasing N/Z ratios in this region, on the other hand, are expected to yield very long-lived high- K isomers in the $A \approx 180$ region, due to increased availability of high- Ω orbitals near the fermi surface. Long-standing predictions exist for yrast high- K configurations in neutron-rich Hf nuclei [2,3]. Recent calculations have also raised the intriguing possibility of oblate rotation becoming yrast at high spins in the neutron-rich Hf isotopes [4].

4. How to get neutron-rich

Data on high N/Z ratios, however, have been extremely sparse till very recently. This deficiency stems from a limitation of the fusion-evaporation reaction mechanism, which has been the workhorse for the production of high-spin states in nuclei for the past four decades. A combination of two lighter nuclei fusing to form a heavier one automatically leads to neutron-deficient final products, since the line of β -stability bends towards the neutron axis with increasing Z . This is exacerbated with a few neutrons being typically evaporated following fusion. Recent advances in the production of heavy beams such as U , with energies to surmount the Coulomb barrier, have led to the use of deep-inelastic and transfer reactions on the heaviest stable isotopes in the $71 \leq Z \leq 76$ nuclei in the $A \approx 180$ region, and allowed us to make significant inroads into neutron-rich territory. The majority of this talk will focus on our latest experiments that have been successful in extending K -physics to higher N/Z ratios, beyond the β -stability line. A short section towards the end will provide a brief report of a recent experiment to take a closer look at a 6-quasiparticle (6-qp) high- K isomer in ^{176}Hf .

Over the past three years, the map of high- K isomers along the neutron-rich β -stability line in this mass region has been significantly altered through the use of inelastic and transfer reactions. With conventional wisdom generated from earlier experiments on transfer reactions [5], we have chosen a beam with the highest N/Z ratio available, and a bombarding energy roughly 15% above the Coulomb barrier for our experiments. Most of our experiments have been performed with 1.6 GeV U beams, incident on thick targets of the heaviest stable isotopes of Lu, Hf, Ta, and W nuclei. Strong inelastic excitation of the target nuclei have been observed with cross-sections of ≈ 100 mb [6,7]. Neutron transfers to the target have allowed observation of K -isomers in nuclei up to four neutrons beyond the β -stability line [8]. The expectations of long isomer half-lives seem to be borne out in the new data. The presence of long half-lives in the decay scheme of a nucleus, however, creates experimental problems for the spectroscopist, since standard coincidence techniques fail. Specialized delayed correlation techniques have to be brought into play, which in-

clude advanced manipulation of the time parameter, as well as cross-coincidences with projectile-like fragments. The following section describes, in some detail, the power of the time parameter when coupled to a sophisticated and efficient array such as gammasphere.

5. Playing with time

In our experiments, a beam of ^{238}U at 1.6 GeV provided by the ATLAS facility at Argonne National Laboratory was incident on a thick Pb-backed enriched ^{180}Hf target, the heaviest stable isotope. The aim was to study excitations in $^{180+x}\text{Hf}$ nuclei, with $x \geq 0$. All reaction products were stopped at the target position, and the γ - and X-rays emitted were detected by 98 Compton-suppressed co-axial HPGe and 3 planar LEPS detectors in the gammasphere array. While the ATLAS beam has a natural separation of 82.5 ns between sub-nanosecond beam pulses, an additional beam sweeper was used to switch the beam on and off in macro-pulses. The primary experiment used a beam-sweeping cycle of 8.25 μs on/16.5 μs off, with a second shorter data set using a 2 ms on/4 ms off cycle. The first detector firing in the ‘beam off’ period was used as a master trigger. A coincidence window of ~ 800 ns following the trigger allowed data from all detectors firing within that time interval to be recorded. A short prompt data set with no beam sweeping was also collected. In addition to recording the standard time parameter of the firing of each detector with respect to the master trigger, the time between the master trigger and the beam sweeper signal was also recorded. We will focus on the ^{181}Hf nucleus for our discussion on analysis techniques using the time parameter. Figure 2 shows a partial level scheme of ^{181}Hf [8,9]. We had established the decay of the 80 μs $9/2^+$ isomer in our previous work [7]. All data above that level are new. Two new isomers, with half-lives of ≈ 1 μs and ≈ 1 ms have been identified.

Figure 3 shows how the event logic in the data acquisition set-up for gammasphere allows γ - γ correlations across isomers with $t_{1/2} > \mu\text{s}$. A coincidence (i.e. a single event) in gammasphere electronics is defined by a ~ 800 ns acceptance window. This is long enough to record two γ -ray bursts from the successive decay of two isomers in a single

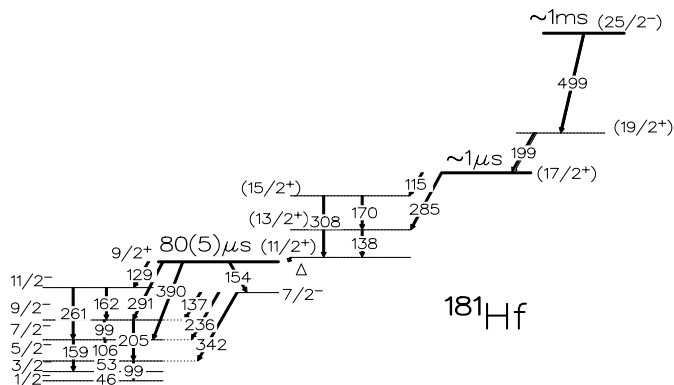


Figure 2. Partial level scheme of ^{181}Hf , with three isomers in the μs to ms range.

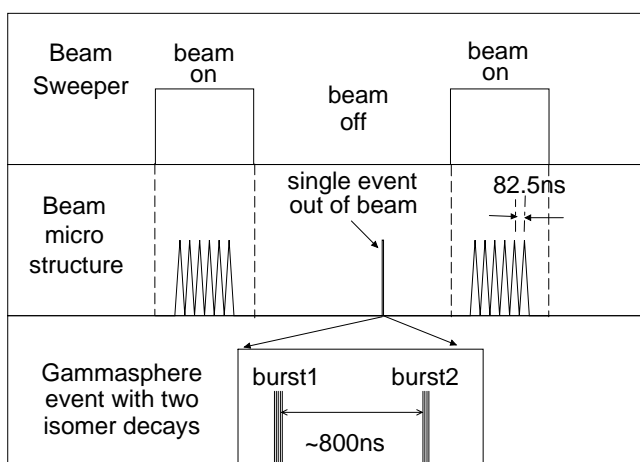


Figure 3. Gammasphere event logic that allows γ - γ correlations across isomers with $t_{1/2} > \mu\text{s}$.

event window. This feature was effectively used in our analysis to correlate γ -rays across the $80 \mu\text{s}$ and $\sim 1 \mu\text{s}$ isomers in ^{181}Hf . The time difference between any two γ -rays in an event was histogrammed (see figure 4), and by appropriate gating of this parameter ($>150 \text{ ns}$ in our analysis) on the ‘early’ and ‘late’ wings of the time-difference spectrum, an ‘early-late’ γ - γ correlation matrix was created. This suppresses the dominant background of prompt cascades as well as isomers with ns half-lives, and only retains the delayed coincidences that occur in a 150 – 800 ns time window. The detection efficiency is greatest for isomers with $\approx \mu\text{s}$ half-lives, and decreases for longer half-lives. Gating on a ‘late’ transition depopulating an isomer generates a spectrum of the ‘early’ transitions feeding the isomer, and vice versa. The high detection efficiency of gammasphere is seen to make this correlation technique effective for isomers with half-lives as high as $80 \mu\text{s}$ (see figure 4). Once a group of new transitions are identified through this ‘early-late’ technique, the new γ -rays can be arranged in a decay scheme through standard coincidence techniques. Single- and double-gated spectra from γ - γ matrices and γ - γ - γ cubes, generated with time windows of appropriate width centered around $\Delta t = 0$ in the time difference spectrum, can be analysed. The whole process can be repeated to bootstrap up to higher and higher isomers till either isomers or detection efficiency runs out. For example, by further gating on the new transitions as ‘late’, two new ‘early’ γ -rays were observed to feed the $\sim 1 \mu\text{s}$ isomer from a third higher-lying isomer, with a half-life of $\approx 1 \text{ ms}$.

X- γ coincidences are an additional tool that may be used to place γ -ray cascades in a nucleus, especially when the isomer half-lives get too long for correlation techniques to work. All transitions placed in the level scheme were also observed to be in coincidence with hafnium X-rays. The coaxial HPGe detectors have poor efficiency and resolution in the X-ray region, while the planar LEPS detectors are ideal. The small number of LEPS detectors available in our experiment made this technique applicable only for reasonably strong cascades. Figure 5 shows a comparison of the X-ray region of the spectrum for both the HPGe and LEPS detectors.

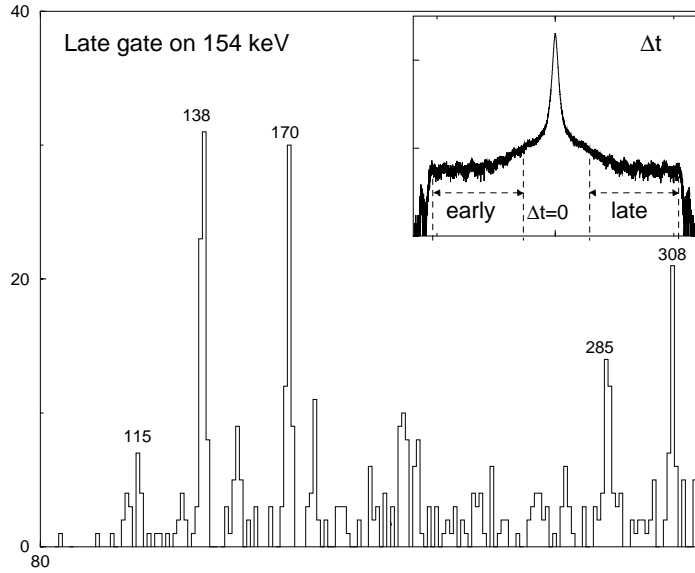


Figure 4. A spectrum obtained from the 'early-late' correlation matrix by gating on a 154 keV transition from the decay of the 80 μ s isomer as 'late'. The associated time difference spectrum is shown in the inset.

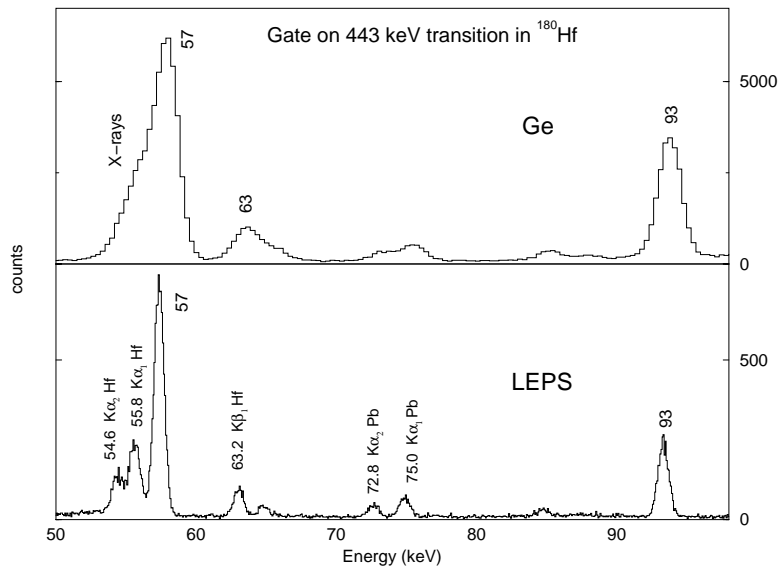


Figure 5. Comparison of the energy resolution in the Hf X-ray region for HPGe and LEPS detectors.

When the isomer half-lives get so long that ‘early-late’ techniques described above do not work any more, prompt cross-coincidences between target- and projectile-like fragments in a transfer reaction can be used to assign a cascade to a particular nucleus. This technique has been used to place transitions above the 8^- isomers in both ^{180}Hf and ^{182}Hf , which have half-lives of 5.5 hrs and 61.5 min, respectively (see figure 6). Transitions of the inelastic excitation of the ^{180}Hf target should be in coincidence with transitions of

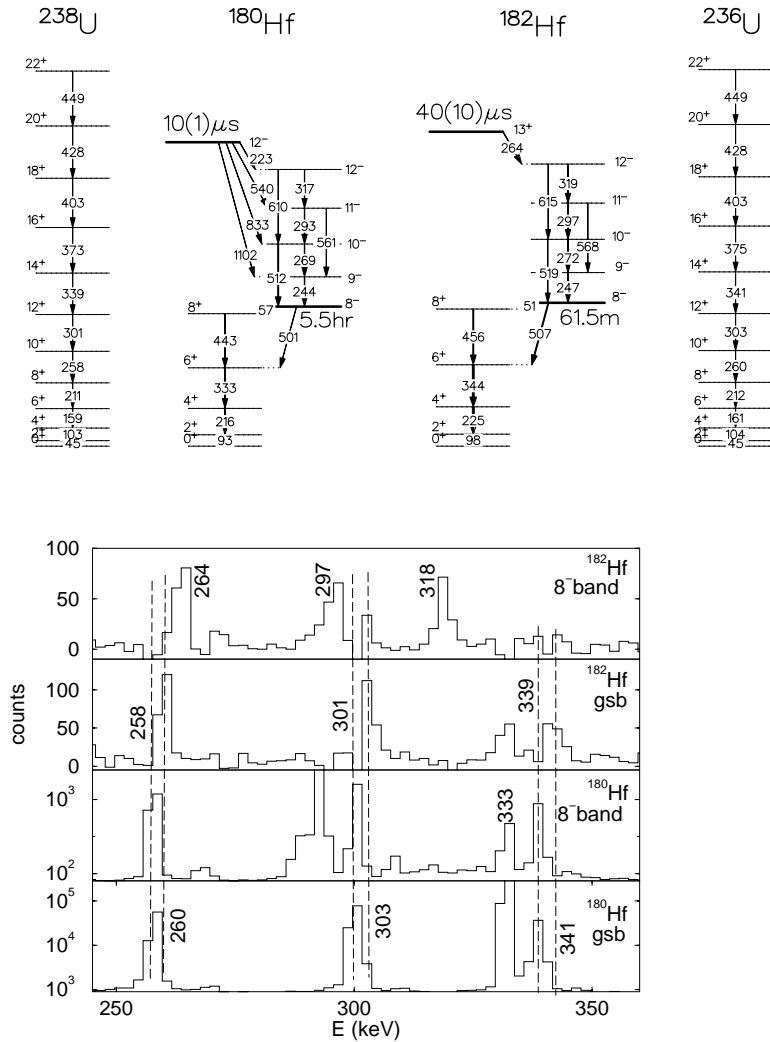


Figure 6. Cross-coincidences between target- and projectile-like fragments. Partial level schemes of the nuclei involved in inelastic excitation and two-neutron transfer are shown on top. In the bottom panel, ^{180}Hf transitions are in coincidence with ^{238}U γ -rays (258–301–339 keV), while ^{182}Hf transitions are in coincidence with ^{236}U γ -rays (260–303–341 keV).

the mutually excited projectile, ^{238}U . If two neutrons are transferred from the projectile to the target, transitions in ^{182}Hf should be in coincidence with transitions in ^{236}U . This can only be observed in-beam. While the principle is straightforward, complications arise for this particular projectile, since transitions in ^{236}U and ^{238}U are very nearly identical. Out of the first eleven quadrupole transitions of the ground state band, all except four transitions are within a keV of each other, and the four differ by 2 keV. Figure 6 shows the quality of the cross-correlation spectra in this particularly difficult case, that could not have been achieved without an array like gammasphere.

6. Less neutrons, more spin

A small aside and update on our analysis of another recent gammasphere experiment, which was primarily designed to push the limits of spin and number of quasiparticles and look for 9- and 11-qp high- K states in ^{175}Hf , using fusion-evaporation reactions with a ($^{48}\text{Ca}, 3n$) reaction on a ^{130}Te target. A small fraction of the beam-time was used to reconfigure the experiment and focus on the $2n$ evaporation channel leading to ^{176}Hf , where the highest state is a 6-qp K -isomer with a half-life of 43 μs . This isomer has a spin-parity of 22^- , and decays via a K -allowed E2 transition to another 6-qp 20^- state. In this experiment, the primary motivation was to look for prompt transitions feeding this isomer. The small statistics accumulated was not enough for what we were aiming for, but we did find a new decay branch of the isomer to the 20^- state of a rotational band built on a $K^\pi = 14^+$ isomer (see figure 7) [10]. The level of the statistics involved is shown in figure 8, where a spectrum is shown from an out-of-beam γ - γ - γ cube, double-gated on two of the transitions of the rotational band populated in the new decay branch. This transition has a K -forbiddenness $\nu = 6$, and is seen to compete with a K -allowed decay branch. This provides new material for discussing the robustness of the K quantum number with increasing number of unpaired particles.

A last note on time parameters: all gammasphere events are also stamped with a microsecond clock, that is free-running in real time. This is a powerful tool that can be used for the study of isomers and isomer chains with half-lives greater than tens of μs . If the beam is turned off for an interval of 100 μs or greater, one can record multiple events (of 800 ns each). Time differences between the clock values for *successive events* can be histogrammed, and ‘early-late’ techniques brought into play. The level scheme of ^{176}Hf is a classic laboratory for the use of this particular method, since it has three isomers, with half-lives of 10 μs , 401 μs and 43 μs , which trap and channel the decay intensity along the yrast line.

7. Small steps and giant leaps

With advanced microscopes such as gammasphere, and new reaction mechanisms, we are now being able, for the first time, to venture into regions that has remained unexplored for decades. In this talk, I have concentrated primarily on the experimental techniques. Detailed discussion of the physics issues are available in the references cited. Figure 9 shows the systematics of yrast isomers in the Hf isotope chain, which we have extended into neutron-rich territory. New experimental methods of production are being planned, which would turn these small steps into giant leaps. The rare isotope accelerator (RIA)

project that is currently being reviewed by federal funding agencies in the U.S. would allow fusion reactions with neutron-rich beams that would change our map of known neutron-rich nuclei in giant leaps. For example, the most neutron-rich stable isotope beam of ^{136}Xe on ^{48}Ca forms the ^{184}W compound nucleus. With projected intensities of 10^8 particles of ^{145}Xe from RIA, the compound nucleus would be ^{193}W , a giant leap indeed!

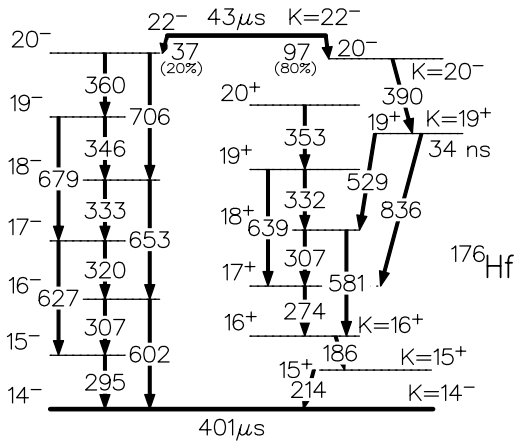


Figure 7. Partial level scheme of ^{176}Hf . Only the levels above the $K^\pi = 14^-$ isomer are shown.

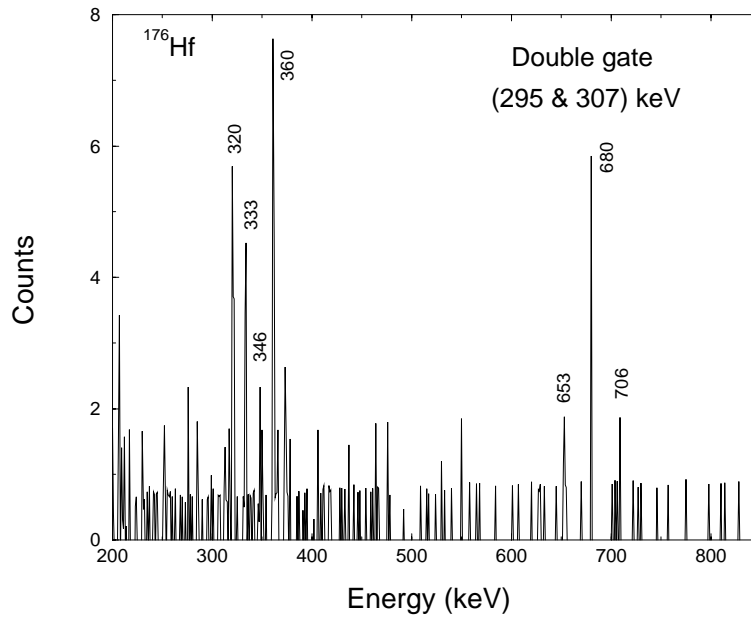


Figure 8. Double-gated spectrum highlighting the new weak decay branch from the known 6-qp isomer in ^{176}Hf .

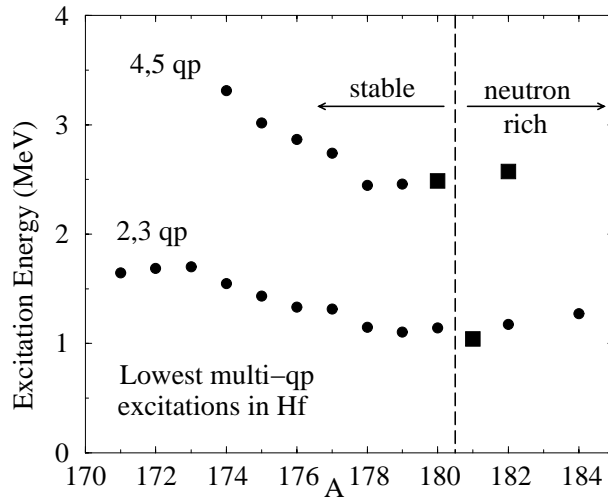


Figure 9. Systematics of the most yrast 2, 3, 4 and 5 quasiparticle excitations in Hf isotopes. The squares denote our recent successes of populating 3, 4-qp states in neutron-rich Hf nuclei.

Acknowledgements

It has been my distinct pleasure to be able to take part in the golden jubilee celebrations of the Saha Institute of Nuclear Physics. I thank the organizers for inviting me to present a perspective from the other side of the globe. I would like to acknowledge many of my fellow 'isomer-hunters' who have participated in the experiments. Special thanks to Gopal Mukherjee and Irina Shestakova who made significant contributions towards the preparation of this presentation. This work is supported by the U.S. Department of Energy, Nuclear Physics Division, under contract DE-FG02-94ER40848.

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