The Search for Long Lived Isomers in the $A \sim 180$ Region at the Experimental Storage Ring, GSI

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Outline

- GSI
- The Experimental Storage Ring at GSI
- Schottky Detectors
- SMS vs S+IMS
- Why study isomers?
- Isomers in the $A \sim 180$ region
- Overview and early results from experiment GG-00203

GSI/FAIR

- Research lab located near Darmstadt, Germany
- Carries out research mainly on atomic and nuclear physics, as well as biophysics
- Best known for the discovery of several elements including bohrium, meitnerium, hassium, roentgenium, copernicium, and darmstadtium
- In the coming years, it will develop into FAIR, with a new SIS-100 synchrotron, Super-FRS fragment separator, and several storage rings
- First experiments planned to begin in 2027

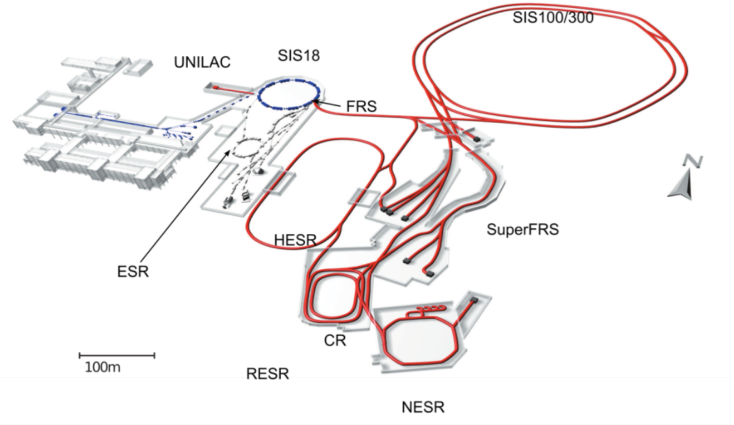
GSI/FAIR

Aerial view of GSI, with construction of FAIR visible in the foreground

GSI/FAIR

Expected aerial view of FAIR after all construction is complete

GSI and FAIR Beamlines

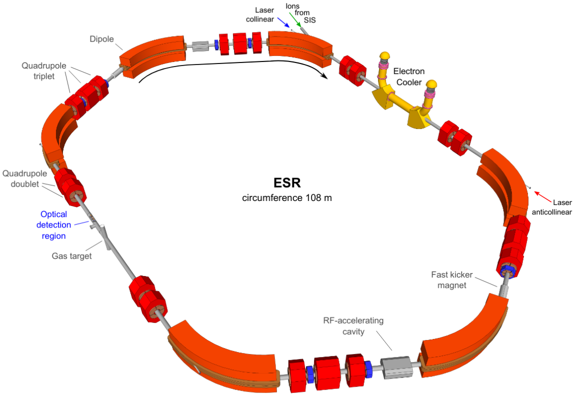


Current beamlines at GSI and future beamlines of FAIR

The Experimental Storage Ring "ESR" at GSI

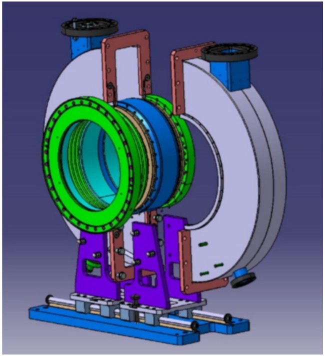
- Takes beam from the SIS-18 synchrotron
- Set of six dipole magnets allow the ions to circulate around the ring
- High vacuum, down to a pressure of 10^{-11} mbar, prevents losses due to collisions with gases $\rightarrow$ store the beam for as long as days or weeks
- Momentum acceptance of $\pm 1.5\%$ so many species can be stored and measured simultaneously

The Experimental Storage Ring “ESR” at GSI

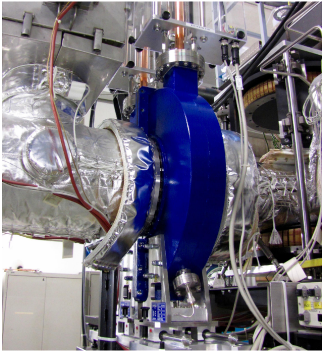


Overview of the ESR (V. Hannen *et al*, Journal of Instrumentation, 8(09), 2013)

Our Detectors of Choice - Schottky Resonant Cavities



Schematic diagram of a Schottky resonant cavity (M. S. Sanjari *et al*, Phys. Scr., 014088, 2013)



Schottky resonant cavity installed in the ESR (Yu. Litvinov, M. Steck, Progress in Particle and Nuclear Physics, 103811, 2020)

Schottky Detectors

- Charged particles travelling through a beam pipe drag an opposite charge along the pipe's surface
- In isolated sections, like the walls of a cavity, the surface charge oscillates, measurable as an induced current
- Fourier transform of the signal reveals peaks in the frequency domain corresponding to the revolution frequency of the ions
- Sensitive enough to detect single ions $\rightarrow$ detect every species that enters the ring

Schottky Detectors

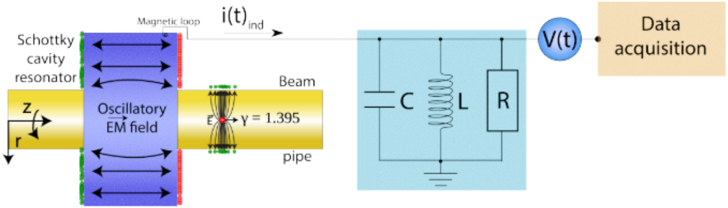
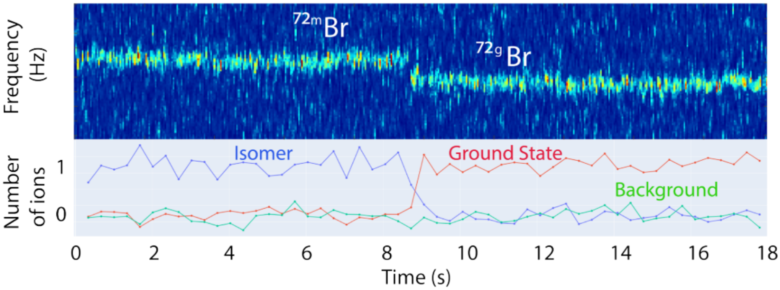


Diagram demonstrating the principle of resonant Schottky detectors (D. F. Fernandez, PhD Thesis, 2024)

Example Spectrogram



Decay of a single ^{72}Br isomer with 101keV excitation energy to the ground state (D. F. Fernandez, PhD Thesis, 2024)

SMS *vs.* S+IMS

Revolution frequency of ions circulating in a storage ring is related to their mass to charge ratio and velocity spread:

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v} \tag{1}$$

To get a simple relationship between frequency and mass to charge ratio, the second term on the right hand side needs to be eliminated. We have two options:

1. Reduce Δv to zero by cooling the beam $\rightarrow$ "SMS"
2. Set the Lorentz factor of the ions, γ, to the transition energy of the ring, γ_t $\rightarrow$ "S+IMS", "Isochronous mode"

Use Case for the ESR

- Can store a broad range of ions for extended periods of time, and can unambiguously measure each one

So the ESR is ideal for:

1. Measuring lifetimes of long lived species, which wouldn't be possible with decay spectroscopy
2. Measuring masses and lifetimes of rare species with very low production cross-sections
3. Measuring a broad range of species at the same time, so that each experiment can cover a broad section of the nuclear chart

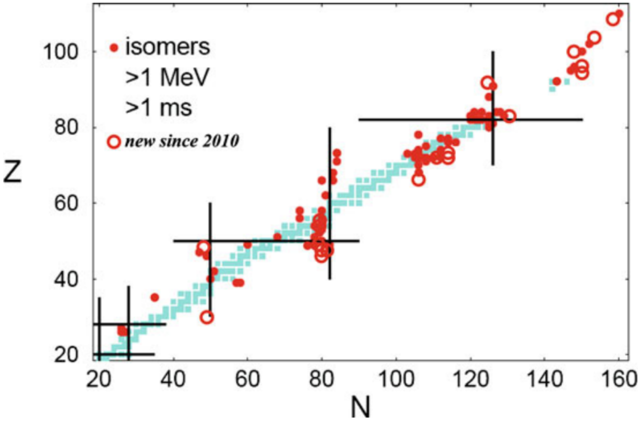
Why look at Isomers?

- Given its properties, the ESR is ideal for studying exotic and long lived nuclear isomers
- Masses and lifetimes are needed for nucleosynthesis models to make accurate predictions
- The presence of isomers and their properties can significantly influence the accuracy of these models

Isomers

- Isomers are metastable nuclear excited states, with lifetimes much longer than other excited states. Generally a state is considered an isomer if it has a lifetime of nanoseconds or longer
- Isomers arise when one or more physical constraints prohibits its decay:
  1. Spin isomer: large change in magnitude of angular momentum
  2. K isomer: large change in the direction of angular momentum
  3. Shape isomer: large change in the shape of the nucleus

Isomers

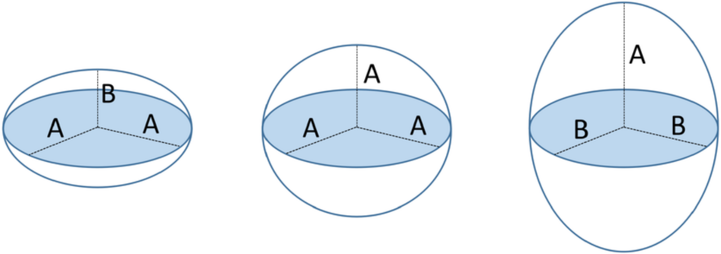


Long lived and high excitation energy isomers across the nuclear chart (P. M. Walker, Z. Podolyák, Nuclear Isomers (Handbook of Nuclear Physics), 2023)

Isomers in the $A \sim 180$ Region

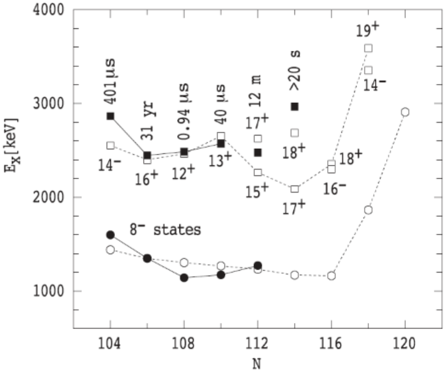
- Many K-isomers known, many predicted
- Also in the region, there is expected to be a transition in shape from prolate (rugby ball shaped) to oblate (M&M shaped)
- This would mean that high-K isomers would decay to low-K states
- In heavier elements *e.g.* W and Os this transition has been observed, but not for Hf or lighter

Nuclear Shapes



Comparison between oblate (left), spherical (centre), and prolate (right) shapes (A. Albio *et al*, Sensors 21 2232, 2021)

Hafnium Isomers

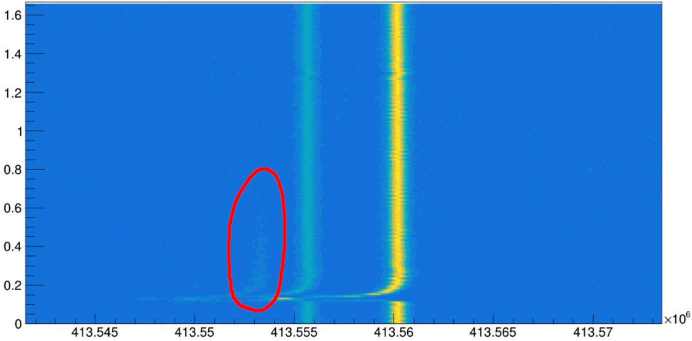


Excitation energies of two/four-quasiparticles in various hafnium isotopes. Open squares mark predictions, filled squares mark experimental measurements (Yu. Litvinov *et al*, experiment GG-00203 proposal, 2024)

Experiment GG-00203

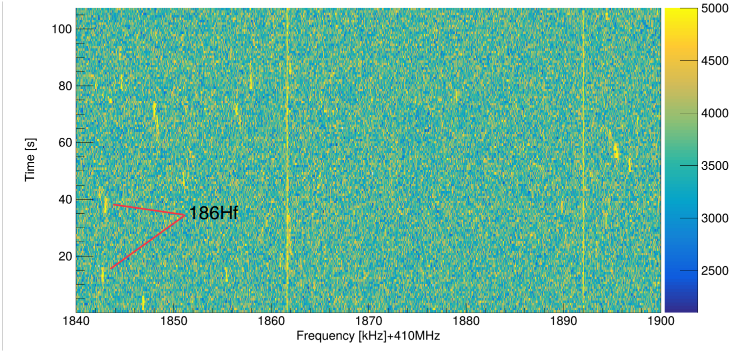
- April 3^{rd} to April 9^{th}
- ^{208}Pb primary beam impinging on a ^{9}Be target
- ESR operating in isochronous mode
- Measuring neutron rich fragments from Yb to Au
- Will finally access an isomer in ^{188}Hf that is predicted to be very long lived

Early Results - ^{204}Au 12^- Isomer



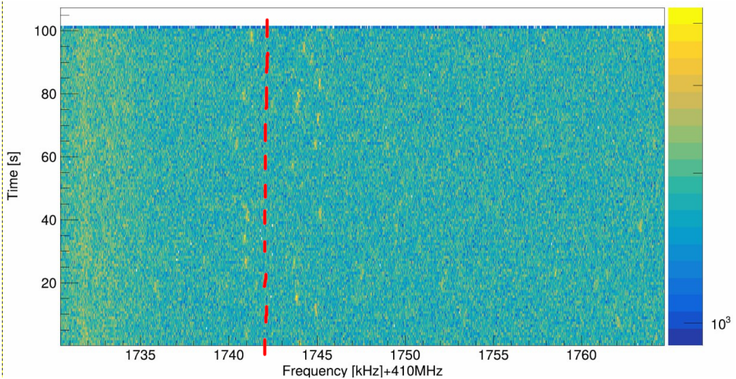
Circled in red, possible ^{204}Au 12^- isomer (near-line analysis by R. S. Sidhu, 2025)

Early Results - ^{186}Hf



Single ions of ^{186}Hf (near-line analysis by R. J. Chen, 2025)

Early Results - ^{188}Hf



Expected frequency to find ^{188}Hf (near-line analysis by R. J. Chen, 2025)

Acknowledgements

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