GSI Research Proposal

G-22-00203

Experiment title: **Mass & half-life measurements in the neutron-rich N≈116 Hf region**	**Proposal type: (ST)** Standard
	Scientific College: G-PAC

Co-Proposers of entire sub-collaboration:	ILIMA

Abstract:
The novel cavity-based non-destructive Schottky detector has been developed within the ERC CoG "ASTRUm". Based on it, the combined Schottky+Isochronous Mass Spectrometry was established in the ESR. Every individual stored in the ESR ion is unambiguously detected and, if sufficiently short-lived, monitored until it decays. In May 2024, within the G-22-00018 experiment (spokesperson W. Korten), an isomer with half-life of just 3 ms could be measured. Hence, equipment with superior sensitivity and speed is available for precision experiments at the ESR. By employing the above detector and profiting from the capability of the ESR to cover simultaneously a large region of the nuclear chart, we aim at: Examine the region of neutron-rich Yb-Os 208Pb projectile fragments for known and unknown short- and long-lived rare isomers. Measure their excitation energies and lifetimes; Measure ground state masses of several ten neutron-rich nuclides; Finally access to the exceptional isomer

Proposer (All correspondence concerning this proposal will be sent to the proposer)

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FAIR Experiment Pillar: NUSTAR	**Collaboration:** ILIMA

Declaration of peaceful purpose

GSI pursues scientific work solely for peaceful purposes.
In this respect, only proposed research projects that serve and promote exclusively peaceful purposes can be accepted.

I confirm the peaceful purpose of the proposal ☒

Experiment time requested for

Target station	Requested experiment time	Link scientist
1.1-E: ESR (Parasitic beam)	9 Shifts	Yury Litvinov

Next page: scientific case

Proposal of the ILIMA Collaboration for FAIR Phase-0 Research Program

Mass & half-life measurements in the neutron-rich N≈116 Hf region

Spokesperson and GSI contact person:
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Equipment: ESR

Beam: 500 A.MeV, 2x10^9 ions/spill, ^{208}Pb

Target station: ESR

Experiment facility: ESR, isochronous mode

Main goals: By employing the new Schottky detector developed within the ERC Grant "ASTRUm" at GSI, which is sensitive to single circulating ions with lifetimes > 3 ms, we aim at measuring masses and half-lives in the region of neutron-rich Yb-Os nuclei, thereby we will in particular focus on studying extremely rare isomers in $^{186-188}$Hf and surrounding nuclei.

This proposal as well as the second part of G-22-00018 are herewith put forward by the ILIMA Collaboration for the 7-days ^{208}Pb beamtime window in 2025. The most time-demanding part of the tuning of the ESR is its set into the isochronous mode. It will be done once for both experiments which shall facilitate the efficiency of beam-time and resource usage.

21 shifts (7 days) of parasitic beam are requested for both, this proposal and the remaining part of G-22-00018 (Spokesperson W. Korten)

Mass & half-life measurements in the neutron-rich N≈116 Hf region

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B.H. Sun, H. Watanabe (Beihang Univ.)
B. Jurado, C. Berthelot, B. Wloch, G. Leckenby (CENBG, Borddeaux)
and the ILIMA Collaboration

Abstract:
The novel cavity-based non-destructive Schottky detector has been developed within the ERC CoG "ASTRUm". Based on it, the combined Schottky+Isochronous Mass Spectrometry was established in the ESR. Every individual stored in the ESR ion is unambiguously detected and, if sufficiently short-lived, monitored until it decays. In May 2024, within the G-22-00018 experiment (spokesperson W. Korten), an isomer with half-life of just 3 ms could be measured. Hence, equipment with superior sensitivity and speed is available for precision experiments at the ESR.

By employing the above detector and profiting from the capability of the ESR to cover simultaneously a large region of the nuclear chart, we aim at

(1) Examine the region of neutron-rich Yb-Os ^{208}Pb projectile fragments for known and unknown short- and long-lived rare isomers. Measure their excitation energies and lifetimes;
(2) Measure ground state masses of several ten neutron-rich nuclides;
(3) Finally access to the exceptional isomer in $^{188}Hf_{116}$, which is predicted to be prolate with $K^{\pi} = 18^{+}$, and to be the most energetically favoured (most yrast) of all high-K states.

Combined Schottky+Isochronous Mass and Lifetime Spectrometry

The combined Schottky+Isochronous Mass Spectrometry (S+IMS) has been developed at the ESR within E143 experiment conducted in May 2021 [1]. Revolution frequency of every stored ion can be determined within a few milliseconds. In May 2024, within G-22-00018 experiment, nuclear species with half-life as short as 3 ms could successfully be measured. Moreover, the ESR can simultaneously store nuclides in a broad range of mass-over-charge ratios. These properties: (i) ultimate sensitivity to single stored ions; (ii) extremely quick measurement duration (a few 10 ms) and (iii) large bandwidth, make S+IMS an ideal tool for determining basic properties (masses and half-lives) of multiple nuclear species at the same time. Within this proposal we suggest to implement S+IMS to explore the region of neutron-rich Yb-Os ^{208}Pb projectile fragments.

The anticipated measurement time in the ESR, before the fresh ions are injected, will be 2 seconds. Taken the requested data taking time of 3 days, nuclear species with production rates as small as 1 particle in 1.5 days will be in reach. Masses and half-lives for all these nuclides will be measured. The resolving power of the S+IMS allows the resolution of low-lying isomeric states. Excitation energies, isomeric ratios, half-lives and possibly also decay branching channels will be possible to determine. An illustrative example of the S+IMS spectra is shown in Figure 1.

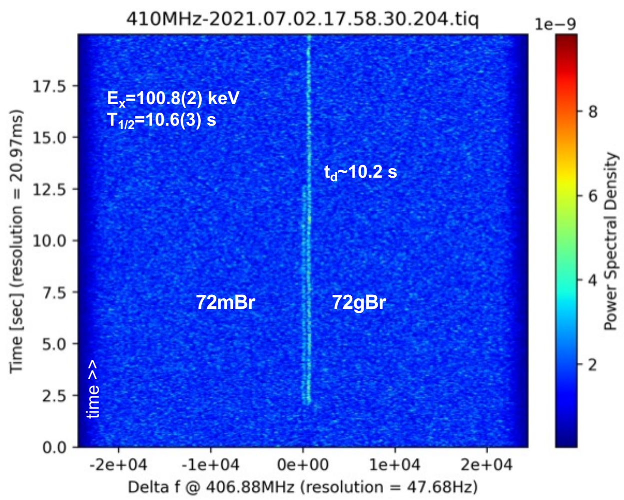

Figure 1. Schottky frequency spectra of ^{72}Br in ground and isomeric states stored in the ESR in isochronous mode (E143 Experiment). The time resolution in this figure is about 21 ms per bin. The isomer excitation energy is about 100 keV which is reflected by slightly different revolution frequencies. Both states are represented by a single ion. The decay of the isomer is clearly observed at about 10.2 s. [Unpublished]

This proposal aims at taking beam during the ^{208}Pb beam time block in 2025. During this time, the FRS is not available. Hence, we propose to use the direct TE transfer line connecting SIS18 and the ESR. It is equipped with 10 mm ^{9}Be target which has routinely been used in the past, when the FRS is blocked by a different experiment. Dedicated LISE++ simulations of the Target-TE-line-ESR have been prepared and benchmarked during the E143 and G-22-00018 experiments.

The region of interest of the proposed experiment is shown in Figure 2.

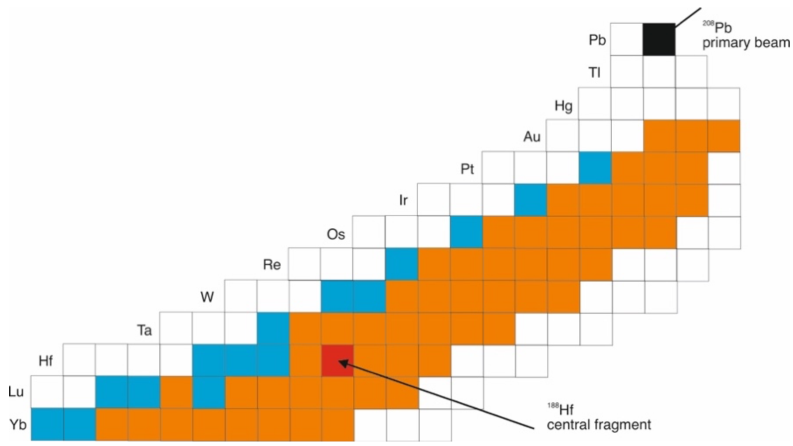

Figure 2. Simulated with LISE++ expected range of nuclei to be studied (assumed primary beam intensity is 2x10^9 per spill, spill is every 2 s, lowermost yield is 1 particle/day). Primary ^{208}Pb beam is shown as a black square. The central fragment $^{188}Hf^{72+}$ is shown in red. The blue and orange squares indicate known and unknown masses according to the Atomic Mass Evaluation 2022 [2]. Only the fully-ionized ions are considered in this figure. Isobars with charge states of up to Q=Z-4 are expected, which are closer to stability and will be used for mass calibration analogously to previously accomplished mass measurements, see e.g. [3].

Ground state mass and lifetime measurements

Masses and lifetimes are basic nuclear properties which are key for comprehending nuclear structure and nucleosynthesis. The new data for nuclei shown in Figure 2 will be used to test nuclear models, the predictive power of which deteriorates rapidly when entering into unknown regions. Furthermore, these will be the nearest to the astrophysical r-process path data.

Regarding the masses, various mass filters are used as sensitive probes for searching indications for nuclear structure changes. For instance, irregularities in the systematic trends of one and two nucleon separation energies versus proton or neutron numbers may point to shell structure changes or onsets of deformation. Odd-even staggering of binding energies is used to conclude on the strength of nucleon-nucleon correlations. All these as well as other systematic studies will be conducted. In particular, N = 116 is the critical point for a prolate-to-oblate shape/phase transition, which will be studied through its effect on nuclear masses.

Isomeric states

Long-lived isomers in exotic nuclides give key structure information. By employing time-resolved Schottky mass spectrometry, direct isomer observations have been achieved in ^{133}Sb [4] and ^{184}Hf [5], the latter being one of several long-lived isomers discovered in the A ≈ 180 region. Half-lives of seconds and minutes were measured for different Hf and Ta isomers [5], which are crucial for follow-up spectroscopy studies. The latter were indeed conducted at KISS facility at RIKEN [6,7].

We plan to scan the region illustrated in Figure 2 for known and new isomeric states. We will measure their excitation energies and, where applicable, also lifetimes. For known isomers, the absence of most or all bound electrons will enable us to extract the conversion coefficients [8].

Specific case of ^{188}Hf isomer

The hafnium (Z = 72) isotopes are well known [9,10,11] to contain long-lived isomers, such as the 31-y, 2.4-MeV yrast trap in ^{178}Hf, with $K^{\pi} = 16^{+}$. This remarkable case has attracted considerable attention and controversy with regard to its potential as an energy-storage medium [12]. Nevertheless, the exceptional combination of high spin and low excitation energy is almost certainly not unique. Nilsson and Woods-Saxon-Strutinsky calculations [9,10] indicate the existence of an even more favoured $K^{\pi} = 18^{+}$ isomer in neutron-rich ^{188}Hf.

Hafnium two- and four-quasiparticle isomer energies are shown in Figure 3. Although the 18^{+} isomer of ^{188}Hf has a higher calculated energy than the 17^{+} isomer of ^{186}Hf, this does not take account of the unfavoured residual interactions in the 17^{+} configuration. Furthermore, the higher spin in ^{188}Hf (18) makes the four-quasiparticle isomer the most energetically favoured of all the hafnium isotopes.

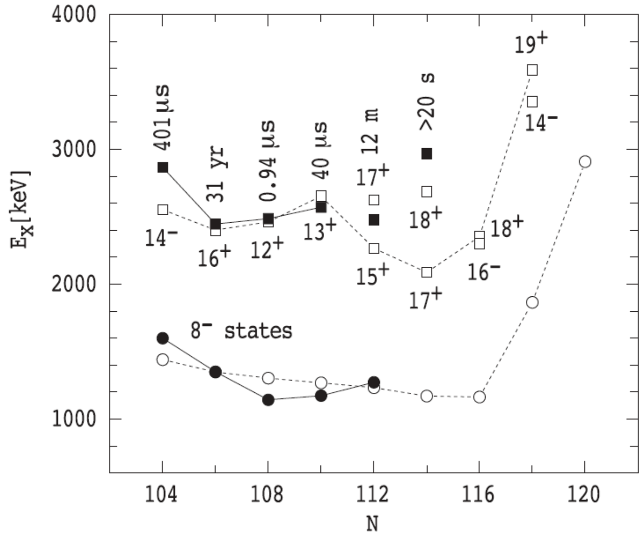

Figure 3: Experimental (filled symbols) and calculated (open symbols) isomer excitation energies, shown as a function of neutron number for low-lying two- and four-quasiparticle states in even-even hafnium (Z = 72) isotopes with N ≥ 104 [10,11]. Calculated spin values are given, together with experimental four-quasiparticle half-lives.

We will choose ^{188}Hf as the central fragment. We will strive to employ automatic algorithms to monitor online whether the isomer is produced in the experiment and, if detected, the cycling of the ESR will be halted for a short time to record its lifetime (within reasonable limits).

Beam-time request

This request aims specifically at a ^{208}Pb block available in the beamtime schedule in 2025. It is proposed to combine it with the second half of the G-22-00018 experiment. In doing so, the setting up of the isochronous ion optical setting of the ESR can be done once, which is the most time-consuming tuning operation in such kind of experiments.

After the tuning is completed, this experiment relies on accumulation of statistics. We will measure every particle which gets stored in the ESR. Assuming a new shot every

2 seconds, every shift adds 14400 chances to produce a rare species. We ask for 3 days of beam time, thereby approaching production cross-sections of a few 10 pb.

Altogether, there are 7 days of ^{208}Pb beam available, which can be shared as 2 days for setting up, 2 days for G-22-00018 and 3 days for this experiment.

Conclusion and importance for FAIR

The exploitation of storage rings at GSI-FAIR provides an excellent opportunity to discover the predicted high-spin isomer in ^{188}Hf, as well as other isomers predicted in the region. Owing to the ultimate sensitivity of ILIMA detection techniques, the storage of a single particle is sufficient to measure its mass. Many new masses and lifetimes will enable systematic studies in this region which will undoubtedly give new insights into the nuclear structure. Serendipitous discoveries are as well not excluded.

Although the achieved performance of the combined Schottky+Isochronous mass spectrometry is remarkable (see also the report on G-22-00018), there are further developments which will be pursued within this proposal and which are essential for ILIMA. One of them is the upgrade of the triger-less broad-band data acquisition system which shall compliment the presently used ones. Further, we will investigate the application of automatic and/or machine learning/AI algorithms for particle identification and control of data taking.

References

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[2] F. G. Kondev et al., Chin. Phys. C45 (2021) 030001.
[3] D. Shubina et al., Phys. Rev. C88 (2013) 024310.
[5] M.W. Reed et al., Phys. Rev. Lett. 105 (2010) 172501; PRC86 (2012) 054321.
[6] M. Mukai et al., Phys. Rev. C105 (2022) 034331.
[7] P. Walker et al., Phys. Rev. Lett. 125 (2020) 192505.
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[12] P.M. Walker and J.J. Carroll, Physics Today 58 (June 2005) 39.

Technical requirements ESR

G-22-00203-1.1-E

Target station	Requested experiment time:	Link scientist:
ESR	**9 Shifts**	Yury Litvinov

Mode of operation: **Parasitic beam**

Comments, e.g. on n° of runs: Run in parallel to FRS, combined with the second part of G-22-00018 as: 2 days set up of isochronous mode of the ESR, 2 days of G-22-00018 and 3 days of this experiment.

N° of days for set-up and disassembling w/o beam (if > 2 days) 0 [days]

Ion Beam Specifications (*for parasitic mode please enter 'none' or '0' in the obligatory fields)*:

Ion Species and Isotope (e.g. 197-Au) 208-Pb

Enriched? ☐ Yes ☒ No

Charge State (e.g. 67) 82

Energy (e.g. 1250 MeV/u) 800 [MeV/u]

Intensity [particle nA, ions/s] e.g. 1e11 ions/s 2e9 ions/s

Pulse Duration 500 [ns]

Duty Cycle (e.g. 5 Hz) 0.5 [Hz]

On SIS18 ☐ slow extraction ☒ fast extraction

Extraction time needed? (e.g. 10 s) [s]

Special requests on beam properties cooled in the SIS, one bunch

Additional information

Use of ... ☒ an existing setup ☐ a new setup

Detector(s) used in experiment SPARC/ILIMA Schottky cavity detectors

Safety Declaration

G-22-00203/UR

1. General Safety

Do you use combustable or hazardous gases within your experiment (e.g. gas target, gas detectors) ?

☐ Yes ☒ No

If yes, what sort of gases?

Which quantities or flow rates?

(A flow scheme and description of the safety concepts have to be submitted to the Safety Engineers at GSI)

Upload safety concept

Do you use any other dangerous (e.g. toxic, inflammable, biologically hazardous, etc.) materials / chemicals within your experiment?

☐ Yes ☒ No

(Note: Only biological material of biological safety level 1 must be irradiated at GSI)

If yes, what sort of materials/chemicals?

Which quantities?

Is your vacuum setup equipped with fragile parts like thin glass or foil windows, etc. (danger of implosion)?

☐ Yes ☒ No

Is it intended to move heavy parts for setting up your equipment or during the experiment?

☐ Yes ☒ No

If yes, brief description of the equipment and working procedure:

2. Radiation Safety

Do you use radioactive sources or materials onsite?

☐ Yes ☒ No

If yes, which isotopes/type?

Which activities [Bq]?

Do you use a target?

☒ Yes ☐ No

If yes, position: TE-line 9Be stripper

Indicate thickness of target [mm] or [g/cm²]**, and Interaction probability** [%] **with primary beam:**
10 mm

Material: 9-Be

Do you use a secondary target/degrader?

☐ Yes ☒ No

If yes, position:

Indicate thickness of target [mm] or [g/cm²]/ and Interaction probability [%] with primary/secondary beam:

Material:

Do you use a beam stop for primary/secondary beam?

☐ Yes ☒ No

If yes, position:

3. Electrical / Laser Safety

Do you use electrical instruments that you bring on site?

☐ Yes ☒ No

If yes, please describe devices above 1kV, self-made equipment etc.

Do you use high-intensity radio frequency (rf) sources onsite?

☐ Yes ☒ No

If yes, frequency region/power:

Brief description of the rf sources:

Do you use lasers in your equipment?

☐ Yes ☒ No

If yes, laser-type(s):

Max. power/energy:

Class:

Repetition rate:

4. Special Safety

Is there any other special safety aspect to be considered in connection with your proposal?

☐ Yes ☒ No

If yes, brief description:

Host Lab Resources

G-22-00203/UR

The timely knowledge on requirements of host lab resources by our users permits a solid in-house planning and allocation of respective resources. Please indicate here roughly, what you will need, and discuss details with the respective department later, if beamtime is granted. You might discuss your entries here with your link scientist before submission of your proposal.

Target Laboratory

Do you need targets from the department Target Laboratory?
☐ Yes ☒ No

If yes, please specify targets:

Detector Laboratory

Do you need support from the Detector Laboratory?
☐ Yes ☒ No

If yes, please specify:

Experiment Electronics

Do you need support from the Experiment Electronics department?
☒ Yes ☐ No

If yes, please specify: We need to repair the NTCap system. The work is already ongoing.

IT Department

Do you need resources from the IT department?
☒ Yes ☐ No

Needed data storage: ~20 TB

Computing requirements:

Indicate further requirements here:

Vacuum Systems

Do you need support from the department Vacuum Systems?
☐ Yes ☒ No

If yes, please specify:

Transport and Installation

Do you need support from the department Transport & Installation for transporting or installing heavy equipment? (formerly "Großraummontage")
☐ Yes ☒ No

If yes, please specify:

Mechanical Workshop

Do you need resources from the department Mechanical Workshop?
☐ Yes ☒ No

If yes, please specify:

Other Host Departments

Do you need resources from other host departments?

☒ Yes ☐ No

If yes, please specify: ATP and SPD - help with conducting the experiment