Nuclear Physics Research at GSI/FAIR: Precision experiments with stored and cooled exotic nuclei

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Meeting of the Nuclear Physics Division Board of the EPS
30 September - 01 October 2019, GSI and University of Frankfurt, Germany
GSI and FAIR Facilities

- **Intensity gain:** $x \ 100 – 1000$
- **10 x energy** (comp. to GSI)
- **Antimatter:** antiproton beams
- **Precision:** System of storage and cooler rings
Experimental Facilities available for FAIR Phase-0

Accelerated ions: $H^+, \ldots, U^{92+}$

- Linear accelerator UNILAC
- M-branch
- Z6
- PHELIX
- Heavy-ion synchrotron SIS 18
- Fragment Separator
- Storage ring ESR
- Cave A
- Cave C, mCBM, HADES
- CryRING

Ion sources

8% - 15% speed of light

Up to 90% speed of light
Physics at Storage Rings

**Storage rings stay for:**
- Single-particle sensitivity
- Broad-band measurements
- High atomic charge states
- High resolving power

CRYRING at GSI

ESR at GSI

R3 at RIKEN

CSRe at IMP
Why storage rings?

- Storage - efficient use of rare species
- Cooling - high quality beams
- Recirculation - high luminosities though thin targets
- Removing of contaminants
- Ultra-high vacuum – preserving atomic charge state
- Laser-ion interaction
- Various gaseous internal targets, electrons, (neutrons)
- High detection efficiencies for recoils
Storage ring facilities at GSI

Experimental Storage Ring (ESR)

In operation since 1990
Circumference = 108.3 m
Vacuum = $10^{-10} - 10^{-12}$ mbar
Electron, stochastic cooling
Energy range = 4 – 400 MeV/u
Slow and fast extraction

CRYRING
(transported from Stockholm University)

Planned start of operation (stable ions) – 2016
Planned start of operation (exotic nuclei) – 2020
Circumference = 54.15 m
Vacuum = $10^{-11} - 10^{-12}$ mbar
Electron cooling
Energy range = ~0.1 – 15 MeV/u
Slow and fast extraction
Physics with Storage Rings

**Nuclear Physics**
- Nuclear structure through transfer reactions
- Long-lived isomeric states
- Atomic effects on nuclear half-lives
- Half-life measurements of $^7\text{Be}$
- Nuclear effects on atomic decay rates
- Exotic decay modes (NEEC/NEET, unbound states, …)
- Di-electronic recombination on exotic nuclei
- Purification of secondary beams from contaminants
- Nuclear magnetic moments
- Neutron–induced reactions
- Capture reactions for p-process
- …

**Atomic Physics**
- Precision x-ray spectroscopy
- Super-Critical fields
- Electron-Ion collisions
- Atomic lifetimes
- Nuclear effects on atomic decay rates
- Photoionization
- Di-electronic recombination on exotic nuclei
- Electron spectroscopy / electron scattering
- Atom/Molecule fragmentation
- Ion-molecule interactions
- Laser induced recombination
- …
### PROPOSALS SUBMITTED TO G-PAC IN 2017

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Facility</th>
<th>Target</th>
<th>Conditions</th>
<th>Details</th>
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<tbody>
<tr>
<td>E131</td>
<td>CRYRING</td>
<td>A</td>
<td>Z&gt;54, Be-like</td>
<td>Slowing down, E-cooling, Vacuum</td>
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<tr>
<td>E138</td>
<td>CRYRING</td>
<td>A</td>
<td>U91+</td>
<td>Slowing down, E-cooling</td>
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<tr>
<td>E121</td>
<td>ESR</td>
<td>A</td>
<td>206Pb-&gt;205Tl81+</td>
<td>FRS, Stacking, E-cooling, Gas-Jet</td>
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<tr>
<td>E122</td>
<td>ESR</td>
<td>B</td>
<td>208Pb-&gt;fragments</td>
<td>FRS, S-cooling, E-cooling</td>
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<tr>
<td>E123</td>
<td>ESR</td>
<td>B</td>
<td>238U</td>
<td>E-cooling, Drift-tubes</td>
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<tr>
<td>E124</td>
<td>ESR</td>
<td>B</td>
<td>238U89+, 91+</td>
<td>E-cooling, Gas-Jet, E-spectrometer</td>
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<tr>
<td>E125</td>
<td>ESR</td>
<td>A</td>
<td>238U89+, 91+</td>
<td>Slowing down, E-cooling, Gas-Jet</td>
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<tr>
<td>E126</td>
<td>ESR</td>
<td>B</td>
<td>238U88+</td>
<td>Slowing down, E-cooling, Gas-Jet</td>
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<td>E127</td>
<td>ESR</td>
<td>A</td>
<td>Z~50</td>
<td>Slowing down, E-cooling, Gas-Jet, Vacuum</td>
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<td>E128</td>
<td>ESR</td>
<td>A</td>
<td>209Bi82+, 80+</td>
<td>(Stacking), E-cooling, Lasers, Drift tubes</td>
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<tr>
<td>E130</td>
<td>HITRAP</td>
<td>A</td>
<td>209Bi82+, 80+</td>
<td>Slowing down, (Stacking), E-cooling</td>
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<td>E132</td>
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<td>132Xe</td>
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<td>E133</td>
<td>ESR</td>
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<td>Z&gt;54</td>
<td>E-cooling, Gas-Jet</td>
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<tr>
<td>E136</td>
<td>ESR</td>
<td>B</td>
<td>12C3+</td>
<td>E-cooling, Lasers</td>
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<tr>
<td>E135</td>
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<td>84Kr32+</td>
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<td>E137</td>
<td>ESR-C. A</td>
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<td>238U89+</td>
<td>E-cooling, Extraction to Cave-A</td>
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<td>S461</td>
<td>CRYRING</td>
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<td>40Ar-&gt;30P15+</td>
<td>FRS, Slowing down, E-cooling</td>
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</table>

**TOTAL** 278
Proposal for an experiment to be conducted at FRS/ESR

**Measurement of the bound-state beta decay of bare $^{205}$Tl ions**

Updated from previously accepted proposal E100

For the LOREX, NucCAR, SPARC and ILIMA Collaborations

Regarding the proposal “Measurement of the bound-state beta decay of bare $^{205}$Tl ions” (Proposal E121), the G-PAC recommends this proposal with highest priority (A) and that **21 shifts of main beam time** be allocated for this measurement.
Bound-State $\beta$-decay
Bound-State Beta Decay of $^{205}\text{Tl}$ Nuclei

\[ Q_{EC} = 50.5(5) \text{ keV} \]

$^{205}\text{Tl}^{0+}$ stable

$^{205}\text{Pb}^{0+}$

\[ T_{1/2} = 17.3(4) \text{ My} \]
Bound-State Beta Decay of $^{205}$Tl Nuclei

$^{205}$Tl $^{81+}$

$1/2^+$

g.s.

$T_{1/2} \sim 120$ d (?)

$Q_{\beta b}(K) = 31.1$ keV

$1/2^-$

$2.3$

$5/2^-$

g.s.

$^{205}$Pb $^{82+}$

stable
Solar Neutrino Flux
Regarding the proposal "Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process" (Proposal E127), the G-PAC recommends this proposal with **highest priority (A)** and that **15 shifts of main beam time** be allocated for this measurement.
Nuclear reaction studies in a storage ring

- High revolution frequency
  - high luminosity even with thin targets
- Detection of ions via in-ring particle detectors
  - low background, high efficiency
- Well-known charge-exchange rates
  - in-situ luminosity monitor
- Ultra-thin windowless gas targets
  - excellent resolution
- Applicable to radioactive nuclei
Normalization of Nuclear Cross Sections

**total e⁻ capture rate [NRC + REC]**
measured by particle detection

**radiative e⁻ capture rate [REC]**
X-ray spectroscopy

Courtesy Jan Glorius
$^{124}\text{Xe}(p,g)^{125}\text{Cs}$ Experiment at the ESR

```
<table>
<thead>
<tr>
<th>si position</th>
<th>Entries</th>
<th>Mean x</th>
<th>Mean y</th>
<th>RMS x</th>
<th>RMS y</th>
<th>Integral</th>
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<tbody>
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<td>921</td>
<td>3.481</td>
<td>7.71</td>
<td>2.694</td>
<td>3.222</td>
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Entries | 0 | 0 | 0
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Mean x   | 0 | 921 | 0
Mean y   | 0 | 0 | 0
RMS x    | 0 | 0 | 0
RMS y    | 0 | 0 | 0
Integral | 0 | 0 | 0
$^{124}\text{Xe}(p,g)^{125}\text{Cs}$ Experiment at the ESR

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0 0 0

0 64209 0

0 0 0
$^{124}$Xe(p,γ) - Results

Approaching the Gamow Window with Stored Ions: Direct Measurement of $^{124}$Xe(p,γ) in the ESR Storage Ring

PHYSICAL REVIEW LETTERS 122, 092701 (2019)

J. Glorius, 1 C. Langer, 2 Z. Slavkovská, 2 L. Bott, 2 C. Brandau, 1,3 B. Brückner, 1 K. Blaum, 1,4 T. Davinson, 7 P. Erbacher, 2 S. Fiebiger, 7 T. Gaßner, 1 K. Göbel, 2 M. Groothuis, 7 A. Gumberidze, 1 R. Hess, 1 R. Hensch, 2 P. Hillmann, 2 P.-M. Hillenbrand, 1 O. Hinrichs, 2 B. Jurado, 9 T. Kaus, 1 T. Kisselbach, 2 N. Klapper, 2 C. Kožuharov, 1 D. Kurtulgil, 7 G. Lane, 10 C. Lederer-Woods, 7 M. Yu. A. Litvinov, 1 B. Löher, 11,1 F. Nolden, 1 N. Petridis, 1 U. Popp, 1 T. Rauscher, 12,13 M. Reed, 19 R. D. Savran, 1 H. Simon, 1 U. Spillmann, 1 M. Steck, 1 T. Stöhlker, 14 J. Stumm, 2 A. Surzhykov, 15,16 A. Taremi Zadeh, 2 B. Thomas, 2 S. Yu. Torilov, 13 H. Törnqvist, 11,1 M. Träger, 1 C. Trageser, 1,3 M. Volkmantl, 2 H. Weick, 1 M. Weigand, 2 C. Wolf, 2 P. J. Woods, 7 and Y. M.
The CRYRING facility

- CRYRING is a dedicated low-energy storage ring
  - all GSI beams available between ~100 keV/u and ~15 MeV/u
  - longer beam lifetimes for highly charged ions at low energies
- first commissioning phase is finished
- CRYRING is the ideal machine for astrophysical reaction studies
E131: Precision collision spectroscopy of Be-like ions at the electron cooler

Technical requirements:

- Be-like ions from ESR with $Z \geq 54$ and $I = 0$ (e.g. $^{132}\text{Xe}^{54+}$, $^{142}\text{Nd}^{56+}$, $^{208}\text{Pb}^{78+}$, $^{238}\text{U}^{88+}$).
- Highest possible energy in CRYRING to minimize electron capture from residual gas.
- Number of stored ions in CRYRING $> 10^4$.
- Ion-beam diagnostics (current transformer, beam profile monitor, Schottky analysis).
- Cold electron beam (expansion factor 100).
- Control of electron and ion beam positions in order to be able to achieve coaxial beams of electrons and ions in the electron cooler.
- Flexible programming control of high-voltage amplifier at electron cooler.
- Movable single-particle detector with 100% detection efficiency at position “30<q”.
- Hardware timing signals for data acquisition such as “injection”, “start of voltage ramp”, and “new voltage”.

![Graph and diagram illustrating the technical requirements.](image-url)
E138: 1s Lamb Shift in $U^{91+}$

Two microcalorimeters, each at a distance of roughly 3 m from the electron cooler region.

Basic parameters

- **Active area**: $1 \text{ cm}^2$
- **FWHM @ 60 keV**: 30 to 50 eV
- **Absorption eff.@ 100 keV**: 50% to 75%
- **total efficiency**: $0.5 \times 10^{-6}$
- **Operation temperature**: 50 mK
NUSTAR

ILIMA Isomeric Beams, Lifetimes and Masses

EXL Exotic nuclei studied in light-ion induced reactions at the NESR storage ring Experiment

SPARC

PANDA
Isochronous Mass Spectrometry
- Time of Flight Detectors
- Ultra-sensitive non-destructive Schottky detectors
ILIMA: Masses and Lifetimes

- stable nuclei
- nuclides with known masses
- to be measured with SUPER-FRS-CR-RESR-NESR
  Conceptual Design Report, GSI 2001

r-process path

ILIMA
FAIR Phase-1: SPARC@HESR

\[ \gamma_{\text{max}} = 6.3 \]

stochastic cooling

locations of target station

2 TDRs approved in 2016

- species: p, pbar, HCl, RIB
- circumference 574 m
- injection energy 740 MeV/u
- \( B_p = 50 \) Tm
- for \( U^{92+} \): 4.937 GeV/u
- \( \gamma_{\text{MAX}}=6.30; \beta_{\text{MAX}}=0.987 \)
- momentum (energy) range 1.5 to 15 GeV/c (0.8-14.1 GeV)
- stochastic cooling / e-cooling
Ion Beam Facilities / Trapping & Storage

Stored and Cooled
Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei
From Rest to Relativistic Energies (up to 4.9 GeV/u)

Worldwide Unique
HESR Parameters

- Storage ring for internal target
- Initially also used for accumulation
- Injection of $\bar{p}$ at 3.7 GeV/c
- Slow synchrotron (1.5-15 GeV/c)
- Luminosity up to $L \sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

<table>
<thead>
<tr>
<th>Mode</th>
<th>High luminosity (HL)</th>
<th>High resolution (HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p/p$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 4 \times 10^{-5}$</td>
</tr>
<tr>
<td>L (cm$^{-2}$s$^{-1}$)</td>
<td>$2 \times 10^{32}$</td>
<td>$2 \times 10^{31}$</td>
</tr>
<tr>
<td>Stored $\bar{p}$</td>
<td>$10^{11}$</td>
<td>$10^{10}$</td>
</tr>
</tbody>
</table>

- Stochastic & electron cooling
- Resolution $\sim 50$ keV
- Tune $E_{CM}$ to probe resonance
- Get precise $m$ and $\Gamma$
The combination of PANDA’s discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world.
Thank you for your attention!