Super-FRS the Next-Generation Facility for Physics with Exotic Nuclei

Hans Geissel
Santiago de Compostela, October 27, 2003

- Motivation
- Production and Separation of Exotic Nuclei
- The Superconducting FRagment Separator
- The Experimental Branches
- Status and Technical Challenges
Physics with Exotic Nuclei

- Fundamental Symmetries and Interactions
- Parity Violation and Time Reversal in Atoms
- Test of the Standard Model CKM-Matrix
- Superheavy Elements
- New Decay Mode 2 p-Emission
- r-process, Novae and X-ray Bursts
- Structure & Dynamics of Exotic Nuclei
- Applications
- Halo, Skin, Molecule Nuclei
- New Shells, New Shapes
- r-process and Supernovae
- Sp = 0
- Sn = 0
- Nuclear Astrophysics
High Energies RIB →
Discovery of the Proton Halo

W. Schwab et al.,

1500 MeV/u

T. Kobayashi et al.,

H. Lenske,
Prog. Part. Nucl. Phys. 46 (2001)
Production of Exotic Nuclei at relativistic Energies

**Projectile Fragmentation**

- Projectile
- Target
- Fragment

Nucleon-nucleon collisions, abrasion, ablation

\[ \vec{v}_f \approx \vec{v}_p \]

**Projectile Fission**

- Projectile
- Target
- Fission Fragments

Electromagnetic excitation, fission in flight

\[ \vec{v}_f \approx \vec{v}_p + \vec{v}_{\text{fission}} \]
Kinematics of Projectile Fragmentation and Fission

\[
\frac{\Delta p}{p} \alpha \text{[mrad]} \\
\begin{array}{c|cccccc}
\text{Energy, MeV/u} & 200 & 400 & 600 & 800 & 1000 & 1200 & 1400 \\
\hline
\frac{\Delta p}{p} & 0.00 & 0.01 & 0.02 & 0.03 & 0.04 & 0.05 & 0.06 \\
\end{array}
\]

\[
\sigma_\alpha \text{[mrad]} \\
\begin{array}{c|cccccc}
\text{Energy, MeV/u} & 200 & 400 & 600 & 800 & 1000 & 1200 & 1400 \\
\hline
\sigma_\alpha & 5 & 10 & 15 & 20 & 25 & 30 & 35 \\
\end{array}
\]

\[
400 \text{ MeV/u} \ 238\text{U} + 0.1 \text{mg/cm}^2 \rightarrow 12\text{C} \rightarrow 132\text{Sn}
\]

\[
400 \text{ MeV/u} \ 124\text{Xe} + 0.1 \text{mg/cm}^2 \rightarrow 100\text{Sn}
\]
$B_\rho - \Delta E - B_\rho$ Separation Method

GANIL: LISE, RIKEN: RIPS, JINR: COMBAS, MSU: A1900, GSI: FRS
Operating Domain of the $B_\rho-\Delta E-B_\rho$ Separation

Energy (MeV/u)

Fragments → Nb

50% nuclear absorption

$q=Z$

95%

90%

80%

$Z_f$

H. Geissel et al. NIM B 204 (2003) 71
Limitations of the Present Facility

- Low primary beam intensity (e.g. $10^8$ $^{238}$U ions /s)

- Low transmission for projectile fission fragments (4-10%)

- Low transmission for fragments to the experimental areas (cave B,C) and into the storage ring ESR (a few %)

- Limited maximum magnetic rigidity
  - @ FRS: for U-like fragments
  - @ ESR: cooler performance and magnets
  - @ALADIN, to deflect break-up fragments
SIS-100/300, Super-FRS, CR, NESR

SIS-100/300 $^{238}$U ions $10^{12} / s$

Large Acceptance Superconducting FRagment Separator (Super-FRS)

Ion-optical Parameters:

\[
\varepsilon_x = \varepsilon_y = 40 \, \pi \, \text{mm mrad}
\]

\[
\phi_x = \pm 40 \, \text{mrad}, \quad \phi_y = \pm 20 \, \text{mrad}
\]

\[
\frac{\Delta p}{p} = \pm 2.5 \, \%
\]

\[
B \rho_{\text{max}} = 20 \, \text{Tm}
\]

\[
R_{\text{ion}} = 1500
\]
Comparison of FRS and Super-FRS

H. Geissel et al. NIM B 204 (2003) 71
The Super-FRS is ideal for Studies of r-Process Nuclei

Rates for Doubly Magic Nuclei
The International Accelerator Facility for Beams of Ions and Antiprotons
The Super-FRS and its Branches
Experiments with Low-energy and Stopped beams

6 Precision measurements in ion and atom traps

6 Decay spectroscopy

6 Laser spectroscopy

C. Scheidenberger
Combination of ISOL and In-Flight Separation Methods

Production Separation

Beam Preparation

Precision Spectroscopy

In-Flight

ISOL

$t_{sep} \sim \mu s$

Gas Cell

Cooler/Buncher

$t_{sep} \sim s$

Storage Ring

 Trap

MeV/u

keV
Identification of the Doubly Magic Nucleus $^{100}\text{Sn}$

The same Experimental Setup was used for Discovery of the 2p Radioactivity of $^{45}\text{Fe}$

$\sigma(100\text{Sn})=1.8\text{ pb}$

A. Stolz (TUM)  M. Pfützner, B. Blank
The Super-FRS and its Branches

- Pre-Separator
- Main-Separator
- High-Energy Cave
- Low-Energy Cave
- Energy Buncher
- eA-Collider
- Gas target
- NESR
- CR complex
- SIS-100
- SIS-12/18
- Production Target

GSi
Reactions with Relativistic Radioactive Beams

Experiments in the High Energy Branch of the Super-FRS

T. Aumann, H. Emling, B. Jonson

Experiments
- knockout and quasi-free scattering
- electromagnetic excitation
- charge-exchange reactions
- fission
- spallation
- fragmentation

Physics Goals
- single-particle occupancies, spectral functions, correlations, clusters, resonances beyond the drip lines
- single-particle occupancies, astrophysical reactions (S factor), soft coherent modes, giant resonance strength, B(E2)
- Gamov-Teller strength, spin-dipole resonance, neutron skins
- shell structure, dynamical properties
- reaction mechanism, applications (waste transmutation, ...)
- γ-ray spectroscopy, isospin-dependence in multifragmentation
The High Energy Experimental Setup

Reactions with Relativistic Radioactive Beams R3B

A versatile setup for kinematical complete measurements

**Large-acceptance measurements**

\[ B_\rho = \frac{m_\gamma v}{Z} \]

*High-resolution momentum measurement*

T. Aumann
Low-lying Dipole Strength observed for n-rich Nuclei

⇒ Photo-neutron cross sections for unstable nuclei from virtual photons

\[ \sigma(\gamma, xn) \text{ (mb)} \]

\[ \sigma(\gamma, p) \text{ (mb)} \]

\[ E \text{ (MeV)} \]

\[ N-Z=0 \]

\[ N-Z=4 \]

\[ N-Z=5 \]

\[ N-Z=6 \]

R. Palit et al., to be publ.

A. Leistenschneider et al., PRL 2001
Isovector Dipole Excitations of Asymmetric Nuclei

**Stable Nuclei:** 100% of strength absorbed into giant resonance (GDR)

**Exotic Nuclei:**
- Strong fragmentation of strength
- Appearance of low-lying strength
- ‘Threshold’ strength (low-lying, non-resonant \((\gamma,n)\) strength)
- New coherent ‘soft’ excitation modes

![Diagram of iso vector dipole excitations](image)

- Strong non-resonant transitions

- Effective forces
dependence on isospin

- Single-particle structure

- Astrophysical implications
The Super-FRS and its Branches
Predictive Power of Mass Models
Precision Mass Measurements in the ESR

B. Franzke, H. Geissel, G. Münzenberg, H. Wollnik
2. Pairing-Gap energy, deduced from 5-point binding difference

\[ \Delta_{n5}(Z, N) = \frac{1}{8} (m(Z, N + 2) - 4(Z, N + 1) + 6m(Z, N) - 4m(Z, N - 1) + m(Z, N - 2)) \cdot c^2 \]

\[ \Delta_{p5}(Z, N) = \frac{1}{8} (m(Z + 2, N) - 4(Z + 1, N) + 6m(Z, N) - 4m(Z - 1, N) + m(Z - 2, N)) \cdot c^2 \]
Predictive Power of the Hatree-Fock-Bogoliubov Model

M. Samyn et al. NP A700 (2001) 142

\[ \sigma_{\text{rms}} = 674 \text{ keV} \]

\[ \sigma_{\text{rms}} = 650 \text{ keV} \]

Comparison of measured masses with HFB

Yu. Litvinov

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Predictive Power of the Relativistic Mean Field Model (RMF)

G.A. Lalazissis et al. ADNDT 71 (1999)1
even-even nuclei, NL3, $\sigma_{\text{rms}} = 2.6$ MeV

$\sigma_{\text{rms}} = 3831$ keV

Yu. Litvinov
Observation of Bound-State Beta Decay

continuous state $\beta$-decay

$^{207}_{81}$Tl $\rightarrow$ $^{207}_{82}$Pb$^+$

bound state $\beta$-decay

$^{207}_{81}$Tl$^{81+}$ $\rightarrow$ $^{207}_{82}$Pb$^{81+}$

T. Ohtsubo
Lifetime Measurements of Short-lived Nuclei
Applying Stochastic and Electronic Cooling

D. Boutin
Observation of the Short-Lived Isomer $^{207m}$Tl with Stochastic Cooling

$$T_{1/2} = \frac{T_{1/2_{\text{lab}}}}{\gamma} = \frac{\ln 2}{\gamma \lambda _{\text{lab}}} = 1.48 \pm 0.12 \text{ s}$$

$$\lambda _{\text{lab}} = 0.328 \pm 0.026 \text{ s}^{-1}$$

$$\gamma = 1.4305$$

D. Boutin, F. Nolden
Measured Bound-State Beta Decay of $^{207}$Tl

\[ \frac{\lambda_{\beta_b}}{\lambda_{\beta_b} + \lambda_{\beta_c}} = 0.183 \pm 0.002 \]

D. Boutin
Electron Scattering

Conventional

- Point like particle
- Pure electromagnetic probe ⇒ formfactors $F(q)$
- $F(q)$ transition formfactors ⇒ high selectivity to certain multipolarities

eA collider

- Unstable nuclei
- Large recoil velocities ⇒ full identification (Z,A)
- Kinematics ⇒ $4\pi$ - geometry, small angles complete kinematics
- Bare ions ⇒ no atomic background
Advantage and Opportunities of eA Experiments

$^{48}\text{Ca}(e,e')$

$E_0 = 88$ MeV

$\Theta_e = 40^\circ$

$^{48}\text{Ca}(e,e'n)$

Coincidence with recoils

H. Simon, H. Weick
Opportunities of eA Experiments


H. Simon, H. Weick
Technical Challenges at the Super-FRS

- Magnet System in front of the Production Target
- Targets, Beam Dump, Degraders (Remote Control, Shielding)
- Superconducting Magnets up to the First Focal Plane
- High Rate Detectors and Data Acquisition
- Isotope Separation Quality with the High Acceptance System
- Ion Optical Matching of the Super-FRS and the Storage Rings
Summary

◆ Studies of exotic atoms and exotic nuclei will contribute significantly to the basic knowledge of matter.

◆ Precision experiments with stored exotic nuclei open a new field for nuclear structure physics and astrophysics.

◆ The next–generation facility will present unique conditions for research and education.

◆ There are many technical challenges inviting especially also the next-generation scientists.
## Staged Construction of the International Facility for Beams of Ions and Antiprotons

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Description</th>
<th>Key Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>General Planning</td>
<td>SIS18 Upgrade 70 MW Connection Proton-Linac</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>TDM*</td>
<td>Civil Construction 1</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>I</td>
<td>SIS100 Transfer Line SIS18-SIS100 High Energy Beam Lines</td>
<td>2.7x10^{11} s^{-1} \mathcal{L}_{\pi^+} (200 \text{ MeV/u})</td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td></td>
<td>5x10^{12} protons per pulse</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td>SIS100/200 Tunnel, SIS Injection+Extraction+Transfer</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>II</td>
<td>Transfer Buildings/Line Super-FRS, Auxiliary Bldgs, Transfer Tunnel to SIS18, Building AFT, Super-FRS, CR-Complex</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td>RIB High+Low Energy Branch</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>III</td>
<td>RIB Prod.-Target, Super-FRS RIB High+Low Energy Branch Antiproton Prod.-Target CR-Complex</td>
<td>1x10^{11} s^{-1} \mathcal{L}_{\pi^+} (0.4-2.7 \text{ GeV/u})</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td>2.5x10^{12} p (1-30 \text{ GeV})</td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
<td>3-30 GeV pbar -&gt; fixed target 10.7 GeV/u \mathcal{L}_{\pi^+} \rightarrow \text{HADES}^*</td>
</tr>
<tr>
<td>2014</td>
<td>IV</td>
<td>HESR &amp; 4 MV e^+ Cooling NESR</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td>HESR (ground level), NESR, AP-cave, e-A Collider, PP-cave</td>
</tr>
<tr>
<td>2016</td>
<td>V</td>
<td>SIS200* 8 MV e^- Cooling e-A Collider</td>
<td>1x10^{12} s^{-1} \mathcal{L}_{\pi^+}</td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td>100% duty cycle pbar cooled p (1-90 \text{ GeV})</td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td></td>
<td>35 GeV/u \mathcal{L}_{\pi^+} \rightarrow \text{NESR Physics}</td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td>Plasma Physics</td>
</tr>
</tbody>
</table>

* Construction
* Tunnel Drilling Machine
* SIS200 installation during SIS100 shut down

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