Results from the FRS Ion Catcher with projectile and fission fragments

Timo Dickel
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt
II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Germany

Overview

• The FRS Ion Catcher a test facility for the LEB
• Prototype of the Stopping Cell for the Super-FRS at FAIR
• Multiple-Reflection Time-of-Flight Mass Spectrometer
• Measurements at the FRS Ion Catcher in 2014
• Conclusions and Outlook
Low Energy Branch of the Super-FRS at FAIR

LEB of the Super-FRS:
universal and fast production - high selectivity - cooled exotic nuclei

MATS (Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly charged ions)

LaSpec (Laser Spectroscopy)

Stopping Cell Principle

Range Bunching

- Ion Beam with Different Momenta $p + \delta p$, $p$, $p - \delta p$
- DC (+RF) Dispersive Stage
- Monoenergetic Degrader

Decreases range straggling by more than an order of magnitude
→ Enables stopping of ion produced at relativistic energies in gas-filled stopping cells

Stopping Cell

- High-energy ion beam
- DC (+RF) to DC+RF
- Low-energy ion beam
- RF structure: funnel or carpet

Converts high energy, large emittance beam in low energy, low emittance beam

References:
- H. Geissel et al., NIM A 282 (1989) 247
- H. Weick et al., NIM B 164 (2000) 168
- C. Scheidenberger et al., NIM B 204 (2003) 119
- M. Wada et al., NIM B 204 (2003) 570
- G. Savard et al., NIM B 2004 (2003) 582
Stopping Cell Design

Cryogenic Operation
Operate He-filled stopping cell at cryogenic temperature (~70 K)

- Ultra-pure helium (freezing-out of contaminants)
  - Ideal for ion survival, 2+ charge state possible
  - No formation of molecules/adducts
- Reduced radial ion diffusion
- Reduced requirements for cleanliness → easier, more flexible construction

High-density Operation
Use RF structure with small spacing to achieve high RF repelling field
(PCB-based RF carpet instead of RF funnel)

- High stopping gas densities
- Less complex construction than RF funnels

P. Dendooven et al., NIM A 558 (2006) 580
S. Purushothaman et al., NIM B 266 (2008) 4488

M. Wada et al., NIM B 204 (2003) 570
M. Ranjan et al., Europhys. Lett. 96 (2011) 52001

Diameter: 250 mm
Electrode spacing: 0.25 mm
Prototype of the Stopping Cell for the LEB

- **Outer chamber (room temperature)**
- **Insulation vacuum**
- **Inner chamber (cooling by cryo-cooler ~ 70 K)**
- **223Ra source**
- **DC cage electrodes**
- **RF carpet**
- **Extraction RFQ**
- **Exit hole**

Motivation: TOF Mass Spectrometry in Nuclear Physics

Enables high performance

• Fast → access to very short-lived ions ($T_{1/2} \sim \text{ms}$)
• Sensitive, broadband, non-scanning → efficient, access to rare ions

Conventional TOF-MS achieve medium mass resolving power only → Solution to achieve high mass resolving power and accuracy:

Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)

Applications in nuclear physics

• Direct mass measurements of exotic nuclei

  C. Scheidenberger et al., Hyperfine Interact. 132 (2001) 531

• High-resolution isobar separator

  W.R. Plaß et al., NIM B 266 (2008) 4560

• Diagnostics measurements: Monitor production, separation and low-energy beam preparation of exotic nuclei

Multiple-Reflection Time-of-Flight Mass Spectrometer

T. Dickel et al., NIM A 777 (2015) 172 - 188
M. I. Yavor et al., IJMS (2015) in press

Full Mass Range, m/Δm ~ 10^3-10^4
Mass Accuracy ~ 10^-6-10^-7
m/Δm > 10^5

T. Dickel, Results from the FRS Ion Catcher with projectile and fission fragments, NUSTAR Annual Meeting, Darmstadt/GSI, March 2 – 6, 2015
MR-TOF-MS: Mass Resolving Power

Mass Measurement
Accuracy
\(~10^{-7}\)

Transmission efficiency
up to 70%

Sensitivity
\(~10\) ions

Isobar separator with high ion capacity
\(>10^6\) ions/s

World-wide unique combination of performance characteristics!

\(^{133}\)Cs\(^+\), Ion kinetic energy 1.3 keV
FRS Ion Catcher a Test Facility for the LEB

100...1500 MeV/u ~ MeV/u ~ eV ~ keV

Target → Fragment Separator → Buncher / Degrader → Stopping Cell → MR-TOF MS → Experiments (Trap, Laser,..)

Primary Beam

In-flight Production

In-flight Separation

Momentum Compression

Stopping / Thermalization

Isobar Separation

SuperFRS

LEB

MATS / LaSpec

$^{238}\text{U} @ 1000 \text{ MeV/u}$

Production Target 1.6 g/cm² Be+Nb

Slits

Scintillator

Degraders

TOF

Middle Focal Plane

TPCs MUSIC

Slits

Scintillator

Degraders

MUSIC

Cryogenic Stopping Cell

Diagnostics Unit

W.R. Plaß et al., NIM B 317 (2013) 457

T. Dickel, Results from the FRS Ion Catcher with projectile and fission fragments, NUSTAR Annual Meeting, Darmstadt/GSI, March 2 – 6, 2015
Setup at the FRS Ion Catcher at GSI

Cryogenic Stopping Cell
Diagnostics Unit
Time-of-Flight Mass Spectrometer
Cooling System

Beam from FRS
Extraction time:
- Extraction time independent of areal density
- given by mechanical design of stopping cell

Stability of operation:
from production to mass measurement
Stable over one week beam time
Improved Total Efficiency

- Carpet with improved electrical design:
  - Higher RF-amplitude possible and lower temperatures

<table>
<thead>
<tr>
<th>Year</th>
<th>Max. RF-amplitude</th>
<th>Temperature of RF coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>80 Vpp</td>
<td>270 °K</td>
</tr>
<tr>
<td>2014</td>
<td>140 Vpp</td>
<td>150 °K</td>
</tr>
</tbody>
</table>

- Improved bake-out + New carpet
  - Better cleanliness
  - Higher ion survival and extraction efficiency (eg. $^{223}$Th)

- Higher differential pumping
  - Higher areal density → Higher stopping efficiency
    - 2012: 3.1 mg / cm²
    - 2014: 6.3 mg / cm²

→ Improved total efficiency up to 30%
   Factor 2 higher than 2012
Mass Measurement: Uranium Projectile Fragments

- Mass window of ~ 30 u
- Mass resolving power ~ 120,000
- Doubly charged
- Shortest half-life
- Highest sensitivity

220Ra

Half-life: 17.9 ms
11 ions

T. Dickel, Results from the FRS Ion Catcher with projectile and fission fragments, NUSTAR Annual Meeting, Darmstadt/GSI, March 2 – 6, 2015
Measurement and Separation of Isomers

**Measurement of Isomers**

- Identification of $^{211}\text{Po}$ and $^{211m}\text{Po}$
- Measurement of excitation energy
- Measurement of isomeric ratio

**Spatial separation of ground state and isomeric state**

- Separation using the ion gate of the MR-TOF-MS
- Proof-of-principle: production of isomerically clean beams

T. Dickel, Results from the FRS Ion Catcher with projectile and fission fragments, NUSTAR Annual Meeting, Darmstadt/GSI, March 2 – 6, 2015
• Mass measurement of uranium fission products produced at 1000 MeV/u
• MR-TOF-MS will enable efficient search and measurement of new isotopes and isomers

Mass Measurement: Uranium Fission Fragments

\[ m/\Delta m = 360,000 \]

1.6 MeV

0.3 MeV

133Cs

133I

133mI

133Te

133mTe

Counts

Mass-to-Charge / (u/e)

T. Dickel, Results from the FRS Ion Catcher with projectile and fission fragments, NUSTAR Annual Meeting, Darmstadt/GSI, March 2 – 6, 2015
FRS identification may not always be accurate (need to identify one isotope in the identification plot)

→ MR-TOF-MS as mass tagger
→ helped to correctly identify $^{134}\text{I}$

Universal and fast technique (~20 min)
Conclusions and Outlook

(Prototype) Stopping cell for the Super-FRS and the FRS Ion Catcher

- Cryogenic, high density operation, suitable for exotic nuclei produced at relativistic energies
- Unprecedented efficiencies for relativistic ions
  Access to short life times (extraction time ~ 25 ms)

High-performance multiple-reflection time-of-flight mass spectrometer

- High-accuracy mass measurements at m/Δm up to ~ 450,000
  Harvest of 6 shifts of beam time:
  ≥ 8 first direct mass measurements,
  e.g. \(^{220}\)Ra (T\(_{1/2}\) = 17.9 ms, 11 ions only)
- Powerful tool for the measurement of isomers:
  Identification, excitation energies, isomeric ratios
- High-resolution mass separator for isobars and isomers
- Diagnostics tool: identification and quantification

Development of the future stopping cell for the Super-FRS

- Higher areal densities
- Shorter extraction times
- Higher rate capabilities
Acknowledgements

FRS Ion Catcher / S411 Collaboration

F. Amjad², S. Ayet², T. Dickel¹,², P. Dendooven³, M. Diwisch¹, J. Ebert¹, A. Estrade², F. Farinon², H. Geissel¹,², F. Greiner¹, E. Haettner¹, F. Heiße², C. Hornung¹, C. Jesch¹, N. Kalantar-Nayestanaki³, R. Knoebel², J. Kurcewicz², J. Lang¹, W. Lippert¹, I. Miskun², I. Moore⁴, C. Nociforo², A. Pikhtelëv⁵, M. Petrick¹, M. Pfuetzner², W.R. Plaß¹,², S. Pietri², I. Pohjalainen⁴, A. Prochazka², S. Purushothaman², M. Ranjan³, M.P. Reiter¹, A.-K. Rink¹, S. Rinta-Antila⁴, C. Scheidenberger², M. Takechi², Y. Tanaka², H. Weick², J.S. Winfield², X. Xiaodong¹,², M.I. Yavor⁶

¹ II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany
² GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
³ KVI, University of Groningen, The Netherlands
⁴ University of Jyväskylä, Jyväskylä, Finland
⁵ Institute for Energy Problems of Chemical Physics, RAS, Chernogolovka, Russia
⁶ Institute for Analytical Instrumentation, RAS, St. Petersburg, Russia

Funding:
BMBF (06GI185I, 06GI9114I, 05P12RGFN8),
State of Hesse (HMWK) (LOEWE Center HICforFAIR),
Univ. Groningen and GSI,
JLU Giessen and GSI (JLU-GSI strategic Helmholtz partnership agreement)