Radioactive Ion Beams at the HRIBF
Present Status and Future Development Plans

HRIBF Workshop - Near and Sub-barrier Fusion of Radioactive Ions with Medium and Heavy Targets
December 2-3, 2005
Oak Ridge, TN

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Physics Division, ORNL
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This file last modified Wednesday, July 13, 2005
Proton-rich Radioactive Ion Beams

- Seven different targets used
- Three different ion sources
- 14 radioactive beams
## Accelerated Proton-rich Radioactive Ion Beams

<table>
<thead>
<tr>
<th>RIB</th>
<th>Energy Range (MeV)</th>
<th>Highest Intensity (pps on target)</th>
<th>ORIC Current (µA on target)</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁷Be</td>
<td>4 - 100</td>
<td>2.0 x 10⁷</td>
<td>n/a</td>
<td>100</td>
</tr>
<tr>
<td>¹⁷F</td>
<td>10-170</td>
<td>1.0 x 10⁷</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>¹⁸F</td>
<td>10-108</td>
<td>6.0 x 10⁵</td>
<td>1.5</td>
<td>100</td>
</tr>
<tr>
<td>⁶⁷Ga</td>
<td>160</td>
<td>2.5 x 10⁵</td>
<td>5</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>⁶⁹As</td>
<td>160</td>
<td>2.0 x 10⁶</td>
<td>5</td>
<td>~ 10</td>
</tr>
<tr>
<td>⁷⁰As*</td>
<td>140</td>
<td>2.0 x 10³</td>
<td>0.01</td>
<td>&lt; 10⁻⁶</td>
</tr>
</tbody>
</table>

* This beam was used for commissioning of the RIB Injector

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Available Neutron-rich Radioactive Ion Beams
(over 110 beams with intensities $\geq 10^3$ ions/sec)

E/A = 3 MeV/amu
# Accelerated n-rich RIBs (A<100 amu)

<table>
<thead>
<tr>
<th>RIB</th>
<th>Energy Range (MeV)</th>
<th>Highest Intensity (pps)</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Cu}$</td>
<td>220</td>
<td>15</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{77}\text{Cu}$</td>
<td>220</td>
<td>1.6</td>
<td>0.03</td>
</tr>
<tr>
<td>$^{78}\text{Cu}$</td>
<td>220</td>
<td>0.15</td>
<td>0.003</td>
</tr>
<tr>
<td>$^{79}\text{Cu}$</td>
<td>220</td>
<td>0.006</td>
<td>0.00012</td>
</tr>
<tr>
<td>$^{78}\text{Ge}$</td>
<td>175</td>
<td>$1.5 \times 10^6$</td>
<td>67</td>
</tr>
<tr>
<td>$^{80}\text{Ge}$</td>
<td>179</td>
<td>$1.8 \times 10^6$</td>
<td>95</td>
</tr>
<tr>
<td>$^{82}\text{Ge}$</td>
<td>183 - 327</td>
<td>$1.8 \times 10^4$</td>
<td>22</td>
</tr>
<tr>
<td>$^{83}\text{Ge}$</td>
<td>220 - 327</td>
<td>1500</td>
<td>43</td>
</tr>
<tr>
<td>$^{84}\text{Ge}$</td>
<td>220 - 327</td>
<td>95</td>
<td>12</td>
</tr>
<tr>
<td>$^{85}\text{Ge}$</td>
<td>220</td>
<td>1.3</td>
<td>18</td>
</tr>
<tr>
<td>$^{86}\text{Ge}$</td>
<td>220</td>
<td>0.006</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>380</td>
<td>$4.7 \times 10^5$</td>
<td>78</td>
</tr>
<tr>
<td>$^{83}\text{Se}$</td>
<td>327</td>
<td>$1.7 \times 10^5$</td>
<td>95</td>
</tr>
<tr>
<td>$^{84}\text{Se}$</td>
<td>327 - 380</td>
<td>$1.1 \times 10^4$</td>
<td>10</td>
</tr>
<tr>
<td>$^{92}\text{Sr}$</td>
<td>450</td>
<td>500</td>
<td>72</td>
</tr>
</tbody>
</table>
## Accelerated n-rich RIBs (A>100 amu)

<table>
<thead>
<tr>
<th>RIB</th>
<th>Energy Range (MeV)</th>
<th>Highest Intensity (pps)</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{117}$Ag</td>
<td>460</td>
<td>$1.2 \times 10^6$</td>
<td>95</td>
</tr>
<tr>
<td>$^{118}$Ag</td>
<td>236 – 455</td>
<td>$1.7 \times 10^6$</td>
<td>90</td>
</tr>
<tr>
<td>$^{126}$Sn</td>
<td>378</td>
<td>$1.0 \times 10^7$</td>
<td>50</td>
</tr>
<tr>
<td>$^{128}$Sn</td>
<td>384</td>
<td>$3.0 \times 10^6$</td>
<td>&gt; 99</td>
</tr>
<tr>
<td>$^{130}$Sn</td>
<td>391 – 550</td>
<td>$5.0 \times 10^5$</td>
<td>&gt; 99</td>
</tr>
<tr>
<td>$^{131}$Sn</td>
<td>550</td>
<td>$2.5 \times 10^5$</td>
<td>&gt; 99</td>
</tr>
<tr>
<td>$^{132}$Sn</td>
<td>316</td>
<td>$8.6 \times 10^5$</td>
<td>96</td>
</tr>
<tr>
<td>$^{132}$Sn</td>
<td>453 – 620</td>
<td>$1.5 \times 10^5$</td>
<td>96</td>
</tr>
<tr>
<td>$^{133}$Sn</td>
<td>316</td>
<td>$1.7 \times 10^4$</td>
<td>33</td>
</tr>
<tr>
<td>$^{134}$Sn</td>
<td>316 – 560</td>
<td>$2.8 \times 10^3$</td>
<td>38</td>
</tr>
<tr>
<td>$^{136}$Sn</td>
<td>400</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{129}$Sb</td>
<td>400</td>
<td>$2.9 \times 10^7$</td>
<td>49</td>
</tr>
<tr>
<td>$^{132}$Te</td>
<td>350 – 396</td>
<td>$3.0 \times 10^7$</td>
<td>87</td>
</tr>
<tr>
<td>$^{134}$Te</td>
<td>396 – 565</td>
<td>$2.4 \times 10^6$</td>
<td>95</td>
</tr>
<tr>
<td>$^{136}$Te</td>
<td>396 – 470</td>
<td>$5.0 \times 10^5$</td>
<td>80</td>
</tr>
</tbody>
</table>
RIB Production Targets

- **HfO₂ fibers** (¹⁷F and ¹⁸F)
- **Uranium carbide** (n-rich beams via proton-induced fission)
- **Molten metals**
  - Germanium (Ga, As, and Se beams)
  - Nickel (Cu beams)
- **Ni pellets** (⁵⁶Ni via (p,p2n) reaction – ⁵⁶Co contamination)
- **Cerium sulfide** (³³Cl and ³⁴Cl)
  - Thin layers deposited on W-coated carbon matrix
- **Silicon carbide** (²⁵Al, and ²⁶Al)
  - Fibers (15 μm), powder (1 μm), thin layers on carbon matrix
- **Aluminum oxide** (²⁶Si and ²⁷Si)
  - Thin fibers (6μm) with sulfur added for transport
- **⁷Be** sputter targets (mixed with copper or niobium powder)
Radioactive Ion Beam Injector System

- 300 kV (design) platform
- 2-stage mass separation
  - $M/\Delta M \sim 1000$
  - $M/\Delta M \sim 20000$
- Robotic handling of activated targets and ion sources
RIB Development and Testing Facilities

- **Ion Source Test Facility I (ISTF-1)**
  - characterize ion sources (efficiency, longevity, emittance, energy spread, effusion)
  - some target tests (e.g. effusion through matrix)
  - ion cooler for negative ions (gas-filled RFQ)

- **Ion Source Test Facility II (ISTF-2)**
  - laser ion source
  - ECR ion source

- **On-Line Test Facility (OLTF)**
  - low intensity tests of target and ion source performance
  - compatible with the RIB Injector and results are scaleable

- **High Power Target Laboratory (HPTL)**
  - **NOW** available for target tests using high power beams from ORIC
Ion Source Test Facility I (ISTF-1)
Laser-induced Photodetachment of Ni\textsuperscript{−} and Co\textsuperscript{−} in a He-filled RFQ Ion Cooler

![Graph showing ion current as a function of time with laser on and off]

**Neutralization:**
- Co\textsuperscript{−}: ~95%
- Ni\textsuperscript{−}: ~10%

- Laser: Nd:YAG, 5 W, CW, 1064 nm
- About 50% of laser beam passed through the RFQ (40 cm long)
- The energy of the negative ions was reduced from 5 keV to <50 eV in the cooler
- Laser interaction time in the RFQ cooler is on the order of 1 ms
Ion Source Test Facility II (ISTF-2)

Mass Analyzing Magnet
Faraday Cup
Emittance Measurement Device
Faraday Cup
Einzel Lens
Ion Source
High Voltage Insulator
High Voltage Platform
Fence
High-Voltage Interlocked Sliding Door
Motor Generator

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U.S. Department of Energy
Laser Ion Source Experiments (8/31/04 – 9/23/04)

• Laser ion source set up and operated at HRIBF in collaboration with a group from Mainz (Klaus Wendt and students)
• Three-step ionization of Sn, Ge, and Ni obtained
• Last ionization step:
  – autoionization state for Sn and Ge
• No surface ionized Sn, Ge, and Ni ions observed
  – hot-cavity temperatures ~ 1700-2000 C
• Overall LIS efficiencies:
  – 22% for Sn (compared to 10% achieved at ISOLDE)
  – 3.3% for Ge
  – 2.7% for Ni
Laser setup for the initial test at the HRIBF

Laser beam into the hot cavity through the mass-analysis magnet

Ti:sapphire lasers (supplied by the Mainz group)

Nd:YAG Pump laser (60 W, 10 kHz, 532 nm)
Sn Ionization Scheme

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Ni Ionization Scheme

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Ge Ionization Scheme

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On-Line Target and Ion Source Testing Facility

Beam from Tandem Accelerator

Target / Ion Source

Beam Diagnostics

Dipole Magnet
$M/\Delta M = 2000$

Mass Measurements

Charge Exchange Measurement System

Moving Tape System and $\gamma$-ray Detector

TIS Fabrication Area
HfO$_2$ Fiber Target for Production of $^{17,18}$F Beams

- Thin Fibers (5 µm) - fast diffusion
- High porosity (density is 1.15 g/cm$^3$)
- Refractory (m.p. is 2770 C)
- Free of volatile impurities
- 4 rolls of HfO$_2$ cloth used for target
  - 1.5 cm diameter x 1 cm thick each
- Al$_2$O$_3$ felt sheath
  - Provides aluminum vapor
  - Fluorine is transported as AlF molecule
- HfO$_2$ cloth sheath
  - Keeps alumina away from the Ta wall
UC Targets for Production of Neutron-rich Beams

- RVC fiber diameter: 60 µm
- Matrix density: 0.06 g/cm³
- UC coating thickness: 8 - 10 µm
- Target density: 1.2 g/cm³
- Long useful lifetimes
  - (>50 days with 10 µA on target)
SiC targets (for the production of $^{25}\text{Al}$ and $^{26}\text{Al}$ beams)

- 15 \( \mu \text{m} \) diameter SiC fibers
- 1 \( \mu \text{m} \) diameter SiC powder
- SiC does not sinter
- Maximum operating temperature is 1650 \( \text{C} \)
- $^{25}\text{Al}$ yields were about the same – \( 10^4 \) ions/sec/\( \mu \text{A} \)
- Can increase yield significantly (x10) by adding fluorine to system and extract as AlF
- Next target is a thin layer of SiC on a graphite matrix

\[
\begin{align*}
28\text{Si}(p,\alpha)^{25}\text{Al} \\
28\text{Si}(d,\alpha n)^{25}\text{Al} \\
28\text{Si}(p,2\text{pn})^{26}\text{Al} \\
28\text{Si}(d,\alpha)^{26}\text{Al}
\end{align*}
\]
Production Rates for Sn, Sb, Te, and I isotopes in a UC target

Production Rate from proton-induced fission in uranium
(using 40 MeV protons)

Mass Number (amu)

Cumulative Production Rate (nuclei/second/microAmp)

I
Te
Sb
Sn

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Purity of radioactive Sn Beams

Sn Purity as a percentage of total (%)

Mass of Sn Isotope (amu)

extracted as Sn⁺
extracted as SnS⁺
Intensities for Sn, Sb, and Te Isotopes

- Measured with Bragg detector (gas chamber)
- Beam energy is 316 MeV
- $^{132}$Sn beam intensity is $8.6 \times 10^5$ pps (96% of total)
- $^{133}$Sn beam intensity is $1.5 \times 10^4$ pps (33% of total)
- $^{134}$Sn beam intensity is $2.8 \times 10^3$ pps (38% of total)
- These beams were extracted as sulfide molecules from the ion source
- The percentages of Sn in the atomic ion beams are <1%
- The $^{134}$Sb/$^{133}$Sb ratio is small due to a much shorter half-life
Production Rates for Ge, As, and Se isotopes in a UC target

Production Rates from proton-induced fission of uranium (using 40 MeV protons)

Cumulative Production Rate (nuclei/second/microAmp)

Mass Number (amu)

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Purification of $^{80}\text{Ge}$ beam

Cocktail beam

Beam purified with sulfur ($^{80}\text{Ge}$ is 95%)
Elevation View of HPTL
RIB Analysis Beam Line

- Target/Ion Source
- Quad 1
- Object Slits & Diagnostics
- Quad 2
- Image Slits & Diagnostics
- 90° Magnet
- Beam Diagnostics
- Diagnostic End Station

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Ion Sources at the HPTL

- The target station and the RIB analysis beam line are designed to be flexible enough to accommodate a variety of ion sources
  - Electron-Beam Plasma ion source (EBPIS)
  - Kinetic Ejection Negative ion source (KENIS)
  - Laser ion source (LIS)
  - Positive surface ionization sources (hot Ta or W tubular ionizer)
  - Negative surface ionization sources (e.g. LaB$_{6}$ ionizer)
  - Cs-sputter type ion sources (multi-sample, batch-mode)
  - Close-coupled designs (e.g. FEBIAD ion source – GSI design)
  - Electron Cyclotron Resonance (ECR) ion sources
  - Ion guide (cooler) techniques
Plans for Target Development at the HPTL

- Materials tests with high power (54 MeV protons, up to 20 µA)
  - SiC, M₅Si₃ (M = Zr, Ta, W, Nb, ...) for ⁵²⁵Al and ²⁶ᵐAl beams
  - CeS for ³³Cl and ³⁴Cl beams
- UC target tests
  - Proton-induced fission vs. deuteron-induced fission (direct)
  - Investigate 2-step targets (larger volumes)
  - Higher density UC targets
    - Measure release efficiency for short-lived isotopes
    - Lifetime of target with high power density
- Thin target geometries
  - Liquid targets
    - As and Se from liquid germanium
    - Cu from liquid nickel
  - Irradiation with ³He and ⁴He beams (Al₂O₃ → P, SiC → S, C → ¹⁵O)
- Production beam manipulation (rastering)
  - HfO₂ target for increased ¹⁷F beam intensity
- Ion sources
  - LaB₆ ion source to make pure Br and I beams (investigate long-term poisoning with high intensity production beams)
  - Close-coupled target to reduce effusion times