NEUTRON-RICH BEAMS FROM $^{252}$CF FISSION AT ATLAS – STATUS of THE CARIBU PROJECT

The 11$^{th}$ International Conference on Heavy Ion Accelerator Technology

June 8, 2009
Venice, Italy

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Outline

CARIBU - CAlifornium Rare Ion Breeder Upgrade

- CARIBU in the context of low-energy nuclear physics research
- Project Description, Status & Expected Performance
  - Technical approach
    - Source and radiological issues
    - Gas catcher/RFQ cooler
    - ECR Charge-breeder
    - Isobar separator - beam purity
    - Low-Intensity Diagnostics
- Commissioning Plans
Low-energy nuclear physics research

Continued progress in nuclear physics and associated fields needs radioactive beams

Proton-rich side reached by existing facilities

Neutron-rich side will be the focus of new facilities

n-rich region is the next frontier
A Californium Fission Source for ATLAS

- $^{252}$Cf fission yield is complementary to uranium fission
- Provides access to unique, important areas of the N/Z plane
- Significant yield extends into the r-process region
- Technology and experience useful for FRIB

$^{252}$Cf spontaneous fission yield
$T_{1/2}=2.6$ a 3.1% fission branch

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$p$-induced $^{238}$U Fission yield region

Limit of “known” masses

1 Ci Source
Extracted fission Product yield
- $>10^6$
- $10^5 - 10^6$
- $10^4 - 10^5$
- $10^3 - 10^4$
- $10^0 - 10^3$
**252Cf Fission Source System**

- New ~1600 ft² building.
- 1 Ci $^{252}$Cf fission source in shielded cask.
- Gas catcher/RFQ to thermalize ions and create beam.
- Isobar separator with $\delta m/m: 1/20,000$.
- Un-accelerated ion & atom trap area
- ECR charge breeder ion source.
- Mounted on HV (up to 200kV) platform.
- Weak beam diagnostics.
### Examples of Yields for Representative Species

Calculated maximum beam intensities for a 1 Ci $^{252}$Cf fission source using expected efficiencies.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life (s)</th>
<th>Low-Energy Beam Yield (s$^{-1}$)</th>
<th>Accelerated Beam Yield (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{104}$Zr</td>
<td>1.2</td>
<td>6.0x10$^5$</td>
<td>2.1x10$^4$</td>
</tr>
<tr>
<td>$^{143}$Ba</td>
<td>14.3</td>
<td>1.2x10$^7$</td>
<td>4.3x10$^5$</td>
</tr>
<tr>
<td>$^{145}$Ba</td>
<td>4.0</td>
<td>5.5x10$^6$</td>
<td>2.0x10$^5$</td>
</tr>
<tr>
<td>$^{130}$Sn</td>
<td>222.</td>
<td>9.8x10$^5$</td>
<td>3.6x10$^4$</td>
</tr>
<tr>
<td>$^{132}$Sn</td>
<td>40.</td>
<td>3.7x10$^5$</td>
<td>1.4x10$^4$</td>
</tr>
<tr>
<td>$^{110}$Mo</td>
<td>2.8</td>
<td>6.2x10$^4$</td>
<td>2.3x10$^3$</td>
</tr>
<tr>
<td>$^{111}$Mo</td>
<td>0.5</td>
<td>3.3x10$^3$</td>
<td>1.2x10$^2$</td>
</tr>
</tbody>
</table>

~65 species have accelerated intensities of over 10$^5$

>150 additional species have accelerated intensities of over 10$^4$
Californium source characteristics

- CARIBU will (eventually) use fission fragments from a 1 Ci source of $^{252}$Cf.
  - Start with two weaker sources – ~2 mCi and ~80 mCi
- $^{252}$Cf is produced at the High Flux Reactor at Oak Ridge and will be produced by ORNL as an open source electroplated on a polished SS plate.
- $^{252}$Cf has a fairly short lifetime of 2.645 yrs so that source thickness is small
  - 1 Ci of $^{252}$Cf is 1.9 mg; over an 1.9 cm diameter circle this yields a density of ~660 $\mu$g/cm$^2$
- A 1 Ci source has significant radiation and radioactivity emissions
  - 46 rem/hr neutrons at 30 cm
  - 5 rem/hr $\gamma$-rays at 30 cm
  - Radioactive and noble gas emissions must be trapped or exhausted
CARIBU Shielding

Required: Access to equipment near source for extended periods.

• Shielding Design Goals
  • Less than 1 mrem/hr at 30 cm
  • Fully shielded even during source installation
  • Manual operation of shielding and source movement during installation

• Shield requirements:
  • ~0.65 m. 5% borated polyethylene for neutrons
  • Additional 5 cm. heavy metal shielding for γ-rays
  • Exhausting system through HEPA filters for volatile species.
CARIBU Shield Cask

Required: Access to equipment near source for extended periods.

- Unshielded 1Ci $^{252}$Cf source
  - 46 rem/hr neutrons
  - 5 rem/hr $\gamma$-rays
- Work area radiation goal is:
  - 1 mrem/hr @ 30 cm
- The CARIBU source is installed in a shielded cask.
  - Store & transport $^{252}$Cf source
  - Tungsten for $\gamma$ absorption
  - Borated polyethylene for neutrons
  - Outer steel for secondary $\gamma$, fire suppression, & strength for transport
- For the 1 Ci source, 1.9 mg of material is deposited in a ~2cm diameter disk on a stainless steel plate.
- The plate is mounted on a shielded plug which provides shielding for emergency work.
**Californium source and gas catcher relationship**

- For installation in the gas catcher, the source and shielding plug are pushed from the storage location into position at the end of the helium gas catcher.
- The assembly is sealed to the gas catcher, the source being inside the gas catcher.
Gas catcher shielding

- Interlocked pieces to remove line of sights
- Removable to provide access for maintenance
- Leave ports for pumping and RF feeding access
- Polyethylene enclosed in metal shield to minimize fire hazard
- Whole shielding assembly sitting at 50 kV above platform

Additional shielding will be installed around beamline
Monitoring and exhausting radioactive volatiles

- CARIBU building is kept at negative pressure by HEPA exhaust system
  - Contains any spill/leakage
- Cask storage space purged by N₂ flow
- Combined with gas catcher exhaust
  - 100 second holdup time
  - Charcoal traps for iodine
  - Additional small HEPA
    - Particulate trap
- Continuous exhaust monitor
  - Exhaust β activity logged
- Work area n/γ monitored
**CARIBU gas catcher requirements (1)**

- Detailed simulations of fission fragment stopping in the gas catcher, incorporating contaminants in the californium source, source size, protective foil, spherical degrader thickness and size, and proper energy-mass distribution for different fragments indicate that
  - a **50 cm gas catcher diameter** is required
  - **3 different degraders** can cover the full fission fragment mass range
    - *degrader is a half sphere of 4 cm radius (≈11 mg/cm² Al thickness)*
    - *degrader will be removable locally*

![Graphs of ion stopping position for Mo and Xe](image-url)
The 1 Ci $^{252}$Cf source will generate significant ionization in the gas catcher:

- ~ $10^9$ fission per second with two fission fragments per fission (one emitted towards the gas catcher volume)
  - Fission fragments lose roughly 5 MeV in gas volume (most energy lost in degrader)
- ~ $4 \times 10^{10}$ alpha particles per second, half of which go through the gas catcher
  - Alphas lose roughly 0.5 MeV in gas volume (most go through the gas and hit the enclosure where they deposit the rest of their energy)
- Both sources contribute almost equally to ionization density
- Build up of beta decaying activity has a negligible effect
- Total ionization density ~ $1.5 \times 10^{16}$ eV/s over a 160,000 cm$^3$
  - ~ $9 \times 10^{10}$ eV/cm$^3$.s $\Rightarrow$ high intensity operation

~ 10-100 times higher ionization than normal CPT operation
~ 10 times below FRIB-like ionization density
Gas catcher operation at FRIB/CARIBU intensity

Series of high intensity tests at ATLAS in late 2006 confirmed redesigned gas catcher.

• High efficiency obtained at up to $10^9$ incoming particles per second
• Extracted ions identified as ions, not molecular ions
• All modifications had a clearly identifiable positive effect
**CARIBU gas catcher**

- Device similar to ANL-proposed FRIB gas catcher
  - Same operating principle (RF + DC + gas flow)
  - Similar construction
  - Similar length
  - Twice the diameter (50 cm inner diameter)
**RFQs for gas cooler**

- **Design criteria**
  - Accept and transport all heavy-ions from gas catcher
    - *Large initial RFQ aperture of 15 mm*
  - Pressure in the acceleration region (at the end of the cooler) must be <10⁻⁵ mbar
    - *Two large sections of RFQ cooler and two μRFQs for differential pumping*
  - Minimal final emittance and energy spread < 1 eV
    - *Matching of RFQs (and μRFQs) sections to minimize reheating during transitions*
    - *Individual lengths tuned to assure thermalization*
    - *Conical extraction structure to minimize field penetration*
  - Total length: Less than 1 meter
RFQ cooler simulations

- Energy spread ~ 0.5 eV
- Emittance ~ $1\pi$ mm•mrad
- Differential pumping sufficient
- Acceleration by 50 kV DC potential yields spot size diameter below 1 mm
- Total length just below 1 m

Corrected energy distribution at x=650 mm

Phase space diagram of y-Vy

Phase space diagram of z-Vz

Calculations by Tao Sun using SIMION
CARIBU gas catcher status

- Gas Catcher/RFQ cooler installation on platform underway
  - Vacuum systems in place
  - RF tank circuits being tuned
  - First ions (stable) late June 2009
**CARIBU gas catcher status**

- Gas Catcher/RFQ cooler isolated from main platform and biased to 50 kV.
- Status of installation on June 1, 2009
CARIBU gas catcher status

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**Purification of radioactive ion beam**

- Contaminant of neighboring masses are handled easily by most experiments. Same mass contaminants are more difficult.
- The resolution required to remove contamination is:
  - neighboring masses: \( R = 250 \)
  - molecular ions: \( R = 500 - 1000 \)
  - isobars: \( R = 5000 - 50000 \) (far/close to stability)
  - isomers: \( R = 10^5 - 10^6 \)
“Compact” isobar separator

- Takes advantage of low emittance and energy spread of extracted beams:

  Beam Properties from gas catcher:
  \[ \varepsilon \approx 3 \pi \text{ mm}\cdot\text{mr} \quad \delta E \approx 1\text{eV} \]
  \[ 1\text{ mm dia. (circular) beam} \]
  \[ \theta_{\text{max}}, \varphi_{\text{max}} = \pm 6\text{ mr} \]

- Matching sections at entrance and exit transform beam to a ribbon beam.
- 2 x 60 degree bends
- \( R = 50 \text{ cm} \)
- Dispersion 22.8 meters
- First order mass resolution: \( 1/20,000 \)
- Magnet delivery 1.5 years late, expect in June
- 3 electrostatic multipoles correct through 5\(^{th}\) order
- Small enough footprint to fit on HV platform
$X$ and $Y$ Projections at Focal Plane

@50keV: $\delta E = 0.05$ eV

- Separator has no energy compensation.
- Relies on very low energy spread from gas catcher
1+ $\rightarrow n+$ Implementation with ECR-I – CARIBU

Acceleration in ATLAS requires the ion’s $q/m \geq 0.15$

- Radioactive beams from a 1.0 Ci $^{252}$Cf fission source
  - Fission products are collected and thermalized in a helium gas catcher
- High resolution mass analysis (1:20,000) limits the number of isobars in the 1+ beam
- Transported to the ECR charge breeder source and stopped in plasma.
  - To achieve required mass resolution, source must operate at 50 kV (0.5 V stability)
  - High efficiency into one charge
CARIBU ECR Charge-Breeder System

- Shielding
- Fission Source
  - Gas catcher
  - RFQ cooler
- Einzel Lens
- Steering Correction
- Mass Analysis
- MCP Diagnostics
- ECR Source
- Faraday Cup/MCP Diagnostics
- ±δ V
- Source Z-axis
- 50 kV HV
- Charge Analysis

6/8/09
HIAT09: Status of the CARIBU Project
Pardo 27
ANL ECR-I modified to function as a Charge Breeder

- Necessary to increase ion charge state for acceleration in ATLAS. \( (q/m > 0.15) \)
- Injection side iron modifications to allow injection tube and optics
- Injection capture optics modeled with SIMION & GEM codes of Far-Tech, Inc.
- High voltage isolation
  - Increase to 50 kV as required by isobar sep.
- RF injection
  - Open hexapole structure allows radial injection
  - Two frequency heating: 10 & 14 GHz for improved efficiency
**ECR Charge Breeder Status**

- Initial operation of rebuilt source: January 2008
- Charge Breeding Studies with alkali metal began in May 2008
- Long-term charge breeding efficiency goal:
  - 5% solid materials
  - 10% gases

### Breeding Efficiency in August 2008

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Efficiency Single/Two Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{133}\text{Cs}^{16+}$</td>
<td>0.9%/1.4%</td>
</tr>
<tr>
<td>$^{133}\text{Cs}^{18+}$</td>
<td>1.0%/1.5%</td>
</tr>
<tr>
<td>$^{133}\text{Cs}^{20+}$</td>
<td>2.4%/2.9%</td>
</tr>
<tr>
<td>$^{133}\text{Cs}^{23+}$</td>
<td>0.5%/1.1%</td>
</tr>
</tbody>
</table>

Hear R. Vondrasek’s Presentation for latest Rb Efficiency Results
**Weak Beam Diagnostics**

- **Beam Profile & Current integration**
  - ANL-designed Beam Profile Monitoring Device
    - *Secondary electrons → MCP → phosphor screen → CCD image*
  - Commercial (Quantar Technologies) position sensitive device
    - *Secondary electrons → MCP using a 2D charge division anode*
  - Phosphor surface → high sensitivity CCD camera (profile only)
    - *$Gd_2O_2S:Tb$ and $Y_2O_2S:Tb*$

- **Longitudinal beam quality and mass determination/beam contamination**
  - Silicon detectors in dE/E format

- **Tape station: β counting**
  - Decay constant and isotope identification

1000 ions/s
Single frame capture
CARIBU Project Status

- ECR Charge Breeder commissioned
  - Charge state distributions are as expected
  - Minimum efficiency goals met (with stable beams)
  - Approaching CARIBU long-term efficiency goals
- Installation of Gas Catcher/RFQ underway
  - First stable ion extraction, late June or July
- Dipole magnets shipment now (June 2009)
  - Commissioning and calibration in July and August 2009
- Weak beam diagnostics available for commissioning
  - Four of six stations in place
  - First radioactive beam using 2.2 mCi source ~July 2009.
- Commissioning: September 2009.
Summary
CARIBU is an exciting, cost effective enhancement to the capabilities of the ATLAS facility that provides the tools necessary for cutting-edge nuclear physics research.

- The $^{252}$Cf fission source project compliments other existing facilities.
  - Provides tools to address an important class of physics questions during the era leading up to a national exotic beam facility.
  - Interesting array of radioactive beams.
  - Energy regime not generally available at other RIB facilities.
  - Leverages the expertise and technologies available at ATLAS.
  - The proposed upgrade has great synergy with future RIB facilities on both the technical and physics fronts.
- Serves as a bridge to higher intensity facilities.
- First beams are planned in Fall 2009 with an 80 mCi source.
- 1 Ci source not available until near end of calendar 2009.