ATLAS Users’ Workshop
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The CARIBU project

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Outline

- Brief recall of motivation for CARIBU project
  - open physics questions in neutron-rich nuclei
    - what is needed to address them
    - how can ATLAS contribute

- CARIBU project overview
  - technical approach
    - Production
    - Extraction
    - Purification
    - Post-acceleration
  - development and implementation
  - match to physics case
Where the field is going … big picture

ATLAS and other facilities provide access to this region. We have been there, lots of great physics left and we know how to proceed.

Limited access to this region. If changes are to occur, they will take place here and no existing facility can bring you to most of this region.

Maintain capabilities in p-rich region and increase access to the next frontier … the n-rich region!
Nuclear structure of neutron rich nuclei

- Heavy neutron rich nuclei region:
  - Region mostly unexplored even for the most basic properties
  - weakly bound with diffuse surface … reduced spin-orbit coupling, shell model possibly modified
  - Signature can take many forms: single particle structure, ground state properties, etc …
Neutron rich region: $r$-process path

- **$r$-process:**
  - Process known to exist
  - Exact site unknown
  - Path critically depends on nuclear properties of neutron rich nuclei:
    - Mass
    - Lifetime
    - Beta delayed neutrons
    - Fissionability
Important physics questions

- modification of nuclear structure in neutron-rich systems
  - *shell-structure quenching*
  - *single particle structure near neutron-rich magic nuclei*
  - *pairing interaction in weakly-bound systems*
- collective behavior in neutron-rich systems
- r-process path
  - *ground-state information*
    - *mass*
    - *lifetime*
    - *beta-delayed neutron branching ratio*
  - *neutron capture rate*
  - *fissionability of very heavy neutron-rich isotopes*
Requirements of n-rich physics: Nucleon transfer reaction ... single particle state

- Single particle/hole states around magic nuclei
  - $^{132}\text{Sn}$, $^{104}\text{Zr}$, $^{78}\text{Ni}$

- (d,p) reactions
  - best done well above Coulomb barrier in both entrance and exit channels ... i.e. about 7.5 MeV/u around $^{132}\text{Sn}$
  - requires $10^4$ per second to get information on angular distribution

- ($^3\text{He, }\alpha$), ($\alpha,t$) reactions
  - Well matched to higher angular momentum transfer
  - Energy requirements again set by Coulomb barrier
  - Required beams are not available anywhere at present

(d,p) reactions can also be important to determine (n,$\gamma$) rates close to r-process path:
- e.g. (d,p) on $^{84}\text{Ge}$ or $^{138}\text{Te}$

Available $^{132}\text{Sn}$ intensity vs energy (HRIBF)

$^{132}\text{Sn}(d,p)$ 7.5 MeV/u

$^{132}\text{Sn}(\alpha,^3\text{He})$ 11 MeV/u

CARIBU yield
Combined to improvement in instrumentation: Solenoid for Transfer Studies
Requirements of n-rich physics: BE(2) strength in neutron-rich nuclei

- Fission products have been studied with fission sources working off-line inside spectrometers like Gammasphere
  - Gamma ray energies measured
  - Low-energy levels determined
  - Little additional information except for most intense fragments
- Coulomb excitation of beams of these fission fragments would yield precision BE(2)’s and other information via multiple Coulomb excitation
- Gammasphere is an ideal instrument for these studies
Requirements of n-rich physics: Ground state properties close to r-process path

- r-process path determined by nuclear masses
- r-process evolution dominated by nuclear lifetimes
- beta-delayed neutrons affect final isotope distribution
- very little information in the refractory element region around Mo, Zr, Tc, ...
- need element independent technique to access these regions

- these measurements are done with unaccelerated beams
**ATLAS capabilities versus neutron-rich physics requirements**

- **ATLAS** → low-energy accelerator for stable ions operating as a user facility
  
  *with well documented characteristics (reliability, beam quality, transmission, timing, ...)*

- Excellent and varied physics program with a large active user community (~ 200+ on-site users per year)

- Requirements to start addressing open questions in neutron-rich nuclei
  - Production of heavy neutron-rich isotopes outside uranium low-energy fission peaks
  - Access to refractory and reactive species where little information is available
  - Good beam properties and energy range sufficient for transfer reaction (up to 10 MeV/u)
    - **ATLAS accelerator**
  - Beam purity or event by event identification
  - Intensity between 0.1 per second and $10^6$ per second depending on the properties to be studied
What does ATLAS have to offer for neutron-rich beams?

- New target/source approaches
  - gas catcher, ECR technology

  can be used to efficiently turn a non-conventional source of n-rich isotopes such as a spontaneous fission source into a low-energy beam

- Very high acceleration efficiency
  - RIA post-accelerator based on ATLAS

- Existing experimental equipment and infrastructure for radioactive beam physics
Research with neutron-rich isotopes at ATLAS

High-precision mass measurements on fission fragments at the CPT
Gas catcher developed at the Canadian Penning Trap (CPT) at ATLAS

- 20 cm long gas cell with second generation RF cone
- $\varepsilon \sim 45\%$
- mean delay time below 10 ms
- tested off-line with fission products and on-line with fusion–evaporation reactions
- routinely used for physics with CPT at Argonne for mass measurements on short-lived isotopes
A combination of forces working together is required to obtain

- Fast extraction times over the full volume
- High efficiency over the full volume
- Tolerance to high intensity
Accelerated neutron-rich radioactive ion beams

252Cf fission provides unique beams
Effort complementary to HRIBF
New opportunity: $^{252}$Cf source + large gas catcher as neutron-rich isotope source

- Shortened version of RIA gas catcher can efficiently stop fission products from a fission source
  - ~ 50% stopped in gas for backed source

- About 45% of those can be extracted as charged ions

- Very efficient and fast source, provides cooled bunched beams for post-acceleration

- Production peaks in new regions and extraction is element independent … new isotopes available
Extraction in the presence of large gas flow

Transport ions to lower pressure region via open structures that guide ions while letting the gas escape and be pumped away.

In DC mode, a limiting emittance (corresponding to roughly the gas temperature) is obtained after two such sections separated by small apertures (acceleration takes place in the lower pressure region after second section).
Extracted isotope yield at low energy

- 1 Ci $^{252}$Cf source
- about 20% of total activity extracted as ions
- works for all species
- large improvement over existing ISOL based facilities
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: $R = 10^5 - 10^6$
Purification of radioactive beams (2)

Purity is not only a function of mass separator resolution, other factors are important as well:

- relative intensity
- lifetime
- other means of separation

Yield and mass of $A=108$ isotopes

Yield and mass of $A=132$ isotopes
“Compact” isobar separator

• Modified scaled down version of first half of RIA mass separator …
  taking advantage of low emittance and energy spread of extracted beams

• Matching sections at entrance and exit

• 120 degrees total bend

• R = 60 cm

• Dispersion about 25 meters, 1mm slit size

• Small enough footprint to fit on HV platform
Resolution of compact isobar separator

Energy spread of 0.05 eV
R ~ 26000

Energy spread of 0.5 eV
R > 20000

Calculations by C.N. Davids and D. Peterson
New building addition for CARIBU project

New ~1650 ft² building

Isolation of source and other high-activity components

Building is a separate project:
Construction of new addition by Project Management and Engineering Division (PME)
With General Plant Project Funds (GPP)

CARIBU contribution will provide
Facility Space Enhancements:
• 2-ton Crane
• beamline hole in wall
• HEPA exhaust system for room and pumps
• Isolation door
• Utilities for CARIBU & Experiments
New CARIBU building addition under construction
Handling activity: $^{252}\text{Cf}$ Ion Source Preparation

- **$^{252}\text{Cf}$ Source Requirements**
  - Thin Source for Fission Fragment Release
  - 1 Ci Total for Radioactive Beam Production
  - ~ 5 cm Maximum Diameter

- **Shipping Requirements**
  - Certified Cask for Shipment from ORNL to ANL

- **Source Handling at ANL**
  - Mounting of Source in Source Holder in Hot Cell
  - Transfer of Source Holder to Special Purpose Cask
  - On-Site Transport of Cask to ATLAS Accelerator
  - Elevation of Cask to High Voltage Platform
  - Opening of Cask and Mating of Source Holder with Gas Catcher using Metal Vacuum Seal
Shielding Geometry on HV platform

5% Borated Polyethylene (BPE)

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

- Shield requirements:
  - ~0.75 m, mostly polyethylene for neutrons
  - Additional 5 cm. lead shielding for γ-rays
Post-acceleration: ANL ECR-I Modified as a Charge Breeder

- Existing ECR-I
- Modified as Charge Breeder
- Two frequency operation
  - 10 & 14 GHz
### Phoenix Charge Breeder Ionization Efficiency

**Gases**

<table>
<thead>
<tr>
<th>Gases</th>
<th>Efficiency</th>
<th>A/Q</th>
<th>Time(ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{40}\text{Ar}^{9+})</td>
<td>11.9%</td>
<td>4.4</td>
<td>25</td>
</tr>
<tr>
<td>(^{84}\text{Kr}^{14+})</td>
<td>10.3%</td>
<td>6.0</td>
<td>60</td>
</tr>
</tbody>
</table>

**Solids**

<table>
<thead>
<tr>
<th>Solids</th>
<th>Efficiency</th>
<th>A/Q</th>
<th>Time(ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{115}\text{In}^{18+})</td>
<td>4.6%</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>(^{109}\text{Ag}^{19+})</td>
<td>3.9%</td>
<td>5.7</td>
<td>25</td>
</tr>
<tr>
<td>(^{120}\text{Sn}^{22+})</td>
<td>4.0%</td>
<td>5.5</td>
<td>20(19+)</td>
</tr>
</tbody>
</table>

- 1+ beam emittance used: 55\(\pi\) mm•mr

(ISN/TRIUMF data)

Emittance extracted from gas catcher system is below 3\(\pi\) mm•mr and one may expect even higher charge breeding efficiency.
Proposed Charge-Breeder Scheme

- Shielding
- Fission Source
- Gas catcher
- RFQ cooler
- Einzel Lens
- Steering Correction
- Mass Analysis
- HV
- ±δ V
- ECR Source
- Charge Analysis
- Faraday Cup
- Source Z-axis
Modifications to ATLAS

ATLAS floor plan showing planned low-intensity profile monitors and beam current monitors. Beam delivery to four stations is assumed.
Main technical aspects for operation within ATLAS

- Operation of gas catcher system at high voltage ... as a facility component, not an experiment
- Confinement of contamination ... new building is great for that
- Connection between high-voltage platforms (easily removable)
- Modifications of ECR source for charge breeding (remains operational as ECR source)
- Finely tunable injection into charge breeder

Minimize disruption of ATLAS operation

Long term aspects

- Can make good use of ATLAS energy upgrade capabilities
- Good match to instrument improvements at ATLAS
- Invaluable experience for radioactive beam physics
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 r-process region
- Available energy exceeds that from HRIBF (Holifield Radioactive Ion Beam Facility) and ISAC (Isotope Separator and Accelerator at TRIUMF)

HRIBF yields from $^{238}$U

$^{252}$Cf spontaneous CARIBU yields
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>$^{138}$Xe</td>
<td>846.</td>
<td>9.8x10$^6$</td>
<td>7.2x10$^5$</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>
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### Schedule for project

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<tbody>
<tr>
<td>ATLAS Facility Space</td>
<td>Construct/ Enhance</td>
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<tr>
<td>ECR Charge Breeder</td>
<td>Design</td>
<td>Fabricate/Procure</td>
<td>Install</td>
</tr>
<tr>
<td>HV Platform</td>
<td>Design</td>
<td>Fab./Procure</td>
<td>Install</td>
</tr>
<tr>
<td>HV Transformer</td>
<td>Design</td>
<td>Fabrication/Procurement</td>
<td>Install</td>
</tr>
<tr>
<td>Isobar Separator</td>
<td>Design</td>
<td>Fabrication/Procurement</td>
<td>Install</td>
</tr>
<tr>
<td>Source, Cask, &amp; Transport</td>
<td>Design</td>
<td>Fabrication/Procurement</td>
<td>Install</td>
</tr>
<tr>
<td>Phase I (1 mCi Source)</td>
<td>Design</td>
<td></td>
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<tr>
<td>Phase II (30 mCi Source)</td>
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<tr>
<td>Phase III (1Ci activity)</td>
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<tr>
<td>ATLAS Diagnostics</td>
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<tr>
<td>Low-Energy Beamline</td>
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</table>

**Notes:**
- low-E beams
- Reaccelerated beams
What will CARIBU do?

- Provide unique capabilities with Coulomb-barrier neutron-rich beams of sufficient intensity to access important new physics
  - energy reach
  - refractory region
  - timing, beam properties
  - make ATLAS unique for neutron-rich beams until “RIA’ ” and complementary to other US facilities
- Demonstrates operation of gas catcher in battle conditions with high ionization intensities
- Can be implemented in a timely manner at a competitive cost
  - Low-E neutron-rich beams at increasing intensity during CY2008
  - Reaccelerated neutron-rich beams starting in CY2009