Radioactive Beam Capabilities at ATLAS and Plans for the Future

Jerry Nolen
Physics Division
Argonne National Laboratory

Nuclear Structure and Astrophysics with Radioactive Beams

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Greetings from Chicago!
ATLAS: The Argonne Tandem-Linac Accelerator System

A superconducting linac with beams from protons to uranium above the Coulomb barrier. About 20% of the research is with radioactive beams.
**ATLAS Features**

**ATLAS components:**

- Two injectors, a 9-MV tandem injector and the positive-ion injector, commissioned in 1993.
- 2 ECR ion sources and a negative-ion source.
- A total of 63 SC resonators (6 types) covering the $\beta = 0.008 - 0.2$

**Special features:**

- The first superconducting ion accelerator
- Intense, CW beams of any mass, protons to uranium
- Excellent time structure and energy resolution
- High transmission from source to target
- Data-base of stored and repeatable beam tunes
- Highly modular and reliable
A superconducting linac cryomodule currently in use at ATLAS. This was developed ~1990 for the uranium beam upgrade.
Research with radioactive beams at ATLAS

- Reaction rates relevant to nucleo-synthesis with radioactive beams created via the “two-accelerator” and “in-flight reactions” methods
- Mass measurements relevant to nucleo-synthesis – isotopes created via heavy ion fusion and gas catcher technology
  - Waiting points in the $R_p$ process – $^{68}$Se
  - Masses of isotopes leading to the r-process nuclei
- Nuclear structure at the proton drip line – studies of proton emitters
- Nuclear structure effects in sub-barrier fusion reactions with radioactive beams
- Radioactive isotopes in atom traps
  - Testing ab-initio structure calculations of light nuclei – measurement of the charge radius of $^{6}$He in an atom trap
  - Search for electric dipole moments in nuclei
- Masses and decays in ion traps to test fundamental interactions
  - Masses for superallowed beta decay
  - Beta-neutrino correlations: beta decay in an “open trap”
ATLAS Beams – FY2004

- **28 Beam Species**
- **5559 Beam Hours** (data taking & beam development) – **96.4% availability**
- **~1040 Hours of Rare (Radioactive) Beams** – “In-flight”
# ATLAS: Exotic Beam Production - Yields

<table>
<thead>
<tr>
<th>Ion</th>
<th>Reaction</th>
<th>Intens. #/s/pnA</th>
<th>Open Angle</th>
<th>Prod. Energy</th>
<th>Max. Rate/s</th>
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</thead>
<tbody>
<tr>
<td>$^6$He</td>
<td>$d(^7$Li,$^6$He)$^3$He</td>
<td>150</td>
<td>19$^\circ$</td>
<td>75 (MeV)</td>
<td>1 x $10^4$</td>
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<tr>
<td>$^8$Li</td>
<td>$d(^7$Li,$^8$Li)p</td>
<td>2000</td>
<td>11$^\circ$</td>
<td>71</td>
<td>1.5 x $10^5$</td>
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<tr>
<td>$^8$B</td>
<td>$^3$He($^6$Li,$^8$B)n</td>
<td>10</td>
<td>13$^\circ$</td>
<td>27</td>
<td></td>
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<tr>
<td>$^{11}$C</td>
<td>p($^{11}$B,$^{11}$C)n</td>
<td>2300</td>
<td>4.5$^\circ$</td>
<td>105</td>
<td>2 x $10^5$</td>
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<tr>
<td>$^{14}$O</td>
<td>p($^{14}$N,$^{14}$O)n</td>
<td>1200</td>
<td>2.9$^\circ$</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>$^{16}$N</td>
<td>$d(^{15}$N,$^{16}$N)p</td>
<td>30000</td>
<td>5.4$^\circ$</td>
<td>70</td>
<td>3 x $10^6$</td>
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<tr>
<td>$^{17}$F</td>
<td>$d(^{16}$O,$^{17}$F)n</td>
<td>20000</td>
<td>4.5$^\circ$</td>
<td>~90</td>
<td>2 x $10^6$</td>
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<tr>
<td></td>
<td>p($^{17}$O,$^{17}$F)n</td>
<td>20000</td>
<td>1.7$^\circ$</td>
<td>2 x $10^6$</td>
<td></td>
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<tr>
<td>$^{20}$Na</td>
<td>$^3$He($^{19}$F,$^{20}$Na)2n</td>
<td>~1</td>
<td></td>
<td>148</td>
<td></td>
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<tr>
<td>$^{21}$Na</td>
<td>$d(^{20}$Ne,$^{21}$Na)n</td>
<td>4000</td>
<td>4.0$^\circ$</td>
<td>113</td>
<td>2 x $10^6$</td>
</tr>
<tr>
<td></td>
<td>p($^{21}$Ne,$^{21}$Na)n</td>
<td>8000</td>
<td>2.6$^\circ$</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>$^{25}$Al</td>
<td>$d(^{24}$Mg,$^{25}$Al)n</td>
<td>1000</td>
<td>3.7$^\circ$</td>
<td>204</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p($^{25}$Mg,$^{25}$Al)n</td>
<td>2000</td>
<td>2.2$^\circ$</td>
<td>180</td>
<td></td>
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<tr>
<td>$^{37}$K</td>
<td>$d(^{36}$Ar,$^{37}$K)n</td>
<td>1200</td>
<td>2.2$^\circ$</td>
<td>280</td>
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<tr>
<td>$^{18}$F</td>
<td>Two-accel.</td>
<td></td>
<td></td>
<td>6 x $10^6$</td>
<td></td>
</tr>
<tr>
<td>$^{44}$Ti</td>
<td>Two-accel.</td>
<td></td>
<td></td>
<td>5 x $10^5$</td>
<td></td>
</tr>
<tr>
<td>$^{56}$Ni</td>
<td>Two-accel.</td>
<td></td>
<td></td>
<td>5 x $10^4$</td>
<td></td>
</tr>
<tr>
<td>$^{56}$Co</td>
<td>Two-accel.</td>
<td></td>
<td></td>
<td>2 x $10^5$</td>
<td></td>
</tr>
</tbody>
</table>
Radioactive beam production via in-flight reactions

\[ ^{15}\text{N} \]

\(~ 100 \text{ pnA}\)

\[ d(^{15}\text{N}, ^{16}\text{N})p \]

Particle identification

\[ ^{16}\text{N}, I \sim 5 \times 10^6/s \]

\[ ^{20}\text{Ne}^{8+} \]

\[ ^{16}\text{O}^{7+} \]

\[ ^{16}\text{N}^{7+} \]
Supermassive stars

$^{11}\text{C}(p,\alpha)^{8}\text{B}$

$^{8}\text{B}(\beta^+,\nu) \rightarrow 2\alpha$

$^{21}\text{Na}(p,\alpha)^{18}\text{Ne}$

$^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$

$^{17}\text{F}(p,\alpha)^{14}\text{O}$

$^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$

PRL 82, 3964(1999)
PRC 65, 035803(2002)

NPA 734, 615(2004)

PRL 80, 676(1998)

PRL 82, 3964(1999)

Nuclear Astrophysics with Radioactive Beams

$^{44}\text{Ti}(\alpha,p)^{47}\text{V}$

PRL 84, 1651(2000)

E. Rehm, et al.
Overview of the CPT apparatus at ATLAS

G. Savard, et al.
Mass measurements for nuclear astrophysics in the Canadian Penning Trap

Example: $^{68}\text{Se}$ as a waiting point nucleus

ATLAS upgrades in progress: Energy Upgrade Project + CARIBU + Solenoid Spectrometer

- Important physics planned using beams from CARIBU need the new energy regime opened by Energy Upgrade Project.
- Solenoid Spectrometer will greatly expand the effectiveness of both the fission fragment beams at these higher energies.
- The three projects will combine to form a truly unique facility which complements the capabilities of other world facilities in the era leading to RIA.

CARIBU: Californium Radioactive Beam Upgrade
ATLAS Energy Upgrade: ~25% higher beam energies

ATLAS Energy Upgrade will replace the last ATLAS cryostat with:

- New RIA-style cryostat containing
- New RIA-class resonators:
  - $\beta=0.14$ quarter-wave resonator
  - $\beta=0.26$ half-wave resonator
**ATLAS Energy Upgrade: ~10 MeV/u $^{132}$Sn**

Complete upgrade project will consist of:

- 7 $\beta=0.14$ Quarter-wave resonators
- 1 $\beta=0.26$ Half-wave resonator

**Expected performance improvement from Energy Upgrade**

<table>
<thead>
<tr>
<th>A</th>
<th>Current ATLAS</th>
<th>ATLAS Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Strip</td>
<td>Strip</td>
</tr>
<tr>
<td>16</td>
<td>13.0</td>
<td>15.7</td>
</tr>
<tr>
<td>40</td>
<td>12.4</td>
<td>13.4</td>
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<tr>
<td>58</td>
<td>9.9</td>
<td>11.8</td>
</tr>
<tr>
<td>78</td>
<td>9.5</td>
<td>11.2</td>
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<tr>
<td>132</td>
<td>8.0</td>
<td>9.3</td>
</tr>
<tr>
<td>197</td>
<td>6.6</td>
<td>7.9</td>
</tr>
<tr>
<td>238</td>
<td>6.4</td>
<td>7.4</td>
</tr>
</tbody>
</table>
ATLAS Energy Upgrade: resonator test results

Prototype resonators successfully demonstrated design to be used for ATLAS and RIA

109 MHz
QWR Cavity
\( \beta_s = 0.144 \)
Length = 25cm

170 MHz
HWR Cavity
\( \beta_s = 0.26 \)
Length = 30cm
**CARIBU: Californium Radioactive Beam Upgrade**

- $^{252}$Cf fission & shortened version of RIA gas catcher + charge breeding in ECR source
- high efficiency for refractory elements $\Rightarrow$ large improvement over existing ISOL facilities
- fission isotopes complementary to ones from $^{235}$U and $^{238}$U fission
- 10 MeV/u radioactive beams with the energy upgrade
- first exploration of new regions of n-rich nuclei
**ATLAS & DOE Milestones: Nuclear Astrophysics**

2012 Milestone:

Measure masses, lifetimes, spectroscopic strengths, and decay properties of selected n-rich nuclei in the supernova r-process, and reactions to predicts radionuclide production in supernovae

**Examples from 2004:**

masses from Cf fission fragments at the CPT, proposal for solenoid construction, Cf upgrade of ATLAS
CARIBU layout: fission source, gas catcher, isobar separator, and ECR charge breeder
**CARIBU shielding and remote handling**

- **Shielding Design Goals**
  - Less than 1 mrem/hr on contact
  - Fully shielded even during source installation
  - Remote operation of shielding and source movement during installation

- **Shield requirements:**
  - ~0.75 m polyethylene for neutrons
  - Additional 5 cm. lead shielding for $\gamma$-rays

![Shielding mid-plane view](image)
Solenoid Spectrometer for Transfer Reactions with RIBs

- $4\pi$ solid angle
- Particle I.D. from TOF
- Simple detector and electronics - few channels
- Excellent center-of-mass energy and angle resolution
- Suppression of backgrounds

Ideal tool for physics with RIB’s, prototype for RIA
Research program with n-rich beams from CARIBU

- \((d,p)\), \((^3\text{He}, \alpha)\), \((\alpha,t)\) reactions for single particle states
- \((t,p)\) reaction on n-rich nuclei to study neutron pairing in weakly bound systems
- \((d,p)\) for neutron capture studies

To get sensible spectroscopic factors, momentum matching is important (usually achieved around 2-5 MeV/u above the Coulomb barrier)
For heavy neutron-rich beams, in the essential region where DWBA approximations are valid and angular distributions understandable, the ejectiles have low energies and can be spread over a large solid angle.
The US ISOL Task Force Defined the Key Elements of a Next-Generation Radioactive Beam Facility (RIA)

- Combine advantages of fragmentation and stopped beams: ISOL, fragmentation and gas catcher to cover 4 energy regimes
- Superconducting driver linac and post-accelerator for all ions from hydrogen to uranium. 400 MeV/u uranium to take advantage of in-flight fission mechanism
- Acceleration of ions in multiple charge states to increase performance-important for expensive enriched isotopes and when ion source performance is a limiting factor
- Realizable designs for high power (>100 kW) targets.
- Efficient reacceleration starting with 1+ charge states
Rare Isotope Production Schemes

Physics drives the need for a variety of production mechanisms and rare isotope beams in 4 energy regimes.

- Fast Extraction Times (~msec)
- Chemical independence
- Isobar separation
The RIA facility schematic layout

[Each of four beam energy ranges is required for important physics at advanced radioactive beam facilities]
Current status of planning in the US for an advanced exotic beam facility

- RIA was given very high priority in the US Nuclear Physics Long Range Plan and in the DOE Office of Science 20-year Plan for Scientific Facilities in the US
- The DOE has charged the National Academy to assess the importance of rare isotope science in a global perspective: RISAC – the Rare Isotope Science Assessment Committee
- The DOE and OMB are tentatively considering initiating preliminary engineering design of an advanced exotic beam facility in 2011
  - Emphasis is now on being complementary to other world-class facilities, i.e. a more specialized facility
- The DOE Office of Nuclear Physics plans to continue funding R&D for exotic beam technologies in the coming years
If you need to stage RIA

- For reaccelerated beams, the issue is production rate, impacted by:
  - cross section vs energy,
  - separator acceptance vs energy,
  - charge state purity vs energy,
  - for many isotopes, beam power is more important than energy.
- No other facility proposes reaccelerated beams produced by fragmentation and in-flight fission of heavy ions followed by gas stopping.
- There are only limited plans at other facilities for reaccelerated beams above 9 MeV/u.
- For in-flight experiments, changing the primary beam energy leads to some physics issues – beam purity gets worse for heavy nuclei that are not fully stripped; optimum energy for some types of experiments.
- RIKEN (2008, 350 MeV/u) and GSI (2011, 2000 MeV/u ) will have fast in-flight beams.
Staged RIA concept – the Advanced Exotic Beam Laboratory (AEBL)

- Superconducting linac that accelerates several charge states simultaneously:
  550 MeV protons to 200 MeV/u uranium- 400 kW
  - Same beam power as RIA
  - 1 in-flight target and separator for gas cell
  - 2 ISOL targets
  - TPC $525M-570M ($FY06)
    - 30% contingency
    - includes $30M for new experimental equipment
    - existing ATLAS, and experimental equipment: CPT, FMA, Gammasphere; under construction: reaction solenoid, Gretina.

- Relative to full RIA
  - small in-flight area for identification and collection of implanted ions, i.e. half-lives for r-process.
  - for most isotopes, reaccelerated beam intensities comparable to RIA.
  - in worst cases intensities 10-20% of RIA.
Cost reductions for first stage of AEBL

- 200 MeV/u
  - 216 superconducting cavities vs 300.
  - scales cryo plant, tunnels, beam transport systems
- Remove higher resolution in-flight separator, large in-flight experimental area and most of in-flight experimental equipment
- Number of ISOL target stations reduced to 2
- Smaller astrophysics and reaccelerated beam experimental areas
- Smaller support space for labs and offices
- Limited multi-user capability (for ISOL beams only)
  - important for simultaneous ISOL source development and isotope harvesting
Layout for first stage of AEBL: 200 MeV/u, 400-kW uranium beam driver for intense reaccelerated beams via gas catcher technology
Upgrade path: extension to 400 MeV/u uranium beam driver for in-flight beams plus expanded production and experimental areas
Summary

- ATLAS at Argonne has an on-going research program with radioactive beams with research in nuclear astrophysics, nuclear structure and reactions, and fundamental interactions.
- ATLAS upgrades are in progress to expand the present capabilities especially with neutron-rich radioactive beams.
- RIA is the facility that addresses all the physics issues. It is what the community wants, and what Argonne is committed to.
- A 400 kW 200 MeV/u reaccelerated rare isotope facility focusing on stopped and reaccelerated beams offers unique physics reach in isotopes and reaccelerated beam energy.
- It complements the world-wide efforts in rare isotope physics, in particular the fast beam projects at GSI and RIKEN.
- It is better than any ISOL facility for the many isotopes that do not diffuse easily from a thick target.
- It can be built for about half the cost of RIA.
- It offers natural upgrade paths as we explore the physics of this new regime of unknown nuclei.