The r-process nucleosynthesis: connecting FRIB with the cosmos

June 6-10, 2016
ANL, the facilities and techniques for r-process studies there

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Outline

• What nuclide properties are needed to be measured for ‘r’ process models?
• How do we get access to the nuclides of interest?
• How are ion traps used to make measurements of nuclide properties?
• Results, summary, and outlook
Creation of the elements - the \( r \) process

- \( r \) process thought to be responsible for production of >50% of the elements heavier than iron
- Understanding requires knowledge of astrophysical conditions AND nuclear properties (\( S_n, \sigma_c, t_{1/2}, P_n \))
- Exact site of \( r \) process unknown
- Difficult to study nuclear properties far from stability
- \( S_n \) determines path while gross \( \beta \)-decay properties determines final abundances
Sources of uncertainty in $r$-process models

Uncertainties in the nuclear physics:
- masses
- $\beta$-decay lifetimes
- $\beta$-delayed neutron emission
- $(n, \gamma)$ rates
- fissionability

How do the isotopes made along $r$-process path decay back to stability?

$P_n \sim 40\%$?

stable nuclei


from Matt Mumpower’s talk at the ATLAS Users’ Workshop
Guidance from sensitivity studies

Studies of sensitivity of r-process yields to masses

Guidance from theory, models, simulations, etc. is extremely important to justify beamtime requests (high competition to get beamtime).

Studies of sensitivity of r-process yields to beta-delayed neutron emission


S. T. Marley et al., accepted ATLAS PAC proposal.
CARIBU (Californium Rare Isotope Breeder Upgrade)

- CARIBU: uses $^{252}$Cf spontaneous fission source to provide neutron-rich isotopes
- Have delivered both stopped and reaccelerated beams using 1.7 Ci $^{252}$Cf source

**CARIBU beams can be accelerated through ATLAS to ~15 MeV/A**

- Basic properties of fission fragments can be measured with instruments in ‘stopped’ beam area

**$^{252}$Cf Spontaneous Fission:**
- 1.7 Ci source
- 3% fission branch
- 2.6 year halflife

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**Extracted fission product yield**
- $>10^6$
- $10^5 - 10^6$
- $10^4 - 10^5$
- $10^3 - 10^4$
- $10^2 - 10^3$
- $10^1 - 10^2$

**r-process path**

**Limit of “known” masses**
Overview of CARIBU

1.7 Ci $^{252}\text{Cf}$ source

Gas catcher
(collect fission fragments)

Isobar separator
(select specific fragment)
$R \sim 20,000$

‘Stopped’ beam experimental area

Delivery of beam
- to ‘stopped’ area through low-energy beamline
- reaccelerated through ATLAS after charge breeding

Switchyard
Paul trap for beta-decay studies: Beta-decay Paul Trap (BPT)

**Axial confinement**

**Radial confinement**

DC (V): 50 -40 50
Paul trap for beta-decay studies: Beta-decay Paul Trap (BPT)

RFQ electrodes

SIDE VIEW:

inject ions

trapped ions

END VIEW:

Demonstrate technique by studying well-characterized $^{137}\text{I}$ decay

**Principles**
- Trap $\beta n$ precursors as ions
- Cool by He gas to $\sim 1$-mm$^3$ volume
- Ions decay from rest at trap center
- Trigger on $\beta$’s using plastic
- Measure recoil time of flight (TOF) to MCP
  1. $\beta (+\gamma)$ gives “slow” recoil ($< 170$ eV)
  2. $\beta + n$ gives “fast” recoil (up to $14$ keV)

**Advantages**
- No need to detect neutron
- Insensitive to background $\gamma$’s & $n$’s
- Near-Gaussian detector response
- Several ways to get $P_n$

**Challenges**
- Trapping field perturb ion trajectory
- Other species in trap
- Ion cloud size

\[^{137}\text{I} \rightarrow ^{137}\text{Xe}^* + \beta^- + \nu \]
\[^{136}\text{Xe} + n \]

At rest in center of trap
Measure
Determine

\[ ^{137}\text{I} \rightarrow ^{137}\text{Xe}^* + \beta^- + \nu \]
\[ ^{136}\text{Xe} + n \]

\[ ^{137}\text{Xe}^* \rightarrow ^{137}\text{I} + \beta^- + \gamma \]

\[ ^{137}\text{I} \rightarrow ^{137}\text{Xe}^* + \beta^- + \nu \]
\[ ^{136}\text{Xe} + n \]

\[ ^{137}\text{I} \rightarrow ^{137}\text{Xe}^* + \beta^- + \nu \]
\[ ^{136}\text{Xe} + n \]
Data collected at CARIBU

- **I-137, v.2**: Counts vs. Time of Flight (ns)
- **I-138, v.1**: Counts vs. Time of Flight (ns)
- **I-140, v.2**: Counts vs. Time of Flight (ns)
- **Sb-134, v.3**: Counts vs. Time of Flight (ns)
- **Sb-135**: Counts vs. Time of Flight (ns)
- **Sb-136**: Counts vs. Time of Flight (ns)
- **Cs-144**: Counts vs. Time of Flight (ns)
- **Cs-145**: Counts vs. Time of Flight (ns)

- **137\(^{\text{Sb}}\)** calibration
- **135\(^{\text{Sb}}\)**
- **136\(^{\text{Sb}}\)**
- **144\(^{\text{Cs}}\)**
- **145\(^{\text{Cs}}\)**
Beta-delayed neutron branching ratio results


• Proof-of-principle measurement performed in 2011 showed promise (above)

• Upgraded detector array and stronger source (CARIBU) is providing first results (shown at the right)

Proof-of-principle with $^{137}\text{I}$: Energy spectra


$^{137}\text{I} \beta$ decay in the trap ($P_n = 7\%$)

Counts/6.5 ns

Time of flight ($\mu$s)

$^{136}\text{Xe}$ ions following $\beta$-delayed neutron emission

Expected Recoil Ion TOF Spectrum

0 2 4 6 8 10 12 14

Time-of-flight (ns)

0 2 4 6 8 10 12 14 16 18 20 22

Counts/(6.5 ns)

$\beta/\gamma$ scatter
Potential design of optimized trap for BDN studies

- Compact rod structure for electrodes
- Larger detector array → 4 MCPs, 8 ΔE-E plastic scintillators, 4 HPGe clovers
- Couple to a low-energy CARIBU beamline

<table>
<thead>
<tr>
<th></th>
<th>Proof-of-Principle</th>
<th>New ion trap + CARIBU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap radius</td>
<td>17 mm</td>
<td>7 mm</td>
</tr>
<tr>
<td>$V_{rf}$</td>
<td>200 V</td>
<td>30 V</td>
</tr>
<tr>
<td>$E_n$ resolution</td>
<td>10-20%</td>
<td>5-10%</td>
</tr>
<tr>
<td>$E_n$ threshold</td>
<td>200 keV</td>
<td>75-100 keV</td>
</tr>
<tr>
<td>Beta threshold</td>
<td>150 keV</td>
<td>50 keV</td>
</tr>
<tr>
<td>Beta-recoil eff.</td>
<td>0.04%</td>
<td>3%</td>
</tr>
<tr>
<td>$^{137}$I rate</td>
<td>30 Hz</td>
<td>~20,000 Hz</td>
</tr>
<tr>
<td>$P_n$ statistics</td>
<td>2/hour</td>
<td>$10^5$/hour</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>~20 ions/s</td>
<td>~0.2 ion/s</td>
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</table>
Accessibility at CARIBU for ion trap experiments

There is uncharted territory and significant need for improvement!

Yield of >1 ion/s delivered to low-energy experiments at CARIBU

β-delayed neutron emission energetically allowed

Nuclides where $P_n$ measurement precision < 10%
Canadian Penning Trap (CPT) apparatus

Precision Penning trap situated in the bore of a 5.9 T superconducting magnet

2 kV beam

Cryogenically cooled linear Paul trap to capture, cool, and accumulate ions.
Mass measurements of neutron-rich nuclides (historic)

- Masses determined via a measurement of the ions’ cyclotron frequency (TOF-ICR)
- Mass precision \( \sim 10^{-7} \) to \( 10^{-8} \) (10 - 100 keV/c\(^2\)) for masses approaching the \( r \) process
- Canadian Penning Trap (CPT) has measured more than 150 neutron-rich nuclides, including more than 80 from CARIBU (including >6 isomers)
- Currently reaching isotopes produced at the \( 10^{-6} \) fission branch level ... pushing this limit with new techniques
- For some nuclei measured, no prior information on the nuclide existed!

Comparison with the 2003 atomic mass evaluation

Trends indicate nuclei are less bound with neutron excess (affects the location of the r-process path)

- Good agreement with other Penning trap results and reaction Q value measurements
- Large disagreement with results obtained with β-decay measurements

Effect on the $r$ process: comparisons with the FRDM mass model

Ran simulations to compare our new measurements with mass models for the $r$ process

Result: FRDM (and other mass models) have insufficient mass precision for $r$ process models

Measurements of light $^{252}$Cf fission products

- Recently started making the first measurements of light $^{252}$Cf fission fragments
- Initially started with isotopes to help evaluate performance/yield of light beams from CARIBU

- First measurements show great agreement with JYFLTRAP where overlap exists
- Deviations from 2012 atomic mass evaluation are for those isotopes that were not previously measured with ion traps
Requirements for precision and accuracy

**Precision:**

**Issue:**
- Hard to produce some isotopes
- Isotopes are short-lived

**Solution:**
- Need an efficient system
- Need a fast system

**Accuracy (minimize systematic effects):**

**Issue:**
- Contaminant ions

**Solution:**
- Purify ion bunches
Upgrade to CARIBU: MR-TOF

‘Fast’ isobar separator:

• Based on ISOLTRAP/ISOLDE design:


• ~ 1.3 m long MR-TOF

• Currently mass resolving power, \( R \sim 50,000 \) with \( \sim 50\% \) transmission in \( \sim 15 \) ms.
Upgrade to CPT: position sensitive MCP detector

- Replacing channeltron with position-sensitive MCP detector

Phase imaging – ion cyclotron resonance (PI-ICR)

- The orbital frequency of the ion’s motion is calculated from the phase change over time.

\[
\frac{+2n}{t} = \frac{2r}{tr}
\]

Ions from the Penning trap
Upgrade to CPT: position sensitive MCP detector

- Replacing channeltron with position-sensitive MCP detector

Phase imaging – ion cyclotron resonance

PI-ICR

\[ \frac{+2n}{t} = \frac{2r}{tr} \]

Online testing with $^{133}$Cs at CPT


657844.90(8) Hz
Why PI-ICR is better than TOF-ICR for rare, short-lived isotopes

- Excitation scheme is faster (therefore don’t lose as many ions to decay)
- Spend all of the time at resonance (not spending time measuring background, and therefore make better use of beamtime; 100 ions for a measurement is ‘plenty’)
- Presence of contaminants is less of an issue (spend less time cleaning ions and therefore minimize loss of desired ions due to decay)
- Net effect: factor of 100-1000 gain in sensitivity
  - pushing beyond 0.01 pps ‘limit’
Combining MR-TOF with PI-ICR

- The isobars can be separated at the CPT, but the selection of the species with the MR-TOF helps to clean the spectra and make it possible to look for the most rare, short-lived isotopes ... most of the time!?
Where we are now ... and where we hope to be

- MR-TOF and PI-ICR technique are extending the reach of the CPT to nuclides with 1-2 neutrons more than those within reach previously.
N=126 factory

- Nuclides of interest to r-process studies near N=126 (as shown by sensitivity studies) cannot be produced via fusion and are difficult to reach with fragmentation: need new production technique

N=126 factory

- Use deep-inelastic reactions to produce neutron-rich isotopes in the N=126 region
- But there has been a historic challenge of collecting reaction products efficiently:
  - New N=126 facility at Argonne will capitalize on high-intensity beams and high-intensity gas catcher technology
- Will feed suite of low-energy experiments (masses, decay spectroscopy, …)
Summary

- Elements in the universe were created by a variety of processes.
  - The $r$ process is thought to create half the elements heavier than iron
  - Models of the $r$ process rely on good data of nuclide properties
- Ion traps are revolutionizing the way nuclide properties are measured
  - Penning traps provide most precise mass measurements
  - Paul traps allow studies of decay properties
- Access to previously elusive neutron-rich nuclides is becoming available with new facilities and new techniques
  - CARIBU now provides rare, short-lived neutron-rich nuclides
  - Soon to have access to $N=126$ nuclei with $N=126$ factory