Overview on Reactions on Unstable Nuclei for Astrophysics at FRIB
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Reactions on rare isotopes are critical for most astrophysical processes and are more important than ever.
FRIB will be a game changer.
FRIB Provides New Opportunities for Nuclear Astrophysics

- FRIB has completed all milestones and is on track for delivering first beams to experiments in Spring
- Unique opportunities for Nuclear Astrophysics

Final beam commissioning completed:

![Image of FRIB facility and commissioning data]
FRIB Provides Fast, Stopped, and Reaccelerated Beams

Fast Beams:
- Indirect reaction measurements (>~30 MeV/u)

Stopped Beams:
- Decays for indirect reaction methods
FRIB Provides Fast, Stopped, and Reaccelerated Beams

**ReA3 reaccelerated beams:**
- Direct measurements of astrophysical reaction rates (<\sim 3 MeV/u)
- Indirect measurements at low energy

**Fast Beams:**
- Indirect reaction measurements (>\sim 30 MeV/u)

**Stopped Beams:**
- Decays for indirect reaction methods

**ReA6 beams:**
- Indirect measurements
  - \sim 3-6 MeV/u

**ReA Standalone Capability:**
- ReA3 accelerator can run in parallel with FRIB LINAC
- Batchmode ion source for long lived (10+ days) radioactive beams available (also from FRIB harvesting)
- Beams so far: $^7$Be, $^{10}$Be, $^{32}$Si, and $^{26}$Al

**Gas Stopping**
- Reacceleration to low astrophysical energies
Need Accurate Nuclear Physics for X-ray Burst Models

New Era of Quantitative Analysis

Open Questions:
- What can burst light curves tell us about neutron stars in accreting systems?
- What isotopes are produced forming the neutron star crust

Needs:
\((p,\gamma)\) and \((\alpha,p)\) reactions, \(^{15}\text{O}(\alpha,\gamma)\)
FRIB Will Address X-ray Burst Reactions
(also needed for Novae, p-process, explosive Si burning in supernovae...)

- **Typical \( T_{1/2} \): seconds - minutes**
- **Direct reaction rate measurements with reaccelerated beams:**
  - \((\alpha,p)\): JENSA Gas Target, AT-TPC Active Target, MUSIC
  - \((p,\gamma)\): SECAR Recoil Separator
- **Indirect reaction measurements are also essential**
  - Some important resonances are too weak to be measured directly
  - Pave the way for direct measurements (some resonance properties need to be known)
  - Studies of narrow resonances (low level density):
    - \((d,n\gamma), (^3\text{He},d)\) p-transfer with fast beams (S800 spectrometer, GRETINA \( \gamma \)-array, LENDA n-detector) and with reaccelerated beams (ORRUBA Si-array, SECAR, SOLARIS spectrometer) – can use ANC method (also THM)
    - \((d,p)\) n-transfer on mirror for N=Z nuclei (ORRUBA)
    - \(\beta\)-decay, \(\beta\)-p decay (GADGET gas detector) to study resonance decay branches
  - Studies to improve Hauser-Feshbach calculations (high level density)
    - Level densities and strength functions
SECAR Recoil Separator Enables Direct Measurements of $p, \gamma$ and $\alpha, \gamma$-Astrophysical Reactions at FRIB

Notre Dame – MSU – LSU – Colorado School of Mines – ORNL – CMU- Ohio U collaboration

First recoil detection from $^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}$ concludes construction
FRIB Will Address Reactions for Heavy Element Nucleosynthesis

Open Questions:
- What are the relative contributions of these processes to the origin of the elements?
- What do the abundance patterns tell us about the physics of astrophysical environments?

<table>
<thead>
<tr>
<th>Seed Production</th>
<th>Neutron Production</th>
<th>n-capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>(α,n) reactions 13C, 22Ne, ...</td>
<td>(n,γ) stable and ( t_{1/2} ) days-years</td>
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<td>(α,n) reactions</td>
<td>v-reactions, EOS</td>
<td>Very few (n,γ)</td>
</tr>
<tr>
<td>Stable &amp; n-rich A = 68 - 98</td>
<td>(α,n) reactions 22Ne, ...</td>
<td>(n,γ) on ( T_{1/2} ) 2 min – 30 yr</td>
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<td>-</td>
<td>v-reactions, EOS</td>
<td>(n,γ) on ( T_{1/2} ) 10 ms – 2 min</td>
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</table>

FRIB

Very few (n,γ) on \( T_{1/2} \) 2 min – 30 yr
FRIB Will Directly Measure ($\alpha$,n) Reaction Rates for the Weak r-Process

Important reactions affecting the final abundances have been identified (Pereira et al. 2020, Bliss et al. 2020).

Direct measurement techniques for reaccelerated beams developed:

Neutron detection: MUSIC (Avila, Ong, et al.)

Recoil detection: HABANERO (Meisel, Montes, et al.)

Recoil + Neutron detection: SECAR + LENDA

Focal plane: $^{86}$Kr($\alpha$,$2n$)$^{88}$Sr

With target neutron coincidence

Marshall, Meisel, Montes, et al.
Constraining Neutron Capture Rates on Unstable Nuclei at FRIB

Direct measurements:
• Long lived samples:
  • FRIB Harvesting
  • Transport to external n-beam facility
  • Future n-beam at FRIB?
• Far future: storage ring and n-target (see talk by Mosby)

Indirect studies: if HF is Applicable
• Improve HF calculations: strength functions, level densities (β-Oslo – see talk by Liddick)

Indirect studies: If single resonances or direct capture dominate (talk by Escher)
• Surrogate method (talk by Ratkiewicz)
• d,pγ neutron transfer
FRIB Will Address Reactions in Explosive Stellar Burning

Open Questions:
- What are the abundances of long-lived $\gamma$-ray emitters in supernova ejecta?
- What would observations with $\gamma$-ray observatories (e.g. future COSI) tell us about supernova physics?

Key reactions for broad range of $\gamma$-ray emitters identified (Hermansen et al. 2020)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Impact</th>
<th>Isotope Affected</th>
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</thead>
<tbody>
<tr>
<td>$^{42}$K(n,$\gamma$)$^{43}$K</td>
<td>4.18</td>
<td>$^{43}$K</td>
</tr>
<tr>
<td>$^{44}$Ti(p,$\gamma$)$^{44}$V</td>
<td>2.61, 1.31, 1.12$^g$</td>
<td>$^{44}$Ti, $^{46}$V, $^{49}$V</td>
</tr>
<tr>
<td>$^{44}$K(p,n)$^{44}$Ca</td>
<td>2.51</td>
<td>$^{43}$K</td>
</tr>
<tr>
<td>$^{58}$Ca(p,$\gamma$)$^{59}$Zn</td>
<td>2.16</td>
<td>$^{58}$Ni</td>
</tr>
<tr>
<td>$^{41}$K(p,$\alpha$)$^{41}$Ca</td>
<td>2.13</td>
<td>$^{43}$K</td>
</tr>
<tr>
<td>$^{24}$Na(p,$\gamma$)$^{24}$Mg</td>
<td>2.12, 1.14, 1.13, 1.12$^g$</td>
<td>$^{43}$K, $^{44}$Sc, $^{45}$V, $^{46}$Fe</td>
</tr>
<tr>
<td>$^{27}$Al(p,$\gamma$)$^{26}$Si</td>
<td>1.91, 1.58$^d$</td>
<td>$^{40}$K, $^{47}$Sc</td>
</tr>
<tr>
<td>$^{28}$Al(p,$\alpha$)$^{25}$Mg</td>
<td>1.89, 1.37$^d$</td>
<td>$^{40}$K, $^{47}$Sc</td>
</tr>
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Reaction          | Impact          | Isotope Affected |
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<tr>
<td>$^{41}$Sc(n,$\gamma$)$^{48}$Sc</td>
<td>1.88</td>
<td>$^{47}$Sc</td>
</tr>
<tr>
<td>$^{45}$Ti(n,p)$^{45}$Sc</td>
<td>1.85</td>
<td>$^{47}$Sc</td>
</tr>
<tr>
<td>$^{48}$Cr(n,p)$^{51}$Mn</td>
<td>1.84, 1.16$^d$</td>
<td>$^{48}$V, $^{51}$Cr</td>
</tr>
<tr>
<td>$^{51}$Mn(p,$\gamma$)$^{52}$Fe</td>
<td>1.76</td>
<td>$^{51}$Cr</td>
</tr>
<tr>
<td>$^{41}$K(p,$\alpha$)$^{38}$Ar</td>
<td>1.72</td>
<td>$^{45}$K</td>
</tr>
<tr>
<td>$^{43}$K(n,$\gamma$)$^{43}$K</td>
<td>1.65</td>
<td>$^{43}$K</td>
</tr>
<tr>
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<tr>
<td>$^{52}$Fe(n,p)$^{55}$Mn</td>
<td>1.41</td>
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<td>1.34</td>
<td>$^{49}$V</td>
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<td>$^{52}$Co(p,$\gamma$)$^{52}$Ni</td>
<td>1.32</td>
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<td>$^{45}$Ca(n,$\gamma$)$^{46}$Ca</td>
<td>1.31</td>
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<td>$^{32}$S(n,$\alpha$)$^{28}$Si</td>
<td>1.31, 1.29$^d$</td>
<td>$^{43}$K, $^{47}$Sc</td>
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<tr>
<td>$^{40}$Ar(p,$\gamma$)$^{41}$K</td>
<td>1.30</td>
<td>$^{43}$K</td>
</tr>
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</table>

Broad range of reactions needed:
- $(p,\gamma)$, $(p,n)$, $(p,\alpha)$, $(\alpha,p)$ – techniques discussed so far
  (see talk by Perdikakis on p,n)
- $(n,\gamma)$, $(n,p)$, $(n,\alpha)$ – techniques discussed so far
  n-rich isotopes $T_{12}$ 2 min – 160 d
  p-rich isotopes $T_{12}$ 0.3 s – 60 yr

$\Rightarrow$ Some long-lived enough suitable for harvesting/batchmode/sample production
Need Dedicated Data Efforts for Nuclear Astrophysics

• Dedicated efforts are needed to
  – Evaluate nuclear data for astrophysics
  – Transform nuclear data into data that can be used in astrophysics
    • USNDP data are key input
    • Combine experimental data, incl. resonance strengths, with theoretical data, compute astrophysical reaction rates, and correct for stellar environments (comments by Sharon yesterday)
  – Disseminate data so they can be easily accessed across field boundaries.

• Ongoing activities are very important but address only aspects and need to be greatly expanded
  – (JINA REACLIB, STARLIB, BRUSLIB, nu-Lib, nucastrodata.org, pynucastro, ....)

• A new development: URSA: Unified Reaction Structures for Astrophysics
  – Overcomes limitations from multiple formats and scattered data sources – unified format-independent data flow for all nuclear data needed for astrophysics
  – Initially developed at LANL: T. Sprouse, M. Mumpower, O. Korobkin, J. Lippuner, J. Miller
  – Continued development (B. Cote) in international framework within IReNA (NSF AccelNet Network of Networks connects international nuclear astrophysics networks) – continued support will be critical
Conclusions

• Unprecedented opportunities at FRIB to advance reaction measurements for nuclear astrophysics to address open questions related to the origin of the elements, accreting neutron stars and other extreme astrophysical environments
  – Fast beams
  – Stopped beams (decays)
  – Reaccelerated beams – ReA3 and ReA6
  – Standalone batchmode beams of long-lived species – ReA3 and ReA6
  – Harvesting

• Need close collaboration between experimentalists and reaction theorists

• Need close collaboration between nuclear scientists, computational astrophysicists, observers, cosmo-chemists, .....

• Need dedicated data effort for nuclear astrophysics