Reaction measurements on and with radioactive isotopes for nuclear astrophysics

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NUCL Symposium: Radiochemistry at the Facility for Rare Isotope Beams (FRIB)
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Nucleosynthesis of the elements

Heavy elements (A>56) are produced by the s-process (~50%) and the r-process (~50%)

Fusion up to iron

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Neutron-induced: the s-process

(proton number)

(neutron number)

(n,γ)

(β−)

(β+)
Red Giants become White Dwarfs

Ring nebula illuminated by the White Dwarf in the center.
Meteorites – hints from the sky

Meteorites contain presolar grains!
s-process nucleosynthesis

Two components were identified and connected to stellar sites:

**Main s-process 90<A<210**
- TP-AGB stars 1-3 \(M_\odot\)

<table>
<thead>
<tr>
<th>shell H-burning</th>
<th>He-flash</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 (\cdot)10^8 K</td>
<td>3-3.5 (\cdot)10^8 K</td>
</tr>
<tr>
<td>kT=8 keV</td>
<td>kT=25 keV</td>
</tr>
<tr>
<td>10^7-10^8 cm^{-3}</td>
<td>10^{10}-10^{11} cm^{-3}</td>
</tr>
</tbody>
</table>

| \(^{13}\)C(\(\alpha,n\)) | \(^{22}\)Ne(\(\alpha,n\)) |

**Weak s-process A<90**
- massive stars > 8 \(M_\odot\)

<table>
<thead>
<tr>
<th>core He-burning</th>
<th>shell C-burning</th>
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</thead>
<tbody>
<tr>
<td>3-3.5 (\cdot)10^8 K</td>
<td>~1 (\cdot)10^9 K</td>
</tr>
<tr>
<td>kT=25 keV</td>
<td>kT=90 keV</td>
</tr>
<tr>
<td>10^6 cm^{-3}</td>
<td>10^{11}-10^{12} cm^{-3}</td>
</tr>
</tbody>
</table>

\(^{22}\)Ne(\(\alpha,n\))
Connection between stellar model and experiment

Modern s-process models (AGB stars)

Classical s-process

new n-facility (FRANZ)

DANCE @ LANL

Life Times for Unstable Isotopes, $\rho_n = 10^{11}$ cm$^{-3}$

Life Times for Unstable Isotopes, $\rho_n = 4 \times 10^8$ cm$^{-3}$

- neutron capture
- $\beta$-decay
The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)

Neutron beam for activation
neutron flux: $10^{12}$ s$^{-1}$

2 mA proton beam
250 kHz
< 1 ns pulse width
neutron flux: $10^7$ s$^{-1}$ cm$^{-2}$
Possible experimental program at FRANZ

The Frankfurt neutron source will provide the highest neutron flux for a nuclear astrophysics program in relevant keV region (1 – 500 keV) worldwide.

**Neutron capture measurements of small cross sections:**
- Big Bang nucleosynthesis: $^1\text{H}(n,\gamma)$
- Neutron poisons for the s-process: $^{12}\text{C}(n,\gamma)$, $^{16}\text{O}(n,\gamma)$, $^{22}\text{Ne}(n,\gamma)$.
- ToF measurements of medium mass nuclei for the weak s-process.

**Neutron capture measurements with small sample masses:**
- Radio-isotopes for γ-ray astronomy $^{59}\text{Fe}(n,\gamma)$ and $^{60}\text{Fe}(n,\gamma)$
- Branch point nuclei, e.g. $^{85}\text{Kr}(n,\gamma)$, $^{95}\text{Zr}(n,\gamma)$, $^{147}\text{Pm}(n,\gamma)$, $^{154}\text{Eu}(n,\gamma)$, $^{155}\text{Eu}(n,\gamma)$, $^{153}\text{Gd}(n,\gamma)$, $^{185}\text{W}(n,\gamma)$
Detection of $\gamma$-ray lines from interstellar $^{60}\text{Fe}$ with SPI (INTEGRAL)

$E_\gamma = 1173$ and $1333$ keV

$^{60}\text{Fe}/^{26}\text{Al} = 0.11 \pm 0.03$

ongoing production in massive stars and
distribution by subsequent supernovae
tests stellar model and SN rate

Motivation – $^{60}$Fe on earth

- can be found in deep sea manganese crusts
- Gives hints about a nearby supernova
- 2.8 Ma ago

Production of $^{60}\text{Fe}$

- Weak s-process component in massive stars
- During He-core and C-shell burning
- $^{60}\text{Fe}(n,\gamma)$ cross section needed – no experimental data available yet (estimates: 1-10 mb)
Production and Destruction of $^{60}\text{Fe}$

- $^{60}\text{Fe}(\beta^-)$: done
- $^{59}\text{Fe}(n,\gamma)$: Extremely difficult
- $^{60}\text{Fe}(\gamma,n)$: Coulomb dissociation, scheduled
- $^{60}\text{Fe}(n,\gamma)$: Cyclic activation @ 25 keV, Needs to be improved to meet requirements at $kT=90\text{ keV}$
Sample

- 7.8 \(10^{15}\) atoms \(^{60}\text{Fe}\) (0.78 µg) \((t_{1/2} = 1.5(3)\) Ma\)
- Retrieved from proton-irradiated copper beam stop (PSI)
- carrier: \(^{\text{nat}}\text{Fe}, \text{C}\)
- active impurities:
  - \(^{55}\text{Fe}\) \((t_{1/2} = 2.7\) y\)
  - \(^{60}\text{Co}\) (ingrowth)
- 6 mm diameter

activation only (presently) feasible method
Activation Method

\[ ^{60}\text{Fe}(n,\gamma)^{61}\text{Fe} \] reaction detected via
\[ ^{61}\text{Fe}(\beta^-)^{61}\text{Co} \] decay
(t\(_{1/2}\)=6.0 min)

Determination of neutron flux via
\[ ^{197}\text{Au}(n,\gamma)^{198}\text{Au} \]

Neutron source:
\[ ^{7}\text{Li}(p,n)^{7}\text{Be} \]

\[ ^{60}\text{Fe} \] sample irradiated 40 times for 15 min, then activity counted for 10 min

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Quasi-Maxwellian averaged distribution: \( kT = 25 \text{ keV} \)
\( E_{\text{max}} = 110 \text{ keV} \)

Simulations: Reifarth et al. NIM A 608 (2009) 139
2 Ge-Clovers, face to face

Efficiency @ 1115 keV:

single crystal:
\[ \varepsilon_{\text{tot}} = 11 \% \]
\[ \varepsilon_{\text{peak}} = 1.1 \% \]

addback:
\[ \varepsilon_{\text{peak}} = 15 \% \]
Coincidences: 298 & 1027 keV

- almost no background
- significantly reduced counts

\[ ^{61}\text{Fe} \]

Sample background only

\[ 1333 \text{ keV} \ (^{60}\text{Co}) \]

Uberseder et al. PRL 102 (2009) 151101

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Problem: Sample preparation

- Radioactive material difficult to produce
- Total $\gamma$-activity has to be below 1 MBq
- For TOF measurements:
  - Need isotopically enriched samples (~50% or more)
  - $10^{16} - 10^{18}$ atoms
  - Examples: $^{60}$Fe, $^{85}$Kr, $^{147}$Pm, $^{154,155}$Eu, $^{153}$Gd, $^{170}$Tm, $^{185}$W
- For activation measurements:
  - $10^{13} - 10^{15}$ atoms
  - Examples: $^{10}$Be, $^{59}$Fe

More Details: Reifarth et al. PASA 26 (2009) 255
## Expected yields at FRIB

<table>
<thead>
<tr>
<th>Isotope</th>
<th>FRIB rate [$10^{10}$ pps]</th>
<th>(n,γ) method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$Be</td>
<td>30</td>
<td>activation/TOF</td>
</tr>
<tr>
<td>$^{59}$Fe</td>
<td>13</td>
<td>activation</td>
</tr>
<tr>
<td>$^{60}$Fe</td>
<td>7</td>
<td>TOF</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>50</td>
<td>TOF</td>
</tr>
<tr>
<td>$^{147}$Pm</td>
<td>1</td>
<td>TOF</td>
</tr>
<tr>
<td>$^{154}$Eu</td>
<td>3</td>
<td>TOF</td>
</tr>
<tr>
<td>$^{155}$Eu</td>
<td>3</td>
<td>TOF</td>
</tr>
<tr>
<td>$^{153}$Gd</td>
<td>3</td>
<td>TOF</td>
</tr>
<tr>
<td>$^{170}$Tm</td>
<td>3</td>
<td>TOF</td>
</tr>
<tr>
<td>$^{185}$W</td>
<td>7</td>
<td>TOF</td>
</tr>
</tbody>
</table>

This list is not complete!
Astrophysics motivation: the p-process

- 35 stable neutron-deficient isotopes between $^{74}\text{Se}$ and $^{196}\text{Hg}$
- Dominating reactions: $(p,\gamma)$ for light nuclei; $(\gamma,n)$, $(\gamma,p)$, $(\gamma,\alpha)$ and $\beta^+$ decays for heavier nuclei
- Temperatures of $2-3\times10^9$ K during time scales of a few seconds are required (type II supernovae explosions)
Reaction Studies at the Experimental Storage Ring (ESR) at GSI

Measurements of \((p, \gamma)\) or \((\alpha, \gamma)\) rates in the Gamow window of the p-process in inverse kinematics.

Advantages:

- **Applicable to radioactive nuclei**
- Detection of ions via in-ring particle detectors (low background, high efficiency)
- Knowledge of line intensities of product nucleus not necessary
- Applicable to gases
Layout of the experimental facilities at GSI

- Fragmentation in FRS target
- Stable beam from SIS
- degrader
- separated fragment beam
- LAND/ALADIN in Cave C

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Reaction Studies at the ESR

First pilot experiment performed with stable beams: $^{96}\text{Ru}(p,\gamma)^{97}\text{Rh}$

- Measurements performed at 9, 10, 11 AMeV
- $5\cdot10^6$ particles per spill
- Target density $1\cdot10^{13}$ atoms/cm$^2$
- Luminosity $2.5\cdot10^{25}$
- Cross section 2 mbarn -> ~180 counts/h

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Simulations with LISE++

- \(^{96}\text{Ru} - \text{primary beam}\)
- \(^{96}\text{Ru}(p,\gamma)\)
- \(^{96}\text{Ru}(p,\alpha)\)
- \(^{96}\text{Ru}(p,n)\)
Particle detectors: Double sided silicon strip (16 x 16) inside pockets

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Preliminary result @ 11 MeV – upper limit

Ignore (p,n) component – resulting in an upper limit for \((p,\gamma)\)

\[ \sigma_{PG} \sim 4.0 \text{ mb} \]

Non-smoker: 3.5 mb
Summary

• Nuclear data on radioactive isotopes are extremely important for modern astrophysics
• With new facilities like FRANZ on the horizon, the production of suitable samples provides one of the biggest challenges for neutron capture measurements in the keV-regime
• FRANZ will allow measurements on radioactive samples on a routinely basis
• Storage rings provide a very interesting extension to radioactive beam facilities with many application in astrophysics