X-ray bursts and the JENSA gas-jet target

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X-ray bursts

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The Recoil Separator for Capture Reactions SECAR
Part 1
X-ray bursts
Model: Accreting neutron star
Observation: X-ray bursts

Very regular burst recurrence pattern (from 4U/MXB 1820-30)

Frequent and very bright phenomenon

- Brightness: $10^{36}$-$10^{38}$ erg/s
- Duration: 10 s to 100 s
- Recurrence: hours to days
- Observations: ~100 sources, ~$10^4$ bursts (stars $10^{33}$-$10^{35}$ erg/s)

Irregular burst recurrence pattern (from 4U/MXB 1636-53)


Burst ignition and breakout

- ~0.77 GK breakthrough 2
- $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ (~50 ms after breakthrough 1)
- ~0.68 GK breakthrough 1
- $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$
- ~0.20 GK Hot CNO cycle II
- ~0.20 GK Ignition 3$\alpha$-process
- Prior to ignition: Hot CNO cycle
Burst reactions after the break out

αp-process (α,p) and (p,γ) reactions

rp-process (p,γ) reactions and decay
Calculated abundance evolution

X-ray flux

Time: -3.123e+02 s
Temperature: 0.201 GK

abundance

- $\geq 10^{-3}$
- $\sim 10^{-4}$
- $\sim 10^{-5}$
- $\sim 10^{-6}$
- $\sim 10^{-7}$

Type I X-ray burst
1-dimensional single-zone XRB model
Complete nuclear reaction network

XRB-calculation details in:
The endpoint of the rp-process
Possibilities

- **Cycling** (reactions that go back to lighter nuclei)
- Coulomb barrier
- Runs out of fuel
- Fast cooling

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The Sn-Sb-Te cycle

Known ground state $\alpha$ emitter

Bottleneck reactions

X-ray bursts and the JENSA gas-jet target
Konrad Schmidt, Institute of Nuclear and Particle Physics, TU Dresden
Institute Seminar, IKTP, TU Dresden, October 25, 2018
$^{34}\text{Ar}(\alpha, p)^{37}\text{K}$ cross section

NON-SMOKER (Hauser-Feshbach calculation)
TALYS 1.8 (Hauser-Feshbach calculation)
AZURE (R-Matrix through $^{40}\text{Ca}(p, t)^{38}\text{Ca}$) [1]

Gamow window for 2GK XRB

deviations of $\sim 100$

need direct methods

Light curves from a single-zone X-ray burst calculation

- nominal $^{34}\text{Ar}(\alpha,p)^{37}\text{K}$ reaction rate × 100
- nominal $^{34}\text{Ar}(\alpha,p)^{37}\text{K}$ reaction rate × 0.01

varied only $^{34}\text{Ar}(\alpha,p)^{37}\text{K}$

an increased reaction rate accelerates the reaction flow and the burst burns out faster

XRB-calculation details in:
Final abundance plot
from a single-zone X-ray burst calculation

- nominal $^{34}$Ar($\alpha$,p)$^{37}$K reaction rate $\times$ 100
- nominal $^{34}$Ar($\alpha$,p)$^{37}$K reaction rate $\times$ 0.01

- broad effect on multiple species in the burst ashes
- higher rate decreases the seed to hydrogen ratio of the subsequent rp-process

XRB-calculation details in:
How to study $^{34}$Ar($\alpha$,p)$^{37}$K directly?

Short half-life of $^{34}$Ar 
$\sim 0.8$ s  
No targets  
Inverse kinematics with radioactive ion beams

$^{34}$Ar + $^4$He $\rightarrow$ $^1$H + $^{37}$K  
$^{34}$Ar($\alpha$,p)$^{37}$K

$^4$He + $^{34}$Ar $\rightarrow$ $^1$H + $^{37}$K

$^4$He($^{34}$Ar,p)$^{37}$K
Part 2
Rare isotope beams from NSCL and FRIB
Rare isotope production at NSCL
Available rare isotope beams at ReA3

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FRIB at Michigan State University

- FRIB will be a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion is in 2022, managing to an early completion in fiscal year 2021
- FRIB will serve as a national user facility for world-class rare isotope research

FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.
Low energy astrophysics at FRIB

FRIB completion: 2022

- Fragment separator
- Gas stopping
- ReA3 hall
  - Low energy beams
- ReA3 re-accelerator
  - Low energy beams at astrophysical energies (0.3-2 MeV/u)
- Production target
- LINAC
  - >200 MeV/u

frib.msu.edu

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Planned beams with FRIB

About 3000 known nuclides

Available today

To be explored with FRIB
## Looking for the best target

<table>
<thead>
<tr>
<th></th>
<th>Solid plastic thin-foil or on backing</th>
<th>windowless gas target</th>
<th>Gas cell with window</th>
<th>Gas jet target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High density</strong></td>
<td>✔</td>
<td>?</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Low energy and angular straggling</strong></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Chemically pure</strong></td>
<td>?</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Excellent reaction localization</strong></td>
<td>✔</td>
<td>?</td>
<td>?</td>
<td>✔</td>
</tr>
</tbody>
</table>
Part 3
The JENSA gas-jet target
Recirculating gas system

- Apertures
- Ion beam
- Compressor (30 atm)
- Several pumping stages
- 5 turbo pumps
- 10^{-7} mbar
- 10^{-2} mbar
- Jet (10^{19} \text{ at./cm}^2)
The JENSA gas-jet target

Jet Experiments in Nuclear Structure and Astrophysics
CFD simulation of the jet

Target chamber

Nozzle

Density

arb. units

1 cm

1 in

Jet

computational fluid dynamics (CFD) software: WIND-US

Contribution by graduate student Justin Browne
Setup for jet thickness study

Nozzle

\(\alpha\) source

Highly segmented double-sided Si strip detector

Receiver
Micron-style BB15 detector
Energy calibration and energy-loss spectrum

\[ ^{228}\text{Th source} \]

\[ ^{241}\text{Am source} \]

K. Schmidt et al.: Nucl. Instrum. Meth. A 911, 1–9, 2018
Energy loss profiles

K. Schmidt et al.: Nucl. Instrum. Meth. A 911, 1–9, 2018
$10^{19}$ atoms/cm$^2$ in a 4-mm He jet

K. Schmidt et al.: Nucl. Instrum. Meth. A 911, 1–9, 2018
Comparison with other supersonic gas-jet targets in nuclear astrophysics

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Input pressure (kPa)</th>
<th>$^4$He jet density ($10^{18}$ at./cm$^2$)</th>
<th>$^4$He jet FWHM (mm)</th>
<th>Distance from nozzle (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Münster</td>
<td>1982</td>
<td>200</td>
<td>0.34 ± 0.06</td>
<td>2.5 ± 0.2</td>
<td>1 to 5</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>1991</td>
<td>38</td>
<td>0.078 ± 0.013</td>
<td>2.6 ± 0.2</td>
<td>~1.5</td>
</tr>
<tr>
<td>Notre Dame</td>
<td>2012</td>
<td>150</td>
<td>0.259 ± 0.021</td>
<td>2.2 ± 0.2</td>
<td>~4</td>
</tr>
<tr>
<td>Oak Ridge</td>
<td>2014</td>
<td>2859</td>
<td>10.2 ± 0.9</td>
<td>5.1 ± 0.3</td>
<td>~1</td>
</tr>
<tr>
<td>Caserta</td>
<td>2017</td>
<td>700</td>
<td>1.97 ± 0.21</td>
<td>Not reported</td>
<td>~5.5</td>
</tr>
<tr>
<td>East Lansing</td>
<td>2018</td>
<td>2515</td>
<td>9.0 ± 0.3</td>
<td>2.03 ± 0.09</td>
<td>≤4</td>
</tr>
</tbody>
</table>

Normalized to 2.859 MPa input pressure

K. Schmidt et al.: Nucl. Instrum. Meth. A 911, 1–9, 2018
Part 4
First RIB experiment with JENSA
Setup to study $^{34}$Ar(α,p)$^{37}$K

34Ar beam from ReA3

4He gas jet

Position sensitive ionization chamber (PSIC)

SuperORRUBA [1] in part as telescope

SIDAR [2] as telescope

Rare isotope beam composition measured with PSIC
~3000 pps at 1.625 MeV/u for 108 h

$^{34}\text{Ar}$ ($\sim 60\%$)
$^{34}\text{Cl}$ ($\sim 30\%$)
$^{34}\text{S}$ ($\sim 10\%$)
Proton signals from $^{34}\text{Ar}(\alpha,p)^{37}\text{K}$
Protons with lower energy
Cross section at $E_{\text{CM}} = 5.82$ and $6.12$ MeV

From number of protons and/or recoils, target thickness and effective beam current

- **NON-SMOKER**
- **TALYS 1.8**

Gamow window for 2GK XRB

Measured energies

$\sigma$ (b)

$E_{\text{CM}}$ (MeV)
Capture reaction studies with JENSA

For $\alpha,p$  
Si detectors work

For $\alpha,\gamma$ and $p,\gamma$ 
not enough sensitivity with $\gamma$-ray detectors

Must use recoil separator with JENSA
Part 5
Separator for Capture Reactions SECAR
SECAR
Recoil Separator for Capture Reactions

p rich, rare isotope beams

α and p capture reactions up to A = 65

rejection: $10^{17}$

energy acceptance: ±3%

mass resolution: 750

fribastro.org/SECAR/
SECAR layout

Dipoles
Charge state selection

Gas target

Velocity Filter 1
Mass separation 520

Detectors

Dipoles
Cleanup scattered beam

Velocity Filter 2
Mass separation 775
Summary

X-ray bursts are the most common astrophysical thermonuclear explosions observed.

Broad range of radioactive beam experiments (together with stable beam experiments) are needed.

JENSA in a stand-alone operational mode can measure $(\alpha,p)$ and $(p,\alpha)$ reactions.

$^{34}\text{Ar}(\alpha,p)^{37}\text{K}$ is the first rare isotope beam experiment with JENSA.

SECAR will enable $(\alpha,\gamma)$ and $(p,\gamma)$ capture reaction measurements.