Accreting Neutron Stars

- The outer crust of an accreting neutron star is an unique environment for nuclear reactions
- Identified as the origin of energetic X-ray superbursts (~ $10^{42}$ ergs per burst)
- X-ray superbursts thought to be fueled by $^{12}$C + $^{12}$C fusion in the outer crust
- Temperature of the outer crust is too low (~ $3 \times 10^6$ K) for $^{12}$C fusion

Haensel et al., Neutron Stars 1, 2007
One potential heat source, proposed to heat the crust of neutron stars and allow $^{12}$C fusion, is the fusion of neutron-rich light nuclei (ex. $^{24}$O + $^{24}$O).

$^{24}$O + $^{24}$O Fusion:
- If valence neutrons are loosely coupled to the core, then polarization can result and fusion enhancement will occur.

- $^{24}$O is currently inaccessible for reaction studies.
- Instead study other neutron rich isotopes of oxygen ($^{18,19,20}$O) on $^{12}$C ($^{19,20}$O are radioactive).

State of the art theoretical calculations predict fusion dynamics for neutron-rich light systems.

Experimental measurements of the fusion cross-section provides a test of fusion models.

What do we want to measure?

- Excited nucleus decays:
  
  \[ ^{30}\text{Si}^* \rightarrow ^{28}\text{Si} + 2n \]
  \[ ^{28}\text{Al} + p + n \]
  \[ ^{25}\text{Mg} + \alpha + n \]

- To measure the fusion cross-section we need to count the number of evaporation residues relative to the number of incident O nuclei.

- Emission of evaporated particles kicks evaporation residues off of zero degrees.
**Method for Identifying Evaporation Residues**

 cháu To distinguish fusion residues from beam particles, one needs to measure:

- Energy of the particle
- Time of flight of the particle

- **$^{18}\text{O}$ beam was provided by the Tandem van de Graaff accelerator at Florida State University (Feb. 2014)**

- **$^{18}\text{O} @ E_{\text{lab}} = 16 – 36 \text{ MeV}$**
  - $I_{\text{Beam}} \sim 1 - 4.5 \times 10^5 \text{ p/s}$

Wiedenhover et al., (5th Int. Conf. on Fission & Prop. of Neutron-rich Nuclei, 2012)

www.physics.fsu.edu/Nuclear/Brochures/SuperconductingLinearAcceleratorLaboratory/default.htm
Time of flight of beam measured between US and Tgt gridless MCP detector

Elastically scattered beam particles and evaporation residues:
  - Time of flight measured between Tgt MCP and Si detectors
  - Energy measured in annular Si detectors (T2, T3)

7 CsI(Tl)/photodiode detectors used to measure light charged particles

PMT (coupled to plastic scintillator) measures zero degree beam particles
Gridless MCP Detector

✧ Minimize extraneous material in the beam path
✧ Crossed electric and magnetic field transports electrons from secondary emission foil to the microchannel plate (MCP)
✧ 20 neodymium permanent magnets produce magnetic field (~85 gauss)
✧ 6 grid plates produce electric field (~101,000 V/m)
✧ C foil frame biased to -1000 V
✧ MCP with 18 mm diameter

Bowman et al., Nucl. Inst. and Meth. 148, 503 (1978)
Steinbach et al., Nucl. Inst. and Meth. A 743, 5 (2014)
Si Detector

✧ New design (S5) from Micron Semiconductor Ltd.
✧ Single crystal of n-type Si
  ~ 300 µm thick
✧ Segmented to provide angular resolution
✧ Used to give both energy and time information

<table>
<thead>
<tr>
<th>S5 (T2) Si Design</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Pies</td>
<td>16</td>
</tr>
<tr>
<td>Rings</td>
<td>6</td>
</tr>
<tr>
<td>Inter-strip width</td>
<td>50 µm</td>
</tr>
<tr>
<td>Entrance widow thickness</td>
<td>0.1-0.2 µm</td>
</tr>
</tbody>
</table>

✧ Fast timing electronics gives timing resolution of ~ 450 ps
  (Need ~ 1 ns time resolution)

www.micronsemiconductor.co.uk
Steinbach et al., Nucl. Inst. and Meth. A 743, 5 (2014)
deSouza et. al., Nucl. Inst. and Meth. A 632, 133 (2011)
Identifying Evaporation Residues

$^{18}\text{O} + ^{12}\text{C} \rightarrow E_{\text{Lab}} = 35 \text{ MeV}$

Elastic scattering peak

Fusion residues

Slit Scattering

PRELIMINARY
Identifying Evaporation Residues

$^{18}\text{O} + ^{12}\text{C} @ E_{\text{Lab}} = 35 \text{ MeV}$

$^{20}\text{O} + ^{12}\text{C} @ E_{\text{Lab}} = 41 \text{ MeV} @ \text{GANIL (France)}$

Rudolph, Master’s Thesis, IU, 2012

Tracy K. Steinbach
April 5, 2014
✧ Measured the cross section for $E_{\text{CM}} \sim 6 - 14$ MeV

✧ Capable of measuring to approx. the 10 mb level

✧ Next measurement: $^{19}$O + $^{12}$C @ FSU
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✧ Indiana University Department of Chemistry:
   Mechanical Instrument Services and
   Electronic Instrument Services

✧ DOE under Grant No. DEFG02-88ER-40404
Additional Material
Si Detector Design

- Reduced segmentation and inter-strip width
  - Charge trapping reduced from a 20-30% effect to a 1-2% effect

- Reduced entrance window thickness
  - Beneficial for low energy heavy residues

<table>
<thead>
<tr>
<th></th>
<th>New Si Design</th>
<th>Old Si Design</th>
</tr>
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<tbody>
<tr>
<td>Pies</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Rings</td>
<td>6</td>
<td>48</td>
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<tr>
<td></td>
<td>24 ring segments</td>
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<tr>
<td>Inter-strip width</td>
<td>50 µm</td>
<td>100 µm</td>
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<tr>
<td>Entrance widow thickness</td>
<td>0.1-0.2 µm</td>
<td>~ 0.7 µm</td>
</tr>
</tbody>
</table>

Steinbach *et al.*, Nucl. Inst. and Meth. A 743, 5 (2014)