Light Charged Particle Emission Following the Fusion of $^{18}$O Ions with $^{12}$C Nuclei at Energies Near and Below the Coulomb Barrier

Indiana University
Romualdo T. de Souza
Sylvie Hudan
Justin Vadas
Tracy K. Steinbach
Cody Haycraft
Jon Schmidt

Florida State University
Ingo Wiedenhöver
Lagy Baby
Sean Kuvin

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Accreting neutron stars provide a unique environment for nuclear reactions

- Identified as the origin of X-ray superbursts
  - Releases more energy in a few hours than our sun does in a decade
- 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 ($\sim 3 \times 10^6$ K) relative to the Coulomb barrier for $^{12}$C fusion
- A potential heat source is the fusion of neutron-rich light nuclei (eg. $^{24}$O + $^{24}$O)

References:
Haensel et al., Neutron Stars 1, 2007
Fusion of Neutron-Rich Light Nuclei

• Studying these systems also provides information about the fusion process
  ○ How the fusion cross-section changes as nuclei become more neutron-rich
  ○ How the decay of excited neutron-rich compound nuclei differ from the decay of their $\beta^-$ stable counterparts

$$^{18}O + ^{12}C \rightarrow ^{30}Si^* \rightarrow ^{28}Si + 2n$$
$$\quad \rightarrow ^{28}Al + p + n$$
$$\quad \rightarrow ^{25}Mg + \alpha + n$$

Evaporation residues
Evaporated particles
Florida State University facility

- $^{18}$O beam provided by 9 MV van de Graaf Tandem Accelerator pulsed at 12.125 MHz
- $E_{\text{lab}} = 16 - 36$ MeV
- Intensity of $\sim 1 - 4.5 \times 10^5$ particles/second
To measure the fusion cross-section, we need to count the number of residues relative to the number of incident $^{18}$O nuclei.

In order to distinguish evaporation residues from beam particles, the particles are identified by measuring their energy and time-of-flight.

\[
\sigma = \frac{N}{It}
\]

Cross-section \rightarrow Number of residues \leftarrow Target thickness

\[
E = \frac{1}{2}mv^2 \quad \Rightarrow \quad m \propto Et^2
\]
• Time-of-flight and number of beam particles measured between upstream and target microchannel plate (MCP) detectors

• Energy measured in annular Si detectors (T2, T3)

• Time-of-flight measured between target MCP and Si detectors with sub-nanosecond timing resolution

• Protons and alpha particles measured in Light Charged Particle (LCP) Detector Array

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

- Crossed electric and magnetic field transports electrons from carbon secondary emission foil to the microchannel plate
- 20 NdFeB magnets produce magnetic field (~85 gauss)
- 6 ring plates produce electric field (101,000 V/m)
- Time-of-flight between the two MCP detectors provides beam characterization with a timing resolution of ~300 ps
- Acts as the target (93 μg/cm² thickness) and provides the start time for the time-of-flight measurement for particles incident on the Si detectors

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

- Annular, single crystal Si(IP) ~300 μm thick (S5 design made by Micron Semiconductor)
- Segmented to provide angular resolution and reduce detector capacitance
- Provides both energy and time information
- Fast timing electronics give a timing resolution of ~450 ps

<table>
<thead>
<tr>
<th></th>
<th>S5 (T2) Design</th>
<th>S1 (T3) Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pies</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Rings</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>24 ring segments</td>
<td>64 ring segments</td>
</tr>
<tr>
<td>Inter-strip width</td>
<td>50 μm</td>
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</tr>
<tr>
<td>Entrance window thickness</td>
<td>0.1-0.2 μm</td>
<td>0.7-1.0 μm</td>
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</tbody>
</table>

www.micronsemiconductor.co.uk
Steinbach *et al.*, Nucl. Inst. and Meth. A 743, 5 (2014)
de Souza *et al.*, Nucl. Inst. and Meth. A 632, 133 (2011)

Justin Vadas  
August 12, 2014
Identifying Evaporation Residues

- Intense peak corresponds to elastically scattered beam particles
- Points in the band originating from this peak are slit scattered beam particles
- Evaporation residues are found in the island with longer TOF values than the beam scatter line

Excitation Function

- Measured the fusion cross-section for $E_{\text{CM}} \sim 6 - 14$ MeV
- In good agreement with previous measurements
- Measurement of fusion cross-section approx. one order of magnitude lower than prior measurements (2-3 mb level)

Light Charged Particle Detector Array

- 6 mm thick CsI(Tl)
- 36 mm × 36 mm active area
- ½” Plexiglas light guide
- 2 cm × 2 cm Hamamatsu 3204-03 1J photodiode
- 7 detectors subtend the angles \(36.3^\circ \leq \theta_{\text{lab}} \leq 62.0^\circ\) with a geometric efficiency of \(\varepsilon = 67.3\%
- Two-component decay with time constants \(\tau_{\text{fast}} \approx 0.4 - 1 \, \mu s\), \(\tau_{\text{slow}} \approx 7 \, \mu s\)

Energy resolution of ~270 keV determined by measuring alpha spectrum with a $^{226}$Ra source

Position dependence of the light output was determined by scanning the surface of each detector with the $^{226}$Ra source

Particle identification was tested with the $^{226}$Ra source to see a separation between the alpha and beta particles
• Protons and alphas can be distinguished

• At $E_{\text{lab}} = 27.5$ MeV, separation can be seen above $E_{\alpha} = 8.5$ MeV
Fusion residues coincident with protons and alphas exhibit different masses.
Summary

- Measured fusion cross-section one order of magnitude lower than prior measurements
- Measured protons and alphas in coincidence with evaporation residues to allow comparison with statistical models

Future Plans

- Improve CsI(Tl) detector electronics (develop optimized shaping amp/timing filter amp/discriminator)
- Perform energy calibration for the proton and alpha particles
- Measure fusion excitation function for $^{19}$O+$^{12}$C and $^{16,17,18,19}$O + $^{18}$O
Additional Material
DC-TDHF Theory

- Density Constrained Time-Dependent Hartree Fock theory
- Fully microscopic many-body theory
- No free parameters
- Predicts an enhancement of the fusion cross-section for neutron-rich nuclei