Fusing exotic nuclei below the barrier

The crust of an accreting neutron star is a unique environment for nuclear reactions.

### Outer crust of an accreting neutron star

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density depth</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere: Accreted H/He</td>
<td>~10^5 g/cm^3</td>
<td>5 m</td>
</tr>
<tr>
<td>Ocean: Carbon + heavy elements</td>
<td>~10^9 g/cm^3</td>
<td>30 m</td>
</tr>
<tr>
<td>Crust: heavy elements</td>
<td>~10^10 g/cm^3</td>
<td>100 m</td>
</tr>
</tbody>
</table>

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Motivation

1) **Nuclear astrophysics**: Nuclear reactions in outer crust of a neutron star
2) **Nuclear physics**: dynamics of fusing two neutron-rich nuclei

Fusion reactions in the outer crust result in X-ray bursts and superbursts

Problem: At the temperature of the crust, the Coulomb barrier is too high for thermonuclear fusion of carbon – another heat source is needed.

First proposed (Horowitz et al.) that $^{24}\text{O} + ^{24}\text{O}$ or $^{28}\text{Ne} + ^{28}\text{Ne}$ might be the heat source. More recently mid-mass nuclei have been suggested.
1. Extrapolation necessary both in neutron number (N) and energy (independent)!

2. At $5 \times 10^8$ K Gamow peak $\sim 3.1$ MeV for $^{24}$O + $^{24}$O and $\sim 2.7$ MeV for $^{16}$O + $^{16}$O

3. 1/e width of Gamow peak $\sim 1$ MeV.

$$S = E_{cm} \sigma \exp(2\pi \eta)$$

$$\eta(E_{cm}) = Z_1 Z_2 e^2 \sqrt{\mu / (2\hbar^2 E_{cm})}$$

Polarization of nuclei $\Rightarrow$ fusion enhancement?
Is fusion of neutron-rich light nuclei enhanced relative to $\beta$-stable nuclei?

Density constrained TDHF calculations

- 3D cartesian lattice without symmetry restrictions
- Skyrme effective nucleon-nucleon interaction

Neutron transfer channels for N/Z asymmetric nuclei enhance the fusion cross-section at and below the barrier.

• DC-TDHF does a decent job of describing $^{16}\text{O} + ^{12}\text{C}$
• It predicts a substantial enhancement for $^{24}\text{O} + ^{12}\text{C}$

Closer examination shows that DC-TDHF slightly overpredicts fusion in $^{16}\text{O} + ^{12}\text{C}$ due to its inclusion of breakup channels.
When comparing $^{18}\text{O} + ^{12}\text{C}$ to $^{16}\text{O} + ^{12}\text{C}$ DC-TDHF predicts a larger increase as compared to the experimental data.

What happens (in reality) to the fusion cross-section as the oxygen nucleus becomes increasingly neutron-rich?

Systematic fusion data to address this question is necessary!
Fusion of neutron-rich radioactive beams with light targets

$^{20}\text{O} + ^{12}\text{C} \rightarrow ^{32}\text{Si}^* (E^* \sim 50 \text{ MeV})$

$^{32}\text{Si}^* \rightarrow ^{29}\text{Si} + 3\text{n}$

$^{32}\text{Si}^* \rightarrow ^{29}\text{Al} + \text{p} + 2\text{n}$

$^{32}\text{Si}^* \rightarrow ^{26}\text{Mg} + \alpha + 2\text{n}$

Energy and angular distributions predicted by Bass model + PACE2
Experimental Details

Microchannel plate detector

- Inner hole 20 mm diameter
- 48 concentric rings; 16 “pies”
- Particle entry on ring (junction)
- Fast timing extracted from “pie” side
- Time resolution 425 ps (6 MeV alpha)

Advantages:
- compact
- Simple construction
- good time resolution (200 ps)

Disadvantages:
- Wire planes (4/det.) in path of beam

Silicon detectors

- Inner hole 20 mm diameter
- 48 concentric rings; 16 “pies”
- Particle entry on ring (junction)
- Fast timing extracted from “pie” side
- Time resolution 425 ps (6 MeV alpha)

R.T. deSouza et al., NIM. A632, 133 (2011)
Experimental Setup: GANIL E575S (Summer 2010)

- **Incident Beam:** $^{20,16}\text{O} + ^{12}\text{C}$ @ 3 MeV/A
- **Intensity of $^{20}\text{O}$:** 1-2x10$^4$ pps
- **Degrader ion chamber ($\text{CF}_4$):** reduces energy to 1-2 MeV/A and identifies particle ($\Delta E$)
- **Target:** 100 $\mu$g/cm$^2$ carbon foil
- **T2:** $\theta_{\text{Lab}} = 3.5 - 10.8^\circ$; **T3:** $\theta_{\text{Lab}} = 11.3 - 21.8^\circ$
- **Time-of-Flight (TOF):** between target-MCP and Si (T2, T3)

M.J. Rudolph et al., PRC85, 024605 (2012).

Romualdo deSouza, ACS, Indianapolis 2013
Experimental Setup: GANIL E575S (Summer 2010)

Setup is compact, transportable and provides efficient detection of evaporation residues (>70%).

L to R: Kyle Brown, Mike Rudolph, and Zach Gosser at GANIL
- Slit-scatter ridge extending from elastic peak to lower energies (expected)
- Incomplete charge collection ridge (same TOF as elastic); ~20% of elastic yield!
- "ghost" line in same region as residues but x-section ~70b! (atomic process)

Energy-TOF spectrum has many features

“Ghost” line is due to electrons from carbon foil directly entering the MCP.
Ghost line is due to atomic scattering from wires resulting in an early false start signal

Remove wires from beam path $\Rightarrow$ gridless MCP

Incomplete charge collection due to high segmentation of silicon detector

Reduce segmentation of Si detector $\Rightarrow$ new Si design

Can some useful information be extracted from the existing dataset?

Use detection of a coincident light charged particle to eliminate atomic scattering!
Fusion-evaporation model (evapOR)

1. Fusion stage: Bass model
2. Evaporation stage

Measured cross-section exceeds that predicted by fusion-evaporation model

- Is $\sigma_{\text{fusion}} > \sigma_{\text{Bass}}$?
- Does evapOR handle competition between CP and neutron only decay correctly?

Bench-mark reaction: $^{16}\text{O} + ^{12}\text{C}$

- Measurement made in same expt. (E575S)
- Measurement subsequently at WMU
- Measured cross-section in both expts. is in good agreement with evapOR predictions

$^{16}\text{O} + ^{12}\text{C} \rightarrow ^{28}\text{Si}^* \rightarrow$

- $^{27}\text{Si} + \text{n}$
- $^{27}\text{Al} + \text{p}$
- $^{26}\text{Al} + \text{p} + \text{n}$
- $^{26}\text{Mg} + 2\text{p}$
- $^{24}\text{Mg} + \alpha$
- $^{23}\text{Na} + \alpha + \text{p}$
- $^{20}\text{Ne} + 2\alpha$

Bottom line: We can have confidence in our observation of a fusion enhancement for the charged particle channels of $^{20}\text{O} + ^{12}\text{C}$. 
The path forward: Development of a gridless MCP

Crossed E and B field design:


Time resolution for a single MCP ∼ 350 ps
More than sufficient for measurement
Western Michigan test with gridless (Feb. 2013)

Large cross-section for fusion measured at lowest incident energy \( (E_{\text{cm}}=7 \text{ MeV}) \)
due to large random background (poor beam tune, DC accelerator etc.)
The path forward: new Si detector design (Micron S5)

To resolve the problem of incomplete charge collection/trapping:

- 16 pie sectors on ohmic side
- 6 rings sub-divided into quadrants on junction side
- Thin entrance window of ~0.1 μm (4-5 times less than prior S2 design used)
Conclusions

- Extraction of fusion cross-section for $^{20}\text{O}+^{12}\text{C}$ followed by charged particle emission indicates an enhancement as compared to TDHF and Bass (+evapOR). Two possibilities:
  - Increase in the total fusion cross-section
  - Competition between charged particle emission and neutron only decay in de-excitation phase differs from evapOR prediction

- By implementing a gridless MCP, $\sigma_{\text{fusion}}$ for $^{16}\text{O} + ^{12}\text{C}$ was measured in agreement with the literature.

- Implementation of a low segmentation silicon is underway to resolve the incomplete charge collection / trapping problem.

- Measure fusion excitation functions for neutron-rich light nuclei
  - FSU: $^{18,19}\text{O} + ^{12}\text{C}$; GANIL: $^{20}\text{O} + ^{12}\text{C}$; ReA3@MSU: heavier nuclei