Overcoming Barriers to Forge Elements in the Dark


**Florida State:** I. Wiedenhover, L. Baby, S. Kuvin

**Vanderbilt University:** S. Umar, V. Oberacker

How ever are we going to get to the other side?

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Where I am from …

Bloomington area 18,000 years ago!
Bloomington now!
Where I am from ...
IU Department of Chemistry

• 35 research faculty in all major disciplines of chemistry (analytical, biochem, inorganic, organic, and physical)

• Dedicated support scientists and staff (NMR, mass spec, glass blowing, mechanical instruments, electronics, information technology)

• … and the life blood of any graduate department – energetic, bright graduate students.
Center for Exploration of Energy and Matter (CEEM)

CEEM is a multidisciplinary laboratory performing research and development in the areas of accelerator physics, nuclear science, materials science, life science and biomedical applications of accelerators.

**Accelerator Physics**
Defining the physics of producing and handling beams of sub-atomic particles

**Biomedical and Life Sciences**
Harnessing the power of radiation for research in biology and medicine

**Materials Research**
Imaging, modeling and manipulating macromolecules

**Neutron Physics**
Using neutrons to explore the molecular structure of proteins, crystals, surfaces, and much more

**Nuclear Physics and Chemistry**
Probing matter and forces at the sub-atomic scale
Tracy Steinbach, Jon Schmidt, and Dr. Sylvie Hudan
At Florida State University

http://nuchem.iucf.indiana.edu
Fundamentals of supernova explosions are not understood!

Synthesis of the heavy elements is not understood

Limits of nuclear stability (superheavy elements, N/Z exotic) poorly known

Only elements Z=1-4 produced in the Big Bang

- Fundamentals of supernova explosions are not understood!
- Synthesis of the heavy elements is not understood
- Limits of nuclear stability (superheavy elements, N/Z exotic) poorly known
**Big Bang 13±1Gy**

**T, ρ HI**

- **Expansion: T, ρ drop**
  - H, He, Li, Be formed (3 min.)

- **Inhomogeneities**
  - **aggregation**
  - **T, ρ ↑**

- **H burning**
  - $4 \ p \rightarrow ^4\text{He} + 2\beta^+ + 2\nu$

- **He burning**
  - $3 \ ^4\text{He} \rightarrow ^{12}\text{C}$
  - $4 \ ^4\text{He} \rightarrow ^{16}\text{O}$

- **Mg, Na, Si burning**
  - **Up to $^{56}\text{Fe}$**

- **$^{12}\text{C}/^{16}\text{O}$ burning**
  - Mg, Na,

- **Remnant core:**
  - Neutron star

- **Supernova explosion**
  - Synthesis of elements beyond Fe (r process)

- **Ejecta repopulates interstellar medium enriched with heavy elements**

- **M > 10M$_\text{sun}$**

- **T, ρ increase**
Making elements: The Coulomb barrier problem

The two nuclei are charged and repel each other unless they are very close (touching)

Coulomb’s Law:

$$V(r) \propto \frac{Z_1 Z_2}{r}$$
The two nuclei have to overcome the Coulomb repulsion (barrier) in order to experience the attraction of the strong nuclear force which is short range.

What if the two nuclei do not possess sufficient energy to overcome the barrier?

• Particle can tunnel (exist in classically forbidden region) and emerge on other side. SENSITIVE TO WIDTH OF BARRIER
• Effect of barrier is observed even if $E > U$

Measuring the fusion cross-section is therefore intrinsically related to measuring the detailed shape of the fusion barrier (a dynamic quantity as the nuclei approach)
To overcome this Coulomb repulsion one has to provide kinetic energy to the nuclei. This can be done by:

a) Raising the temperature (e.g. stars, tokamaks)
b) Using an accelerator
Radioactive beam facilities allow one to produce neutron-rich nuclei along the r-process path.

Neutron stars represent an extreme point on this diagram.
Fusion reactions in the outer crust are responsible for the X-ray bursts and superbursts.

More energy release in one superburst than one decade from our sun!

Problem: At the temperature of the crust, the Coulomb barrier is too high for thermonuclear fusion of carbon – another heat source is needed.
The crust of an accreting neutron star is a unique environment for nuclear reactions.

### Structure of an accreting neutron star crust

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density depth</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer crust of an accreting neutron star</td>
<td>~$10^5$ g/cm$^3$</td>
<td>5 m</td>
</tr>
<tr>
<td>Atmosphere: Accreted H/He</td>
<td>~$10^9$ g/cm$^3$</td>
<td>30 m</td>
</tr>
<tr>
<td>Ocean: Carbon + heavy elements</td>
<td>~$10^{10}$ g/cm$^3$</td>
<td>100 m</td>
</tr>
<tr>
<td>heavy elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crust</td>
<td></td>
<td></td>
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</tbody>
</table>
Fusion of Neutron-rich Light Nuclei

✧ One potential heat source, proposed (Horowitz et al.) 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) -- More recently mid-mass nuclei have been suggested.

$^{24}$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

Quantum mechanical calculations can also be performed to investigate the fusion process.

Density constrained TDHF calculations

- Damped dipole oscillation and presence of surface waves clearly visible.
- Fusion events and deeply inelastic events dominate at these near barrier energies.
- Fusion is distinguished from deeply inelastic collisions by the existence of a single heavy nucleus after the collision.

Density constrained TDHF calculations (DC-TDHF)

- TDHF provides good foundation for describing large amplitude collective motion
- 3D cartesian lattice without symmetry restrictions
- Skyrme effective nucleon-nucleon interaction (SLy4)
- Ion-ion potential calculated as:

\[ V(R) = E_{DC}(R) - E_{A1} - E_{A2} \]

Density-constrained energy

\[ E_{DC}(\rho(r,t)) = \langle \Phi_\rho | H | \Phi_\rho \rangle \]

Motivation

1) **Nuclear astrophysics**: Nuclear reactions in outer crust of a neutron star

2) **Nuclear physics**: dynamics of fusing two neutron-rich nuclei

\[ ^{24}\text{O} + ^{24}\text{O} \text{ not possible} \]

Measure fusion in \( ^{16,18,19,20}\text{O} + ^{12}\text{C} \)

\( ^{19}\text{O} \text{ and } ^{20}\text{O} \text{ are radioactive beams!} \)

**Challenge**: Radioactive beams are/will be available at intensities of \( \sim 10^3 - 10^5 \) ions/sec—**a million times less** intensity than previously used in fusion studies.
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!
A “simple” counting experiment

Measure the number of beam particles by counting them individually.

\[ \sigma_{fusion} = k \frac{N_{fusion}}{N_{beam}} \]

Count the number of residues.

Reciprocal of target thickness.
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
- Time resolution (MCP-MCP) ∼ 350 ps

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

\[ ^{18}\text{O} + ^{12}\text{C} \rightarrow ^{30}\text{Si}^* \]
\((E^* \sim 35 \text{ MeV})\)
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 Graaf accelerator at Florida State University (Feb. 2014)

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

Wiedenhover et al., (5\textsuperscript{th} Int. Conf. on Fission & Prop. of Neutron-rich Nuclei, 2012) www.physics.fsu.edu/Nuclear/Brochures/SuperconductingLinearAcceleratorLaboratory/default.htm
18O + 12C Measurement at Florida State U.

- 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
Si Detector

- Single crystal of n-type Si ~ 300 μm thick
- acts as a reverse biased diode
- Used to give both energy and time information
- Fast timing electronics gives timing resolution of ~ 450 ps

<table>
<thead>
<tr>
<th>S5 (T2) Si Design</th>
<th></th>
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<tbody>
<tr>
<td>Pies</td>
<td>16</td>
</tr>
<tr>
<td>Rings</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>24 ring segments</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>

16 pies, 6x4 rings

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

- Evaporation residues are clearly identified from Elastic scattering and beam scatter particles
- Alpha particles are also clearly distinguished

Rudolph, Master’s Thesis, IU, 2012
$^{18}\text{O} + ^{12}\text{C}$ Fusion Excitation Function

- Measured the cross section for $E_{\text{CM}} \sim 6 - 14$ MeV
- Good agreement with existing data
- However we extend the measured cross-section to approx. the 2 mb level (one order of magnitude lower than previously measured and with a million times less in beam intensity!)
Progress on the theoretical front as well…

But even with inclusion of pairing the theoretical excitation function has the wrong SHAPE!

Moreover, the discrepancy becomes worse for $E_{\text{cm}} < 7$ MeV.
$^{18}\text{O} + ^{12}\text{C}$ Excitation Function: Comparison with DC-TDHF

Fit experimental data with penetration of an inverted parabolic barrier (Wong formalism)

$$\sigma = \frac{R_c^2}{2E} \hbar \omega \ln \left\{ 1 + \exp \left[ \frac{2\pi}{\hbar \omega} (E - V_c) \right] \right\}$$

$R_c = 22.88 \pm 0.51 \text{ fm}$

$V_c = 7.62 \pm 0.14 \text{ MeV}$

$\hbar \omega = 2.78 \pm 0.29$

In the sub-barrier region DC-TDHF significantly under-predicts the cross-section
Now on to radioactive beams: $^{19}\text{O} + ^{12}\text{C}$

How does one make a beam of $^{19}\text{O}$?

- Accelerate $^{18}\text{O}$ to ~65 MeV (tandem + linac)
- Pass it through a gas cell of $\text{D}_2$ gas (350 torr; 77K)
- $^{18}\text{O}(d,p)^{19}\text{O}$
- Filter the $^{19}\text{O}$ from the $^{18}\text{O}$
- Some $^{18}\text{O}$ remains so identify $^{19}\text{O}$ from $^{18}\text{O}$ by DE-TOF
Online (preliminary) cross-section for $^{19}$O+$^{12}$C!
Conclusions

- We have developed an approach suitable to measure fusion excitation functions with low intensity (radioactive) beams.
- By implementing a gridless MCP, $\sigma_{\text{fusion}}$ for $^{18}\text{O} + ^{12}\text{C}$ was measured to a level of 2 mb, one order of magnitude lower than previously known.
- Comparison with the TDHF model indicates more quantum tunneling (thinner barrier)
- We have measured the fusion excitation function for $^{19}\text{O} + ^{12}\text{C}$. Preliminary results indicate a SIGNIFICANT enhancement of the cross-section exists above the barrier!

- Measure fusion excitation functions for other neutron-rich light nuclei

MSU: $^{39,47}\text{K} + ^{28,30}\text{Si}$;
GANIL: $^{20}\text{O} + ^{12}\text{C}$;
FSU: $^{19,18}\text{O} + ^{18}\text{O}$; $^{14,15}\text{C} + ^{12}\text{C}$