Getting under the skin of neutron-rich light nuclei with low energy fusion reactions


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Theoretical support: Z. Lin (IU), C.J. Horowitz (IU), S. Umar (Vanderbilt)

**Motivation:** understand the character of neutron-rich nuclear matter

Understanding neutron-rich matter is important for a broad range of phenomena

- Neutron star mergers
- Nucleosynthetic r-process

One laboratory to investigate the character of neutron rich matter is the skin of neutron-rich nuclei

Gain insight into neutron skin by investigating fusion for an isotopic chain of neutron-rich nuclei (interplay of nuclear structure and dynamics)

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Neutron-rich light nuclei allow investigation over a broad range of neutron number.

Most of the extended tail of the neutron density distribution for $^{24}$O is achieved with $^{22}$O

Z. Lin and C.J. Horowitz
Density constrained TDHF calculations (DC-TDHF)

If valence neutrons are loosely coupled to the core, then polarization can result and fusion enhancement will occur.

In DC-TDHF simulations one clearly observes:

- Neck formation
- surface waves
- Damped density oscillations

References:
Density constrained TDHF (DC-TDHF)

- Once Skyrme interaction is fixed for ground state nuclei, fusion cross-section is parameter free and reproduces measured light nuclei cross-section.
- Enhancement of the fusion cross-section at and below the barrier related to neutron transfer for n-rich systems and dynamical effects.

DC-TDHF provides a good description of the fusion excitation function for $^{16}\text{O} + ^{12}\text{C}$ and predicts a substantial enhancement for $^{24}\text{O} + ^{12}\text{C}$
Problem: At the temperature of the crust, the Coulomb barrier is too high for thermonuclear fusion of carbon – another heat source is needed.

Horowitz et al. originally proposed 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.

An enhancement in fusion occurring in outer crust of an accreting neutron star could power an X-ray superburst.

Energy output of a single burst equal our sun’s solar output for a decade!

Such dynamics can have important consequences:
Present experimental status for neutron-rich light nuclei (near symmetric systems)

Little data exists for fusion of light neutron-rich nuclei in near symmetric systems

- Argonne National Lab. experiment
- MUSIC detector with beam intensities of 500 – 5000 ions/sec
- Detector limited at higher beam rate intensities

 Generally good agreement with coupled channels calculations, **BUT all the MUSIC data (closed symbols) are at energies above the barrier**!

At near barrier energies:
- Only low l-waves (s-wave scattering)
- Stronger coupling to collective modes

\[ S = E_{cm} \sigma \exp(2\pi \eta) \]
\[ \eta(E_{cm}) = Z_1 Z_2 e^2 \sqrt{\mu/(2\hbar^2 E_{cm})} \]
Goal

Develop a technique capable of directly measuring the fusion cross-section with a low intensity ($10^3 - 10^6$ ions/s) radioactive beam at near barrier energies ($E/A = 1-3$ MeV/A). Measure the dependence of the fusion cross-section on $E_{cm}$ (fusion excitation function).

Challenges

- Separating the fusion products from beam (1 part in $10^7 - 10^8$ at the lowest energy)
- Low energy of the fusion products
- Experimental setup should be compact and transportable to make use of different RIB facilities worldwide

Approach

1) Develop a highly efficient setup to compensate for the low beam intensity.
2) Demonstrate technique by measuring a well known fusion excitation function: $^{18}\text{O} + ^{12}\text{C}$
3) Apply technique to the measurement of more neutron-rich systems: $^{19,20,21}\text{O} + ^{12}\text{C}$
Measuring $\sigma_{\text{fusion}}$ using low intensity beams

**Standard approach:** thick target & detect $\gamma$-rays

**Problem:** For exotic neutron-rich nuclei, levels unknown or poorly determined

**Alternate approach:** Direct detection of evaporation residues (ERs)

- Emission of evaporated particles kicks evaporation residues away from zero degrees
- To measure the $\sigma_{\text{fusion}}$ count the number of evaporation residues relative to the number of incident O nuclei

$$^{18}\text{O} + ^{12}\text{C} \rightarrow ^{30}\text{Si}^*$$

(E* $\sim$ 35 MeV)

- $^{30}\text{Si}^*$ $\rightarrow$ $^{28}\text{Si} + 2n$
- $^{28}\text{Al} + p + n$
- $^{25}\text{Mg} + \alpha + n$

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

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

18O beam was provided by the Tandem van de Graaf accelerator at Florida State University
Efficient detection of ERs can be accomplished by two annular silicon detectors.

Low energy of ERs requires low threshold detectors.
Efficiency for detection of the ER is high between 75-80%.

Efficiency for detection of ER in coincidence with a proton or alpha particle is 3.5 – 4%.

* Addition of coverage at zero degrees would raise efficiency to ~95%.
Experimental Setup: Florida State Tandem

- Incident Beam: $^{18}\text{O} @ 1-2 \text{ MeV/A}$
- Intensity of $^{18}\text{O}$: $3 \times 10^5$ pps
- Target: $100 \text{ µg/cm}^2$ carbon foil
- T2 and T3: Annular silicon detectors
  - $\theta_{\text{Lab}} = 3.5 - 10.8^°$; $\theta_{\text{Lab}} = 11.3 - 21.8^°$
- Time-of-Flight (TOF) between TGT-MCP and Si (T2, T3)

T.K. Steinbach et al., PRC90, 041603 (2014).
Electrons generated by passage of beam through a thin foil (20 – 100 µg/cm² carbon) are accelerated by an electrostatic field.

Crossed electric and magnetic field transports electrons to the microchannel plate (MCP)

Minimum scattering (no additional wires/foils in the beam path.

20 neodymium permanent magnets ➔ 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)
Si Detector

✧ New design (S5) from Micron Semiconductor developed for measurement of low energy evaporation residues

✧ 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>
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<tbody>
<tr>
<td>Pies</td>
</tr>
<tr>
<td>Rings</td>
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<tr>
<td>Inter-strip width</td>
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<tr>
<td>Entrance widow thickness</td>
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</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

- Evaporation residues are well separated from elastic and slit scattered beam particles
- Slit scattered beam provides a reference line
- Alpha particles are also cleanly resolved

\[
\sigma_{\text{fusion}} = \frac{N_{ER}}{\varepsilon_{ER} N_{O-18} t}
\]

\(N_{ER} \equiv \# \text{ of evaporation residues}\)
\(N_{O-18} \equiv \# \text{ of incident } ^{18}\text{O nuclei}\)
\(t \equiv \text{target thickness}\)
\(\varepsilon_{ER} \equiv \text{efficiency (typically 80\%)}\)
• Measured the cross section for $E_{\text{CM}} \sim 5.3 - 14$ MeV matches existing data ($E_{\text{CM}} \sim 7 - 14$ MeV)
• Extends cross-section measurement down to ~800 µb level (~30 times lower than previously measured)
• Parameterize with penetration of a parabolic barrier (Wong)

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

- $R_c = 7.34 \pm 0.07$ fm
- $V = 7.62 \pm 0.04$ MeV
- $\hbar \omega/2\pi = 2.86 \pm 0.09$ MeV

Lowest Eyal data
Impact of structure and dynamics: DC-TDHF
(S. Umar, Vanderbilt)

- TDHF provides good foundation for describing large amplitude collective motion
- 3D Cartesian lattice w/o symmetry restrictions
- Skyrme effective nucleon-nucleon interaction (SLy4)
- BCS pairing (Lipkin-Nogami extension)

- Sensitivity of $\sigma$ (fusion) to neutron skin thickness (symmetry energy in nuclear EOS)
- High quality data provide stringent test of dynamics in DC-TDHF
Comparison of $^{18}$O + $^{12}$C Fusion Excitation Function with DC-TDHF

- Above the barrier, DC-TDHF with pairing predicts a larger cross-section
- In this energy regime the quantity $\sigma_{\text{expt.}}/\sigma_{\text{DC-TDHF}}$ is roughly constant at 0.8
- Below the barrier the experimental cross-section falls less steeply with decreasing $E_{\text{c.m.}}$ than the DC-TDHF predictions.
- Below the barrier the quantity $\sigma_{\text{expt.}}/\sigma_{\text{DC-TDHF}}$ increases from 0.8 to approximately 15 at the lowest energy measured.
Elimination of pairing acts to increase the fusion cross-section.

- Underscores need to accurately treat pairing during the fusion process.

Coupled channels calculations (CCFULL) provide essentially the same description as DC-TDHF.

CCFULL also over-predicts the cross-section at above barrier energies and decreases more rapidly with decreasing energy as compared to the experimental data.
What additional information is accessible in addition to the total fusion cross-section?

...Decay channels

Two independent measures of the decay channels:

1) From energy and angular distribution of ERs
2) From the emitted particles themselves
Energy and angular distributions of evaporation residues (ERs) reveal a clear two component nature.

- Large angle, low energy component is associated with alpha emission.
- This component is underpredicted by the statistical model codes PACE4 and evapOR.
Direct measurement of the $\alpha$ cross-section

- The increased $\alpha$ emission indicated by the energy and angular distribution of ERS is directly confirmed by the extraction of the $\alpha$ cross-section.
- The statistical model codes significantly under-predict the measured $\alpha$ cross-section.
- At the lowest energies the measured $\alpha$ cross-section is under-predicted by approximately a factor of three.
- A stronger energy dependence is exhibited by the experimental data as compared to the model predictions.
Similar systems exhibit comparable excitation functions for the alpha emission cross-section.
Summary for stable beam experiment: $^{18}\text{O} + ^{12}\text{C}$

- Measured excitation function agrees well with existing data (extending it down by a factor of 30)

- DC-TDHF under-predicts the fusion cross-section at near and sub-barrier energies. The experimental data exceeds the model calculations by a factor of 15 at the lowest energies measured.

- Alpha emission is significantly under-predicted by the statistical decay codes evapOR and PACE4, a common feature for similar systems.

With the experimental approach well established by measurement of $^{18}\text{O} + ^{12}\text{C}$ we turn to radioactive beams…
Radioactive beams at Florida State: The RESOLUT facility

- $^{19}$O produced by: $^{18}$O(d,p) @ $\sim$68 MeV
- Intensity of $^{19}$O: 2-4x10$^3$ ions/s
- Beam tagging by $\Delta E$-TOF
- 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)

Simultaneous measurement of $^{19}$O and $^{18}$O excitation functions!
While the production of the $^{19}$O favors a higher energy, the fusion measurement needs to be conducted at energies near and below the barrier.

Solution: Degrade beam directly in front of target with a compact gas cell (ionization chamber)
Key elements:
1. Resolving components in a radioactive beam
2. Degrading the incident ions

Compact Ionization Detector (CID)

- standard parallel plate design with Frisch grid
- thin window design (1 cm diameter)
- active region 8.8 cm long (6 anodes)
- $\text{CF}_4$ gas : $P = 30 – 200$ torr
- $E_{\text{deposit}} = 8-40$ MeV
- Rate $< 1 \times 10^4$ ions/s

Isobar separation at GANIL
Resolving components in a radioactive beam
Rare Ion Purity Detector (RIPD)

- Axial field design with central anode minimizes charge collection time
- Aluminized windows serve as cathodes (0.5 µm mylar)
- Integrated fast charge sensitive amplifier

- Risetime 60-70 ns; Fall time 100 ns
- Energy resolution ~8%
- At an instantaneous rate of $3 \times 10^5$ ions/s the energy resolution is 14%

J. Vadas et al., NIMA 837 (2016) 28
Evaporation residues are well separated from elastic and slit scattered beam particles.

\[ \sigma_{fusion} = \frac{N_{ER}}{\varepsilon_{ER} N_{O-19} t} \]

- \( N_{ER} \equiv \# \) of evaporation residues
- \( N_{O-19} \equiv \# \) of incident \(^{19}\text{O}\) nuclei
- \( t \equiv \) target thickness
- \( \varepsilon_{ER} \equiv \) efficiency (typically 80%)
• Fusion excitation functions for $^{19}\text{O} + ^{12}\text{C}$ and $^{18}\text{O} + ^{12}\text{C}$ were simultaneously measured

• The excitation function for $^{18}\text{O}$ matches the results of the high resolution measurement previously performed within the statistical uncertainties.

• At all energies $^{19}\text{O} + ^{12}\text{C}$ is associated with a significantly large cross-section.

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<thead>
<tr>
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<th>$^{16}\text{O}$</th>
<th>$^{18}\text{O}$</th>
<th>$^{19}\text{O}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_c$</td>
<td>7.25 ± 0.25 fm</td>
<td>7.39 ± 0.11 fm</td>
<td>8.1 ± 0.47 fm</td>
</tr>
<tr>
<td>$V$</td>
<td>7.93 ± 0.16 MeV</td>
<td>7.66 ± 0.1 MeV</td>
<td>7.73 ± 0.72 MeV</td>
</tr>
<tr>
<td>$h\omega/2\pi$</td>
<td>2.95 ± 0.37 MeV</td>
<td>2.90 ± 0.18 MeV</td>
<td>6.38 ± 1.00 MeV</td>
</tr>
</tbody>
</table>

➢ $R_c$ is larger by 10% for $^{19}\text{O}$ as compared to $^{18}\text{O}$

➢ $h\omega$ is larger by a factor of ~2
Fusion Enhancement in $^{19}\text{O} + ^{12}\text{C}$

For $^{18}\text{O} + ^{12}\text{C}$

- Above the barrier, the fusion cross-section for $^{19}\text{O}$ is roughly 20% larger than that for $^{18}\text{O}$
- Just above the barrier at ~9 MeV the fusion cross-section for $^{19}\text{O}$ increases dramatically as compared to $^{18}\text{O}$.
- At the lowest energy measured the cross-section for $^{19}\text{O}$ exceeds that for $^{18}\text{O}$ by approximately a factor of three.

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Can this fusion enhancement be understood simply as due to an extended neutron density distribution?

Impact of structure

- Standard approach
  - Frozen density distributions
  - Sao Paulo (Barrier penetration model)

Z. Lin, C.J. Horowitz (IU)
While RMF + Sao Paulo provides a reasonable description of the fusion excitation function for $^{16}\text{O} + ^{12}\text{C}$ and $^{18}\text{O} + ^{12}\text{C}$, it **fails** to predict the enhancement observed for $^{19}\text{O} + ^{12}\text{C}$
How extended would the neutron density distribution have to be to describe the observed enhancement?

The neutron density distribution would need to exceed that of $^{22}\text{O}$ for a completely static picture to describe the experimental data.

Dynamics is key to understanding the fusion enhancement!
Although DC-TDHF provides a reasonable description of the $^{19}\text{O} + ^{12}\text{C}$ fusion excitation function at the cross-section level shown, it over-predicts the cross-section for $^{18}\text{O} + ^{12}\text{C}$ and $^{16}\text{O} + ^{12}\text{C}$. 
Fusion in $^{17,19}F + ^{12}C$

Produce $^{17}F$ beam by $^{16}O(d,n)$

Measured excitation function for $^{16}O + ^{12}C$ is in good agreement with the literature.

- Simultaneously measured excitation function for $^{17}F + ^{12}C$ exhibits a dramatic suppression compared to $^{19}F + ^{12}C$.
- Broad resonance at $\sim 15$ MeV?
Conclusions and Outlook

• Developed an efficient method to measure the fusion excitation function for low intensity radioactive beams at energies near and below the barrier.

• For $^{18}\text{O} + ^{12}\text{C}$:
  - Measured the fusion cross-section down to the 800 $\mu$b level (~30x lower than previously measured.)
  - **In the sub-barrier regime** the cross-section is substantially larger than that predicted by the DC-TDHF model suggesting a narrower barrier.
  - Alpha emission is substantially enhanced over the predictions of the statistical model codes.

• For $^{19}\text{O} + ^{12}\text{C}$:
  - This first measurement indicates a **significant fusion enhancement (~ three-fold) due to a single extra neutron** as one approaches and goes below the barrier.
  - DC-TDHF provides a reasonable description for $^{19}\text{O}$ at the cross-section level measured.

High quality measurement of the fusion excitation function for an isotopic chain of neutron-rich light nuclei at energies near and below the barrier provides a stringent test a unique opportunity to investigate the neutron skin and test microscopic models (e.g. DC-TDHF).

Outlook: $^{20}\text{O}$, $^{21}\text{O} + ^{12}\text{C}$ (E739@GANIL); $^{22}\text{O} + ^{12}\text{C}$ (Letter of Intent at GANIL)

$^{39,47}\text{K} + ^{28}\text{Si}$ (ReA3@NSCL)