Measuring the Fusion Cross-Section of $^{18}\text{O} + ^{12}\text{C}$ with Low-Intensity Beams Near and Below the Coulomb Barrier

Tracy K. Steinbach

Indiana University

April 16th, 2016

Supported by DOE under Grant No. DEFG02-88ER-40404
Motivation

✧ Accreting neutron stars provide a unique environment for nuclear reactions
✧ Identified as the origin of energetic X-ray superbursts
✧ Fusion of neutron-rich light nuclei (ex. $^{24}\text{O}$) has been proposed to heat the crust of the neutron star and allow these superbursts
✧ If valence neutrons are loosely coupled to the core, then polarization can result and fusion enhancement will occur

✧ State of the art DC-TDHF calculations, which follow the collision dynamics, predict a fusion enhancement for neutron-rich systems
✧ Experimental measurements of the fusion cross-section provide a test of fusion models
✧ $^{24}\text{O}$ is currently inaccessible for reaction studies – instead study $^{18,19,20,21}\text{O} + ^{12}\text{C}$
Experimental Approach

\[ ^{18}\text{O} + ^{12}\text{C} \rightarrow ^{30}\text{Si}^* (E^* \sim 35 \text{ MeV}) \]

\[ ^{30}\text{Si}^* \rightarrow ^{28}\text{Si} + 2n \]

\[ 
\rightarrow ^{28}\text{Al} + p + n \\
\rightarrow ^{25}\text{Mg} + \alpha + n 
\]

✧ The fusion cross-section can be measured by measuring the number of evaporation residues relative to incident oxygen nuclei.

✧ To distinguish fusion residues from beam particles, need to measure:
  ✧ Energy of the particle (\(\Delta E/E \sim 2\%\))
  ✧ Time-of-flight of the particle (\(\Delta t/t \sim 7\%\))

✧ \(^{18}\text{O}\) beam was provided by the Tandem van de Graaff accelerator at FSU

✧ \(^{18}\text{O}\) @ \(E_{\text{lab}} = 13.75 – 36 \text{ MeV}\)

\[ I_{\text{Beam}} \sim 1 - 4.5 \times 10^5 \text{ p/s} \]
Identifying Evaporation Residues

✧ Time-of-flight of beam measured between US and TGT MCP detectors

✧ Elastically scattered beam particles and evaporation residues (ER):
  ✧ Time-of-flight measured between TGT MCP and Si detectors
  ✧ Energy measured in annular Si detectors

\[
\sigma = \frac{N_{ER}}{N_{Beam} \cdot t \cdot \epsilon_{ER}}
\]

\(\sigma = \) fusion cross-section
\(t = \) target thickness
\(N_{Beam} = \) number of incident beam particles
\(N_{ER} = \) number of ERs measured
\(\epsilon_{ER} = \) efficiency of measuring ERs

Steinbach et al., Nucl. Inst. and Meth. A 743, 5 (2014)
Steinbach et al., PRC 90, 041603(R) (2014)
18O + 12C Fusion Excitation Function

- Measured the cross-section for $E_{cm} \sim 5.25 - 14$ MeV
- Measured down to the 820 $\mu$b level, well below prior direct measurement of 25 mb
- Fit data to functional form that describes the penetration of an inverted parabolic barrier:

$$
\sigma = \frac{R_c^2}{2E_{cm}}\hbar\omega \left\{ 1 + \exp \left( \frac{2\pi}{\hbar\omega} (E_{cm} - V) \right) \right\}
$$

$R_c = \text{barrier radius} = 7.39 \pm 0.10$ fm

$V = \text{barrier height} = 7.66 \pm 0.10$ MeV

$\hbar\omega = \text{barrier curvature} = 2.90 \pm 0.18$ MeV

Wong, PRL 31, 766 (1973)
Steinbach et al., PRC 90, 041603(R) (2014)
V. Singh et al., arXiv:1603.09314
Comparison to DC-TDHF Predictions

- Experimental and theoretical fusion excitation functions have different shapes.
- At high $E_{cm}$ DC-TDHF over-predicts the cross-section due to breakup channels not accounted for.
- Dramatic increase in experimental cross-section relative to DC-TDHF occurs at energies below 7 MeV.
- Increase in the ratio around the barrier can be interpreted as a larger tunneling probability $\rightarrow$ narrower barrier.
- Demonstrates the importance of measuring the sub-barrier fusion cross-section.
Evaporation Residue Angular Distributions

- Residue angular distributions exhibit a clear two component structure
- Statistical model code, evapOR, under-predicts component associated with alpha emission
- Large angle region - populated mostly by $\alpha$, $2\alpha$, and $n+\alpha$ channels
- Small angle region - dominated by $2n$ and $n+p$ channels

- Each $\alpha$ emission channel has to be increased by $\sim 2$ to 7 times its original fraction

6.5 MeV $< E_{cm} < 14$ MeV

<table>
<thead>
<tr>
<th>Nucleon Channels</th>
<th>Unscaled</th>
<th>Scaled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80-92%</td>
<td>50-75%</td>
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</table>

| Alpha Channels       | 8-20%    | 25-50% |

- Scaling assumed that the angular distribution of individual channels was correct but that the relative yields were wrong
Conclusions

✧ Extraction of the fusion cross-section in sub-barrier domain has been accomplished by direct measurement of evaporation residues using low intensity beams

✧ Measurement of the fusion cross-section for $^{18}$O+$^{12}$C has been made 30 times lower than previous direct measurements (820 $\mu$b level)

✧ Comparison of experimental cross-section with DC-TDHF predictions reveals a difference in the shape of the fusion excitation function (ie different barrier)

✧ Demonstrates the importance of measuring the fusion cross-section below the barrier

✧ Reproduction of the evaporation residue angular distributions requires significantly increasing the alpha decay channel yields in evapOR
Acknowledgements

Indiana University Nuclear Chemistry:
R.T. deSouza, S. Hudan, V. Singh, J. Vadas,
B.B. Wiggins, J. Schmidt, J. Huston

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

Vanderbilt University:
A.S. Umar, V.E. Oberacker

DOE under Grant No. DEFG02-88ER-40404
Evaporation Residue Angular Distributions

Unscaled

Scaled

Channel Fraction (%)

\(\frac{dN}{d\Omega}(\text{sr}^{-1})\)

\(\theta \text{ (degrees)}\)

\(\text{E = 32 MeV}\)

\(\text{E = 29 MeV}\)

\(\text{E = 21 MeV}\)

\(\text{E = 18 MeV}\)

\(^{18}\text{O} + ^{12}\text{C}\)

- data
- evapOR

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April 16\textsuperscript{th}, 2016