Measuring the fusion of neutron-rich light nuclei at and below the Coulomb barrier

SYLVIE HUDAN
August, 2012
Neutron Stars

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

Fusion reactions (C burning) in the outer crust result in X-ray bursts and superbursts.

At the temperature of the crust, the Coulomb barrier is too high for thermonuclear fusion of carbon. A heat source, other than neutrinos, is needed.
Fusion of Neutron-Rich Nuclei

For the n-rich system the barrier peak is at a larger R value since the nuclei come into contact sooner due to the extended n skin of the $^{24}$O nucleus.

Enhancement of the fusion cross-section at and below the barrier related to neutron transfer for n-rich systems and dynamical effects.

DC-TDHF calculations: A.S Umar et al., PRC 85, 055801 (2012)
Current Status

Fusion enhancement for $^{18}$O as compared to $^{16}$O.

The sub-barrier fusion enhancement may be due to the neutron skin and extended neutron density distribution of $^9$Li.

Larger cross-section for $^6$He, $^8$He as compared to $^4$He below the barrier.
E575S: Experimental Setup

- Incident beam: $^{20,16}\text{O} @ 3 \text{ MeV/A}$
- 1-2 x $10^4$ pps for $^{20}\text{O}$
- Addition of a steering magnet on G22
- Degrader ion chamber (dual function)
- Target: 100 $\mu\text{g/cm}^2$ (active target)
- Si for energy and time-of-flight
- Time-of-flight for fusion residues between (target) MCP and Si
Fusion of neutron-rich light nuclei at and below the Coulomb barrier

$^{20}\text{O} + ^{12}\text{C} \rightarrow ^{32}\text{Si}^*$

$^{32}\text{Si}^* \rightarrow ^{29}\text{Si} + 3n$
$\rightarrow ^{29}\text{Al} + p + 2n$
$\rightarrow ^{26}\text{Mg} + \alpha + 2n$

Predictions by the Bass model + PACE2

Si:
- T2: $\theta_{\text{Lab}} = 3.5 - 10.8^\circ$ (S2)
- T3: $\theta_{\text{Lab}} = 11.3 - 21.8^\circ$ (S1)
Degrader Ion Chamber

Dual function:
1) Energy degrader
2) Beam identification

- Active degrader
- Filled with CF4
- $P = 90-180$ mbar
- Event by event beam identification
Microchannel Plate Detector

Advantages:
- Compact
- Simple construction
- Good time resolution (FWHM 200 ps)

Disadvantages:
- Wire planes (4/detector) in path of beam
Silicon Detector: Energy Determination

For each gas pressure, the “incident” energy is measured.

Incident energy on target known with good accuracy.
Si Detector

Detectors used for:
1) Energy
2) Time-Of-Flight of charged products.

- T2 (S2): 48 rings, 16 pies
- T3 (S1): 16 rings, 16 pies
- Rings facing the beam.
- Time of the pies.
Fast Timing

5-6 ns rise time

Good time resolution: ~400 ps for MCP-Si TOF (FWHM)
Fusion of neutron-rich light nuclei at and below the Coulomb barrier

Sylvie Hudan

Energy — Time-Of-Flight

$^{20}\text{O} + ^{12}\text{C} @ 59.9 \text{ MeV}$
Gas cell: 90 mbar (CF4)
E on target: 40.5 MeV

- Elastic scattering
- Slit scattering
- Charge trapping
- “Ghost”
Fusion of neutron-rich light nuclei at and below the Coulomb barrier

**Fusion Residue — LCP Coincidence**

\[ ^{20}\text{O} + ^{12}\text{C} \rightarrow \text{Residue} \]

LCP: p, α

Selection of events with:

1) \(^{20}\text{O}\) beam
2) Candidates for residue in T2
3) Good E-TOF in T3 for LCP

\( ^{32}\text{Si}^* \rightarrow ^{29}\text{Si} + 3\text{n} \)
\( \rightarrow ^{29}\text{Al} + p + 2\text{n} \)
\( \rightarrow ^{26}\text{Mg} + \alpha + 2\text{n} \)

Table 5.1: Predictions of the evapOR model of the percentage of the evaporation residue distribution populated by various nuclides.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>22 MeV</th>
<th>27 MeV</th>
<th>42 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{30}\text{Si})</td>
<td>40.5</td>
<td>31.8</td>
<td>15.9</td>
</tr>
<tr>
<td>(^{29}\text{Si})</td>
<td>43.6</td>
<td>51.2</td>
<td>56.9</td>
</tr>
<tr>
<td>(^{30}\text{Al})</td>
<td>5.3</td>
<td>4.0</td>
<td>2.3</td>
</tr>
<tr>
<td>(^{29}\text{Al})</td>
<td>1.4</td>
<td>2.5</td>
<td>5.4</td>
</tr>
<tr>
<td>(^{27}\text{Mg})</td>
<td>7.5</td>
<td>8.4</td>
<td>8.3</td>
</tr>
<tr>
<td>(^{26}\text{Mg})</td>
<td>1.5</td>
<td>9.0</td>
<td></td>
</tr>
</tbody>
</table>
Coincidence Events

Residues in T2 with LCP in T3

- Good energy range
- Good time relative to scattering line

Efficiency to measure coincidence:

- Of the order of 3%
- Independent on scattering in gas cell
- Independent of incident beam spot (0-7 mm)
Fusion of neutron-rich light nuclei at and below the Coulomb barrier

Sylvie Hudan

Fusion Cross-Section

Fusion-evaporation model (evapOR)
Fusion: Bass model
Evaporation: Hauser-Feschbach

Measured cross-section, associated with CP channels, exceeds that predicted by fusion-evaporation model

⇒ Is $\sigma_{\text{fusion}} > \sigma_{\text{Bass}}$?

⇒ Does evapOR handle competition between CP and neutron decay properly?
**Bench-mark Reaction: \( {^{16}\text{O}} + {^{12}\text{C}} \)**

\[ {^{16}\text{O}} + {^{12}\text{C}} \rightarrow {^{28}\text{Si}^*} \rightarrow {^{27}\text{Si}} + \text{n} \]
\[ \rightarrow {^{27}\text{Al}} + \text{p} \]
\[ \rightarrow {^{26}\text{Al}} + \text{p} + \text{n} \]
\[ \rightarrow {^{26}\text{Mg}} + 2\text{p} \]
\[ \rightarrow {^{24}\text{Mg}} + \alpha \]
\[ \rightarrow {^{23}\text{Na}} + \alpha + \text{p} \]
\[ \rightarrow {^{20}\text{Ne}} + 2\alpha \]

- Measurement made in same experiment (E575S)
- Measurement subsequently made at Western Michigan University (6 MV tandem)
- Measured cross-section in both experiments in good agreement with evapOR predictions

\[ \sigma \text{(mb)} \]

\[ E_{\text{c.m.}} \text{ (MeV)} \]
What Have We Learnt From E575S?

- Measurement of $^{20}\text{O} + ^{12}\text{C}$ between 1 and 3 MeV/A
- Extraction of fusion cross-section for $^{20}\text{O} + ^{12}\text{C}$ followed by charged particle emission
- Measured cross-section for these channels is larger than that predicted by evapOR. Two possibilities:
  - Increased overall cross-section as compared to Bass
  - Competition between charged particle emission and neutron only decay in de-excitation phase differs from evapOR prediction (which agrees for $^{16}\text{O} + ^{12}\text{C}$)
- Validity of method with $^{16}\text{O} + ^{12}\text{C}$
- Still some issues to measure the total fusion cross-section
Since E575S...

Three main issues:

- Ghost
- Slit scattering
- Charge trapping
“Ghost” Contribution

Test setup

Entering through the reflector:
Some electrons (ejected from the reflector grids) enter directly the MCP ⇒ early start ⇒ “long” times
Beam Test with $^{16}\text{O} + ^{12}\text{C}$

- Elimination of “ghost” contribution
- Island of residues visible
- Combination of slit scattering AND charge trapping prevents us from extracting the total fusion cross-section.
Development of a Gridless MCP Detector

- Magnetic field: ~ 70G
- Nature of magnets: $^{60}$Nd
- Size: 30 cm x 10 cm x 13 cm
Gridless MCP Detector: Bench Tests

- MCP1
- MCP2
- Si

Source: (226)Ra

Scattering: < 1%

FWHM = 479 ps
FWHM = 481 ps
FWHM = 406 ps
FWHM = 473 ps
FWHM = 584 ps

TOF
Gridless MCP Detector: Efficiency

- Efficiency independent of applied electric field
- Dependence on CFD discriminator threshold
- Efficiency > 60% with alphas (~50% in electrostatic design)
Charge Trapping in Silicon Detector

S2 design

Detector Design | Charge Trapping | Oxide Surface |
--- | --- | --- |
S1 | ~ 9% | 6% |
S2 | ~ 25% | 17% |
SBD | ~ 1.5% | 0% |

- Dependence on segmentation
- Dependence on entry side

Development of a “CD” detector with:
1. Less segmentation
2. Small dead layer
Conclusions
Conclusions

Extraction of fusion cross-section for $^{20}$O+$^{12}$C followed by charged particle emission
Conclusions

- Extraction of fusion cross-section for $^{20}\text{O} + ^{12}\text{C}$ followed by charged particle emission
- Experimental issues now under control
Conclusions

- Extraction of fusion cross-section for $^{20}\text{O} + ^{12}\text{C}$ followed by charged particle emission
- Experimental issues now under control
- Verify technique by re-measuring fusion for $^{16}\text{O} + ^{12}\text{C}$
Conclusions

- Extraction of fusion cross-section for $^{20}\text{O} + ^{12}\text{C}$ followed by charged particle emission
- Experimental issues now under control
- Verify technique by re-measuring fusion for $^{16}\text{O} + ^{12}\text{C}$
- Measure fusion excitation functions for neutron-rich light nuclei
Collaboration and Acknowledgements

- GANIL: A. Chbihi, B. Jacquot
- ORNL: J.F. Liang, D. Shapira
- Western Michigan University: M. Famiano

Thanks to:
- The support of the GANIL staff and facility.
- Dr. A. Kayani for the beam time at WMU.

This work was supported by the DOE Office of Science under the Grant No. DEFG02-88ER-40404