Fusion of Neutron-Rich Light Nuclei: What can we learn?

Sylvie Hudan
Indiana University

- Astrophysical interest
- Fusion dynamics
- Alpha cluster structure
Neutron Star Crust

- Accreting neutron stars present a unique environment for nuclear reactions
- Identified as the origin of energetic X-ray superbursts
  - X-ray superburst: $\sim 10^{42}$ ergs
  - Annual solar output: $\sim 10^{41}$ ergs
- X-ray superbursts thought to be fueled by $^{12}\text{C} + ^{12}\text{C}$ fusion in the outer crust
- However, the temperature of the outer crust is too low ($\sim 3 \times 10^6$ K) for $^{12}\text{C}$ fusion
- Neutron-rich light nuclei fusion as potential “heat source”
- If valence neutrons are loosely coupled to the core, then polarization can result and fusion enhancement will occur

Haensel et al., Neutron Stars 1, 2007
“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.”

- Neck formation, surface vibrations and density fluctuations observed
- Enhancement of the fusion cross-section at and below the barrier related to neutron transfer for n-rich systems and dynamical effects
Alpha Cluster Structure

- Alpha cluster structure has been predicted and observed for light nuclei

\[ \langle 1|\phi_1 \rangle = 0.30 \quad \langle 2|\phi_2 \rangle = 0.25 \quad \langle 3|\phi_3 \rangle = 0.15 \quad \langle 4|\phi_4 \rangle = 0.08 \quad \langle 5|\phi_5 \rangle = 0.94 \]
\[ \langle 1|\phi_1 \rangle = 0.72 \quad \langle 2|\phi_2 \rangle = 0.71 \quad \langle 3|\phi_3 \rangle = 0.61 \quad \langle 4|\phi_4 \rangle = 0.61 \quad \langle 5|\phi_5 \rangle = 0.04 \]

- Observation of rotational bands

Horiuchi and Ikeda, Prog. of Th. Phys. 40, 277 (1968)
Chernykh et al., PRL 98, 032501 (2007)
von Oertzen et al., EPJA 43, 17 (2010)
Fusion Studies with Low Intensity Beams

- MCP detectors: start for TOF, beam counting, beam cleaning
  - ExB design to minimize scattering
- Fusion residues detected in segmented Si detectors: stop for TOF, energy and angle
  - Sub-nanosecond time resolution, small dead layer, lowest segmentation as possible
- Decay products (p/alpha) detected in Si detectors and CsI(Tl) array
- Maximum beam intensity: $\sim 5 \times 10^5$ pps

T.K. Steinbach et al., NIMA743, 5 (2014)
Extracting Fusion Residues

- Evaporation residues identified by energy and time-of-flight
  - Elastic scattering
  - Beam Scatter (largely reduced with ExB MCP detector)
  - Evaporation residue island
  - Emitted particles (p, $\alpha$)
  - Evaporation residues
    - Count: fusion cross-section
    - Energy, Angle, A (via TOF)
Fusion Cross-Section

- Cross-section measured down to 820 µb
- At higher $E_{\text{c.m.}}$: $\sigma_{\text{expt}}/\sigma_{\text{DC-TDHF}} \approx 0.75$
  - Breakup reactions
- For sub-barrier energy: slower fall off of the experimental cross-section as compared to TDHF
  - Larger tunneling probability for the experiment: Narrower barrier?
  - Lack of pairing evolving in time in TDHF?
Alpha Cluster Structure

- Statistical codes under-estimate experimental $\alpha$ cross-section
- Relative enhancement relative is energy dependent
- Similarity of the $\alpha$ cross-section for different systems as a function of $E_{c.m.}$
- Pre-existing $\alpha$ cluster structure in the entrance channel
- Collision dynamics
$^{19,18}\text{O} + ^{12}\text{C} @ \text{Florida State U.}$

- Beam characteristics:
  - $^{18}\text{O}(d,p)^{19}\text{O}$
  - $^{18}\text{O} @ \sim 75$ MeV
  - D$_2$ target: P $\sim$ 350 Torr, T $\sim$ 77K
  - Beam on target: $\sim 1-2 \times 10^4$ pps
  - Beam purity: 25 - 50 % $^{19}\text{O}$

- Active Degrading Ion Chamber (CF$_4$): energy change and PID event by event

- Simultaneous measurement of RIB and know reference beam
$^{19}\text{O} + ^{12}\text{C}$

- Measured fusion cross-section for $^{19}\text{O} + ^{12}\text{C}$ from E$_{\text{c.m.}}$ ~ 7.5 to 18 MeV
- Hint of a small enhancement
- Cross-reference system for systematics errors assessment
- Data also taken for $^{17}\text{F}$ and $^{16}\text{O}$
Conclusion and Future At ReA3

• Ability to measure fusion of with low intensity beams
  • Cross-section to the 800 µb level
  • Decay channels, in particular alpha channels

• Near term at ReA3: $^{39,47}\text{K} + ^{28}\text{Si} (15214)$
  • Addition of a third Si detector at small angles to measure ~75% of residues

• Future needs
  • Systematic fusion measurement with neutron-rich “light” nuclei
  • At and below the barrier to maximize barrier change with neutron number
  • Beam intensity: $10^4$ – few $10^5$ pps
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