Sub-barrier fusion cross-sections for neutron-rich oxygen and carbon nuclei

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1. Astrophysics: Neutron star crusts (pycnonuclear fusion, X-ray superbursts)
2. Nuclear Physics: Structure of neutron-rich nuclei and fusion dynamics

DATA SCARCE

Thermonuclear fusion vs pycnonuclear fusion
Why might neutron-rich nuclei show an enhanced likelihood for fusion?

1. Extrapolation necessary both in neutron number (N) and energy (independent)!

2. At 5 x 10^8K Gamow peak ~ 3.1 MeV for $^{24}\text{O} + ^{24}\text{O}$ and ~ 2.7 MeV for $^{16}\text{O} + ^{16}\text{O}$

3. 1/e width of Gamow peak ~ 1 MeV.
To access the relevant region we need $E_{\text{lab}}/A = 1$ to $3$ MeV for the neutron-rich oxygen beam.

$$^{20}\text{O} + ^{12}\text{C} \rightarrow ^{32}\text{Si}^* \ (E^* \sim 50 \text{ MeV})$$

$$^{32}\text{Si}^* \rightarrow ^{29}\text{Si} + 3\text{n}$$

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

$$^{32}\text{Si}^* \rightarrow ^{26}\text{Mg} + \alpha + 2\text{n}$$
Experimental Setup of E575S

- Degrade in active gas cell to efficiently change energy for excitation function.
- Measure velocity after degrading (TOF) : $\frac{\delta E}{E} = 200 \text{ keV}/20 \text{ MeV}$
- Evaporation residues (ER) detected in Si detectors (angular distribution)

$^{20}$O + $^{12}$C \rightarrow $^{32}$Si* ($E^* \sim 50 \text{ MeV}$)
Stage 1: Active degrader -- Multi-anode ionization chamber

- standard parallel plate design with Frisch grid
- thin window design with support wires for minimal bowing
- active region 8.8 cm long (6 anodes)
- CF$_4$ gas : P = 30 – 150 torr
- $E_{\text{deposit}} = 8$–$40$ MeV

- Need to characterize det. performance
- Measure magnitude of divergence/multiple scattering

Also useful for tagging/rejecting beam contaminants (e.g. fluorine) from $^{20}$O beam
Stage 2: MCPs for Energy determination after degrading

- TOF of 6 ns correct for 5 MeV α
- Time resolution of ≤300 ps (w/o optimization)
Stage 3: Separating evaporation residues from elastic $^{20}$O

Calculations based on assumption of fusion evaporation (PACE) and Rutherford scattering (LISE++)

At higher energies, residues are distinguished on the basis of energy alone.

At lower incident energies, residues are distinguished on the basis of both energy and TOF. A time resolution of $\leq$1ns is necessary.
Stage 3: Residue detection : Annular segmented Si detectors

- Annular Si det. From Micron Semiconductor
- 16 “pies” (φ) on ohmic side
- either 48 (S2) or 16 (S1) “rings” (θ) junction side
- Good angular resolution:
  - $\Delta \theta \approx 0.05^\circ$ for $1.1^\circ \leq \theta \leq 3.5^\circ$
  - $\Delta \theta \approx 0.17^\circ$ for $3.8^\circ \leq \theta \leq 12.1^\circ$
  - $\Delta \theta \approx 0.73^\circ$ for $12.6^\circ \leq \theta \leq 24.2^\circ$
- Good energy resolution
Beam test: Hope College Apr. ‘09 (Thanks to G. Peaslee and P. deYoung)

$^{16}\text{O}$ at 6.8 MeV (elastically scattered from a Cu foil)

Rise time: 7 – 8 ns for oxygen same as 6 MeV $\alpha$ particles.

Simultaneous measurement of slow signals – good energy resolution 0.5%.
Accomplishments

• MCP TOF system exhibits the necessary resolution $\delta t \sim 250$ ps
• 5.1 MeV $^{16}$O is clearly detectable in the Si detector
• Rise time for 5.1 MeV $^{16}$O fast signals was 7-8 ns $\Rightarrow \delta t \sim 750$ ps

Outlook

➢ Measure divergence of beam when degraded (May 10-11 @ ORNL)
➢ Characterize performance of segmented IC (sources + beams)
➢ Understand distribution of fast pulse shapes for a fixed Z,A, and E.
➢ Measure TOF of alpha between MCP and Si detector
➢ Investigate need for position sensitive MCPs and tracking
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Experimental observations: X-ray bursters vs Superbursters

Superbursts are thought to arise from the ignition of the “ashes” of bursts i.e. fusion of carbon.

Problem: At the temperature of the crust, the Coulomb barrier is too high for thermonuclear fusion of carbon – another heat source is needed.

Thermonuclear X-ray bursts and the rp-process

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