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
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.
Why might neutron-rich nuclei show an enhanced likelihood for fusion?

Polarization of nuclei → fusion enhancement?

1. Extrapolation necessary both in neutron number (N) and energy (independent)!
2. At $5 \times 10^8$K Gamow peak $\sim 3.1$ MeV for $^{24}$O + $^{24}$O and $\sim 2.7$ MeV for $^{16}$O + $^{16}$O
3. $1/e$ width of Gamow peak $\sim 1$ MeV.
For neutron rich oxygen, does energy dependence follow simple barrier penetration like $^{16}\text{O} + ^{12}\text{C}$ or is there an enhancement as in $^{9}\text{Li} + ^{70}\text{Zn}$?

For light systems:
Simple barrier penetration with Woods Saxon density distributions is reasonable near and above the Coulomb barrier.

Data is from 1970's and 1980's!

Increase due to dynamics of neutron-rich skin?

In contrast heavy systems require a phenomenological approach (collective excitations, barrier distributions, etc.)

C.L. Jiang et al., PRC 75 015803 (2007)
Extrapolation in energy…

Loveland et al, PRC 74 064609 (2006)

Measure to lowest energy possible (≤ 7 MeV) ; develop technique
Extend measurement to 5-6 MeV
To access the relevant region we need $E_{\text{lab}}/A = 1$ to 3 MeV for the neutron-rich oxygen beam.

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

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

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

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

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

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

- $P_{\text{chamber}} \sim 1 \times 10^{-6} \text{ torr (w/o cryo)}$

$^{12}\text{C}$

Active Gas degrader cell ~8 cm long, 12 mm $\varnothing$ aperture

$\delta t \leq 250 \text{ ps}$
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 – 200 torr (using 90 – 180 mbar in experiment)
- $E_{\text{deposit}} = 8$–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 1: Measurement of Beam Divergence after degrading

Bottom line: Experiment should work
Stage 2: MCPs for Energy determination after degrading

Microchannel plate detectors

- MCP #1
- MCP #2

Alpha source

10 cm

- TOF of 6 ns correct for 5 MeV $\alpha$
- Time resolution of $\leq 300$ ps (w/o optimization)
We presently measure an efficiency for one MCP of $\sim 65\%$ for an $^{241}$Am alpha. We have characterized this efficiency as a function of the accelerating grid voltage and the MCP voltage.
Stage 3: Separating evaporation residues from elastic $^{20}\text{O}$

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

At higher energies, in principle, 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 $\leq 1\text{ns}$ is necessary.
Technique previously used (at ORNL) Sn + Ni

- Based on the angular dist. The ER will be primarily resolved in the Si detectors

48 rings and 16 pies

- Good angular resolution:
  \[ \Delta \theta \approx 0.15^\circ \] for \( 3.2^\circ \leq \theta \leq 9.9^\circ \)
  \[ \Delta \theta \approx 0.6^\circ \] for \( 10.5^\circ \leq \theta \leq 20.3^\circ \)

20 MeV Worst case!

Not an issue at higher energies!
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:
  \[ \Delta \theta \approx 0.17^\circ \text{ for } 3.1^\circ \leq \theta \leq 10^\circ \]
- Good energy resolution

\[\begin{array}{c}
\text{Si det. Pie (x48)} \\
\text{Cap. splitter} \\
\text{Fast Timing Pickoff} \\
\text{LE discriminator} \\
\text{TDC} \\
\end{array}\]

\[\begin{array}{c}
\text{Stage 3: Residue detection: Annular segmented Si detectors} \\
\text{NEW!} \\
\end{array}\]
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

Can trigger at $E_{\text{deposit}} = 0.5$ MeV
Stage 4: Downstream MCP

- 40 mm MCP same design as MCP18
- prototype of position sensitivity in 2D
Stage 5: Zero degree IC (ZDIC)

- conventional transverse field, Frisch gridded IC
- approximately 15 cm diameter window of 2.5 µm mylar
- segmented anodes (side anodes “quiet” relative to center)