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

Thermonuclear fusion vs pycnonuclear fusion
Experimental observations: X-ray bursters vs Superbursters

Thermonuclear X-ray bursts and the rp-process

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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 $\Rightarrow$ 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.

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

Data is from 1970's and 1980's!

Increase due to dynamics of neutron-rich skin?

C.L. Jiang et al., PRC 75 015803 (2007)

Extrapolation in energy…

Loveland et al, PRC 74 064609 (2006)

Measure to lowest energy possible ($\leq 7 \text{ MeV}$) ; develop technique

Extend measurement to 5-6 MeV
Collaboration

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To access the relevant region we need $E_{lab}/A = 1$ 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): $\delta E/E = 200$ keV/20 MeV
- Evaporation residues (ER) detected in Si detectors (angular distribution)

$^20_0$O $+$ $^{12}_2$C $\rightarrow ^{32}_{16}$Si$^*$ ($E^* \sim 50$ MeV)

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

$^20_0$O Active Gas degrader cell ~8 cm long, 12 mm $\varnothing$ aperture

$^{12}_2$C tgt

$\delta t \leq 250$ ps

S1: $10^\circ \leq \theta \leq 24.2^\circ$

S2: $3.1^\circ \leq \theta \leq 10^\circ$

ZDIC: $\theta \leq 3.1^\circ$

MCP18

CID

ZDIC

MCP40

Pchamber $\sim 1 \times 10^{-6}$ torr (w/o cryo)
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)
- CF₄ 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

- 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 \(^{241}\text{Am}\) 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 $^{20}$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 $\leq 1$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:
  \[ \Delta \theta \approx 0.15^\circ \text{ for } 3.2^\circ \leq \theta \leq 9.9^\circ \]
  \[ \Delta \theta \approx 0.6^\circ \text{ for } 10.5^\circ \leq \theta \leq 20.3^\circ \]

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:
  - $\Delta \theta \approx 0.17^\circ$ for $3.1^\circ \leq \theta \leq 10^\circ$
- Good energy resolution

![Diagram of Si detector system](image)

- Si det. Pie (x48) → Cap. splitter → Slow CSA → Shaper → Pk. ADC
- Fast Timing Pickoff → LE discriminator → TDC

NEW!
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%.

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)
Installed in line G22 (May 2010)
• 226Ra source in front of MCP18 and T2 and T3
• time resolution <600 ps
Energy loss on multi-anodes of CID is a convenient way to tag 20F and 20O event by event!
Clean separation of $^{20}\text{F}$ from $^{20}\text{O}$ achieved by CID degrader and TOF! $^{20}\text{F}/^{20}\text{O}$ is $\sim5-15\%$
After degrading from 60 MeV to 20 MeV the 20O energy has a FWHM of 1.1 MeV
- Beam cleanly resolved in ZDIC center anodes at 10 kHz
- Side anodes relatively quiet of beam; elastic visible
- If the MCP40 was position sensitive this would enhance the data from ZDIC (finer angular resolution for residues)
TOF spectrum between MCP18 and MCP40

By combining DE information of ZDIC with TOF information one should be able to extract residues for θ ≤ 3°.
T2 silicon “pies” energy spectrum
- Elastic peak clearly visible. Tail due to charge sharing with adjacent pies and rings. We understand this well from previous experiments. THESE ARE COMPLEX DETECTORS!
- Scattered beam lies along $1/t^2$ line as expected
- What is the “ghost” line separated from the scatter line by ~ 4 ns. This is where the residues are expected!
What the problem is NOT due to:

a) The CFD of the MCP18 jumping in time
b) The LE of the Si det. jumping in time
Accomplishments

• Beam intensity and purity as well as tune to G22 line make measurement feasible
• degrading the beam (a major concern) does not make the measurement impossible.
• individual components CID, ZDIC, fast Si timing, MCPs work
• performance of segmented IC (sources + beams) is well characterized
• TOF of alpha between MCP and Si detector and beam indicates necessary time resolution is achieved.

Outlook

If the source of the background (scattering of MCP wires?) can be resolved (faster discriminators) the excitation function can be measured by this technique