Exploring the Stars with Radioactive Beams

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DOE under Grant No. DE-FG02-88ER-40404
NSF under Grant No. 1342962
IU Department of Chemistry

- 42 research faculty in all major disciplines of chemistry (analytical, biochem, inorganic, materials, organic, and physical)
- Dedicated support scientists and staff (NMR, mass spec., glass blowing, mechanical instrumentation, electronic instrumentation, information technology)
Formation of the elements

Big Bang: H, He, Li, Be

Expansion: T, ρ ↓
3 min.

Inhomogeneities
→ aggregation
→ T, ρ ↑
Formation of the elements

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3 min.

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$\rightarrow$ aggregation

$\rightarrow$ $T, \rho \uparrow$

H burning

$4p \rightarrow {}^4\text{He} + 2\beta + 2\nu$

He burning

$3 \ {}^4\text{He} \rightarrow {}^{12}\text{C}$

$4 \ {}^4\text{He} \rightarrow {}^{16}\text{O}$

Si Burning

$\rightarrow$ up to $^{56}\text{Fe}$

$^{12}\text{C}/^{16}\text{O}$ Burning

$\rightarrow$ Mg, Na, Si

12C/16O Burning
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3 min.

Ejecta repopulates interstellar medium enriched with heavy elements

Inhomogeneities

$\rightarrow$ aggregation

$\rightarrow T, \rho \uparrow$

Supernova Explosion:
Synthesis of elements beyond $^{56}\text{Fe}$ (r-process)

Remnant core:

Neutron Star

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$4\text{p} \rightarrow ^4\text{He}+2\beta+2\nu$

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M $> 10M_{\odot}$

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**r-process nucleosynthesis**

- Nucleosynthesis of heavy elements ($Z > 26$) has been thought to occur predominantly in supernova explosions
  - Large neutron flux $\rightarrow$ rapid neutron capture ($r$-process)
  - Neutron-rich nuclei $\rightarrow$ $\beta$-decay back to stability
  - Competition between neutron capture and $\beta$-decay
r-process nucleosynthesis

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  - Large neutron flux $\rightarrow$ rapid neutron capture ($r$-process)
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  - Competition between neutron capture and $\beta$-decay
- This nucleosynthesis can also happen in neutron star mergers, where the ejecta is very neutron rich
Accreting neutron stars and X-ray superbursts

- Neutron stars are the stellar remnants of supernova explosions
  - High density ($\sim 10^{14}$ g/cm$^3$)
  - relatively low temperatures ($\sim 10^6$ K)
  - large neutron abundance (90% of the mass)

- Neutron stars can exist in binary systems where they accrete matter from a companion main sequence star

- Accreting neutron stars provide a unique environment for nuclear reactions
  - Identified as the origin of X-ray superbursts
  - Release more energy in a few hours than our sun does in a decade

- X-ray superbursts are thought to be fueled by $^{12}$C+$^{12}$C fusion in the outer crust

- At the temperature of the outer crust, the fusion barrier is too high for thermonuclear fusion of carbon
  - Potential heat source: fusion of neutron-rich light nuclei (ex. $^{24}$O + $^{24}$O)
The fusion barrier

Both nuclei are positively charged, and therefore repel each other unless they are close enough to touch.

Coulomb’s Law: \( V \propto \frac{Z_1 Z_2}{r} \)
The fusion barrier

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Coulomb’s Law: \( V \propto \frac{Z_1 Z_2}{r} \)

The two nuclei must overcome the repulsion in order to experience the short range attractive nuclear force.

What if the two nuclei do not have enough energy to overcome this barrier?
The fusion barrier

- A particle can tunnel through a classically forbidden region and emerge on the other side
  - Exponential process
  - Very sensitive to the width and height of the barrier
- Even above the barrier, the particle feels the influence of the barrier
- As the two nuclei approach, the barrier can change

Investigating fusion for an isotopic chain of neutron-rich nuclei provides information on how structure and dynamics evolve with increasing neutron number

Measuring the fusion probability is therefore a probe of the intrinsic shape of the fusion barrier
To overcome the fusion barrier, the nuclei must get kinetic energy from somewhere:

- Raise the temperature (stars, tokamaks)
- Use an accelerator
$^{18}\text{O} + ^{12}\text{C}$

Florida State University

- $^{16}\text{O}$ stable
- $^{17}\text{O}$ stable
- $^{18}\text{O}$ stable
- $^{19}\text{O}$ 26.88 s
- $^{20}\text{O}$ 13.51 s
- $^{21}\text{O}$ 3.42 s
- $^{22}\text{O}$ 2.25 s
- $^{23}\text{O}$ 97 ms
- $^{24}\text{O}$ 65 ms

Stable isotopes:
- $^{16}\text{O}$
- $^{17}\text{O}$
- $^{18}\text{O}$

Unstable isotopes:
- $^{19}\text{O}$
- $^{20}\text{O}$
- $^{21}\text{O}$
- $^{22}\text{O}$
- $^{23}\text{O}$
- $^{24}\text{O}$
18O Beam Production

- 18O⁻ produced at ion source
- Accelerated by 9 MV Tandem Van de Graaf accelerator
- Passes through stripper foil
- 18ON⁺ accelerated by tandem to desired energies
- $E_{\text{lab}} = 13.75 - 36$ MeV
- Intensity of $\sim 1-4.5 \times 10^5$ pps
Experimental setup on the beam line
A “simple” counting experiment

\[ \sigma_{\text{fusion}} = \frac{N}{I \cdot t} \]

- Number of fusion reactions
- Number of target atoms
- Cross-section (fusion probability)
- Number of beam particles
The Reaction and its Products

\[ ^{18}O + ^{12}C \rightarrow ^{30}Si^* \rightarrow ^{28}Si + 2n \rightarrow ^{28}Al + p + n \rightarrow ^{25}Mg + \alpha + n \]

\[ E^* = 30 - 38 \text{ MeV} \]

- Excited compound nucleus decays by emitting protons, neutrons, and particles
- The resulting heavy nucleus is known as an evaporation residue
- Emission of these light particles impart transverse momentum on the residue, kicking them off zero degrees and allowing for direct measurement of the residues and light particles

\[ E = \frac{1}{2}mv^2 \quad m \propto Et^2 \]
Our Detectors

- E x B fields transport electrons from secondary emission foil to MCP
- E field produced by biasing array of ring plates
- B field produced by NdFeB permanent magnets
- Timing resolution ~300 ps

- Annular single crystal Si(IP) detectors ~300 µm thick
- Acts as a reverse biased diode
- Segmented to provide angular information and reduce detector capacitance
- Used to provide both energy and time information:
  - Timing resolution ~450 ps
  - Energy resolution <1%

Beam

Bowman et al., Nucl. Inst. and Meth. 148, 503 (1978)
Steinbach et al., Nucl. Inst. and Meth. A 743, 5 (2014)
Experimental Setup

- $E_{\text{lab}} = 16.25 - 36$ MeV
- Intensity $\sim 10^5$ p/s
- Beam is counted between two MCPs
- Reaction products distinguished by energy and time-of-flight
- Energy measured in segmented annular silicon detectors (T2, T3)
- Fusion product time-of-flight measured between target MCP and silicon detectors
• Intense peak corresponds to elastically scattered beam particles

• Points in the band originating from this peak are scattered beam particles

• Evaporation residues are located in the island with longer TOF values than the beam scatter line

• $\alpha$ particles correspond to the band with very short TOF values

\[
\sigma_{fusion} = \frac{N}{\varepsilon \cdot I \cdot t}
\]

- Cross-section
- Number of residues
- Target thickness
- Efficiency
- Beam count

Elastic Scattering
Evaporation Residues
Beam Scatter

$E_{c.m.} = 11.0$ MeV

$^{18}\text{O} + ^{12}\text{C}$
Fusion excitation function

• Fusion cross-section measured from 5 to 14 MeV
• Good agreement with existing data
• Extended measurement down to the ~820 µb level (30 times lower than previous measurements)
• At high $E_{\text{c.m.}}$, $\sigma_{\text{fusion}}$ decreases gradually with decreasing incident energy
• Near the barrier, $\sigma_{\text{fusion}}$ begins to rapidly fall as $E_{\text{c.m.}}$ decreases below the barrier
Fusion excitation function

- In a simple picture, the height of the barrier determines the energy at which $\sigma_{\text{fusion}}$ begins to rapidly decrease.
- The width of the barrier determines how rapidly it falls.
- One can therefore fit the shape of the fusion excitation function to a functional form that describes a one-dimensional parabolic barrier:

$$\sigma_{\text{fusion}} = \frac{R_c^2}{2E_{\text{cm}}} \hbar \omega \left[ 1 + \exp \left( \frac{2\pi}{\hbar \omega} (E_{\text{cm}} - V_c) \right) \right]$$
$^{19}\text{O} + ^{12}\text{C}$

Florida State University

Radioactive Beam!
Beam production and identification
- Used $^{18}\text{O}(d,p)$ reaction to get just 2-4 x $10^3$ $^{19}\text{O}$ ions/s
- TOF between the two micro-channel plate detectors
  - Count incident beam particles
  - Particle identification using $\Delta E$-TOF with degrading ion chamber (CID)
- Beam energy also changed with CID pressure

Detecting reaction products
- The particle energy is measured in annular Si detectors, for $3.5^\circ \leq \theta_{\text{LAB}} \leq 22^\circ$
- TOF is measured between MCP_{TGT} and Si detectors

Simultaneous measurement of $^{18}\text{O} + ^{12}\text{C}$ and $^{19}\text{O} + ^{12}\text{C}$
Simultaneous measurement of $^{18}\text{O} + ^{12}\text{C}$ is in good agreement with high precision measurement.

This is the first measurement of the fusion excitation function of $^{19}\text{O} + ^{12}\text{C}$.

At all energies, the cross-section for $^{19}\text{O}$ is higher than that for $^{18}\text{O}$.

At low energy, substantial enhancement of the fusion cross-section is observed for $^{19}\text{O}$ relative to $^{18}\text{O}$. 
Relative cross-sections

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![Graph showing cross-sections](image.png)
And now for something completely different…
Measuring evaporation residues

- Energy vs. time-of-flight linearized using the relation
  \[ A \propto Et^2 \]

- Mass resolution \(~2.4\) amu at \( A = 47 \)

- Clear separation is observed between evaporation residues and scattered beam

- Evaporation residues from two reactions:
  - \( K + O \)
  - \( K + Si \)

- ERs from each reaction are better separated by their mass-energy correlation in 2D
Fusion excitation function

• First measurements of $^{39,47}$K + $^{28}$Si

• At all energies, the cross-section for $^{47}$K is higher than that for $^{39}$K

• At low energy, substantial enhancement of the fusion cross-section is observed for $^{47}$K relative to $^{39}$K
• First measurements of $^{39,47}$K + $^{28}$Si

• At all energies, the cross-section for $^{47}$K is higher than that for $^{39}$K

• At low energy, substantial enhancement of the fusion cross-section is observed for $^{47}$K relative to $^{39}$K

• Enhancement reaches approximately a factor of 5 at the lowest measured energy

• This enhancement can be understood in terms of a reduced barrier due to dynamic deformation of the projectile and target
Conclusions/Outlook

Summary

• We have developed a technique suitable to measure fusion excitation functions with low intensity radioactive beams

• The fusion cross-sections for $^{18,19}$O + $^{12}$C have been measured

• The addition of a single neutron in $^{19}$O as compared to $^{18}$O increases the cross-section by a factor of 3 near the barrier

• The fusion cross-sections for $^{39,47}$K + $^{28}$Si have been measured for the first time using the ReA3 facility at NSCL

• A significant enhancement of the cross-section is observed for $^{47}$K relative to $^{39}$K near the barrier

In the future:

• $^{41,45}$K + $^{28}$Si and $^{36,44}$Ar + $^{28}$Si at NSCL ReA3 (E17002)

• $^{20,21}$O + $^{12}$C at GANIL (E739), possibly $^{22}$O (LOI)

• Proposal to perform a Day I experiment at FRIB
Acknowledgements

Indiana University Nuclear Chemistry:

Indiana University Chemistry Department:
Mechanical Instrument Services and
Electronic Instrument Services

http://nuchem.iucf.indiana.edu
desouza@indiana.edu
Thank you for your attention!
Understanding neutron-rich matter is important for a broad range of phenomena:

- Nucleosynthetic r-process
- Neutron star mergers

One laboratory to investigate the character of neutron rich matter is the skin of neutron-rich nuclei

The enhanced fusion of neutron-rich nuclei may serve to ignite X-ray superbursts in accreting neutron stars.

Gain insight into neutron skin by investigating fusion for an isotopic chain of neutron-rich nuclei (interplay of nuclear structure and dynamics)
An X-ray superburst, which occurs in the outer crust of an accreting neutron star, releases more energy in a few hours than the sun does in a decade.

Fusion of light and mid-mass neutron-rich nuclei has been proposed as being responsible for triggering X-ray superbursts.

Measurement of an isotopic chain provides information on how structure and dynamics evolve with increasing neutron number.

\( ^{39,47}K + ^{28}Si \) allows for exploring the effect of a large span in neutron number on fusion.
Low energy rare isotope beams at NSCL

- Primary beam accelerated by two coupled cyclotrons
- Rare isotope beam (RIB) produced via projectile fragmentation and separated by A1900 spectrometer
- Beam significantly slowed down in a linear gas stopper
- Beam ionized to high N+ charge state in charge breeder
- RIB is re-accelerated to desired energy and delivered to the experimental area
Challenges experienced with ReA3

• Timing structure of the beam
  • Beam leaves the charge breeder in macrobursts every 500 ms (2 Hz)
  • The ions are bunched into the first ~100 ms of each macroburst
  • Instantaneous rate experienced by detectors: ~5x higher than the average rate

• Contamination in RIBs
  • Particle identification is required on an event-by-event basis
  • Need detector with good energy resolution and high rate capability
Rare Ion Purity Detector (RIPD)

- Axial field design with central anode minimizes charge collection time
- Aluminized windows serve as cathodes (0.5 µm)
- Utilize CF$_4$ as detector gas based upon its high electron drift velocity
- Integrated fast charge sensitive amplifier
- Energy resolution ~8% above 5 MeV
- Resolution ~10% at an instantaneous rate of $1 \times 10^5$ ions/s

J. Vadas, et al., NIMA 837 (2016) 28
$^{39,47}\text{K} + ^{28}\text{Si} \rightarrow ^{67,75}\text{As}$

- $E_{\text{lab}} = 2.3 - 3 \text{ MeV/A}$
- Average intensity $\sim 10^4 \text{ p/s}$
- Reaction products distinguished by ETOF
- Energy measured in segmented annular silicon detectors ($T_1, T_2$) $1^\circ \leq \theta_{\text{lab}} \leq 7.3^\circ$
- Fusion product time-of-flight measured between target MCP and silicon detectors

- $^{47}\text{K}$ beam contaminated by $^{36}\text{Ar} (\sim 5\%)$
- Particle identification performed using $\Delta E$-TOF
- $\Delta E$ measured in RIPD
- TOF measured between two MCP detectors
Measuring evaporation residues

- Evaporation residues identified by mass are integrated ($N_{ER}$)
- The number of incident beam particles are counted with the two MCP timing detectors ($N_{Beam}$)
- Efficiency correction for detector geometric coverage ($\varepsilon_{ER}$) determined with statistical model (evapOR)
- Target thickness ($t$) determined using the $^{39}$K+$^{16}$O data and $\alpha$ source energy loss measurements ($^{241}$Am and $^{148}$Gd)

\[
\sigma_{fusion} = \frac{N_{ER}}{N_{Beam} t \varepsilon_{ER}}
\]
Determining the target thickness

\[ \sigma_{\text{fusion}} \] for \( ^{39}\text{K} + ^{16}\text{O} \)

Calculated \( \sigma_{\text{fusion}} \) from empirical channel coupling model

Minimized \( \chi^2 \) in calculating \( t \) for \( ^{16}\text{O} \)

\( t^{16}_O \rightarrow t_{\text{SiO}_2} \)

\( t^{16}_O = 97 \ \mu\text{g/cm}^2; \ t_{\text{SiO}_2} \approx 800 \ \text{nm} \)

Determining the amount of \( ^{28}\text{Si} \):

- Measured energy loss of \( \alpha \) particles from \( ^{148}\text{Gd} \) and \( ^{241}\text{Am} \) sources
- Using SRIM and known \( t_{\text{SiO}_2} \), determined \( t^{28}_{\text{Si}_{\text{pure}}} \)
- Total thickness = 327 \( \mu\text{g/cm}^2 \) \( ^{28}\text{Si} \)

\( ^{28}\text{Si} \) enriched target provided by M. Loriggiola (Legnaro National Laboratory)

Estimating the amount of oxidation:

- Extracted \( \frac{\sigma_{\text{fusion}}}{t^{16}_O} \) for \( ^{39}\text{K} + ^{16}\text{O} \)
- Calculated \( \sigma_{\text{fusion}} \) from empirical channel coupling model
- Minimized \( \chi^2 \) in calculating \( t \) for \( ^{16}\text{O} \)
- \( t^{16}_O \rightarrow t_{\text{SiO}_2} \)
- \( t^{16}_O = 97 \ \mu\text{g/cm}^2; \ t_{\text{SiO}_2} \approx 800 \ \text{nm} \)
Fusion excitation function

Enhancement:

<table>
<thead>
<tr>
<th>Ratio</th>
<th>High energy</th>
<th>Low energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(^{47}\text{K})/\sigma(^{39}\text{K})$</td>
<td>1.2</td>
<td>11</td>
</tr>
</tbody>
</table>

Wong fit parameters:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$V_C$ (MeV)</th>
<th>$R_C$ (fm)</th>
<th>$\hbar\omega$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{39}\text{K}+^{28}\text{Si}$</td>
<td>$37.53 \pm 0.25$</td>
<td>$8.34 \pm 0.40$</td>
<td>$3.46 \pm 0.72$</td>
</tr>
<tr>
<td>$^{47}\text{K}+^{28}\text{Si}$</td>
<td>$37.01 \pm 0.77$</td>
<td>$8.94 \pm 0.89$</td>
<td>$6.06 \pm 2.06$</td>
</tr>
</tbody>
</table>

Barrier curvature for $^{47}\text{K}$ is 1.8 times larger than $^{39}\text{K}$

Barrier for $^{47}\text{K}$ is thinner

Conceptually: Thinner barrier $\rightarrow$ Greater penetration $\rightarrow$ Enhanced fusion cross-section