Probing the fusion of neutron-rich nuclei with reaccelerated radioactive beams

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Motivation: To understand the character of neutron-rich nuclear matter

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.

\[ ^{39,47}K + ^{28}Si \] provides a swing of 8 neutrons, made possible by advances in RIB facilities.

Gain insight into neutron skin by investigating fusion for an isotopic chain of neutron-rich nuclei (interplay of nuclear structure and dynamics).
The Reaction an Its Products

\[ ^{47}K + ^{28}Si \rightarrow ^{75}As^* \rightarrow ^{73}As + 2n \]
\[ \rightarrow ^{73}Ge + p + n \]
\[ \rightarrow ^{70}Ga + \alpha + n \]

- 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
$^{39,47}\text{K} + ^{28}\text{Si} \rightarrow ^{67,75}\text{As}^*$ at ReA3

- $E_{\text{lab}} = 2.3 - 3 \text{ MeV/A}$
- 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

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

- Mass resolution \( \sim 2.4 \) 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
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)

\[ \sigma_{fusion} = \frac{N_{ER}}{N_{Beam} t \varepsilon_{ER}} \]
Fusion excitation function

- First measurements of $^{39,47}\text{K} + ^{28}\text{Si}$
- At all energies, the cross-section for $^{47}\text{K}$ is higher than that for $^{39}\text{K}$
- A one-dimensional parabolic barrier penetration formula (Wong formula) is used to parameterize the cross-sections

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

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Fusion excitation function

- Comparison with a static, spherical one dimensional barrier penetration model
  - Relativistic Mean Field density distributions with Sao Paulo model
  - Assesses changes due solely to differences in the density distributions

- RMF+SP agrees with the data for higher $E_{c.m.}$, but underpredicts cross-sections near and below the barrier

- Agreement at high $E_{c.m.}$ indicates that RMF+SP correctly describes the size of the nuclei, however disagreement at low energy suggests that inclusion of dynamics is necessary
Fusion excitation function

- Use a model which includes dynamics: CCFULL
- Potential parameters derived from RMF+SP
- Rotational coupling to the first two excited states in both the target and projectile for each system

<table>
<thead>
<tr>
<th>System</th>
<th>$V_0$ (MeV)</th>
<th>$r_0$ (fm)</th>
<th>$a$ (fm)</th>
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<tbody>
<tr>
<td>$^{39}$K + $^{28}$Si</td>
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- Data is well described by the CCFULL calculations for the entire energy range measured
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Inclusion of neutron transfer ($F_t = 0.25$) for $^{47}$K provides slightly better agreement

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• As $E_{\text{c.m.}}$ decreases near and below the barrier, the ratio increases.

• At high $E_{\text{c.m.}}$, all model calculations converge to the data.

• The onset of the increase is much higher for RMF+SP (no dynamics) than the data.

• CCFULL (with dynamics) agrees well with the data.

• Dynamics acts to lower the onset of the increase in the relative cross-section.

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At energies below the barrier, inclusion of neutron transfer modifies the slope of the relative excitation function, demonstrating sensitivity of the ratio to changes in the fusion dynamics.

The difference in the dynamics due to the additional neutrons can be visualized as a difference in the barriers for the two systems.
Conclusions/Outlook

Summary

• An efficient method of measuring fusion cross-sections with low intensity reaccelerated radioactive beams has been developed
• The fusion cross-section for $^{39,47}$K + $^{28}$Si has been measured for the first time using the ReA3 facility at NSCL
• The energy dependence of $\sigma^{(47K)}/\sigma^{(39K)}$ reflects both the difference in size as well as dynamics associated with the additional neutrons

Outlook

• Implement improved DAQ for higher data throughput (elastic rejection)
• Develop $^{28}$Si targets with minimal oxidation
• Measure $^{41,45}$K + $^{28}$Si and $^{36,44}$Ar + $^{28}$Si at NSCL ReA3 (E17002)
• Measure $^{20,21}$O + $^{12}$C at GANIL (E739), possibly $^{22}$O (LOI)
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    • Antonio Villari, Sam Nash, Alain LaPierre

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Additional Material
X-ray superbursts

- 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.
- $^{39,47}\text{K} + ^{28}\text{Si}$ 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
$^{39.47}\text{K} + ^{28}\text{Si} \rightarrow ^{67.75}\text{As}$

- $E \times B$ 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 $\sim 300$ ps

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

desouza et al., Nucl. Instr. and Meth. A632, 133 (2011)

- Annular single crystal Si(IP) detectors
- Segmented to provide angular information and reduce detector capacitance
- Timing resolution $\sim 450$ ps
- Energy resolution $< 1\%$
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

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Determining the target thickness

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

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

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 \( \mu\text{g/cm}^2 \) \(^{28}\text{Si}\)