Measuring the fusion cross-section of $^{39,47}$K + $^{28}$Si at near-barrier energies

Justin Vadas, V. Singh, B. Wiggins, J. Huston, S. Hudan, R.T. de Souza; Indiana University Bloomington

A. Chbihi, D. Ackermann; GANIL

M. Famiano; Western Michigan University

K. Brown; Michigan State University

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• 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
The Reaction and 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
• Primary beam accelerated by two coupled cyclotrons
• Rare isotope beam (RIB) produced via fragmentation and separated by A1900 fragment separator
• 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 $\sim$100 ms of each macroburst
  - Instantaneous rate experienced by detectors: $\sim$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 $\sim$8% above 5 MeV
- Resolution $\sim$10% at an instantaneous rate of $1 \times 10^5$ ions/s

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\[ ^{39,47}\text{K} + ^{28}\text{Si} \rightarrow ^{67,75}\text{As}^* \]

- \( E_{\text{lab}} = 2.3 – 3 \text{ MeV/A} \)
- Average intensity \( \sim 10^4 \text{ p/s} \)
- Reaction products distinguished by ETOF
- Energy measured in segmented annular silicon detectors (T1, T2) \( 1^\circ \leq \theta_{\text{lab}} \leq 7.3^\circ \)
- Fusion product time-of-flight measured between target MCP and silicon detectors

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

• Evaporation residues identified using E-TOF 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 ($\varepsilon_{ER}$).
• Target thickness determined by measuring energy loss of $\alpha$ particles from $^{148}\text{Gd}$ and $^{241}\text{Am}$ sources ($t$).
• Target:
  • Isotopically enriched $^{28}\text{Si}$
  • Thickness = 442 µg/cm²
  • Provided by Legnaro National Laboratory

\[ \sigma_{fusion} = \frac{N_{ER}}{N_{Beam} t \varepsilon_{ER}} \]
First measurements of $^{39,47}\text{K} + ^{28}\text{Si}$

- $^{39}\text{K}$: ~500 mb to ~3 mb
- $^{47}\text{K}$: ~300 mb to ~15 mb

At high $E_{CM}$, $^{47}\text{K}$ is about equal to $^{39}\text{K}$

Below the barrier, $^{47}\text{K}$ is enhanced relative to $^{39}\text{K}$

Ratio reaches a factor of 7 at the lowest energy measured

<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>37.29 ± 0.26</td>
<td>8.27 ± 0.24</td>
<td>4.89 ± 0.63</td>
</tr>
<tr>
<td>$^{47}\text{K} + ^{28}\text{Si}$</td>
<td>37.35 ± 1.42</td>
<td>8.37 ± 1.32</td>
<td>9.26 ± 2.68</td>
</tr>
</tbody>
</table>
Conclusions/Outlook

Summary

• The fusion cross-section for $^{39,47}\text{K} + ^{28}\text{Si}$ has been measured for the first time using the ReA3 facility at NSCL
• A significant enhancement of the cross-section is observed for $^{47}\text{K}$ relative to $^{39}\text{K}$ near the barrier

In the future:

• Finalize cross-section for $^{39,47}\text{K} + ^{28}\text{Si}$ and compare with theoretical models
• $^{36,44}\text{Ar} + ^{28}\text{Si}$ at NSCL ReA3
• $^{20,21}\text{O} + ^{12}\text{C}$ at GANIL (E739), possibly $^{22}\text{O}$ (LOI)
• $^{18,19}\text{O} + ^{18}\text{O}$ at FSU
Additional Material