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

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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.

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

\[ E = \frac{1}{2}mv^2 \]
\[ m \propto Et^2 \]
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
\[ 39,47^K + 28^Si \rightarrow 67,75^As^* \]

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

- \( ^{47}K^{17+} \) beam contaminated by \( ^{36}Ar (~5\%) \)
- 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 ($\epsilon_{ER}$) 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 $^{148}Gd$).

\[
\sigma_{fusion} = \frac{N_{ER}}{N_{Beam} t \epsilon_{ER}}
\]
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

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

- The relative cross-section can be used to facilitate better comparison between the two systems
As Ecm decreases and approaches the barrier, the cross-sections for 47K begin to drastically increase.
Fusion excitation function

• As Ec.m. decreases and approaches the barrier, the cross-sections for 47K begin to drastically increase

• Semi-empirical channel-coupling model code by Zagrebaev:
  • Initial statically deformed projectile and target
  • Allow projectile and target to deform on approach
  • Include the influence of neutron-transfer

• Observed enhancement can be described in the context of dynamic deformation of the projectile and target nuclei

http://nrv.jinr.ru/nrv/
Conclusions/Outlook

Summary

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

• A significant enhancement of the cross-section (up to a factor of 6) is observed for $^{47}$K relative to $^{39}$K near the barrier

• This enhancement can be understood as dynamic deformation of the system as the projectile and target approach

In the future:

• Compare cross-sections with other models such as DC-TDHF and CCFULL

• $^{41,45}$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)
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Additional Material
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.
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 $1\times10^5$ ions/s

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- 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 $\sim$300 ps

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

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)
Determining the target thickness

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

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

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

- Static deformation results in a too-shallow excitation function for both systems
- Dynamic deformation has the same shape as the data, but is systematically higher for all energies for both systems
- Inclusion of neutron-transfer channels only influences the cross-sections at below-barrier energies for $^{47}$K