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

INDIANA UNIVERSITY

NSF

U.S. DEPARTMENT OF ENERGY | Office of Science

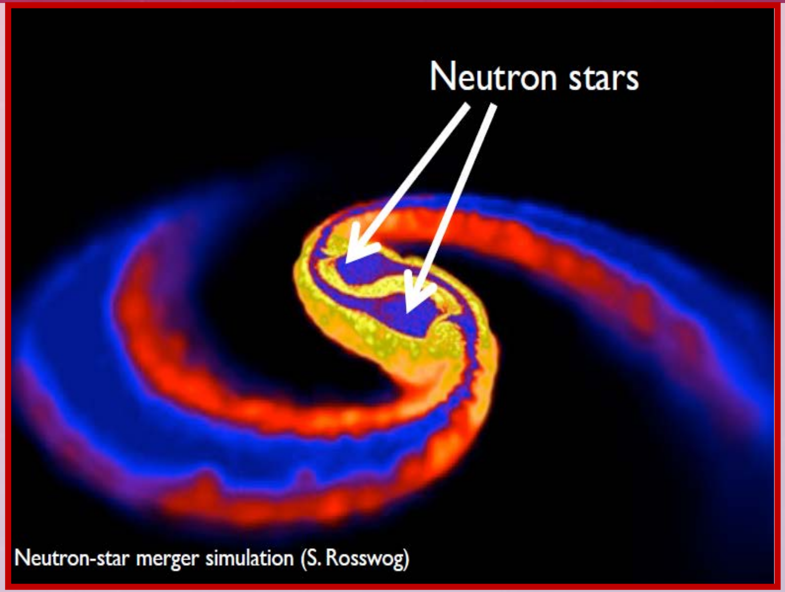
DOE under Grant No. DE-FG02-88ER-40404

NSF under Grant No. 1342962

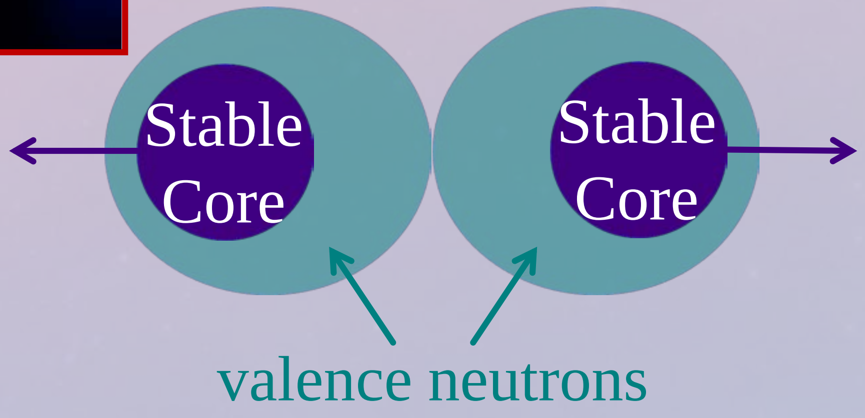
Motivation: To understand the character of neutron-rich nuclear matter

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.

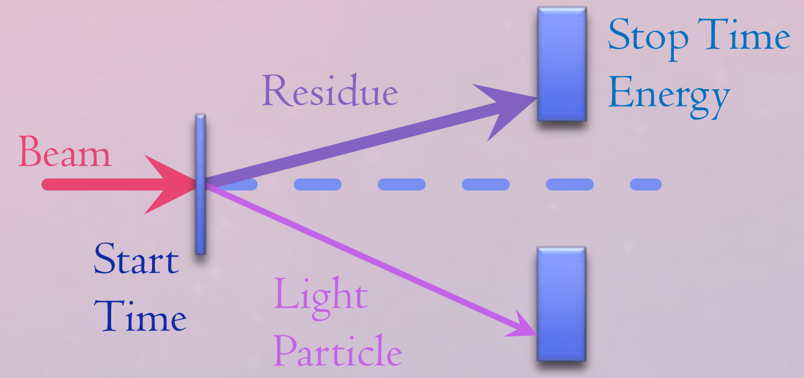
Gain insight into neutron skin by investigating fusion for an isotopic chain of neutron-rich nuclei (interplay of nuclear structure and dynamics)

The Reaction and its Products

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

Evaporation residues

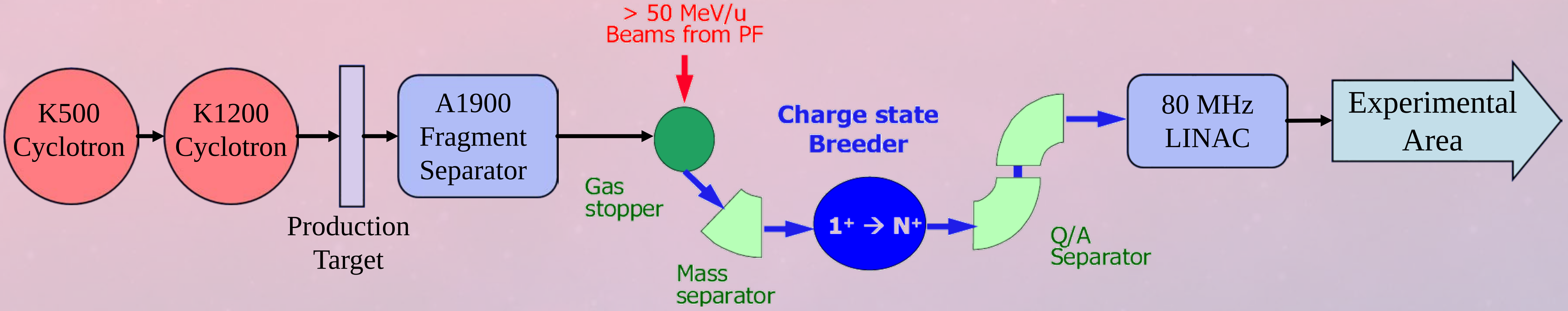
Evaporated particles



$$ E = \frac{1}{2} m v^2 \qquad m \propto E t^2 $$

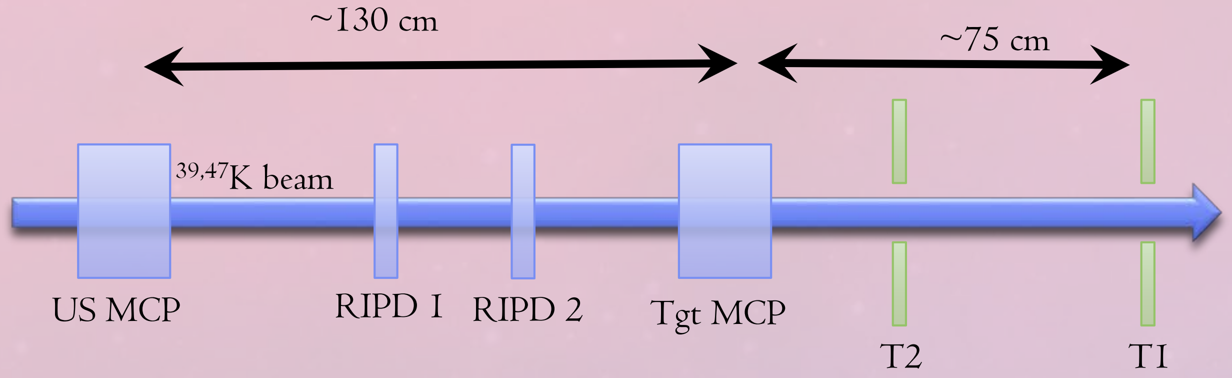
- Excited compound nucleus decays by emitting protons, neutrons, and particles
- The resulting heavy nucleus is known as an evaporation residue
- Emission of these light particles impart transverse momentum on the residue, kicking them off zero degrees and allowing for direct measurement of the residues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

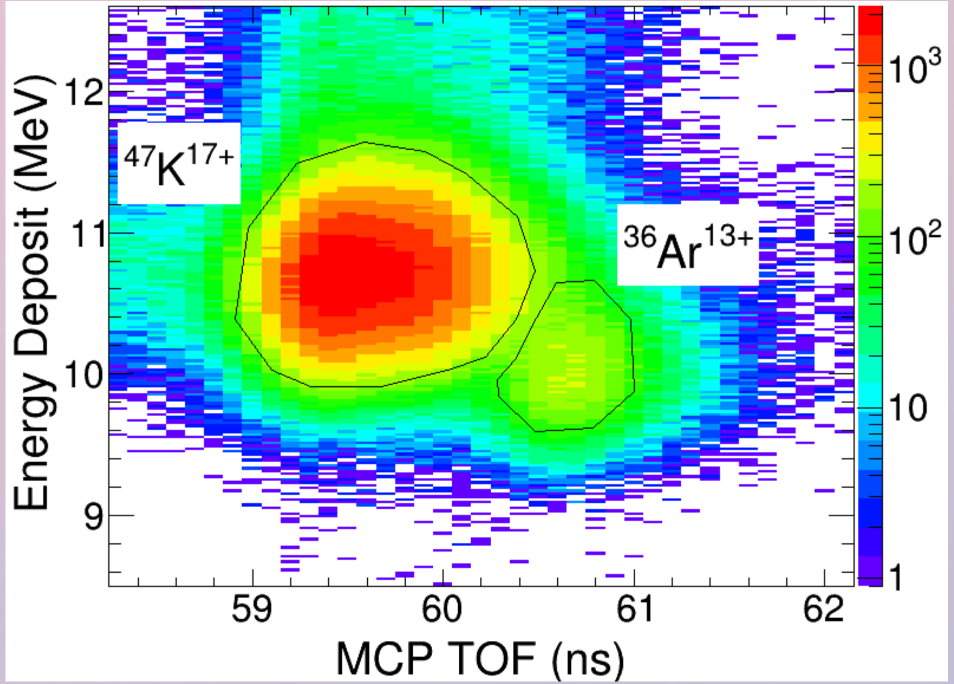
Low energy rare isotope beams at NSCL



- 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

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

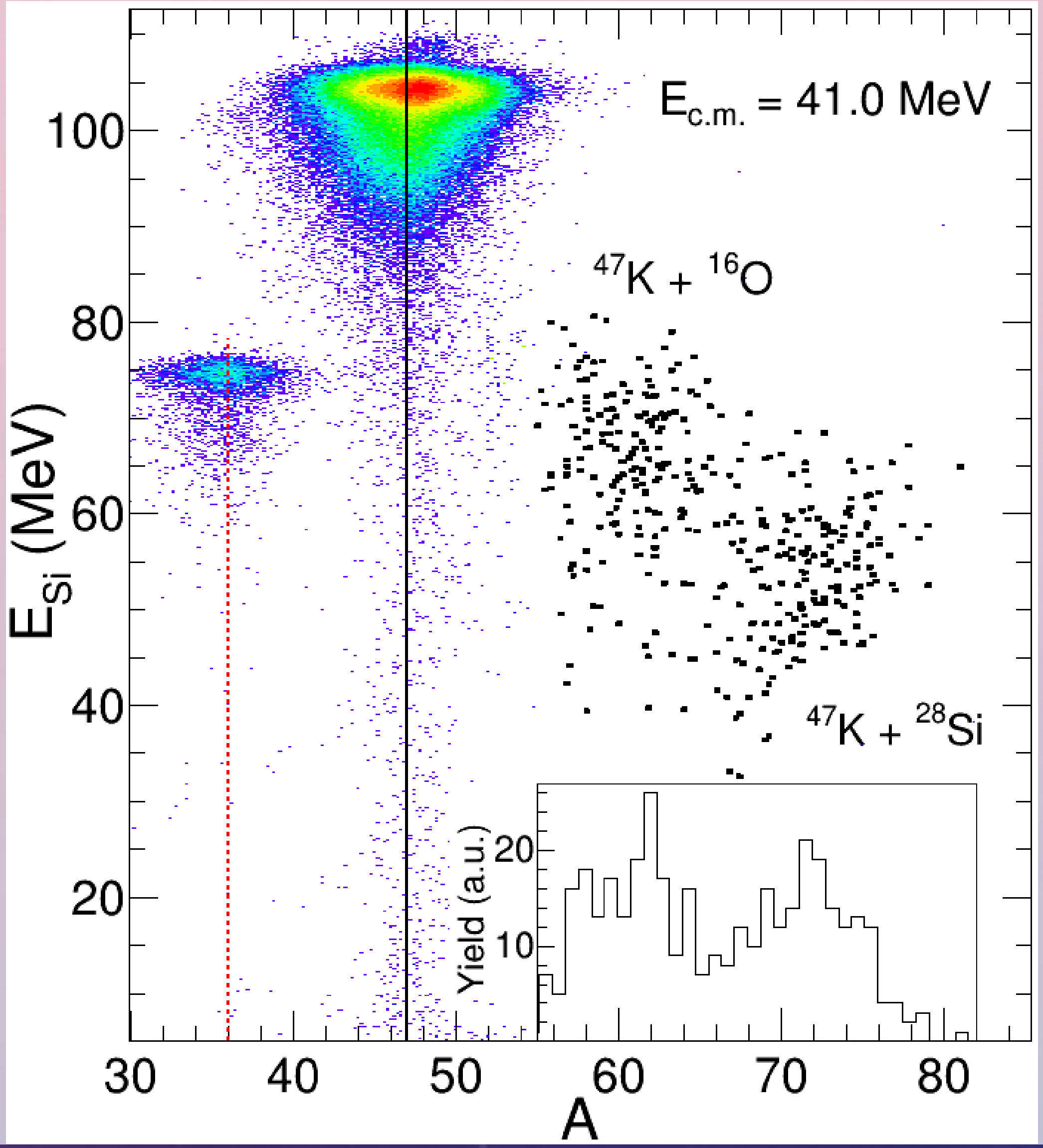




- E_{lab} = 2.3 – 3 MeV/A
- Average intensity ~ 10^4 p/s
- Reaction products distinguished by ETOF
- Energy measured in segmented annular silicon detectors (T1, T2) $1° \leq \theta_{lab} \leq 7.3°$
- Fusion product time-of-flight measured between target MCP and silicon detectors

- ^{47}K beam contaminated by ^{36}Ar (~5%)
- Particle identification performed using ΔE-TOF
- ΔE measured in RIPD
- TOF measured between two MCP detectors

Measuring evaporation residues

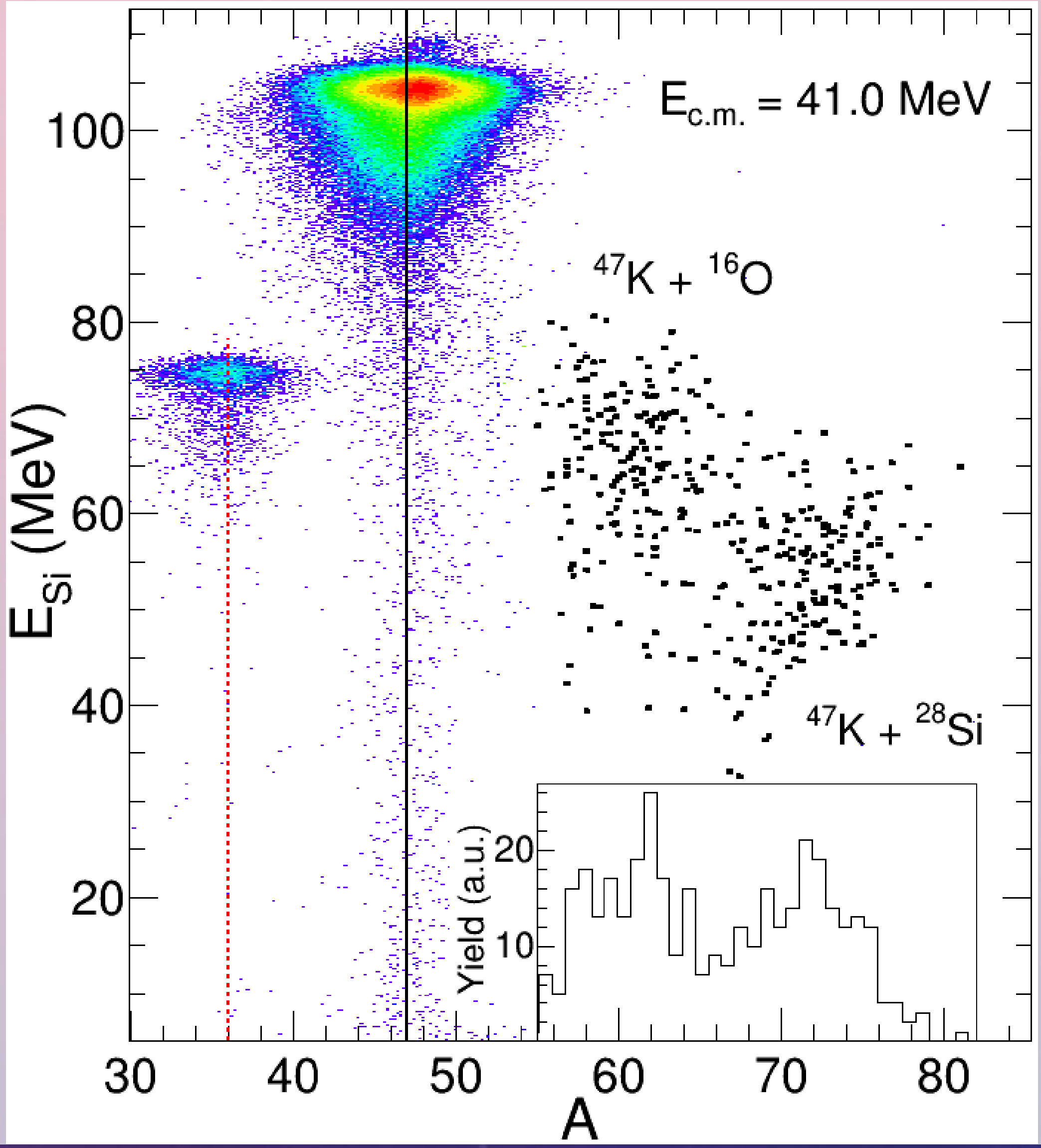


- Energy vs. time-of-flight linearized using the relation

$$A \propto Et^2$$

- 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

Measuring evaporation residues

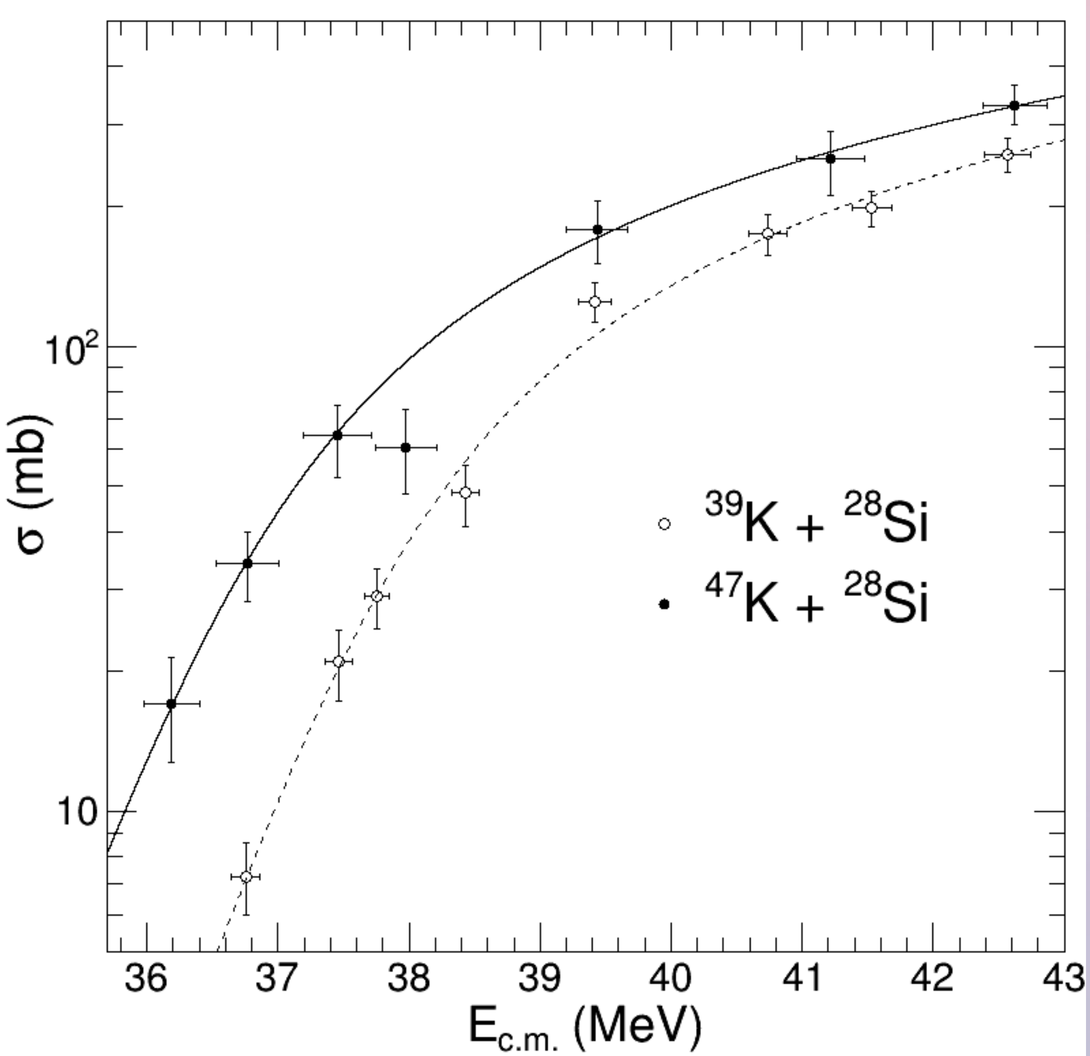


$$\sigma_{fusion} = \frac{N_{ER}}{N_{Beam}\, t\, \varepsilon_{ER}}$$

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

- 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 (ε_{ER}) determined with statistical model (evapOR)
- Target thickness (t) determined using the ^{39}K+^{16}O data and α source energy loss measurements (^{241}Am and ^{148}Gd)

Fusion excitation function

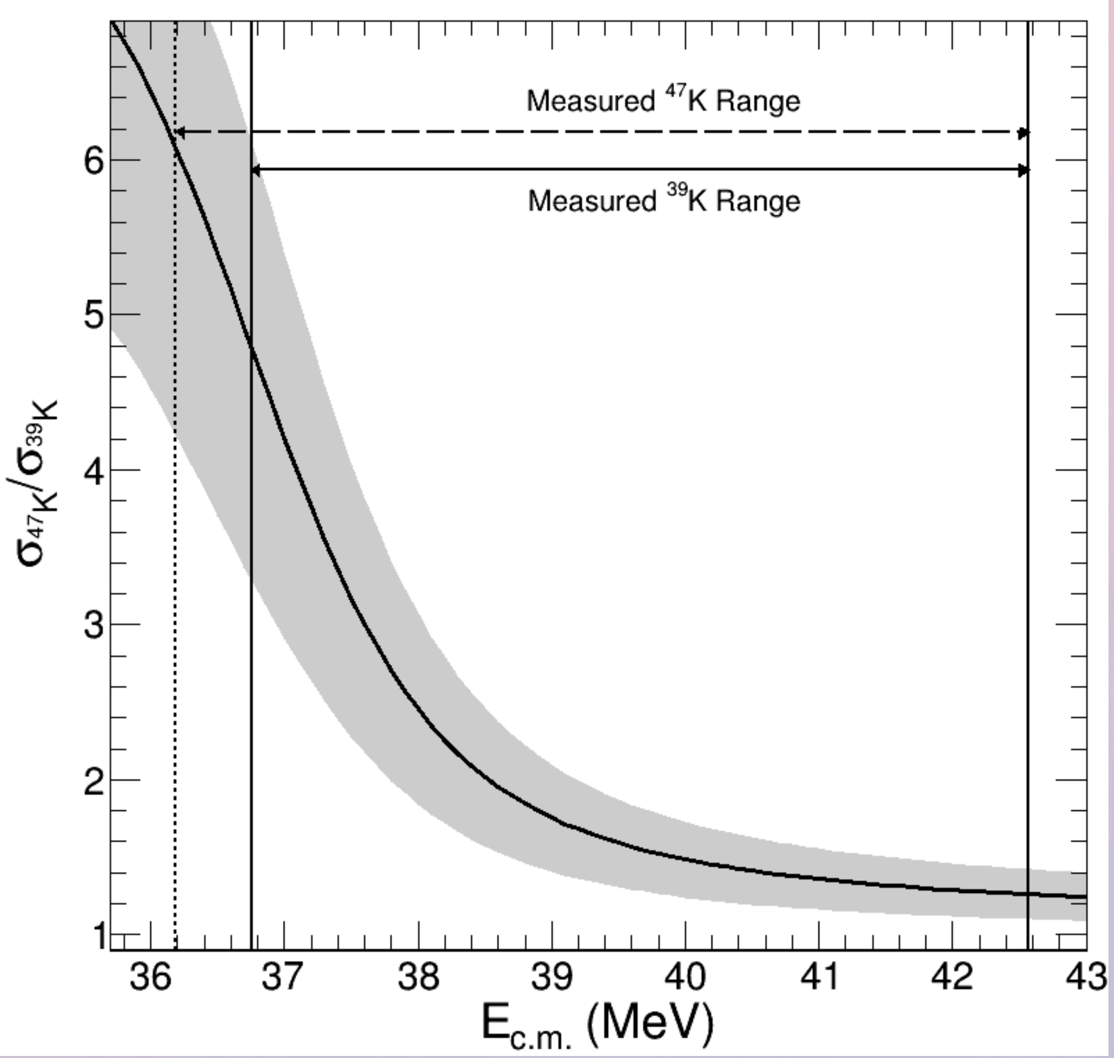


- First measurements of $^{39,47}K + {}^{28}Si$
- At all energies, the cross-section for ^{47}K is higher than that for ^{39}K
- A one-dimensional parabolic barrier penetration formula (Wong formula) is used to parameterize the cross-sections

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

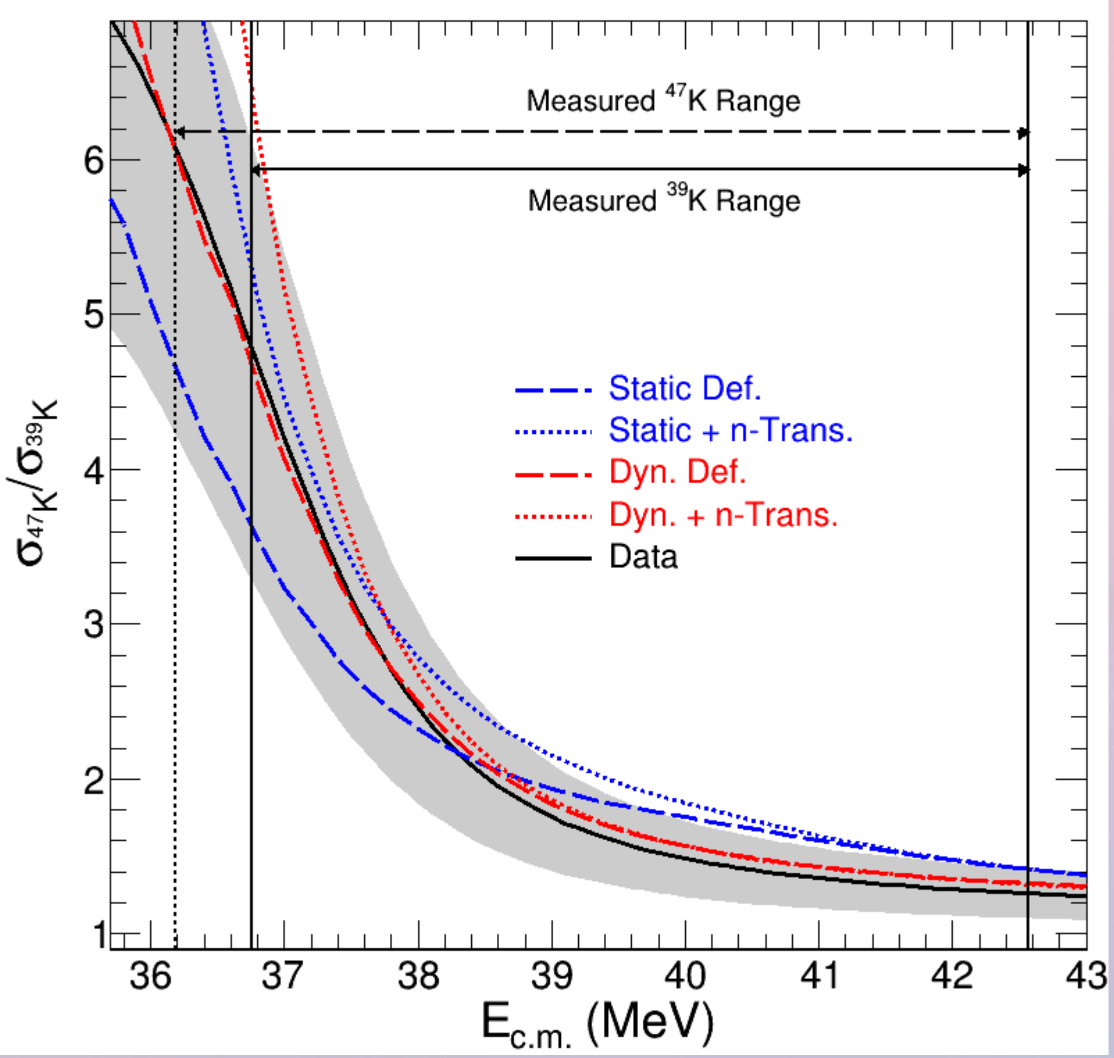
- The relative cross-section can be used to facilitate better comparison between the two systems

Fusion excitation function



- As Ec.m. 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/
V.I. Zagrebaev, Phys. Rev. C 64 (2001) 034606
V.I. Zagrebaev, et al., Phys.Rev. C 65 (2002) 014607

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:

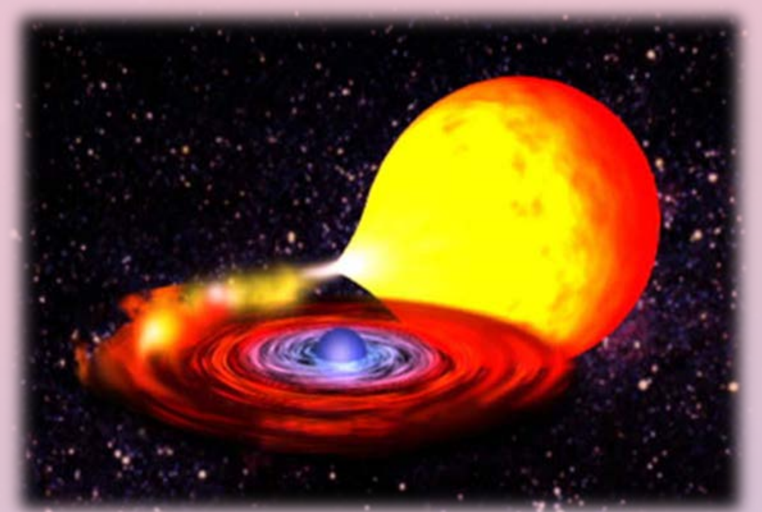
- Compare cross-sections with other models such as DC-TDHF and CCFULL
- ^{41,45}K + ^{28}Si and ^{36,44}Ar + ^{28}Si at NSCL ReA3 (E17002)
- ^{20,21}O + ^{12}C at GANIL (E739), possibly ^{22}O (LOI)

Acknowledgements

- Indiana University:
  - Nuclear Chemistry group
  - IU Mechanical Instrument Services
  - IU Electronic Instrument Services
- GANIL:
  - Abdou Chbihi, Dieter Ackermann
- Western Michigan University:
  - Mike Famiano, Mike Bischak
- Michigan State University:
  - Kyle Brown, Clementine Santamaria
  - Technical staff at NSCL/ReA3
    - Antonio Villari, Sam Nash, Alain LaPierre

Additional Material

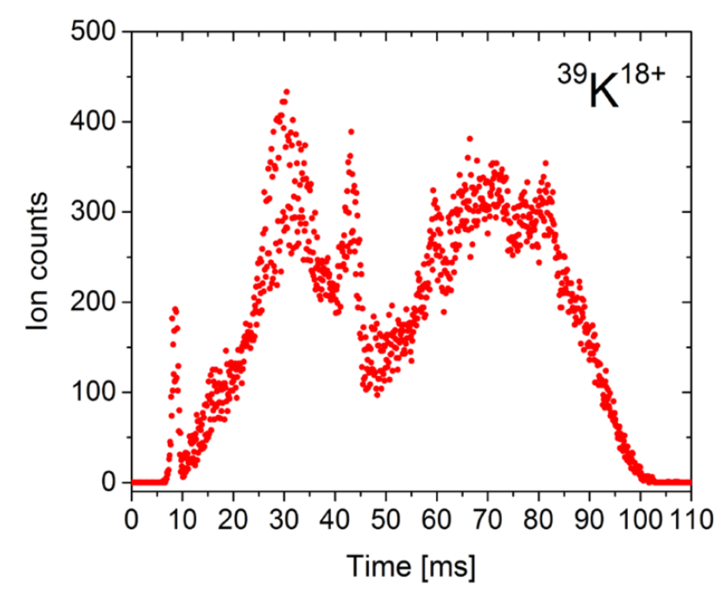
X-ray superbursts



Z \ N	18	19	20	21	22	23	24	25	26	27	28	29
20	^{38}Ca 440 ms	^{39}Ca 860 ms	^{40}Ca 3e21 y	^{41}Ca 1e5 y	^{42}Ca stable	^{43}Ca stable	^{44}Ca stable	^{45}Ca 162.6 d	^{46}Ca 3e17 y	^{47}Ca 4.54 d	^{48}Ca 6e22 y	^{49}Ca 8.72 m
19	^{37}K 1.226 s	^{38}K 7.636 m	^{39}K stable	^{40}K 1e9 y	^{41}K stable	^{42}K 12.3 hr	^{43}K 22.3 hr	^{44}K 22.1 m	^{45}K 17.8 m	^{46}K 105 s	^{47}K 17.5 s	^{48}K 6.8 s
18	^{36}Ar stable	^{37}Ar 35.04 d	^{38}Ar stable	^{39}Ar 269 y	^{40}Ar stable	^{41}Ar 109 m	^{42}Ar 32.9 y	^{43}Ar 5.37 m	^{44}Ar 11.9 m	^{45}Ar 21.5 s	^{46}Ar 8.4 s	^{47}Ar 1.23 s

- 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

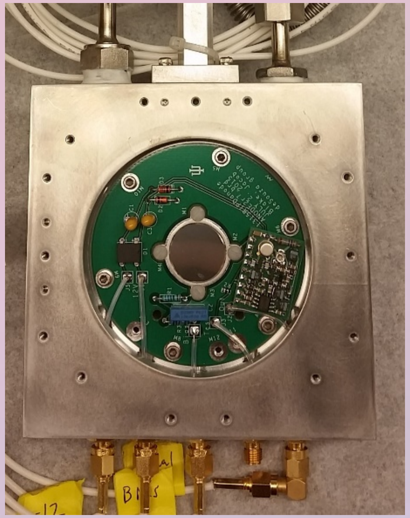
Challenges experienced with ReA3

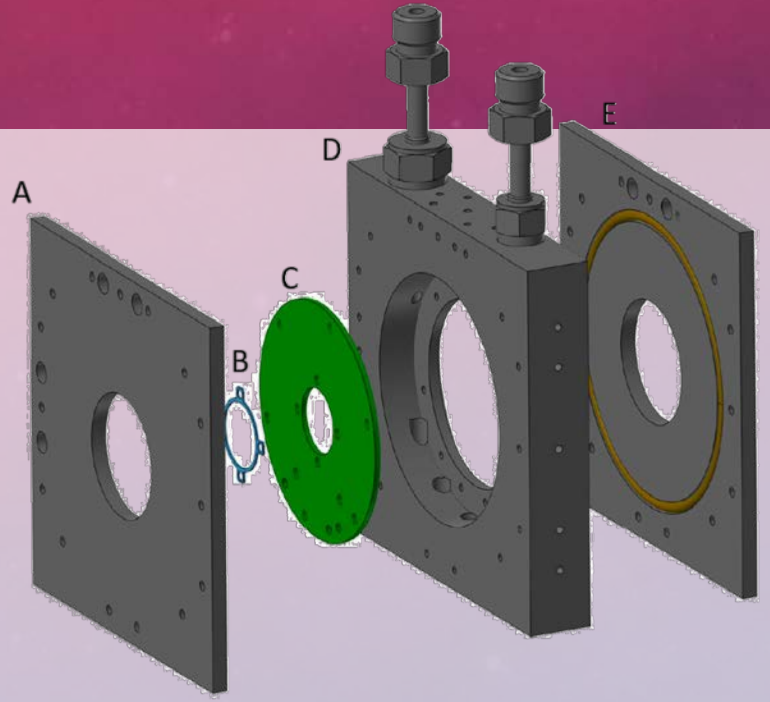


- Timing structure of the beam
  - Beam leaves the charge breeder in macrobursts every 500 ms (2 Hz)
  - The ions are bunched into the first ~100 ms of each macroburst
  - Instantaneous rate experienced by detectors: ~5x higher than the average rate
- Contamination in RIBs
  - Particle identification is required on an event-by-event basis
  - Need detector with good energy resolution and high rate capability

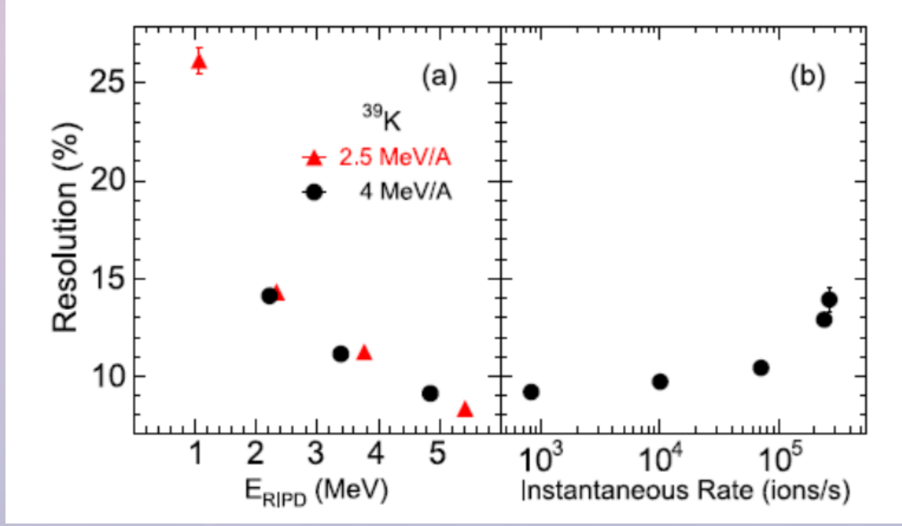
Rare Ion Purity Detector (RIPD)

- 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 1×10^5 ions/s





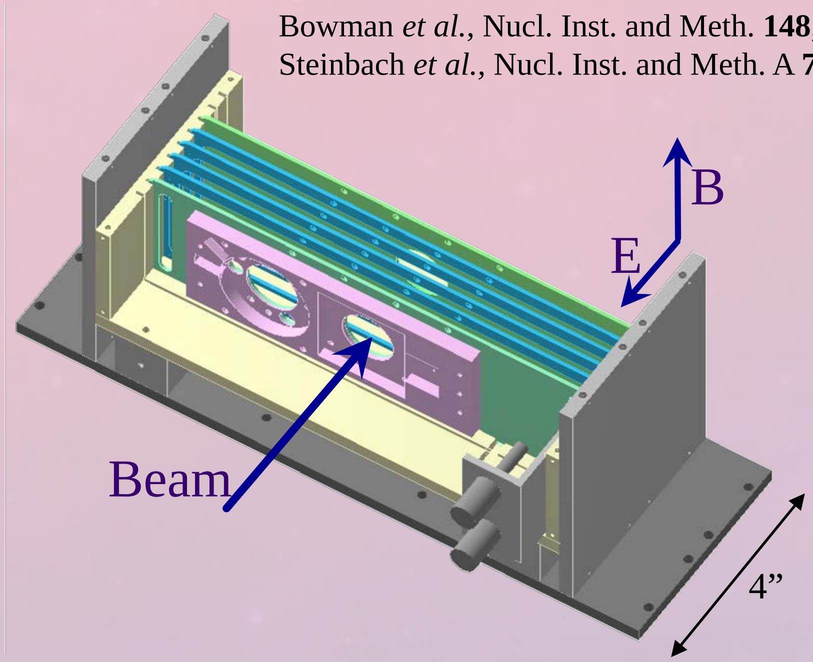
A: Window plate
B: Anode foil ring
C: PCB for charge sensitive amplifier
D: Detector body
E: Window plate



J. Vadas, *et al.*, NIMA **837** (2016) 28

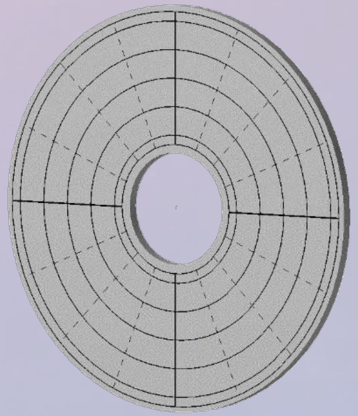
$^{39,47}K + ^{28}Si \rightarrow ^{67,75}As^*$

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



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

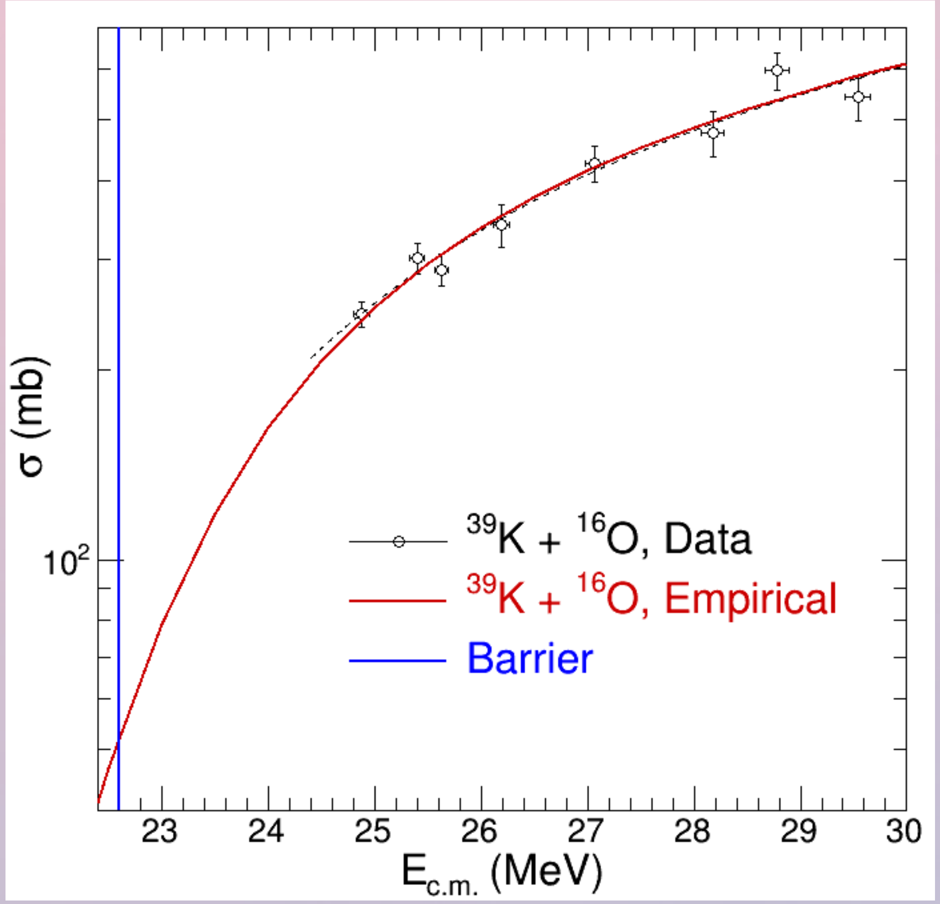
- E x B fields transport electrons from secondary emission foil to MCP
- E field produced by biasing array of ring plates
- B field produced by NdFeB permanent magnets
- Timing resolution ~300 ps



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

Determining the target thickness

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



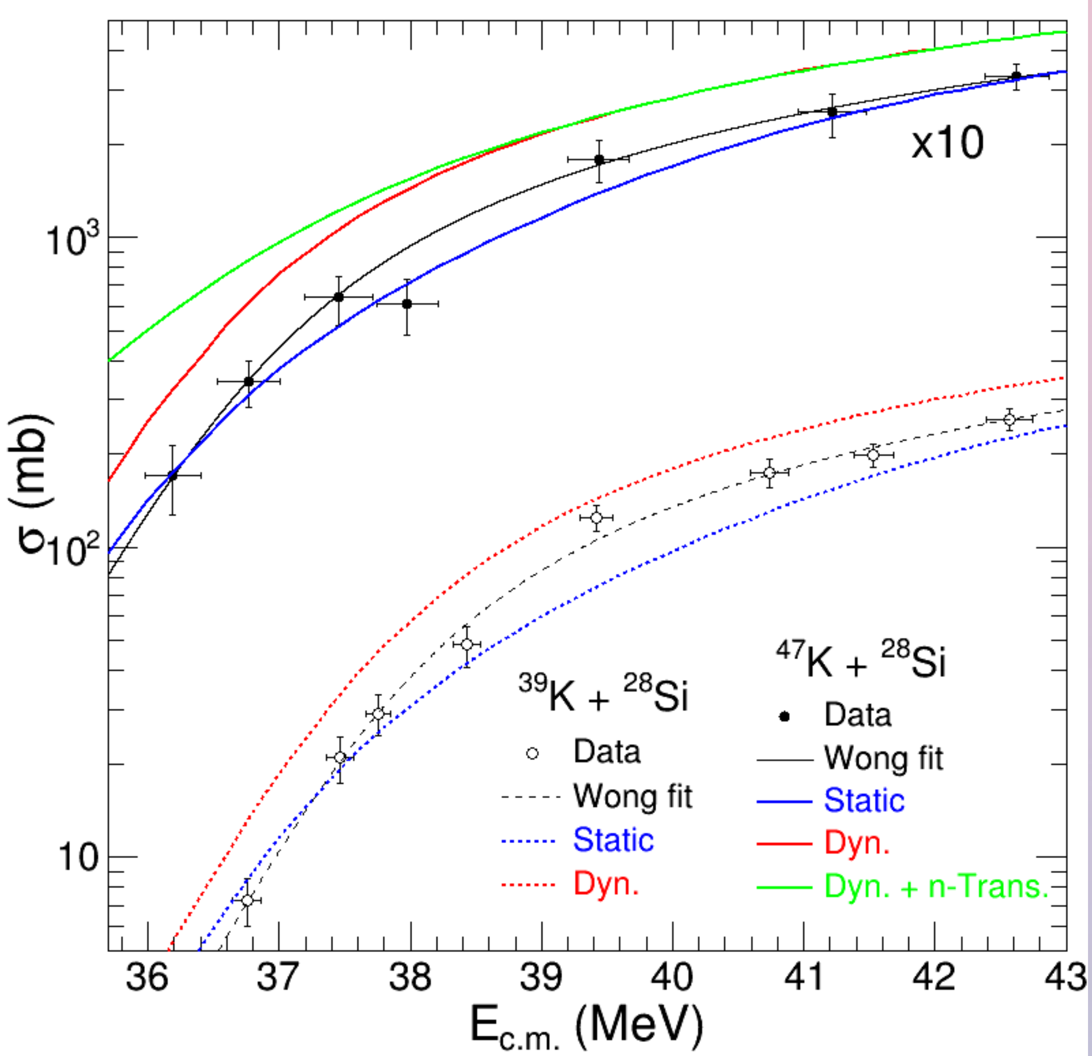
Estimating the amount of oxidation:

- Extracted $\frac{\sigma_{fusion}}{t_{^{16}O}}$ for ^{39}K + ^{16}O
- Calculated σ_{fusion} from empirical channel coupling model
- Minimized χ^2 in calculating t for ^{16}O
- $t_{^{16}O} \rightarrow t_{SiO_2}$
- $t_{^{16}O} = 97$ μg/cm^2; $t_{SiO_2} \approx 800$ nm

Determining the amount of ^{28}Si:

- Measured energy loss of α particles from ^{148}Gd and ^{241}Am sources
- Using SRIM and known t_{SiO_2}, determined $t_{^{28}Si_{pure}}$
- Total thickness = 327 μg/cm^2 ^{28}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