Nuclear Astrophysics at FRIB

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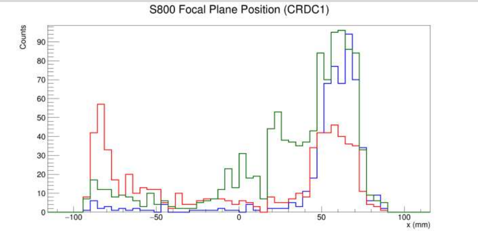
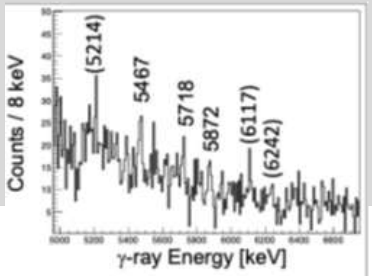
Nuclei in the Cosmos XVIII, Girona, Spain

19 June 2025

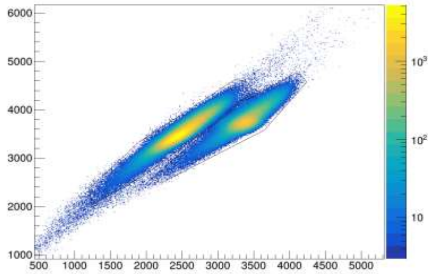
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

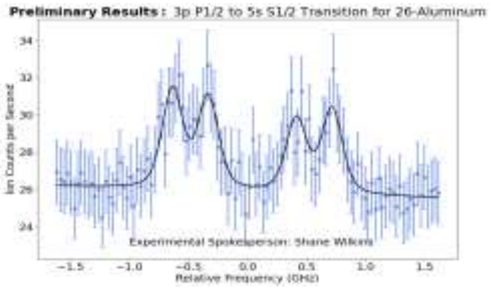


Introduction



Perspective: active in-house FRIB experimental user; not part of FRIB project team; not part of FRIB operations





- Introduction to FRIB facility
- Highlights from FRIB experiments; criteria:

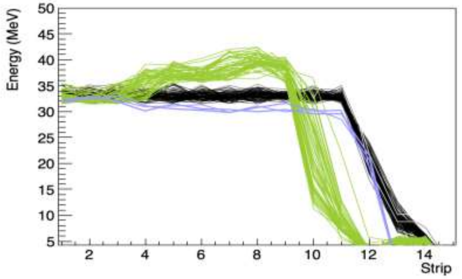
  -primary motivation is nuclear astrophysics

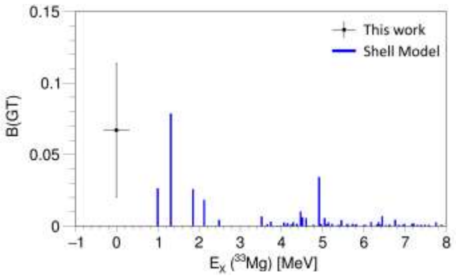
  -indicated as "completed" in FRIB public experiments database

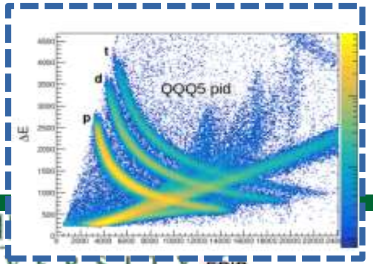
  -data acquired using radioactive beam

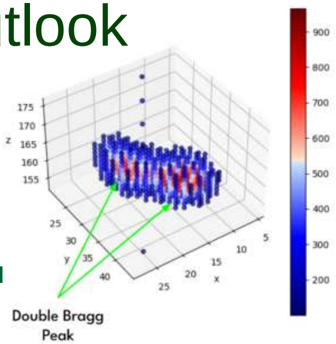
  -slide materials shared by spokesperson

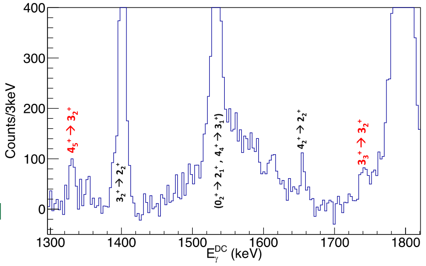
- Summary and Outlook

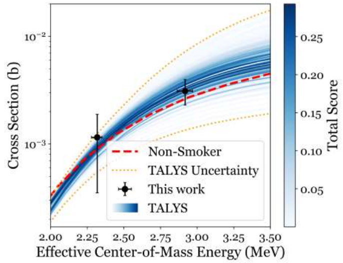


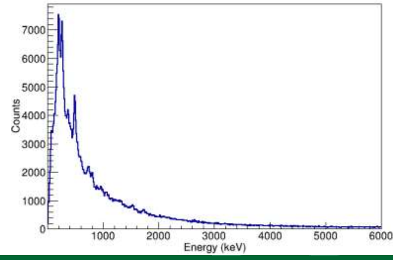












Who we are - FRIB Laboratory

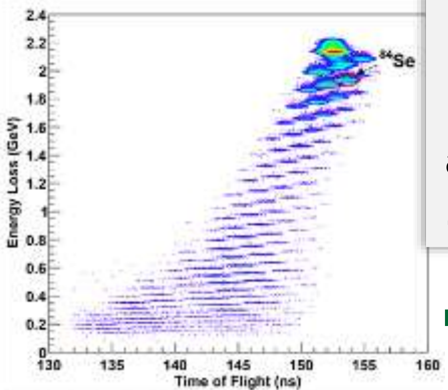
~750 employees, incl. >45 faculty, >150 graduate and ~140 undergraduate students as of Fall 2024

- For decades, NSCL was funded by the U.S. National Science Foundation to operate a user facility for rare isotope research and education in nuclear science, nuclear astrophysics, accelerator physics, and societal applications
- FRIB Project is completed - is a national user facility for the U.S. Department of Energy Office of Science with **first beam to an experiment in May 2022**

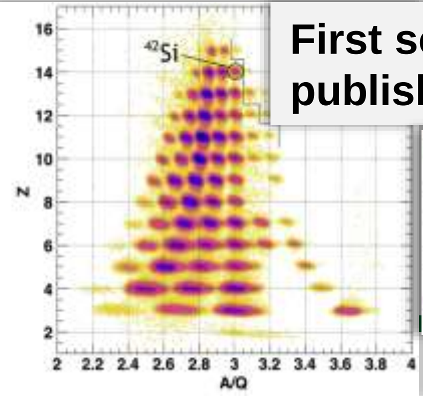
Groundbreaking 03/2014

Beneficial occupancy 03/2017

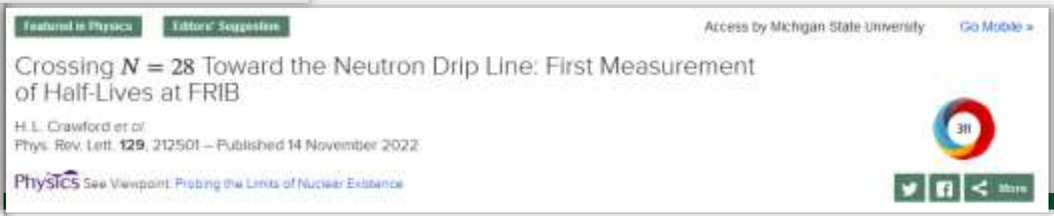
Designated as DOE-SC User Facility 09/2020



First rare isotopes produced and identified 12/2021



First science results published 11/2022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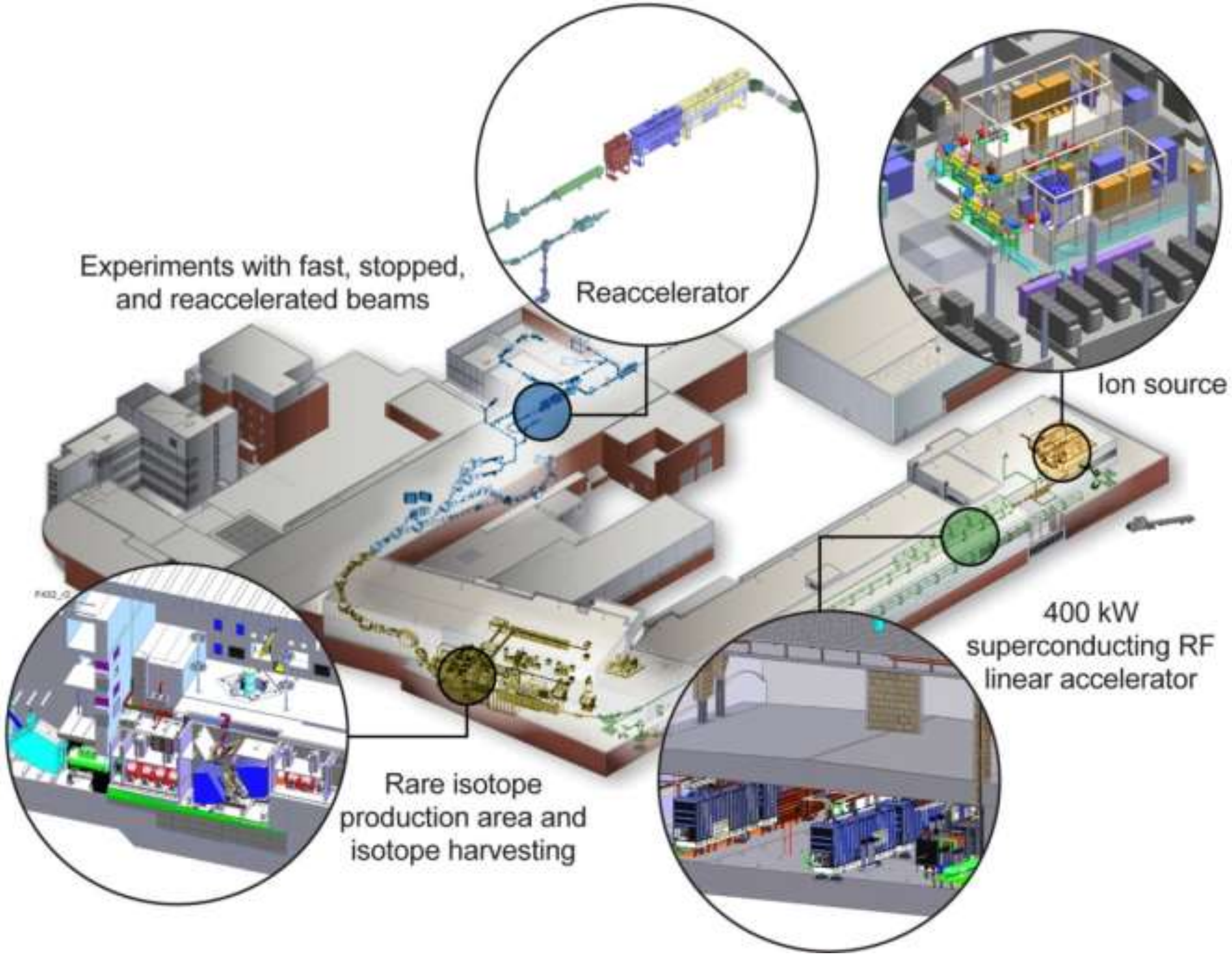
Crossing $N = 28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

H. L. Crawford et al.
Phys. Rev. Lett. 129, 212501 – Published 14 November 2022

Physics See Viewpoint: Probing the Limits of Nuclear Existence

FRIB facility layout



Science at FRIB

Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Determine the limits of elements and isotopes

Astrophysical processes

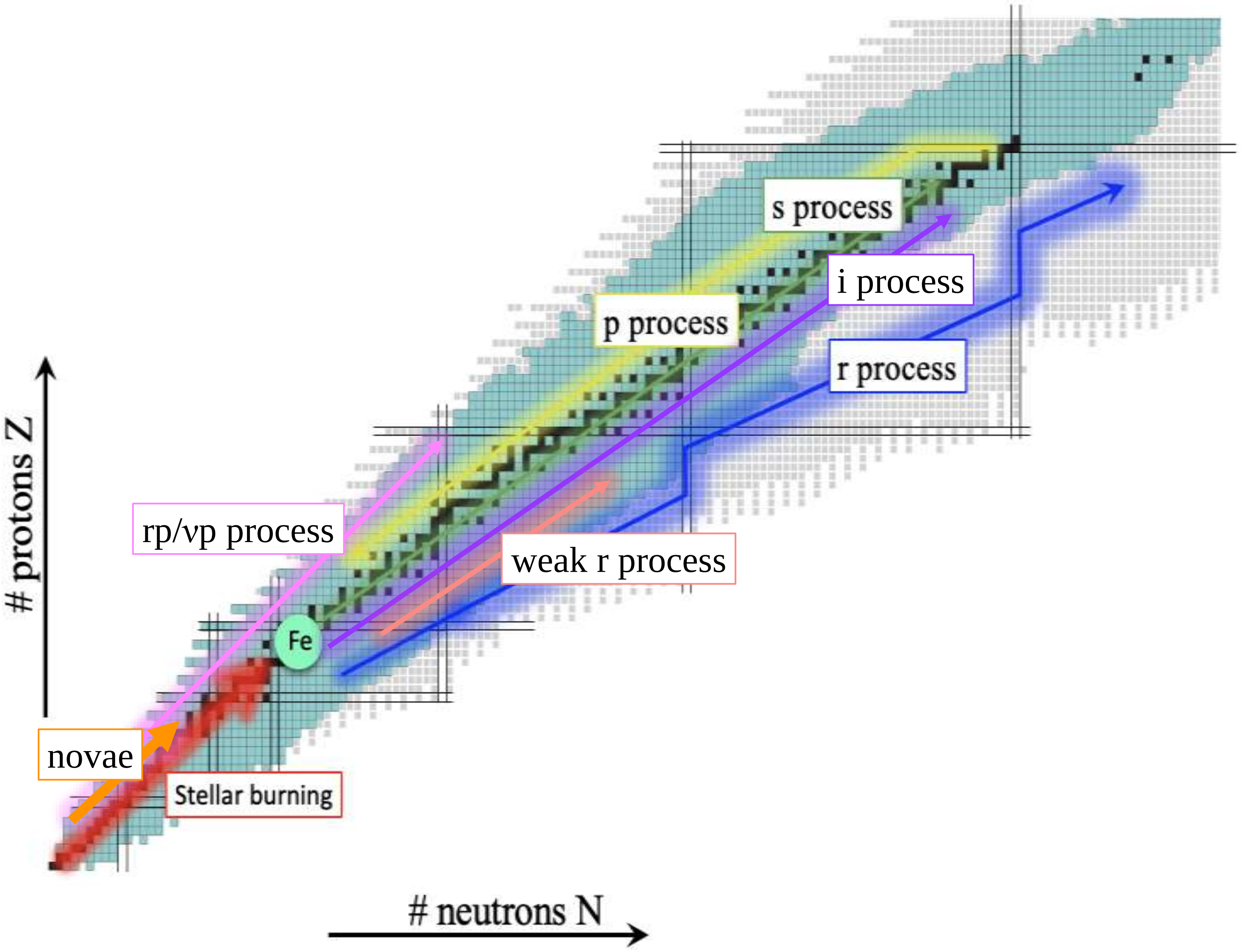
- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars

Societal applications and benefits

- Isotope harvesting for medicine and a variety of fields
- Surrogate reactions: nuclear security

Tests of fundamental symmetries

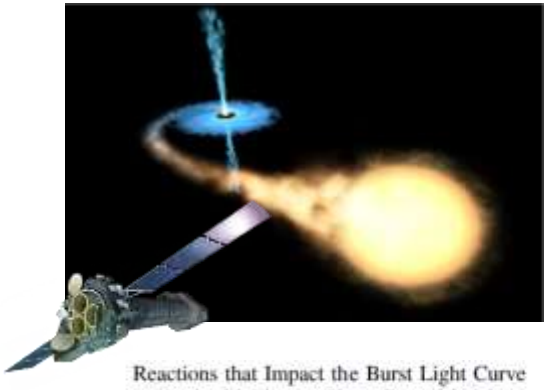
- Effects of symmetry violations are amplified in certain nuclei



^{15}O(α,γ)^{19}Ne rate for XRBs using GADGET II TPC

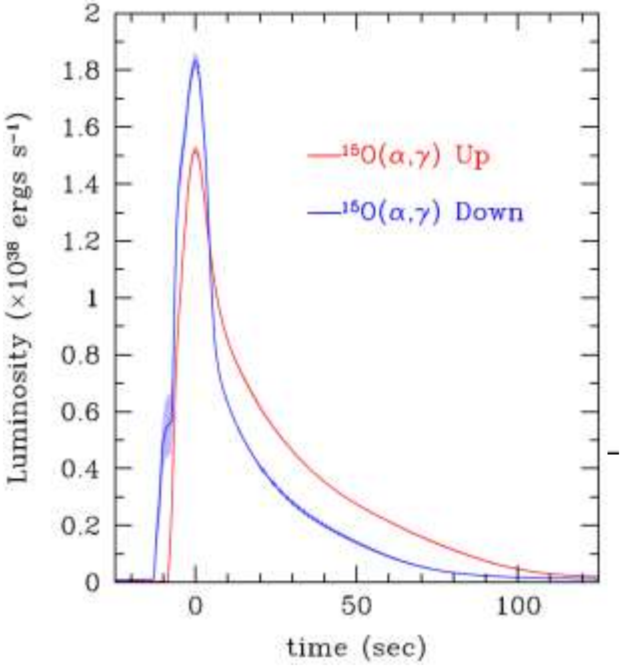
e21072 spokesperson: Chris Wrede

- Goal: measure Γ_α/Γ of key resonance
- Use ^{20}Mg($\beta^+p\alpha$) decay and GADGET II

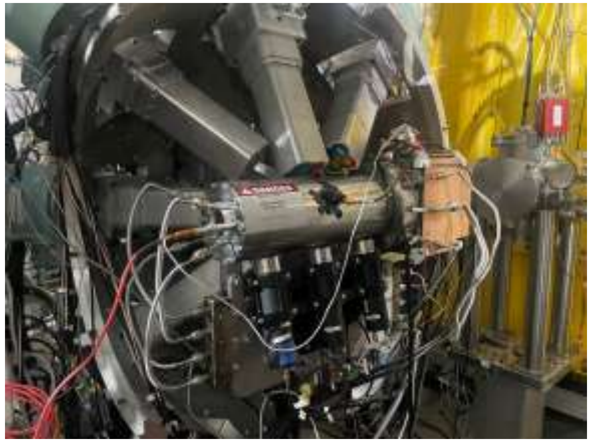


Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

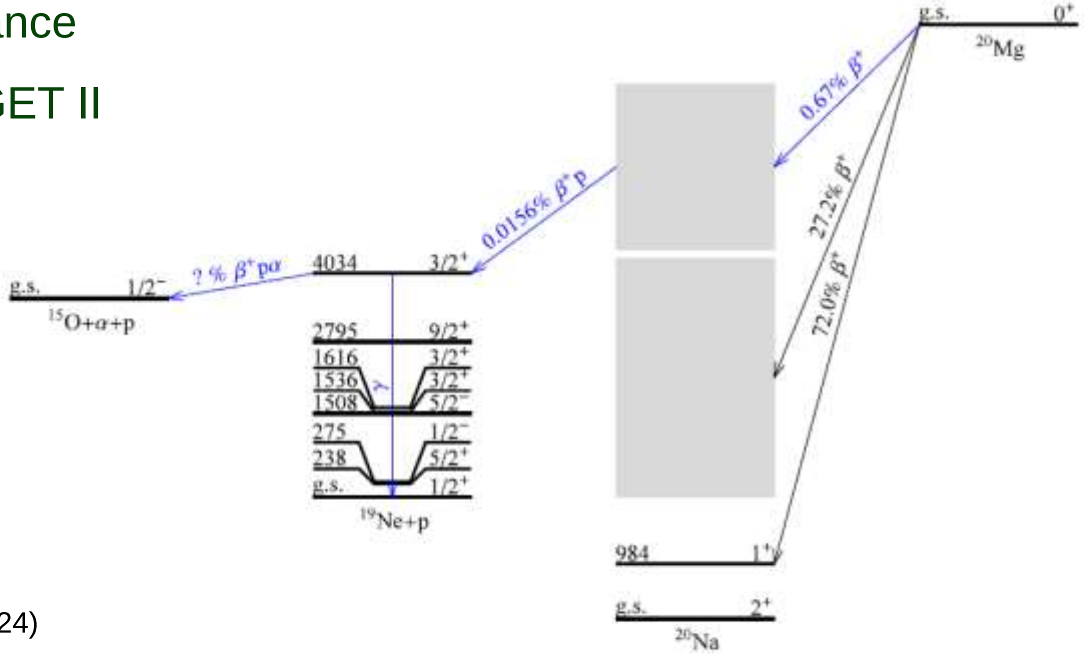
Rank	Reaction	Type[a]	Sensitivity[b]
1	^{15}O(α, γ)^{19}Ne	D	16
2	^{56}Ni(α, p)^{59}Cu	U	6.4
3	^{59}Cu(p, γ)^{60}Zn	D	5.1



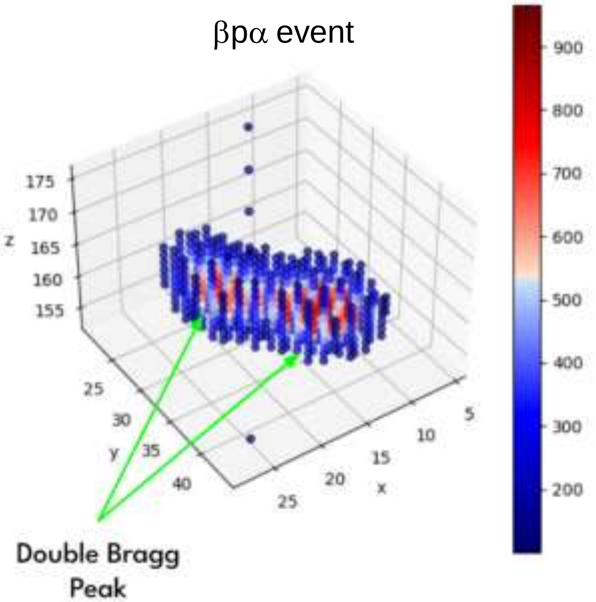
R. Cyburt *et al*., Astrophys. J. 830, 55 (2016)



R. Mahajan *et al*., Phys. Rev. C 110, 035807 (2024)



C. Wrede *et al*., Phys. Rev. C 96, 032801(R) (2017)
B. E. Glassman *et al*., Phys. Rev. C 99, 065801 (2019)

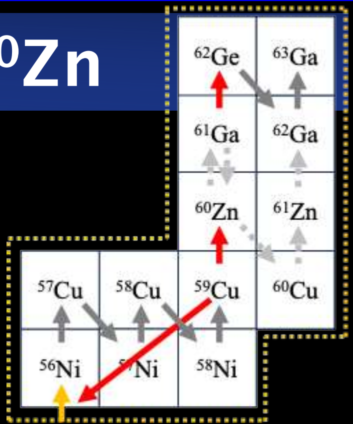


- Commissioned GADGET II on beam line demonstrating sensitivity to $\beta p\alpha$ events using ^{21}Mg beam contaminant
- Developed and verified machine learning techniques to identify $\beta p\alpha$ events
- Insufficient ^{20}Mg beam intensity to reach science goals → Run 2 approved (E25058)

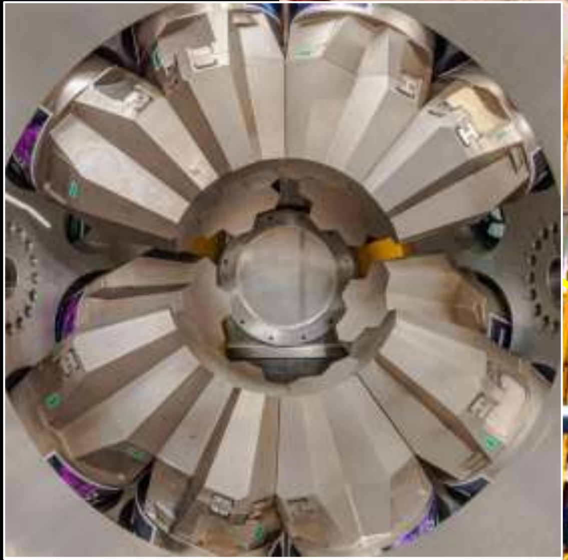
T. Wheeler, Ph.D. thesis (Michigan State University, 2024)
T. Wheeler *et al*. NIMA 1080, 170659 (2025)

GADGET II local support from U.S. National Science Foundation (2209429) and U.S. Department of Energy (DE-SC0016052, DE-SC0023529, DE-SC0024587)

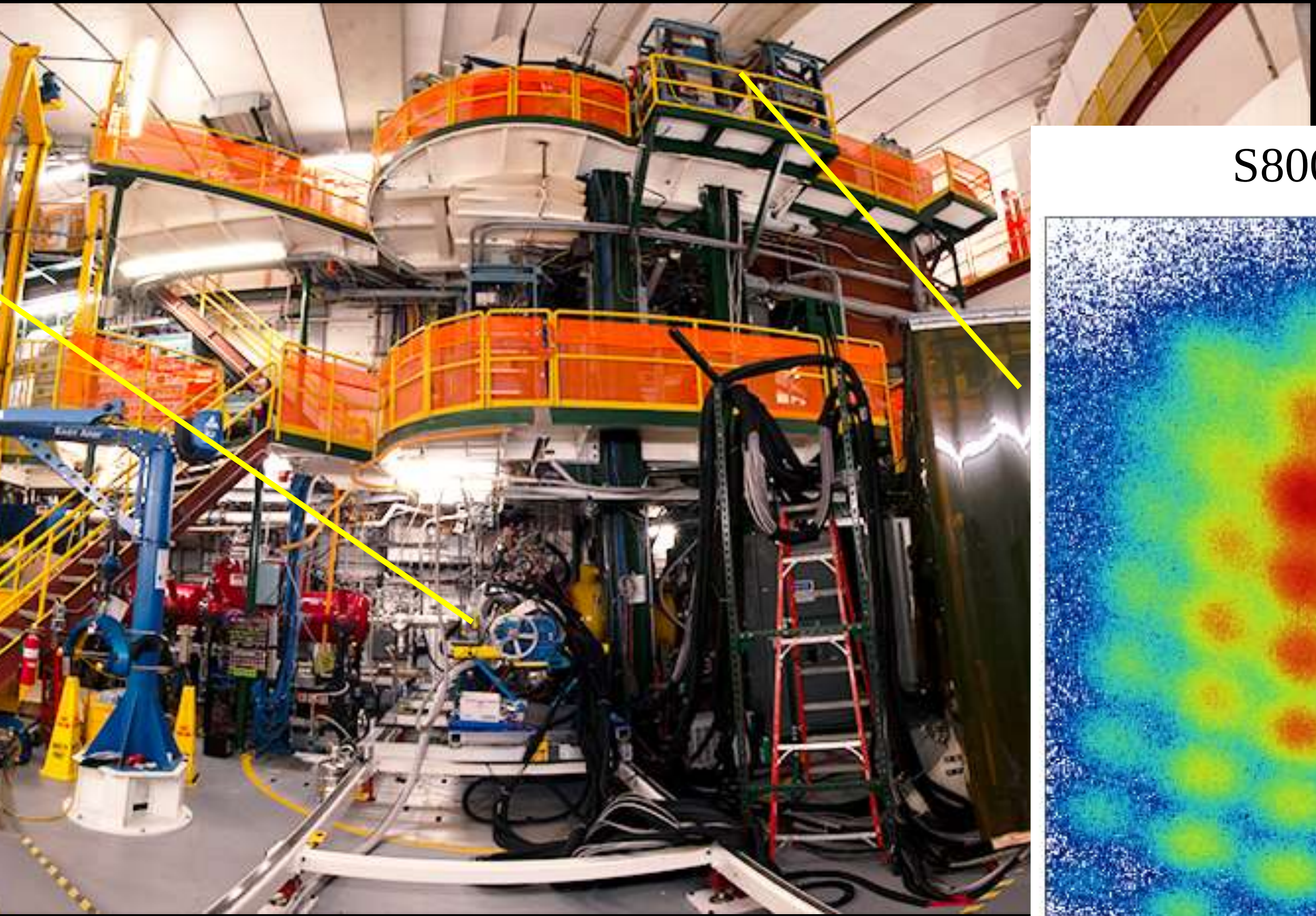
Study of the ^{59}Cu(*d*,*n*)^{60}Zn reaction at FRIB for ^{59}Cu(p,γ)^{60}Zn

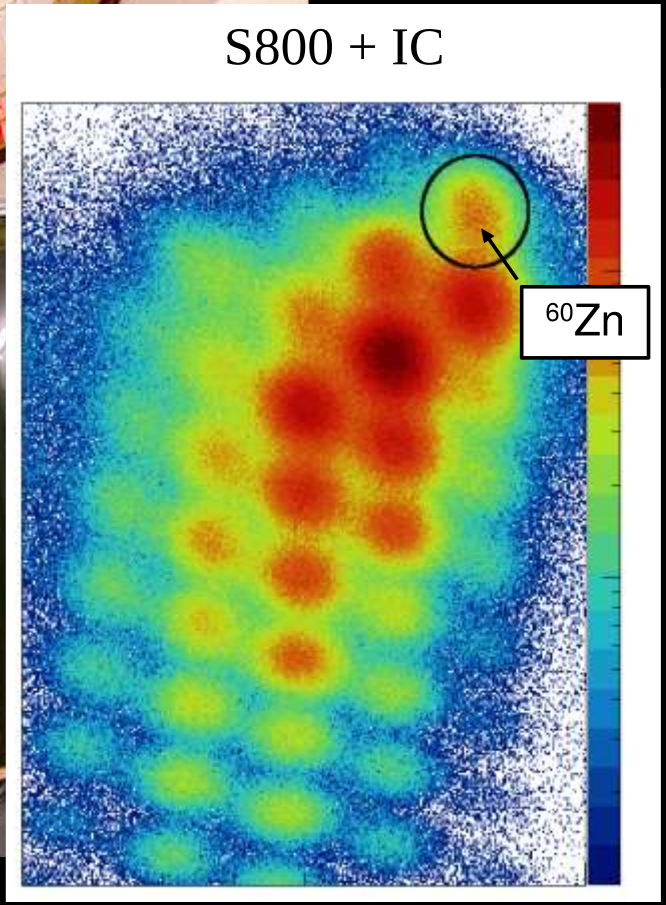


- FRIB capable of producing a beam of ^{59}Cu with an intensity of ~ 5 x 10^6 pps @ 40 MeV/u
- Bombarded ~ 9 mg/cm^2 thick CD_2 to populate excited states in ^{60}Zn



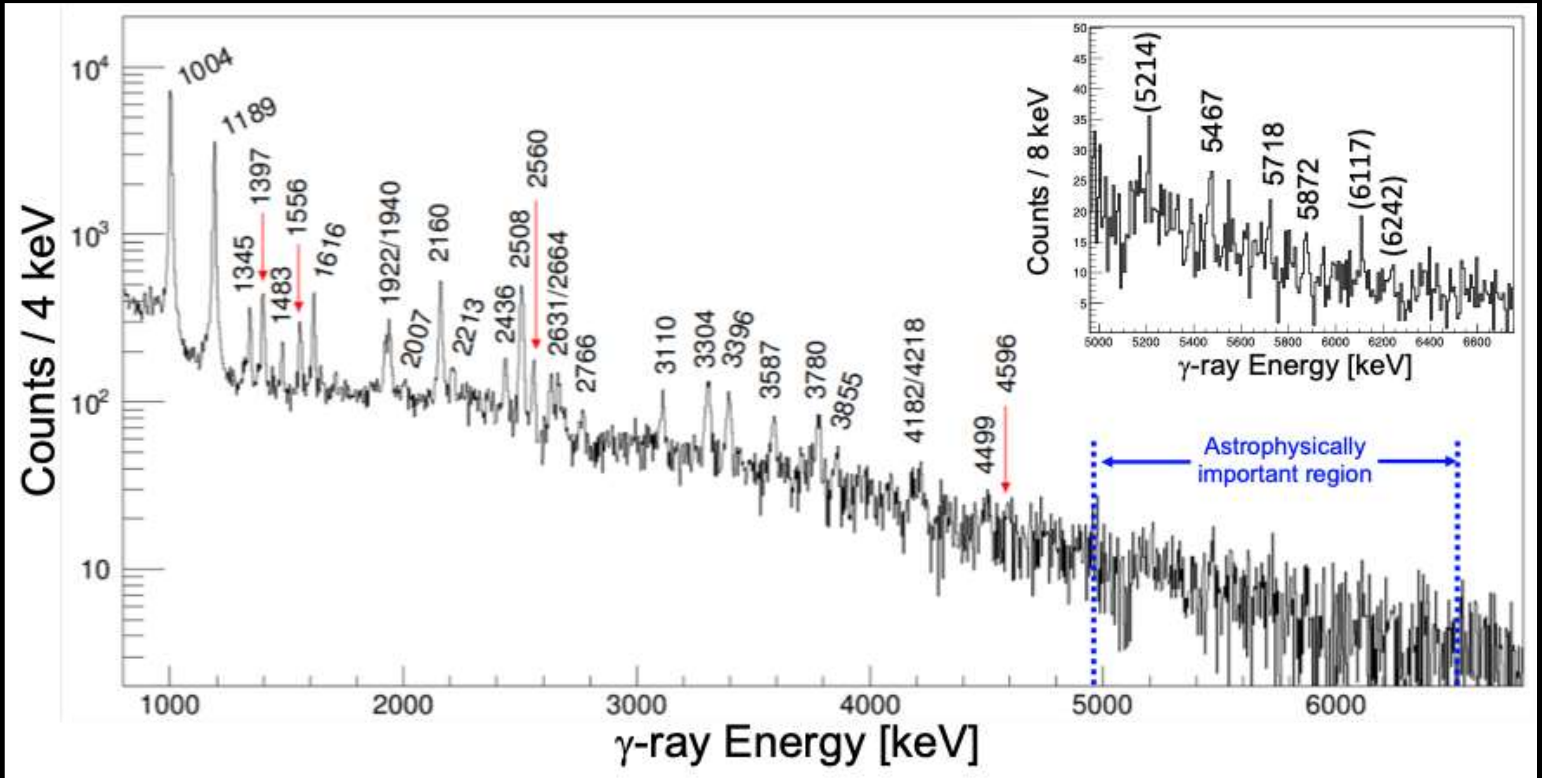
GRETINA

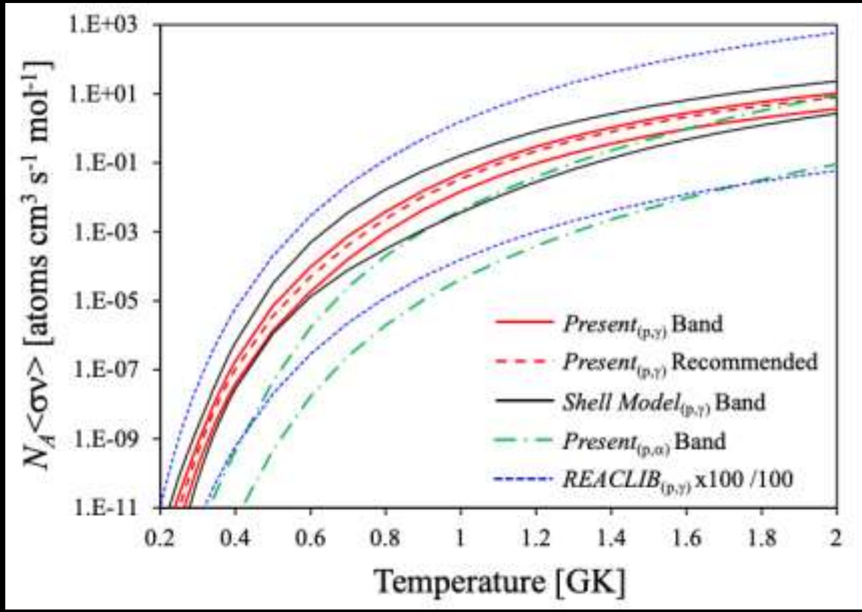




e21014 spokesperson: Gavin Lotay

Study of the ^{59}Cu(*d*,*n*)^{60}Zn reaction at FRIB





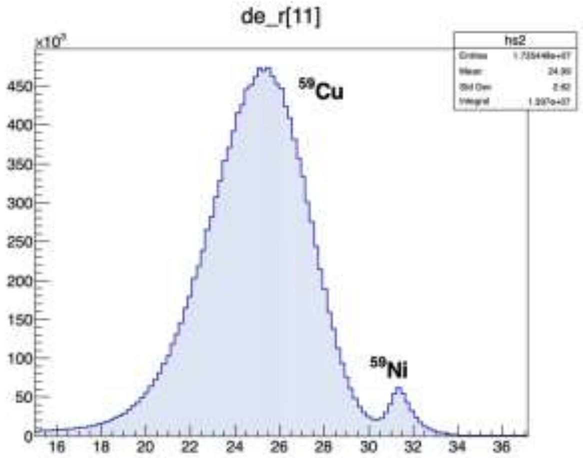
- Observation of strong single particle states
- Tight constraints placed on the ^{59}Cu(p,γ) reaction rate
- Determination of proton widths also allows for estimation of ^{59}Cu(p,α) reaction
- XRB modelling indicates NiCu cycling may be strong (up to 30%)

The $^{59}Cu(p,\alpha)$ ^{56}Ni measurement at FRIB with MUSIC

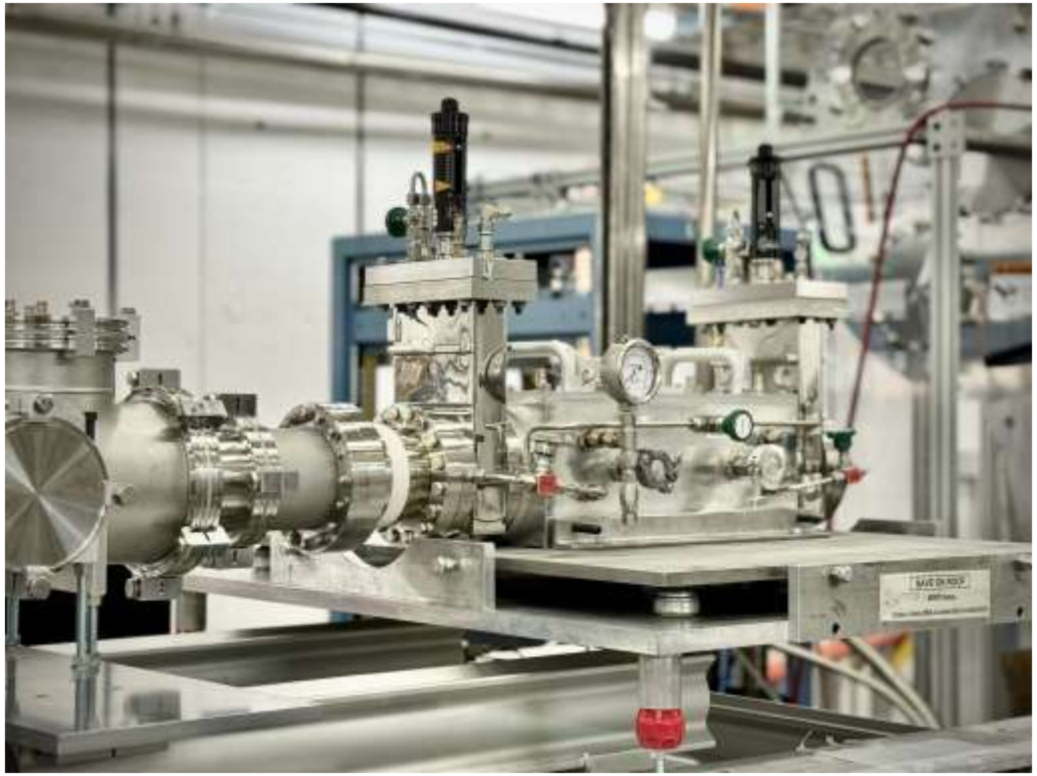
ReA6

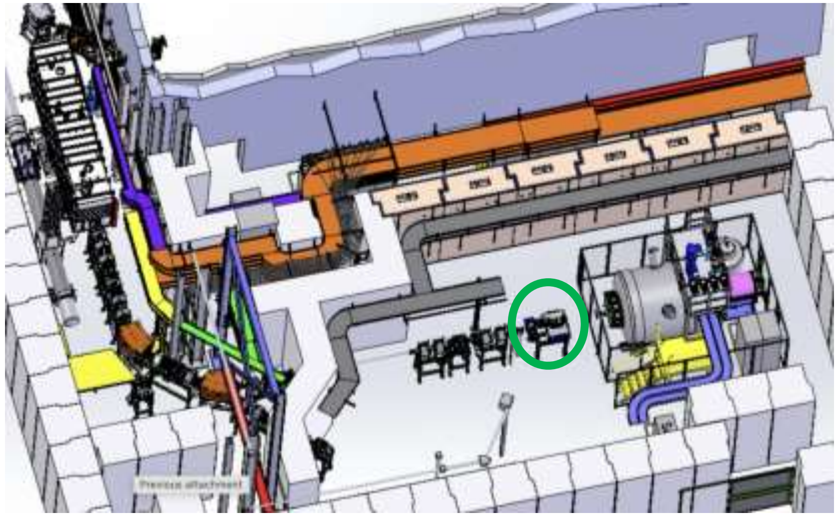
Work done by:
Eilens Lopez-Saavedra
Poster #31

- ^{59}Cu beam at **8.41 MeV/u**
- Average intensity ~9 ×10³ pps (~6 % ^{59}Ni contaminant)
- ~55 Hours of Beam
- CH_4 gas at 450 Torr



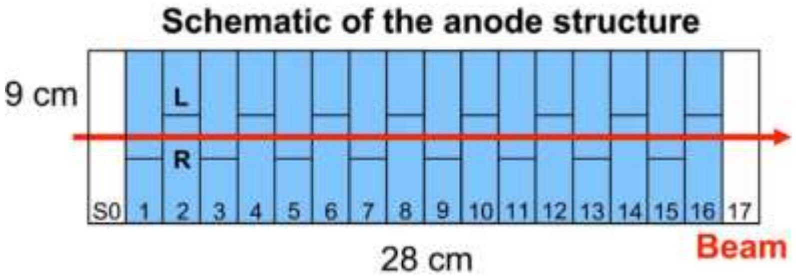
e21016 spokesperson:
Melina Avila

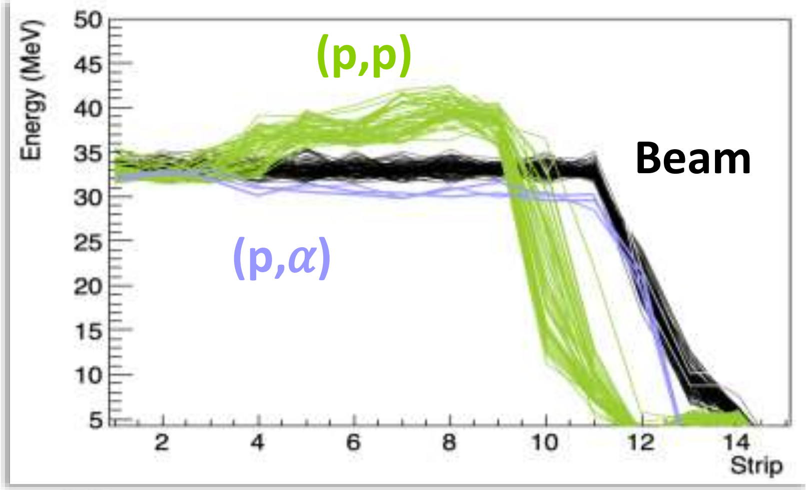


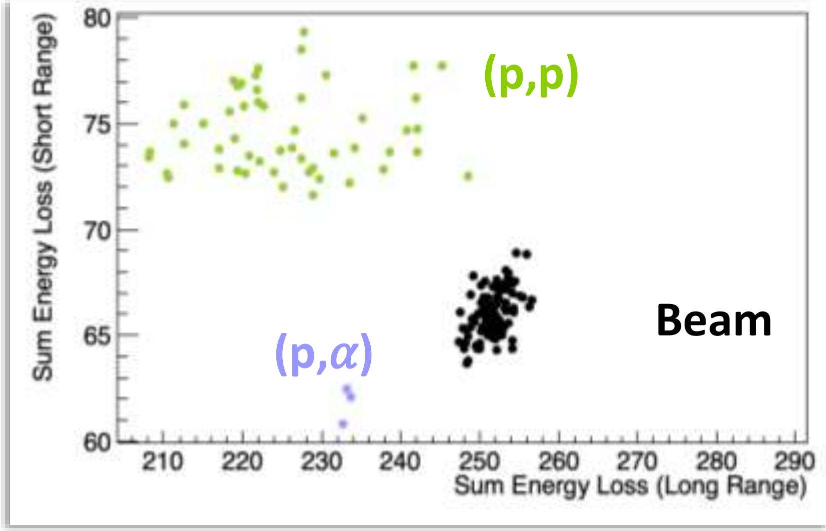


The $^{59}Cu(p,\alpha)\ ^{56}Ni$ Reaction

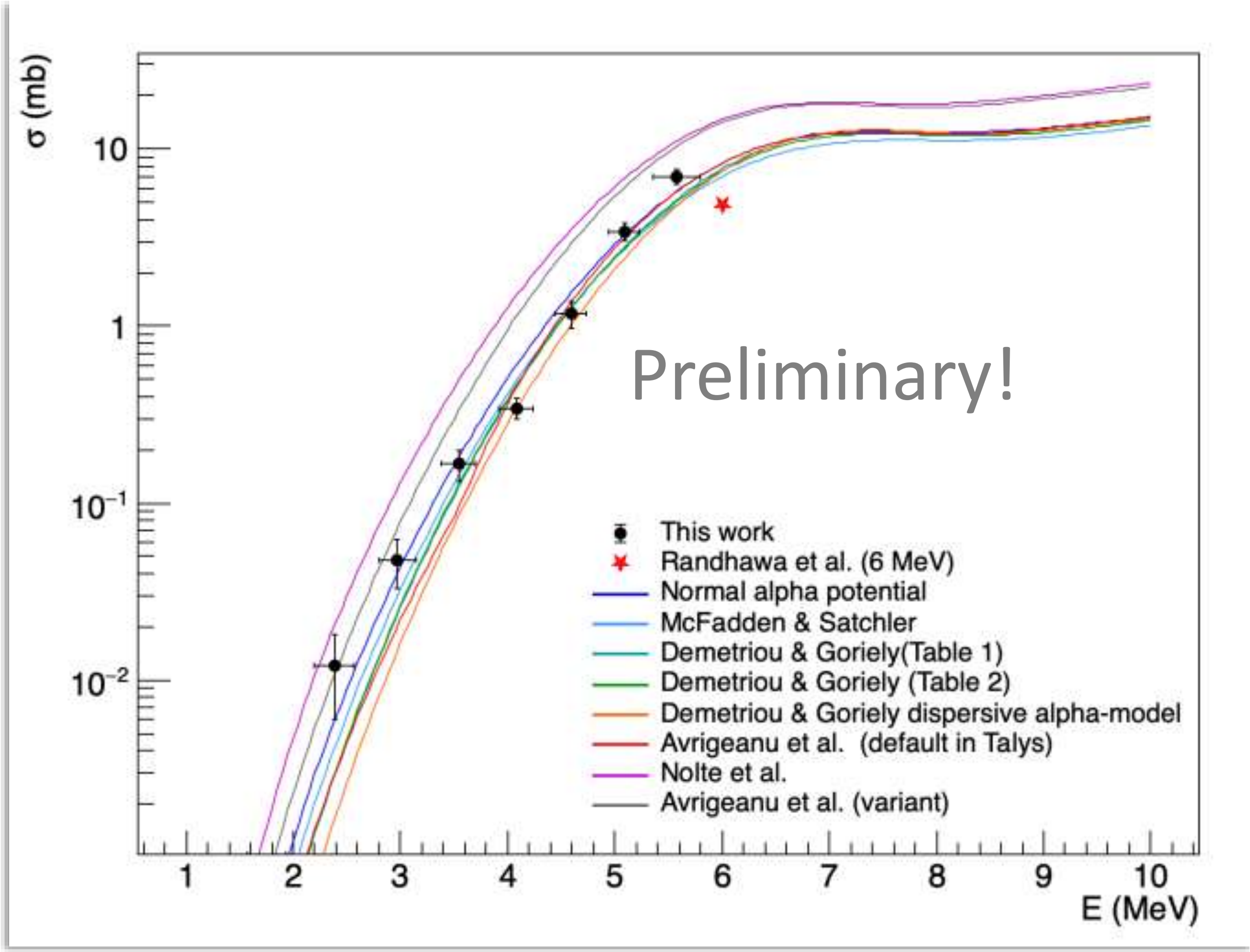
Event identification in strip 4 and preliminary results





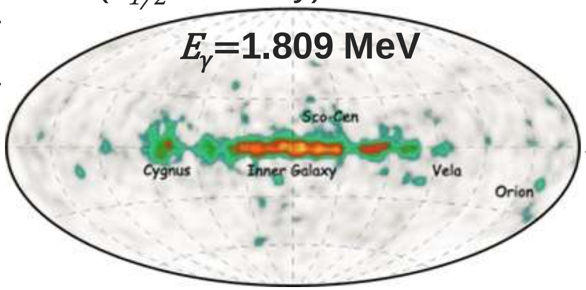


Only one run of ~60 minutes



Resonances in ^{25}Al+p for novae contribution to galactic ^{26}Al

^{26}Al ($\tau_{1/2}$=0.7 My) tracer of star formation rate

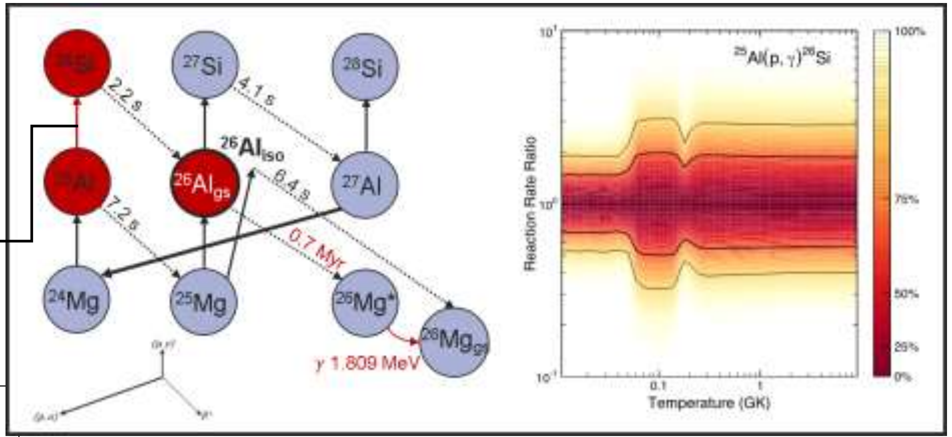


Plüschke et al. (2001)

Young progenitors, massive stars
*Diehl et al Nature **439** (2006)*

Nova contribution?
*José CRC Press (2020), Vasini et al A&A**693** (2025)*
10 – 30 %

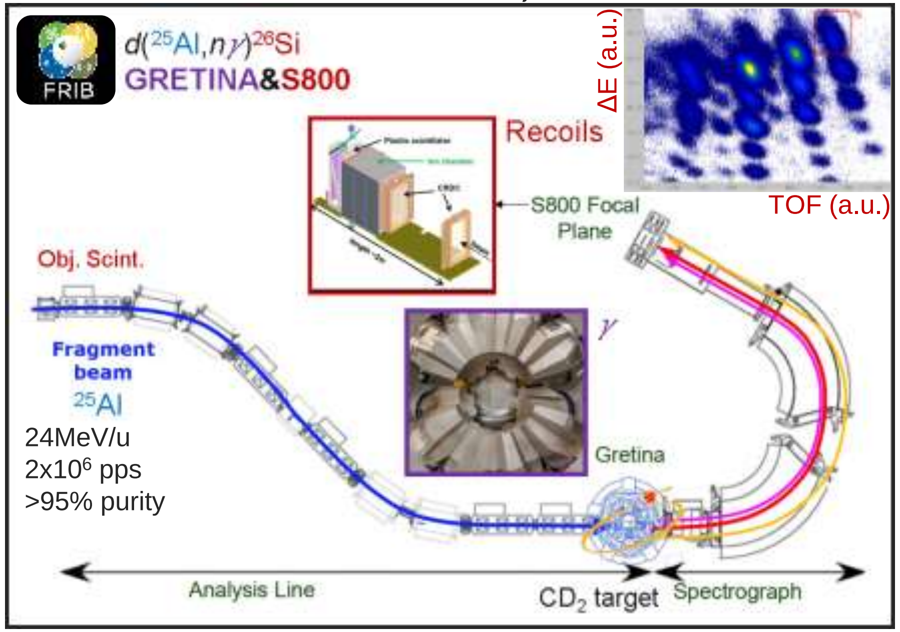
Explosive H-burning ($T_{nova} \lesssim 0.5$ GK)

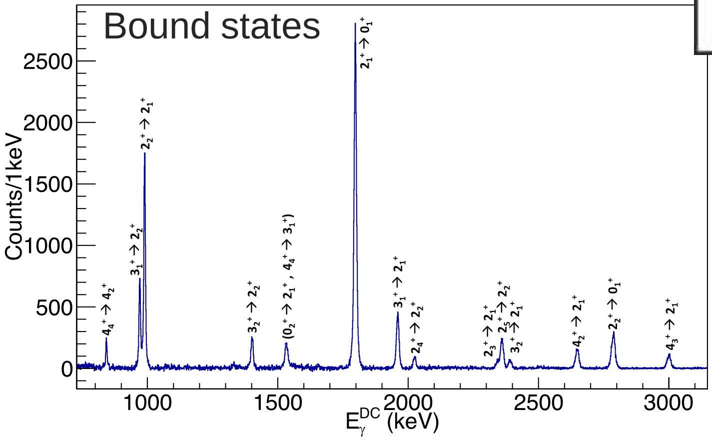


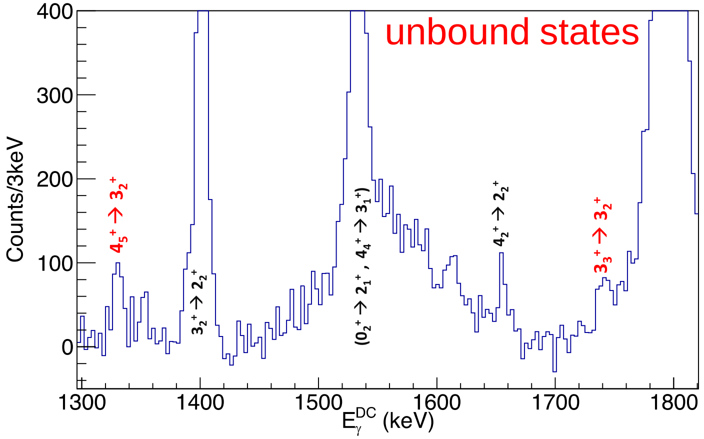
uncertainties x2

Angle-integrated measurement of (d,$n\gamma$) transfer reactions to probe $\omega\gamma_r$
FRIB-e23037 *Fougères et al (2023)*

$$\omega\gamma_r \propto N_\gamma$$

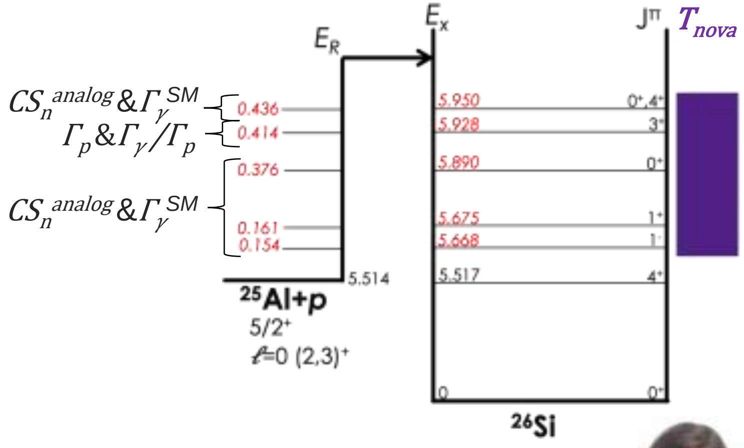






$$<\sigma\nu>_{tot} \propto \sum_r \omega\gamma_r \exp\left(-\frac{E_r}{k_B T}\right)$$

Resonances
*Laird et al JPGNPP**50** (2023)*



Ongoing analysis

- Spectroscopic factors in ^{26}Si
- Contribution of direct radiative capture
- $\omega\gamma_r$

e23037 spokesperson:
Chloé Fougères

➔ **poster #32**

chloe.fougeres@cea.fr

The collaboration

Angle-integrated measurement of the $d(^{25}\mathrm{Al},n\gamma)^{26}\mathrm{Si}$ transfer reaction to probe resonance strengths in $^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}$ relevant for the production of $^{26}\mathrm{Al}$ in novae
FRIB experiment with GRETINA - S800

C. Fougères[1,2], F. Hammache[3], F. de Oliveira Santos[4], N. de Séréville[3], C. Benetti[5], A. Gade[5], S. Gillespie[5], J. Swartz[5], J. Pereira[5], D. Weisshaar[5], S. M. Ali[5], H. Arora[5], M. L. Avila[1], L. Balliet[5], K. Bhatt[1], T. Beck[5], S. Ahn[6], J. Chung-Jung[5], L. Dienis[4], P. Farris[5], V. Girard-Alcindor[3], S. Giraud[5], J. Huffman[5], H. Jacob[3], D. Kim[6], M. Kuich[5], C. Maher[5], F. Montes[5], C. Müller-Gatermann[1], D. Neto[7], M. Portillo[5], B. M. Sherrill[5], O. B. Tarasov[5], A. Tumino[8], and R. Zegers[5]

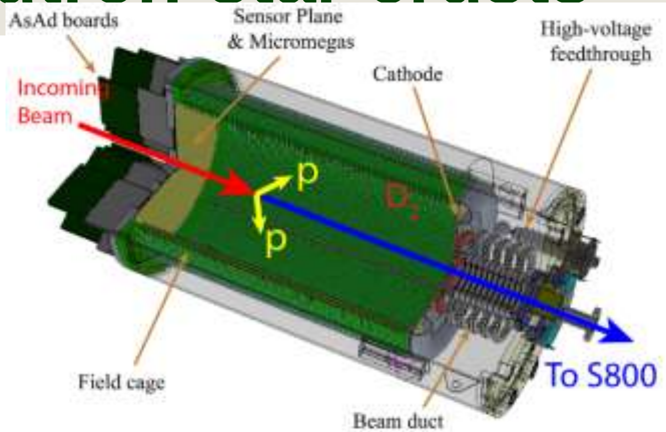
[1] *Physics Division, Argonne National Laboratory, Lemont, IL 60439, USA*
[2] *CEA DAM DIF, F-91297 Arpajon, France*
[3] *Laboratoire de Physique des 2 Infinis Irène Joliot-Curie, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[4] *Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3, Caen, France*
[5] *Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA*
[6] *Center for Exotic Nuclear Studies, Institute for Basic Science, Daejeon, 34126, Korea*
[7] *Department of Physics, University of Illinois Chicago, Chicago, IL 60607, USA and*
[8] *INFN-Laboratori Nazionali del Sud, Catania, Italy*

GRETINA/GRETA

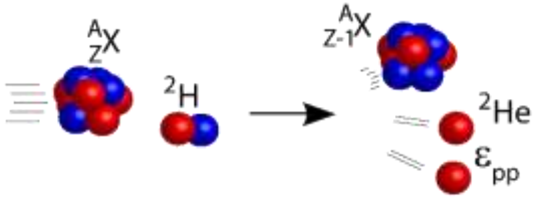
FRIB

Successful ^{32}Mg,^{33}Al(d,^{2}He) experiment in inverse kinematics constrains electron-capture (EC) rates that cool neutron-star crusts

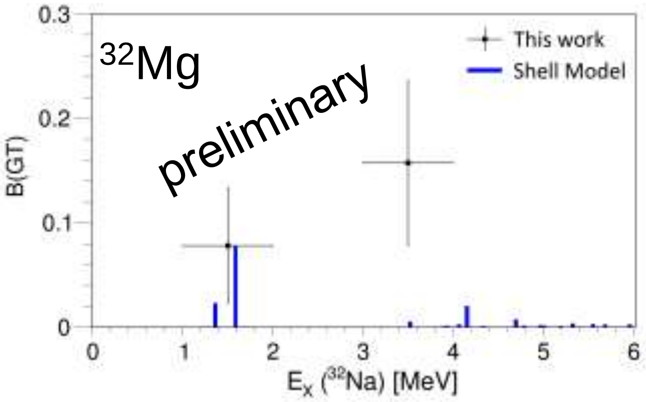
- Experiment aimed at constraining EC rates on nuclei in the island of inversion, which contains candidates for Urca cycles that cool the crusts of neutron stars
- (d,^{2}He) reaction at ~100 MeV/u in inverse kinematics is only way to constrain astrophysical EC rates on neutron-rich nuclei (no Q-value limitation), based on well-established proportionality between the charge-exchange reaction cross section and Gamow-Teller strength
- ^{32}Mg,^{33}Al(d,^{2}He) experiment performed at FRIB using the Active-Target Time Projection Chamber (detection of two protons) and S800 spectrograph (heavy reaction residue)
- Part of larger effort to establish an EC library across the full chart of nuclei for nuclear astrophysics simulations

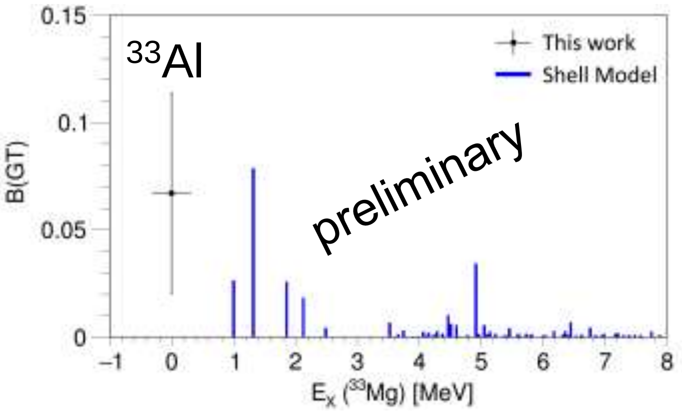


^{13}C,^{14}O(d,^{2}He) prototype experiment
S. Giraud *et al*., Phys. Rev. Lett. 130, 232301 (2023)
Z. Rahman *et al*., Phys. Rev. C 110, 024313 (2024)



- Latest update: https://arxiv.org/abs/2412.00650 – Ravlic *et al*.
- Website: https://groups.frib.msu.edu/charge_exchange/weakrates.html

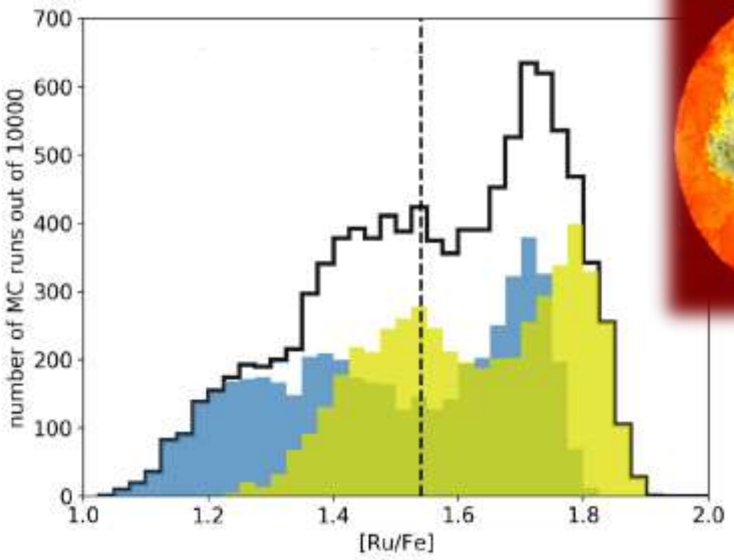


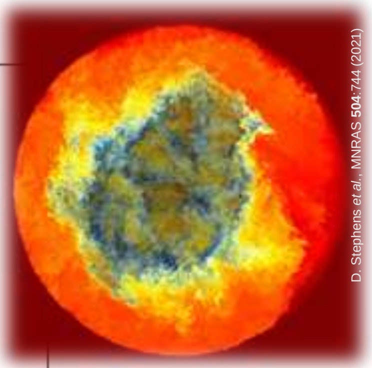


e21018 spokesperson:
Remco Zegers

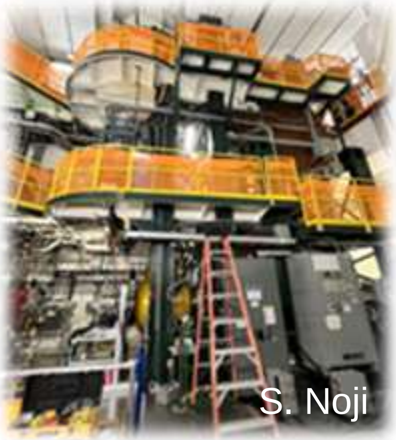
(d,^{2}He) efforts led by R. Zegers, S. Giraud, Z. Rahman

FRIB e23056: Indirect ^{99}Nb(n,γ)^{100}Nb Constraint for the Astrophysical i-Process





Ru abundances in the i-process for higher (blue) and lower (yellow) ^{99}Nb(n,γ)^{100}Nb rates

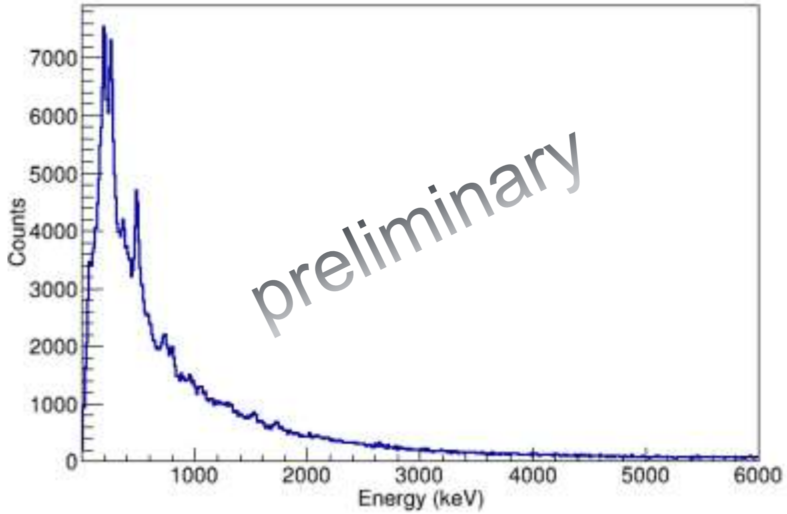


Experimental setup in the S3 vault at FRIB with SuN++ and the S800 Spectrometer

e23056 spokesperson: Andrea Richard

Goal: confirm low [Ru/Mo] abundance ratio as a unique i-process signature

Method: Indirect neutron-capture constraint of **^{99}Nb(n,γ)^{100}Nb** using the **^{100}Mo(t,^{3}He)^{100}Nb** reaction with SuN++ + S800 spectrometer using the novel ***Charge-Exchange Oslo Method***



Preliminary SuN++ $CeBr_3$ spectrum for ^{100}Nb

OHIO UNIVERSITY

FRIB

NNSA National Nuclear Security Administration

e23084 : ^{75}Ga(d,pγ)^{76}Ga for ^{75}Ga(n,γ) with GODDESS+S800 (i-process)

e23084 spokesperson:
Steven Pain

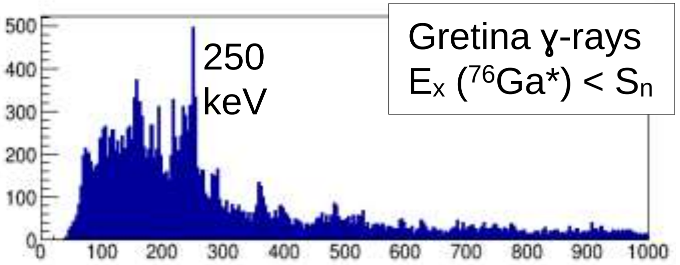
e23084 analysis:
Sudarsan
Balakrishnan

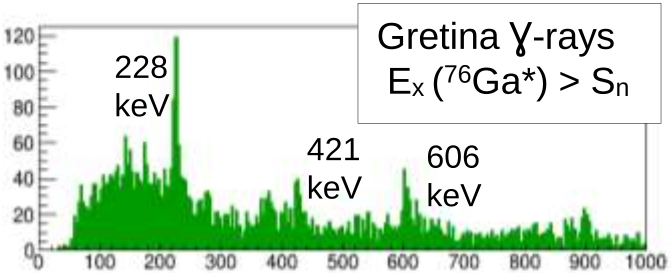
^{75}Ga(n,γ) reaction rate (McKay *et al*, MNRAS **491** (2020))

- *critical to understand anomalous abundances observed in proposed i-process site* HD94028
- no current experimental constraint; odd-odd ^{76}Ga ⇒ large level density

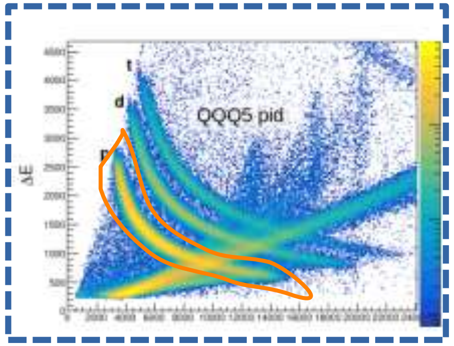
GODDESS: Populate ^{76}Ga* via (d,pγ) → Measure CN decay → Surrogate Reaction Method (SRM) → ^{75}Ga(n,γ)

- **ORRUBA:** measure protons → E_x of ^{76}Ga*
- **GRETINA**, **S800:** Detect decay modes of the compound nucleus vs E_x via
  - Discrete γ in Gretina (conventional SRM)
  - Tag n-unbound recoil in S800 → 'No-Gamma' SRM → direct determination of total n/γ branching
- Gate on **protons** and **n-bound** and **n-unbound** recoils in S800 → distinct Gretina γ-spectra of **^{76}Ga*(E_x<S_n)** and **^{76}Ga*(E_x>S_n) → ^{75}Ga*+n**

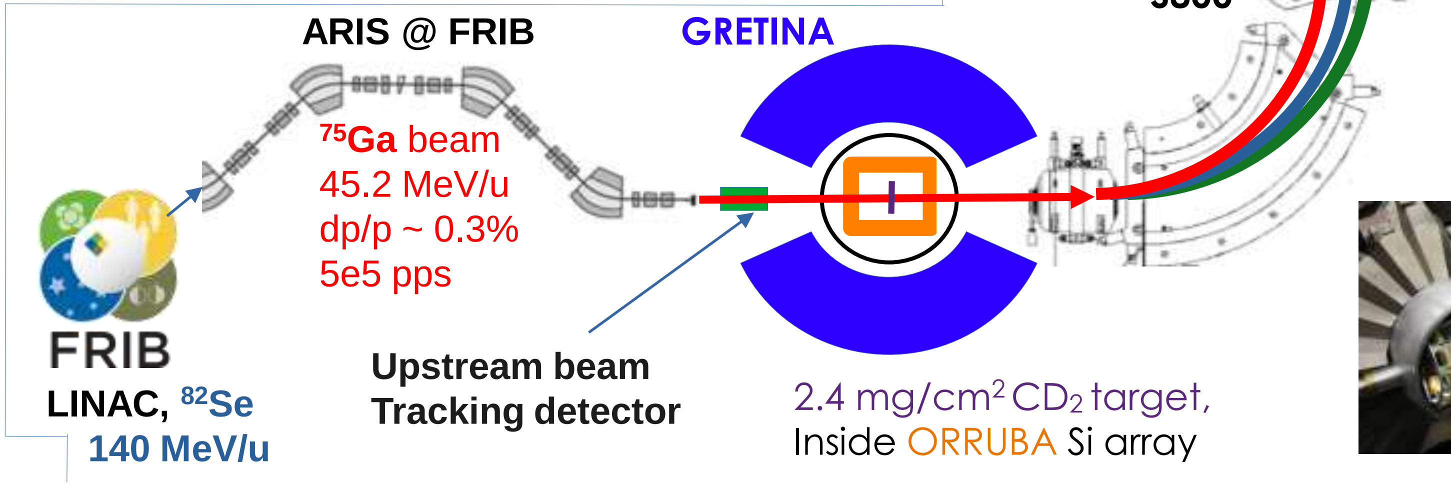




ORRUBA Particle ID



ΔE vs E_{tot} (proton)



^{80}Ge(d,pγ) GODDESS Experiment (2024)

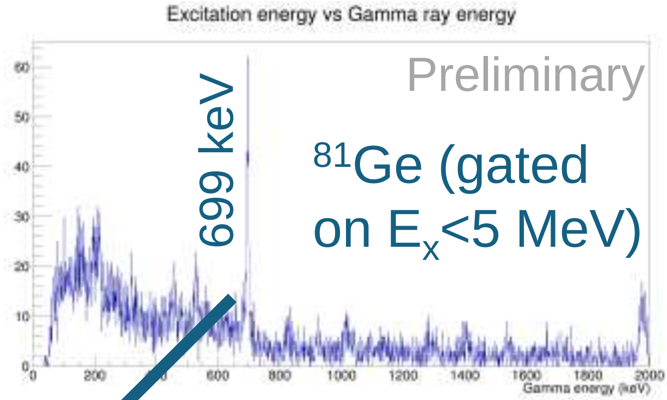
- Motivations
  - A=80 abundance peak
  - Weak r-process nucleosynthesis
- Goals
  - Constrain spectroscopic factors
  - DSD neutron capture cross sections
  - Compound nucleus (n,γ) cross sections via the surrogate reaction method
- Set up
  - FRIB
  - S800-Channel selection
  - GRETINA-Gamma ray information
  - ORRUBA-Excitation Energy

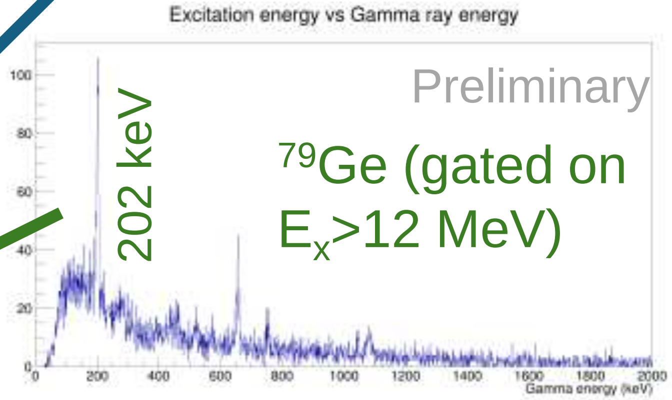
e22510 spokesperson: Mara Grinder

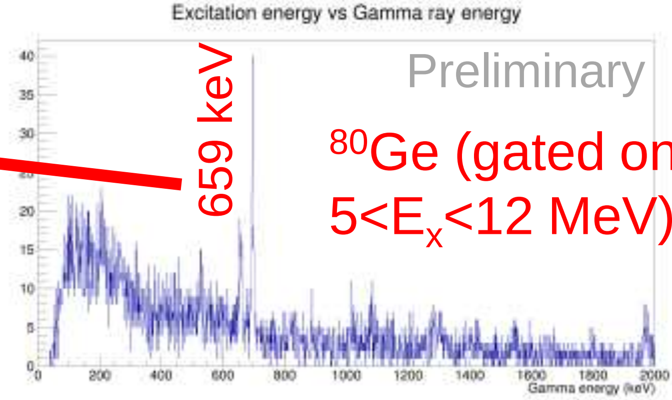
^{80}Ge(d,p)^{81}Ge (32+)

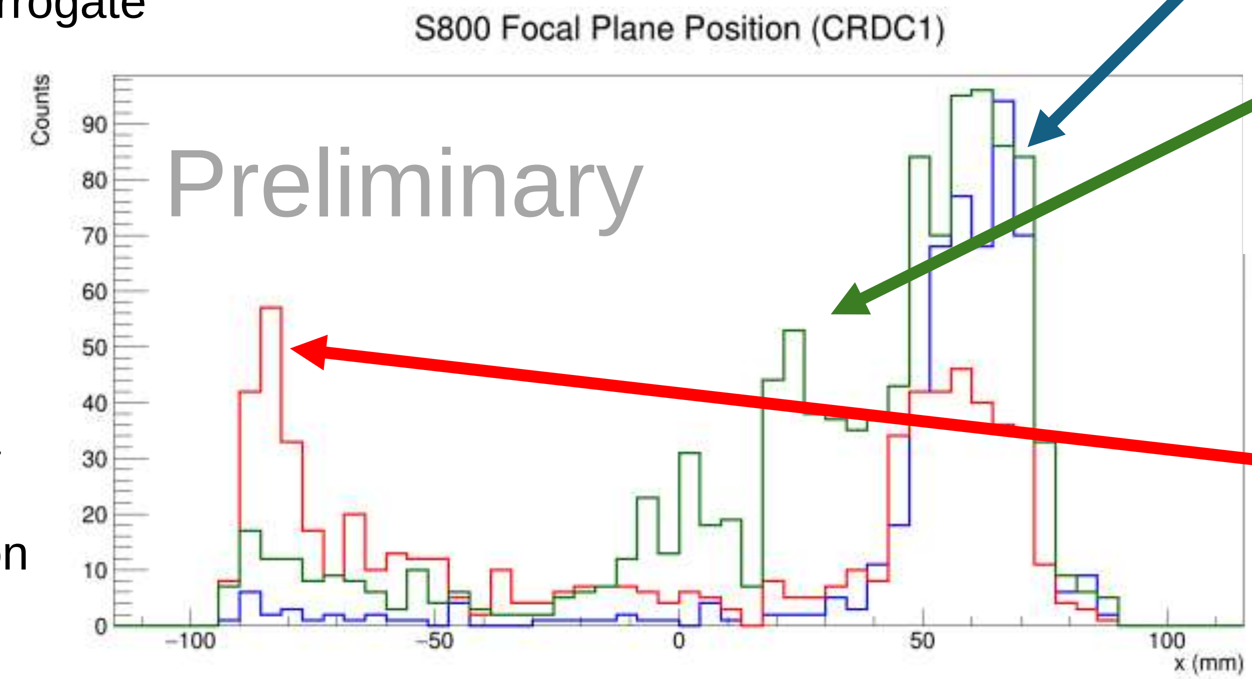
^{80}Ge(d,p)^{81}Ge*(2n)^{79}Ge(31+)

^{80}Ge(d,p)^{81}Ge*(n)^{80}Ge(31+)







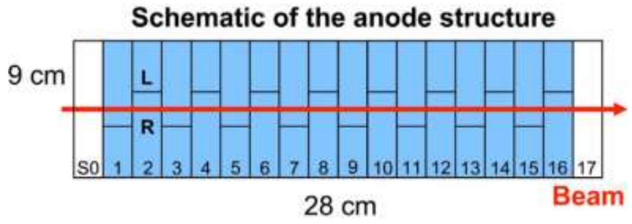


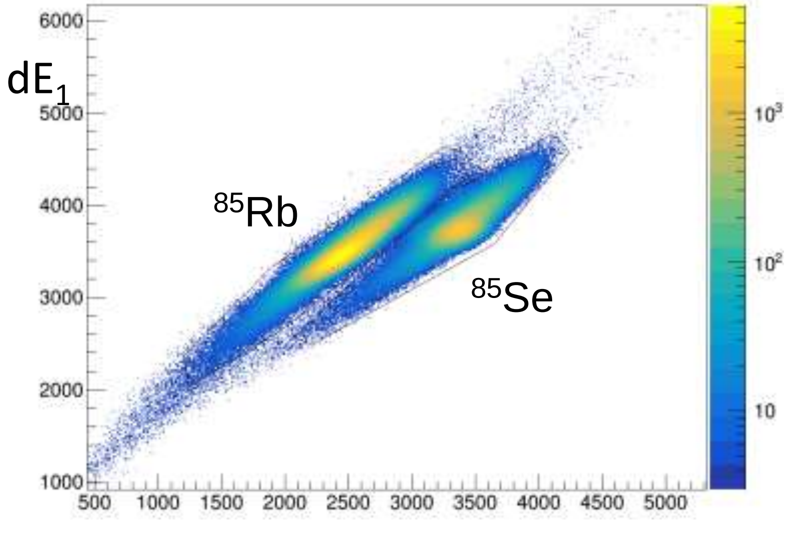
Excitation Energy vs S800 Focal Plane Position

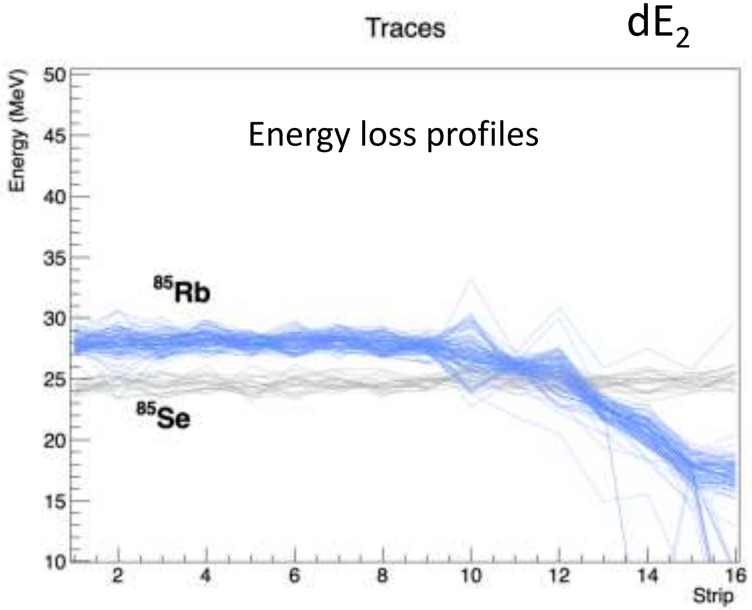
Uncertainties in (α,n) reaction rates produce large variations in calculated abundances in neutrino-driven wind nucleosynthesis

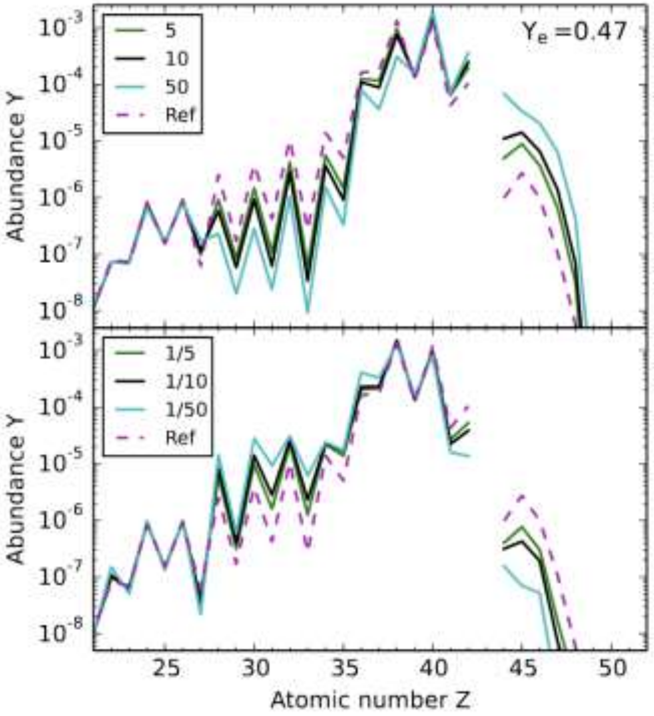
E21048 (Nov 2024):

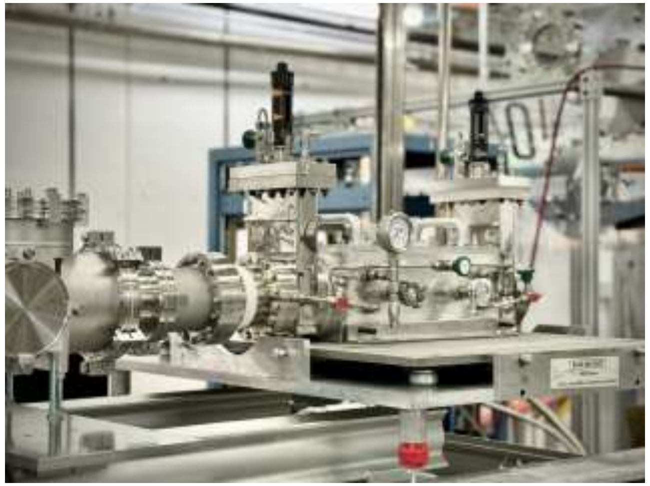
- Use MUSIC detector to measure ^{85}Se(a,xn) in ReA6
- First use of FRIB U beam
- Requested 3000pps ^{85}Se with maximum of 40% contamination
- Actual rates: 850pps ^{85}Rb (76%) and 270pps ^{85}Se (24%)
- FRIB will reschedule experiment for calendar year 2025

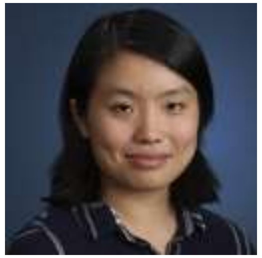










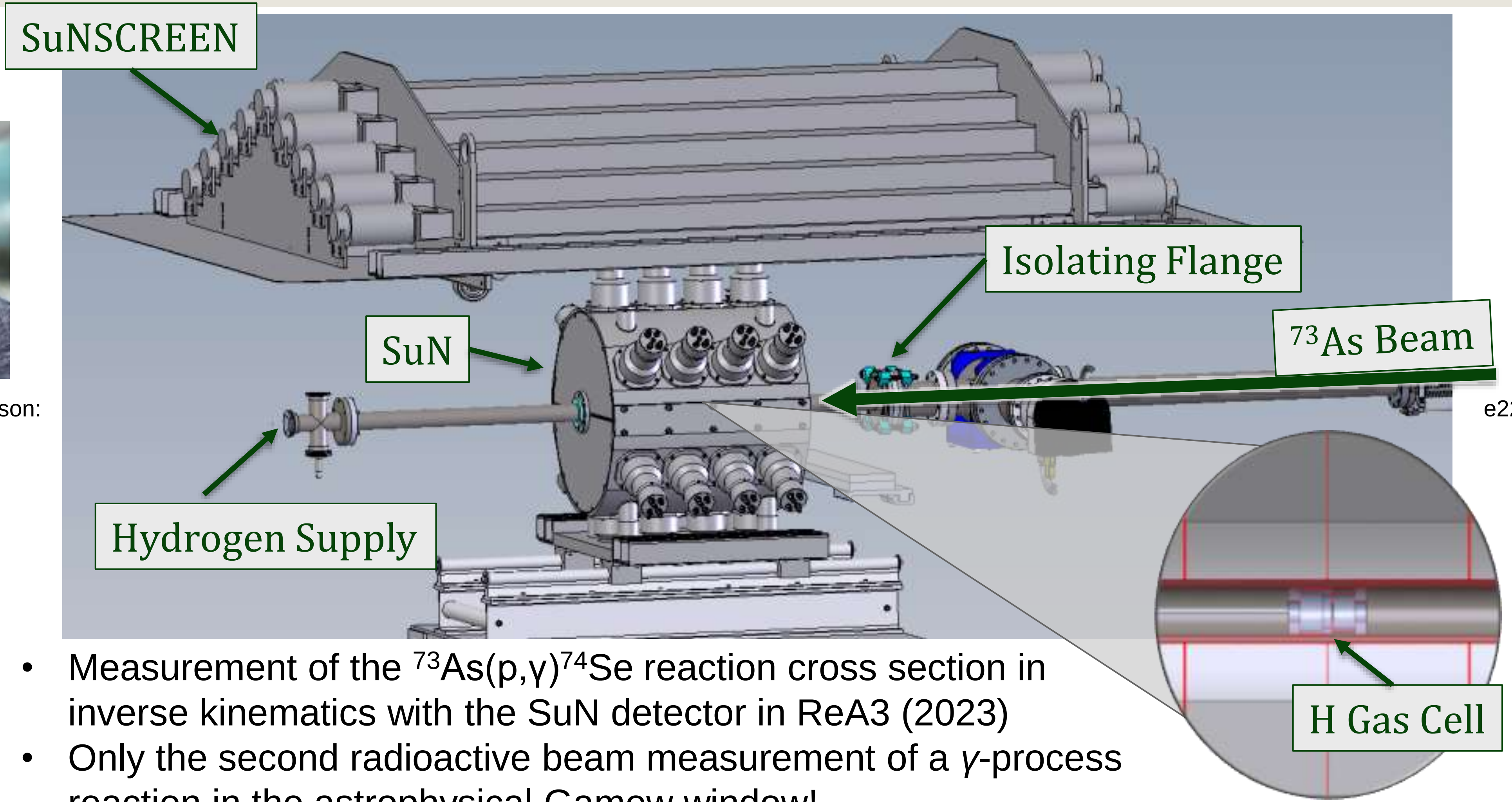


e21048 spokesperson:
Wei-Jia Ong

J. Bliss *et al. J. Phys. G: Nucl. Part. Phys.* **44** 054003 (2017)

Constraining the astrophysical γ process with radioactive ion beams

e22505 co-spokesperson:
Artemis Spyrou



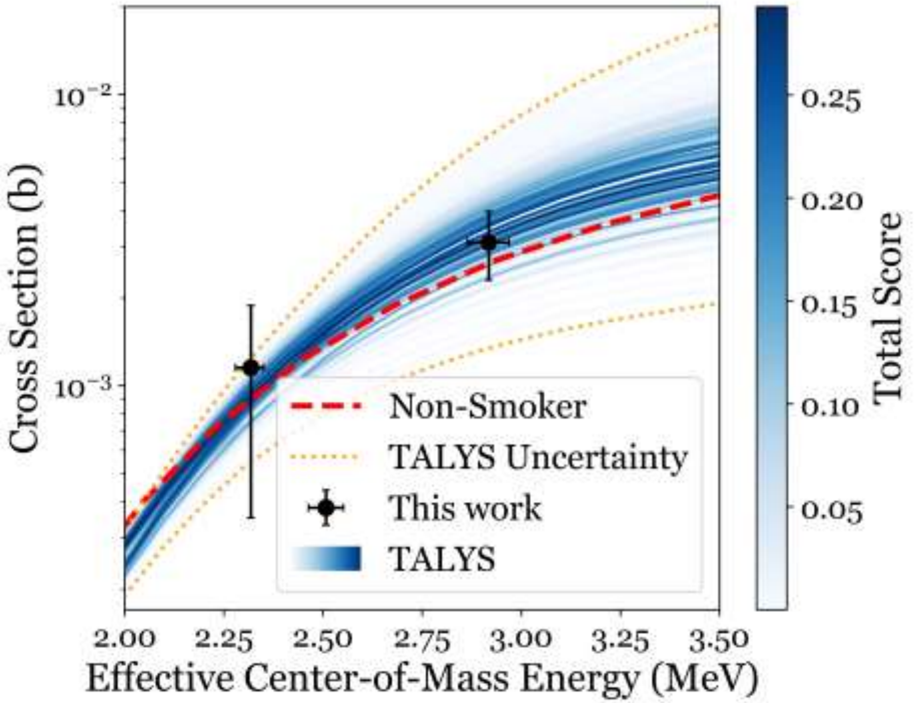
e22505 co-spokesperson:
Artemis Tsantiri

- Measurement of the ^{73}As(p,γ)^{74}Se reaction cross section in inverse kinematics with the SuN detector in ReA3 (2023)
- Only the second radioactive beam measurement of a γ-process reaction in the astrophysical Gamow window!

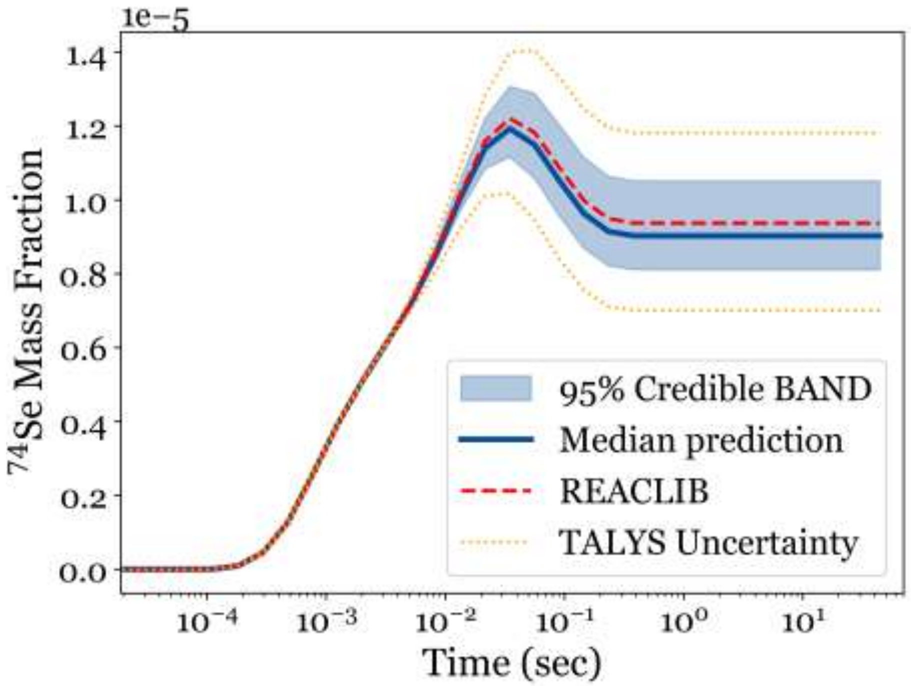
A. Tsantiri, PhD thesis, 2025

Constraining the astrophysical γ process with radioactive ion beams

Constrained reaction rate eliminates final nuclear uncertainty in ^{74}Se production in Type II supernovae



^{73}As(p,γ)^{74}Se cross section results



Impact of ^{73}As(p,γ)^{74}Se measurement on ^{74}Se production in SNII

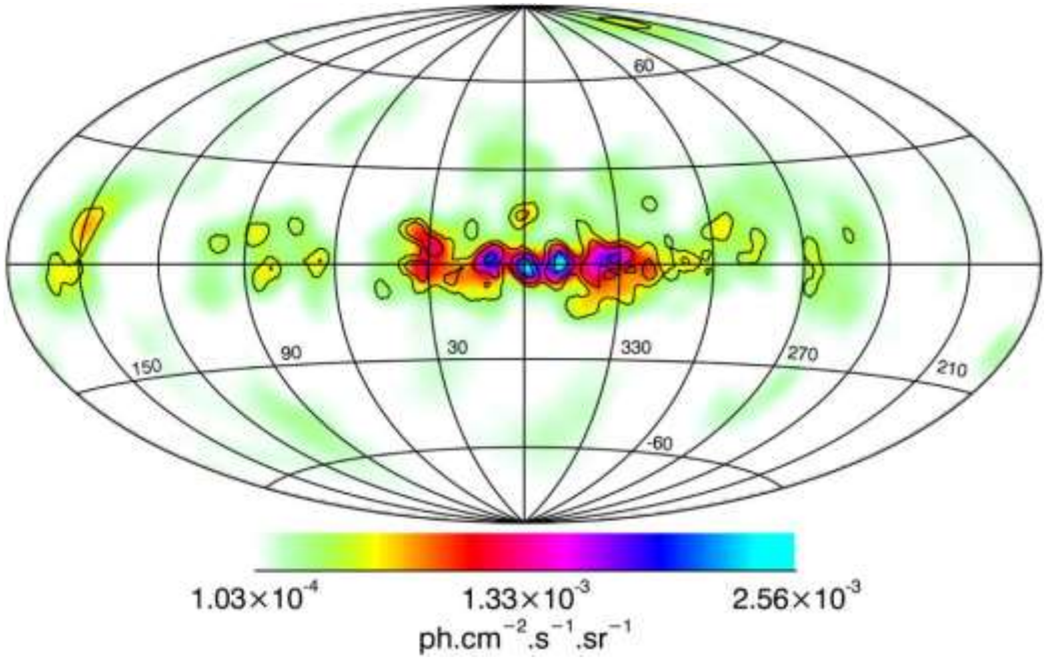
A. Tsantiri *et al.* (2025), in prep

Radioactive molecules for astrophysics

FRIB e23060 aims to precisely measure the rotational fingerprint of radioactive ^{26}AlF, ^{26}AlO and ^{32}SiO to enable the sensitive, high-resolution detection of ^{26}Al and ^{32}Si in space.

Nuclear decay detection

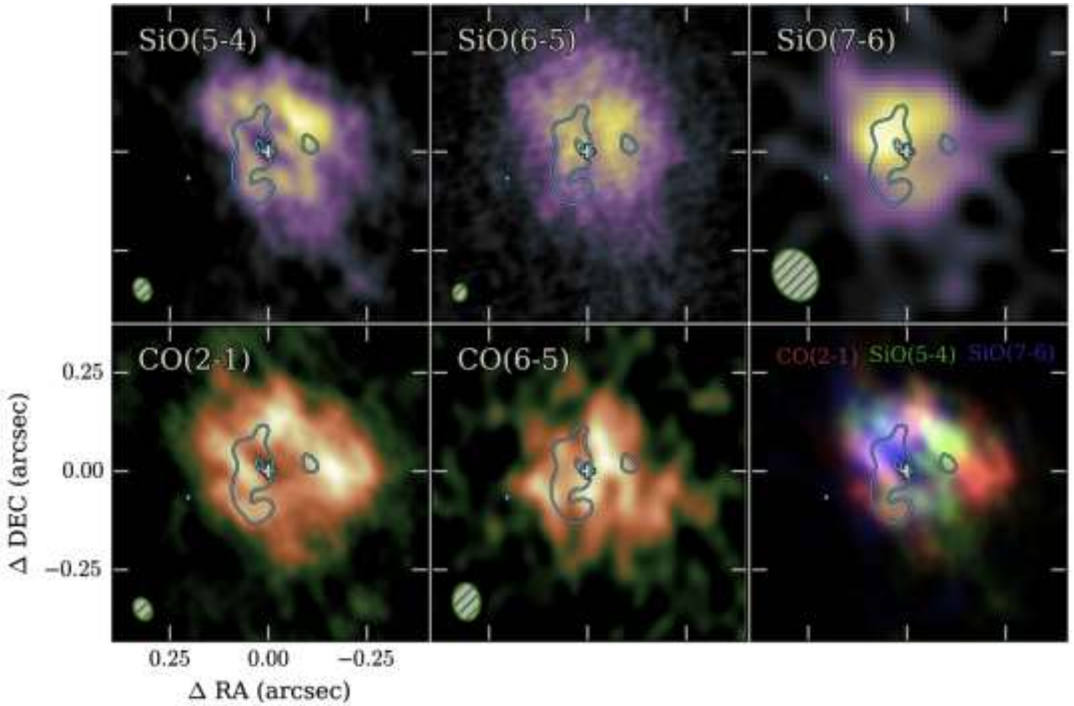
~1x γ-ray per million years for ^{26}Al



Limited sensitivity, resolution and applicability. (Milky Way, Integral-SPI)

Molecular rotation detection

>10^{10} microwave photons per million years for ^{26}AlF/O



Orders of magnitude higher sensitivity and resolution! (SN1987A, ALMA)

e23060 spokesperson: Shane Wilkins

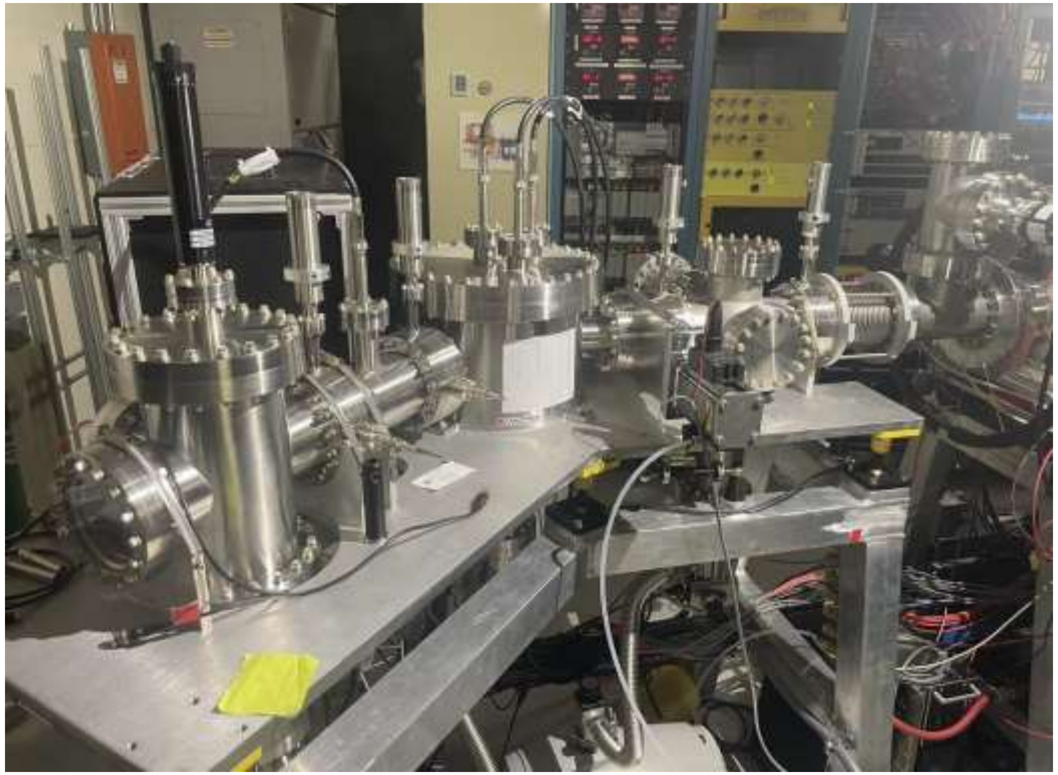
Bouchet *et al.* ApJ **801** 142 (2015), P. Cigan *et al., ApJ* **886** 51 (2019)

Facility for Rare Isotope Beams e23060

Given the long half-lives of these isotopes, we can study them off-line using batch-mode ion source at FRIB in combination with newly commissioned Resonance Ionization Spectroscopy.

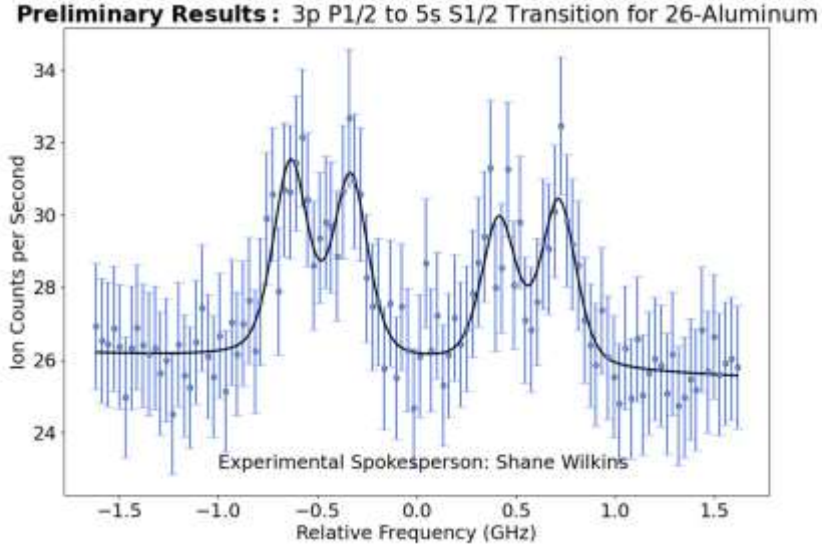
Can run program entirely in parallel to FRIB main accelerator!

A lot of the isotopes can also be made in a nuclear reactor through neutron capture.



We were granted 480 hours to study ^{26}AlO and ^{32}SiO for e23060.

Already took a test ^{26}AlF beam during FRIB maintenance period!

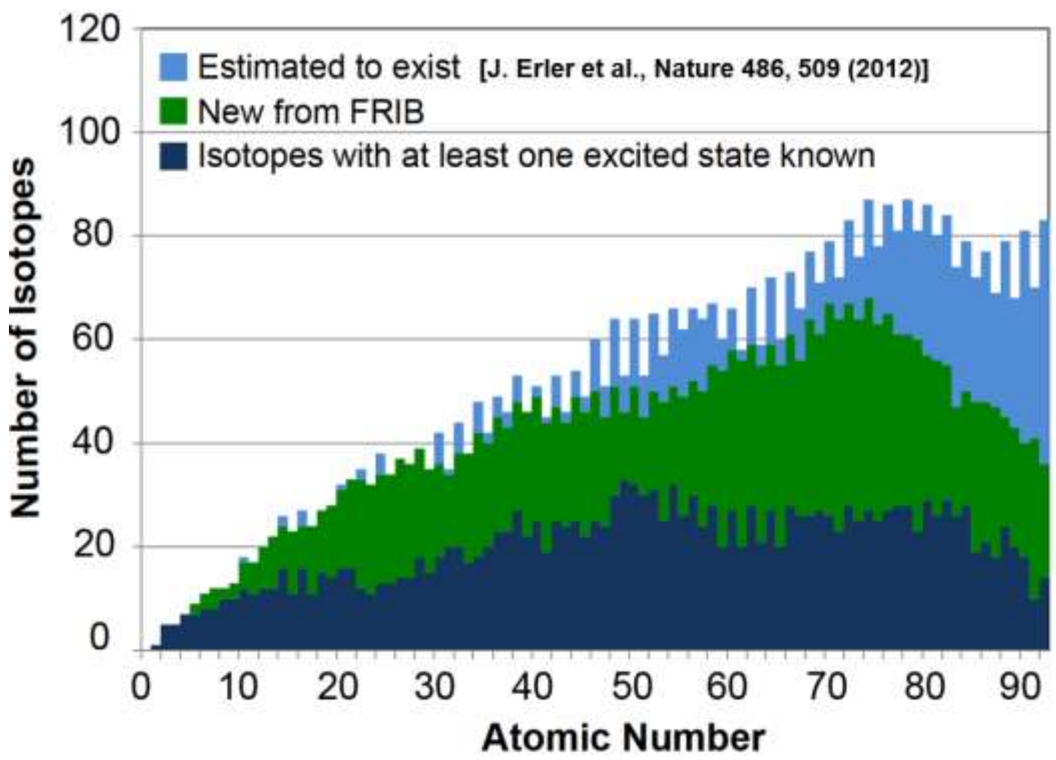


Data analysis: Brooke Rickey

FRIB

Summary and Outlook

- FRIB facility is operational providing RIBs to users since May 2022
- Primary beam power has ramped up from 1 kW to 20 kW since 2022 and continues to increase with ultimate goal of 400 kW
- Intensity and purity of all RIBs continually improving
- Nuclear astrophysics experiments have been acquiring data that is under analysis or approaching publication
- FRIB will produce 80% of all predicted isotopes of elements up to Uranium



Acknowledgements

- Thanks to Alex Gade and FRIB experiment spokespersons below for providing material:

Experiment #	Spokesperson	Title
e21014	Lotay	Constraining the Ni-Cu cycle in X-ray bursts and Core Collapse Supernovae: Spectroscopy of ^{60}Zn
e21016	Avila	Direct measurement of the ^{59}Cu(p,α)^{56}Ni reaction
e21018	Zegers	Constraining electron-capture rates in and near the N=20 island of inversion
e21048	Ong	Constraining Molybdenum and Ruthenium production in neutron-rich neutrino-driven winds
e21072	Wrede	Strength of the key ^{15}O(α,γ)^{19}Ne resonance in X-ray bursts
e22505	Kyle (Spyrou/Tsantiri)	Nucleosynthesis of neutron-deficient isotopes in the A=70 region
e22510	Grinder	^{80}Ge(d,pγ): Informing weak r-process neutron capture
e23037	Fougeres	Angle-integrated measurement of the d(^{25}Al,nγ)^{26}Si transfer reaction to probe resonance strengths in ^{25}Al(p,g)^{26}Si relevant for the production of ^{26}Al in classical novae
e23056	Richard	Indirect ^{99}Nb(n,γ)^{100}Nb Constraint for the Astrophysical i-Process
e23060	Wilkins	Towards determining the rotational fingerprints of the radioactive molecules ^{26}AlF and ^{32}SiO for astronomical studies
e23084	Pain	Informing the i process: constraining the As/Ge abundance ratio in a metal poor star via ^{75}Ga(d,pγ)^{76}Ga

FRIB Public Experiment List:
https://userportal.frib.msu.edu/Pac/Experiments/PublicList

Thank you for your attention!