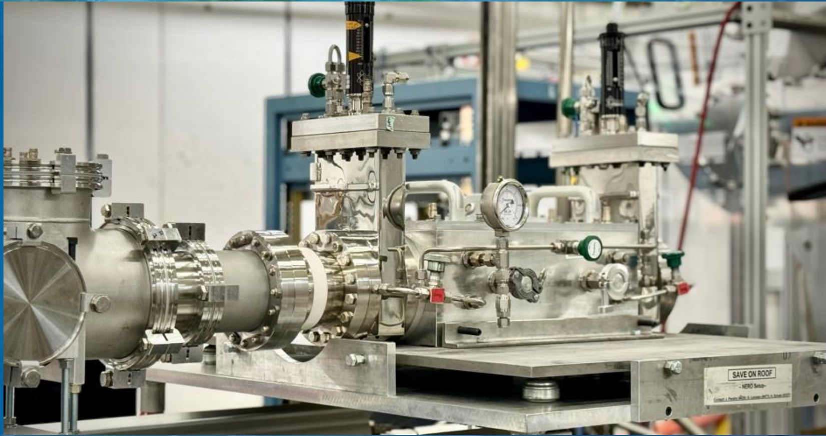
JANUARY 21, 2026

DIRECT MEASUREMENT OF THE 59Cu(p,α)56Ni REACTION WITH MUSIC

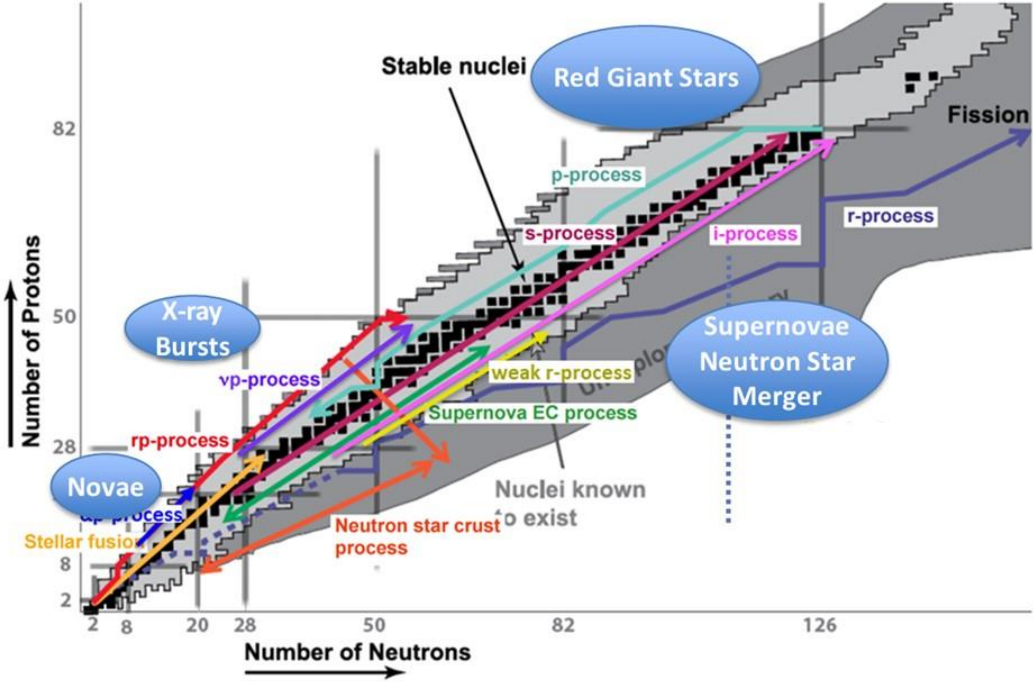


EILENS LOPEZ SAAVEDRA

62nd International Winter Meeting on Nuclear Physics
19 - 23 January 2026
Bormio, Italy

How are the elements in the Universe created?

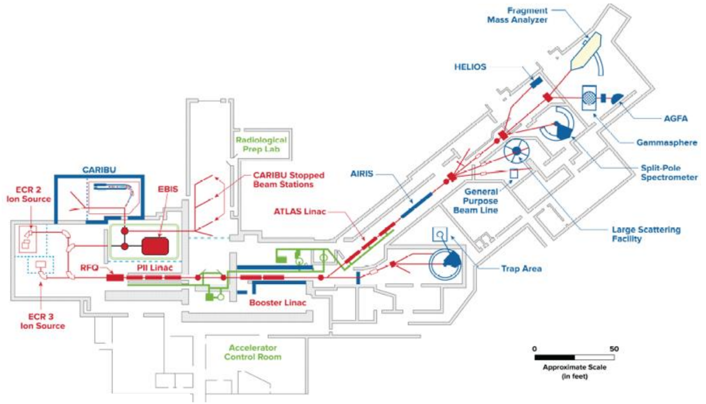
- Nuclear reactions power stars and drive stellar evolution.
- The same reactions shape the chemical history of the cosmos — from hydrogen to uranium.
- **But many key reaction rates are still unknown.**
- Our experiments aim to measure them — unlocking the physics of stellar explosions, neutron stars, and the early Universe.



We're not just observing the cosmos, we're recreating its elemental history in the lab.

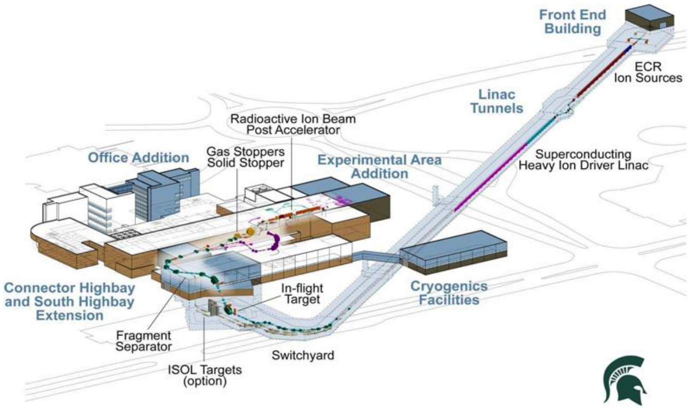
An exciting Era! : Exotic beams for Nuclear astrophysics

ATLAS



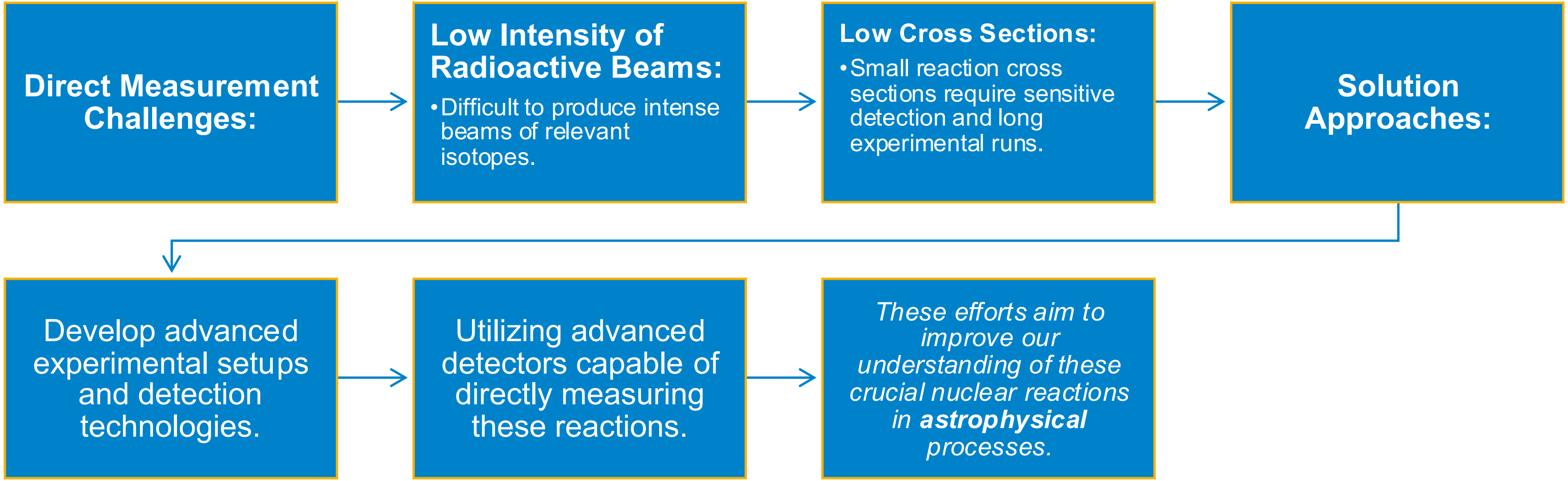
Argonne NATIONAL LABORATORY

FRIB



MICHIGAN STATE UNIVERSITY

MEASUREMENT CHALLENGES OF NUCLEAR REACTIONS OF ASTROPHYSICAL INTEREST



Direct Measurement Challenges:

Low Intensity of Radioactive Beams:
- Difficult to produce intense beams of relevant isotopes.

Low Cross Sections:
- Small reaction cross sections require sensitive detection and long experimental runs.

Solution Approaches:

Develop advanced experimental setups and detection technologies.

Utilizing advanced detectors capable of directly measuring these reactions.

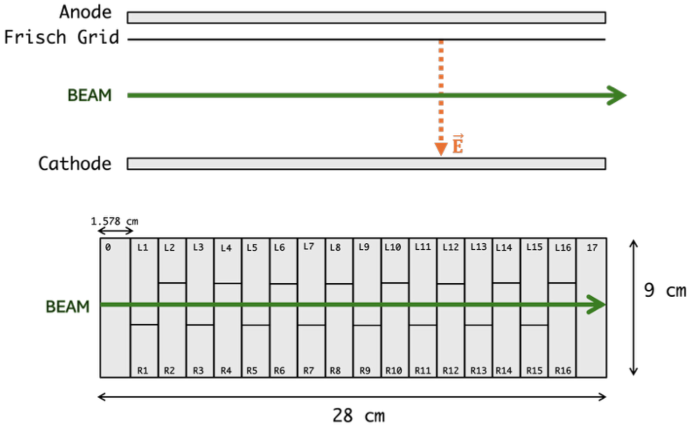
These efforts aim to improve our understanding of these crucial nuclear reactions in ***astrophysical*** *processes.*

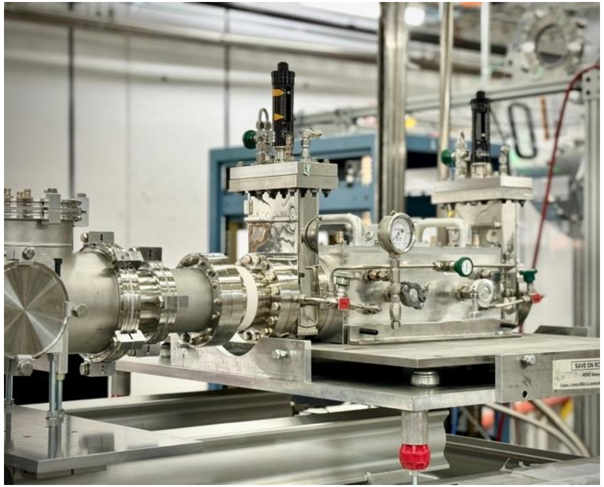
OUR APPROACH: THE MUSIC DETECTOR

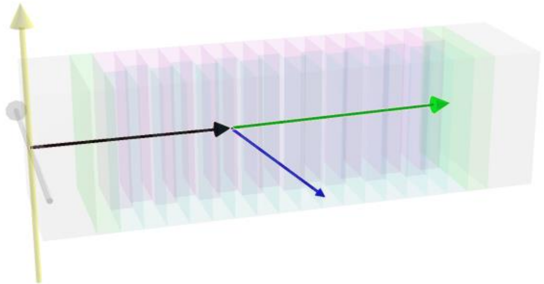
THE MUSIC DETECTOR

The detector operates as an active target, i.e. the ionization gas serves as the target and as detection medium at the same time.

- Close to 100% efficiency
- Measure a large range of excitation functions of energy integrated cross sections using single beam energy
- Self normalizing: No additional monitors for absolute normalization
- 18 Strips, middle 16 are subdivided for event discrimination.

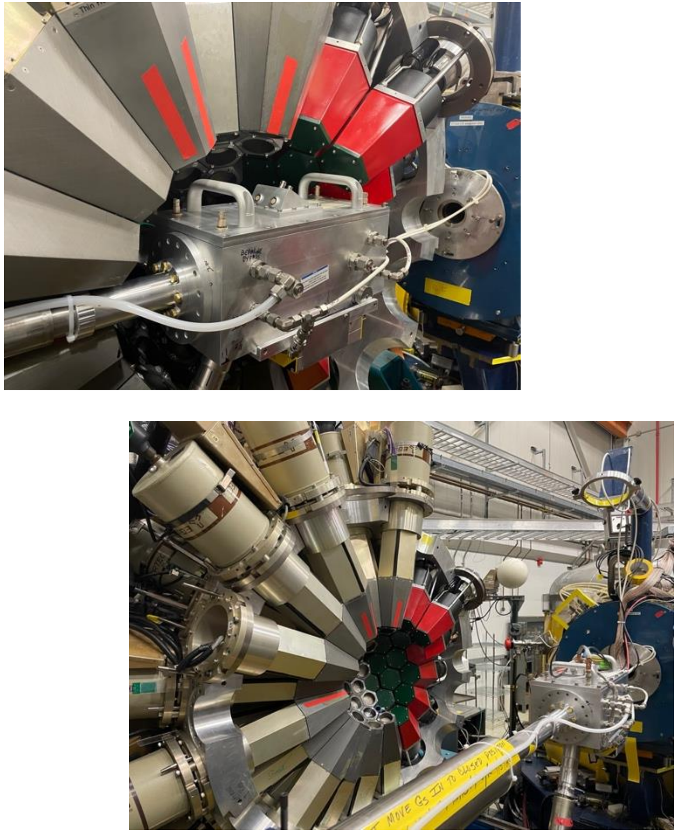






The MUSIC Detector

MUSIC + GAMMASPHERE + NSHELL IN 17O(α,n) measurement



Rate capability: About 1x10^5 pps (^{4}He)
Counting gases: He, CH_4, Ne, Ar, CF_4, CO_2, P10, etc
Typical Pressures: 100-760 Torr

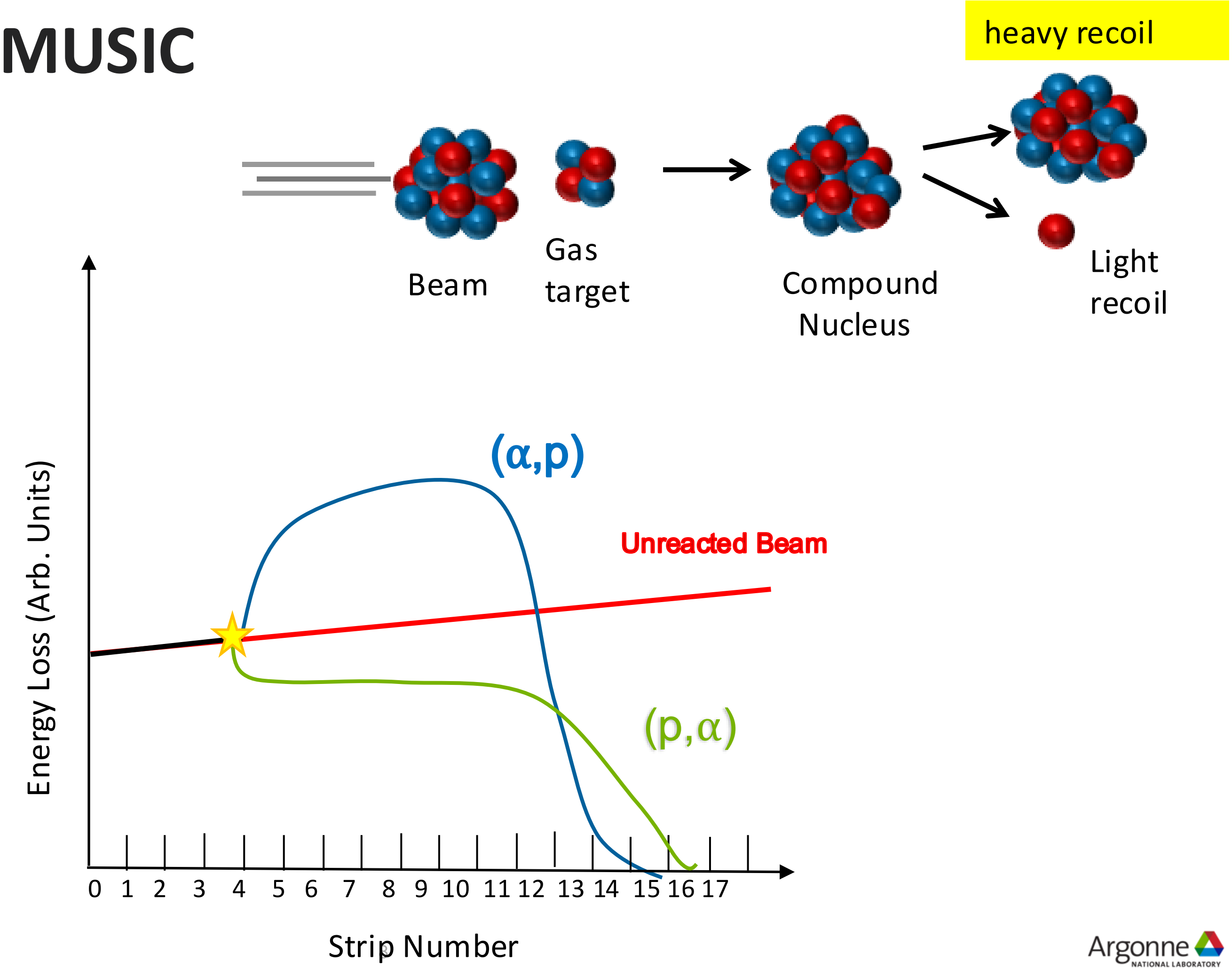
MUSIC is portable, small:

- can be surrounded by auxiliary detectors at close distance.
- Easy to transport to other user facilities.

Bragg Curves in MUSIC

Stopping power:

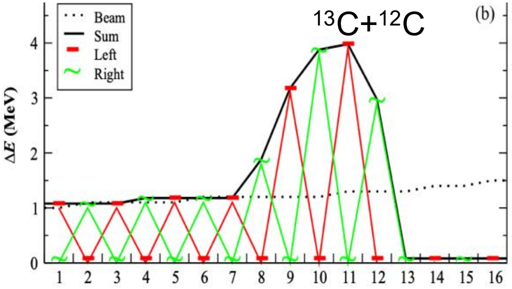
$$\frac{dE}{dX} \propto \frac{Z^2}{E}$$



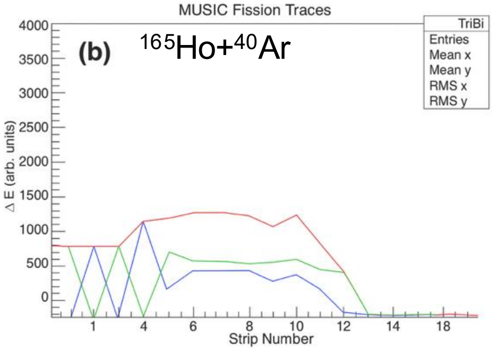
A VERSATILE DETECTOR

#SmallButMighty

Fusion

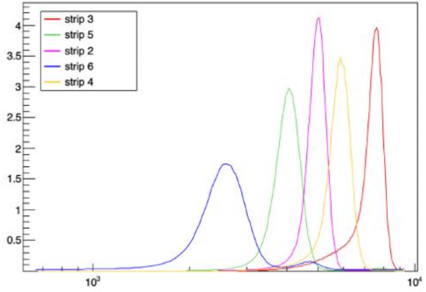


Fission

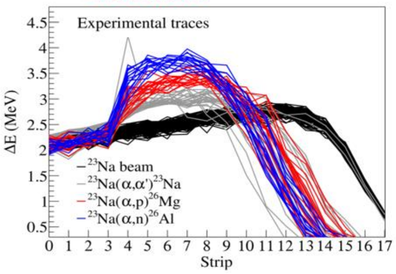


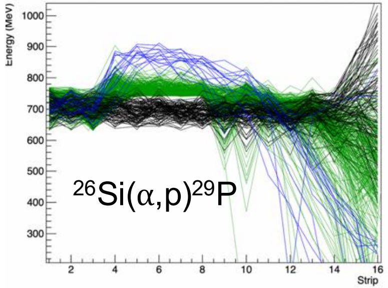
Microdosimetry
For Carbon Ion Therapy

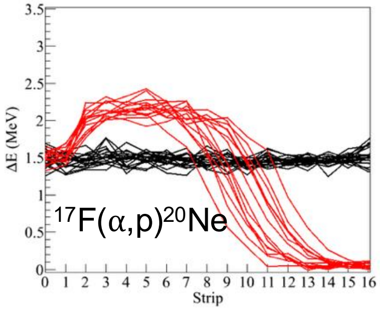
MAYO CLINIC

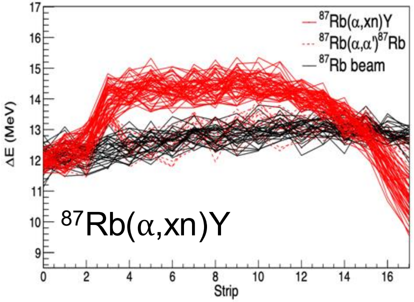


And reactions relevant for Nuclear Astrophysics!









MUSIC AT FRIB!

59Cu(p,α)56Ni

ROLE OF ^{59}Cu(p,α)^{56}Ni IN THE NEUTRINO-INDUCED NUCLEOSYNTHESIS OF A>64: THE νp-PROCESS

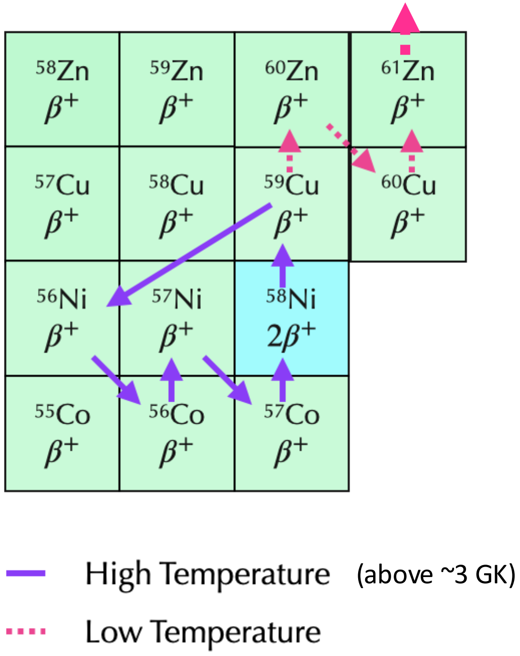
νp-Process : Occurs in proton-rich neutrino-driven winds; builds heavy p-nuclei beyond Fe via (p,γ) and (n,p) reactions

NiCu Cycle Bottleneck: At $T_9 \gtrsim 3$ GK, ^{59}Cu(p,α)^{56}Ni dominates ^{59}Cu(p,γ)^{60}Zn, trapping the flow in a closed Ni–Cu cycle and halting synthesis of heavier nuclei

Breakout Temperature: The (p,α)/(p,γ) crossover sets the threshold ($T_9 \approx 3$ GK) for effective νp nucleosynthesis.

Astrophysical Impact: Accurate ^{59}Cu(p,α)^{56}Ni rates control how far the νp-process can proceed (A ≈ 64–110) in supernova ejecta, shaping predictions of heavy proton-rich isotopes

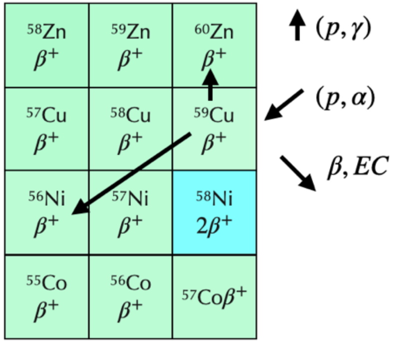
Measurement Imperative: Direct σ(^{59}Cu(p,α)^{56}Ni) data reduce theoretical uncertainties in network rates, improving νp-process models for supernova and ν-driven wind simulations



SENSITIVITY OF X-RAY BURST LIGHT CURVES TO ^{59}Cu(p,α)^{56}Ni

59Cu(p,γ) and 59Cu(p,α) reactions "of key importance" for X ray light curve and affect the composition of burst ashes on the surface of the neutron star significantly.

R.H.Cyburt et al. 2016 ApJ ***830*** *55*



^{58}Zn β^+	^{59}Zn β^+	^{60}Zn β^+
^{57}Cu β^+	^{58}Cu β^+	^{59}Cu β^+
^{56}Ni β^+	^{57}Ni β^+	^{58}Ni $2\beta^+$
^{55}Co β^+	^{56}Co β^+	^{57}Coβ^+

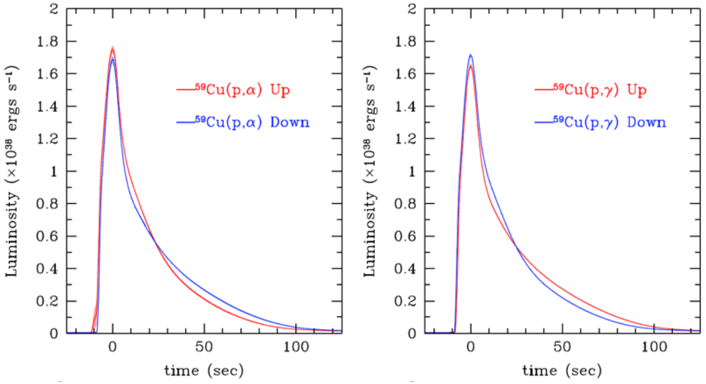
- **X-ray bursts** (thermonuclear flashes on accreting neutron stars) are highly sensitive to nuclear reaction rates
- **Cyburt et al. (2016)** identify 84 reactions whose uncertainties alter burst light curves significantly

Among these, **^{59}Cu(p,α)^{56}Ni** controls the Ni–Cu cycle:

•Variations in its rate shift the burst peak luminosity and shape

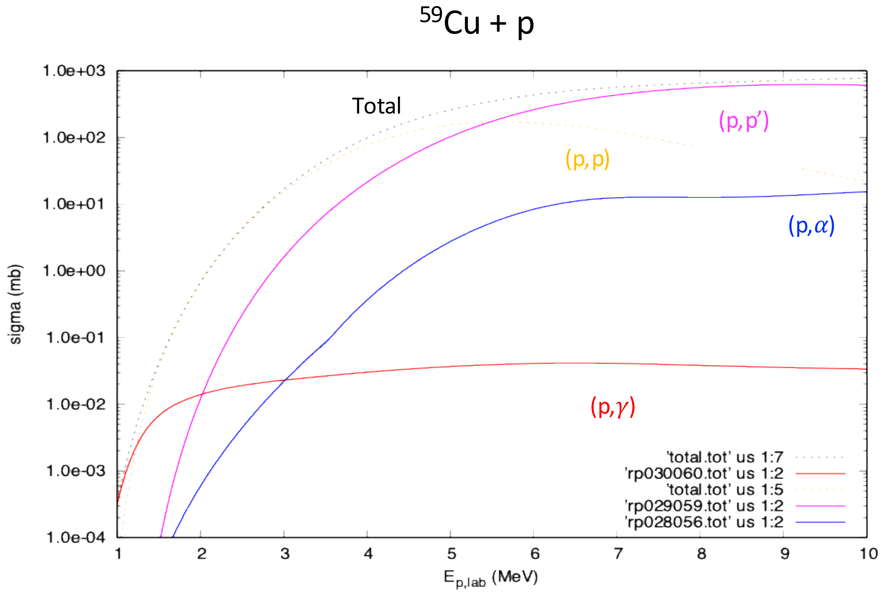
Accurate σ(^{59}Cu(p,α) data thus is critical to:

•Constrain burst model predictions of rise time, peak, and decay profile



OUR PROPOSED MEASUREMENT

- Measure **^{59}Cu(p,α)^{56}Ni** reaction cross section
- Energy range: $E_{cm} \approx 1.75–5.6$ MeV *($T_9 \approx 2–6$ GK)*
- Technique: MUSIC active-target detector, inverse kinematics at FRIB
- **Goal**: **Measure first excitation function for this reaction**



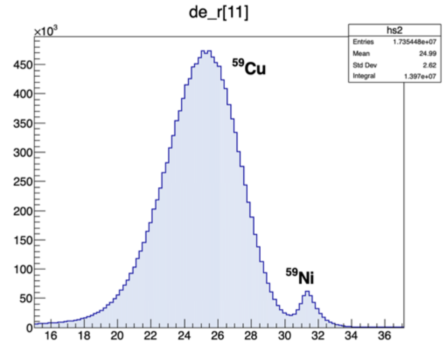
Talys calculation

MUSIC AT FRIB

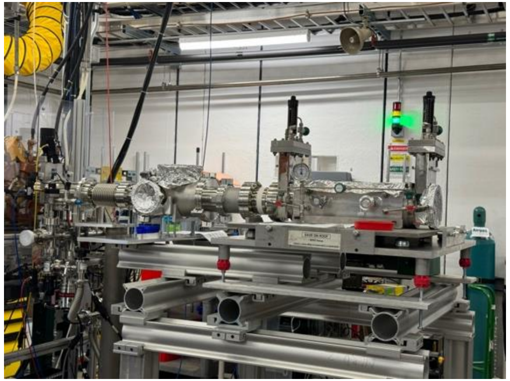
November 2024

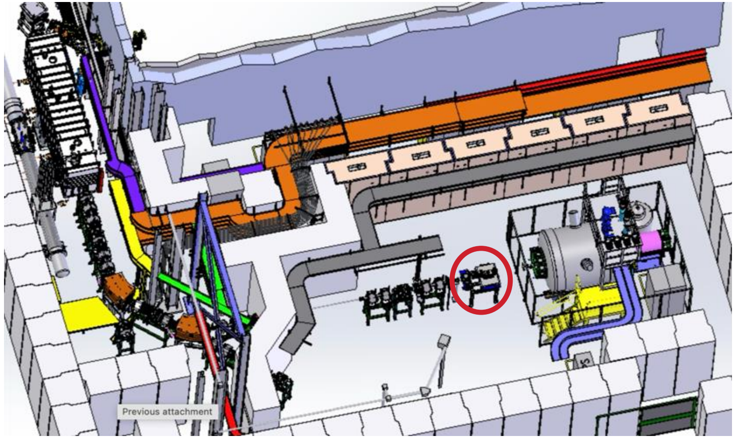
Beam & Target

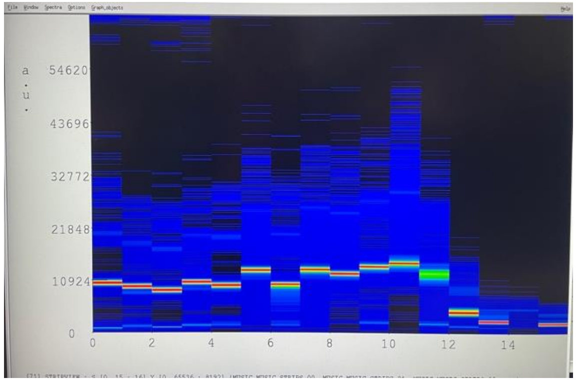
- ^{59}Cu beam at **8.41 MeV/u**, delivered on Average intensity ~9×10^3 pps (~6 % ^{59}Ni contaminant)
- ~55 Hours of Beam
- CH$_4$ gas @ 440 Torr



Beam Contaminant was ~6%

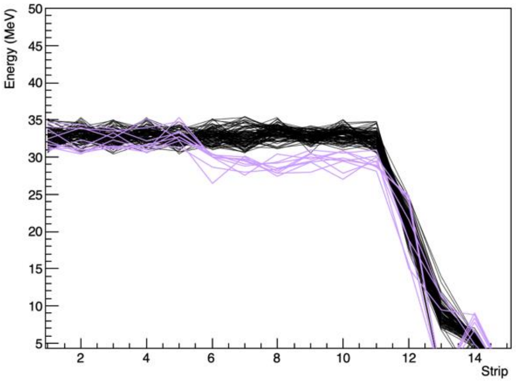


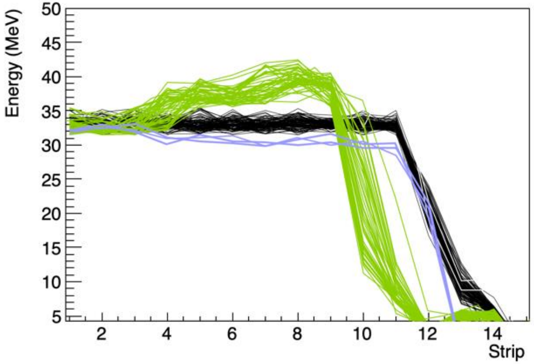




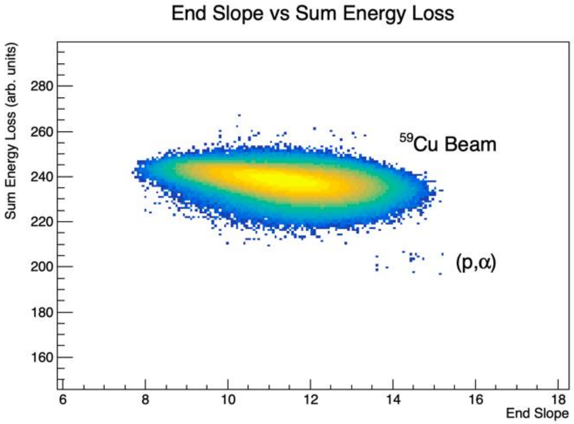
EVENTS IDENTIFICATION

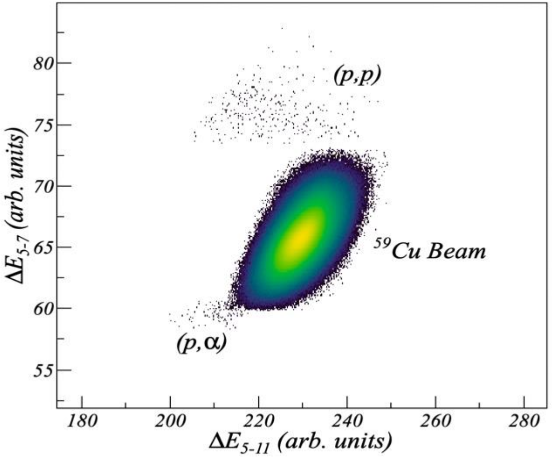
TRACES METHOD





DE-DE METHOD

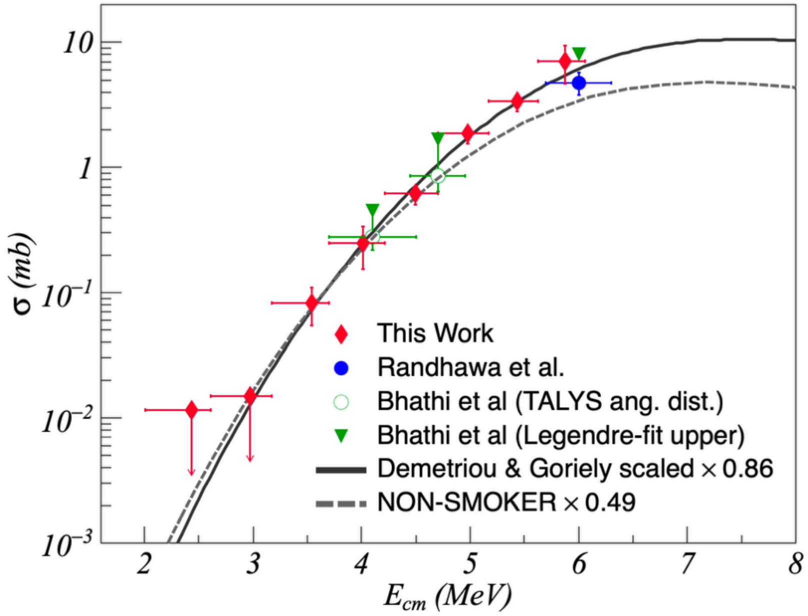


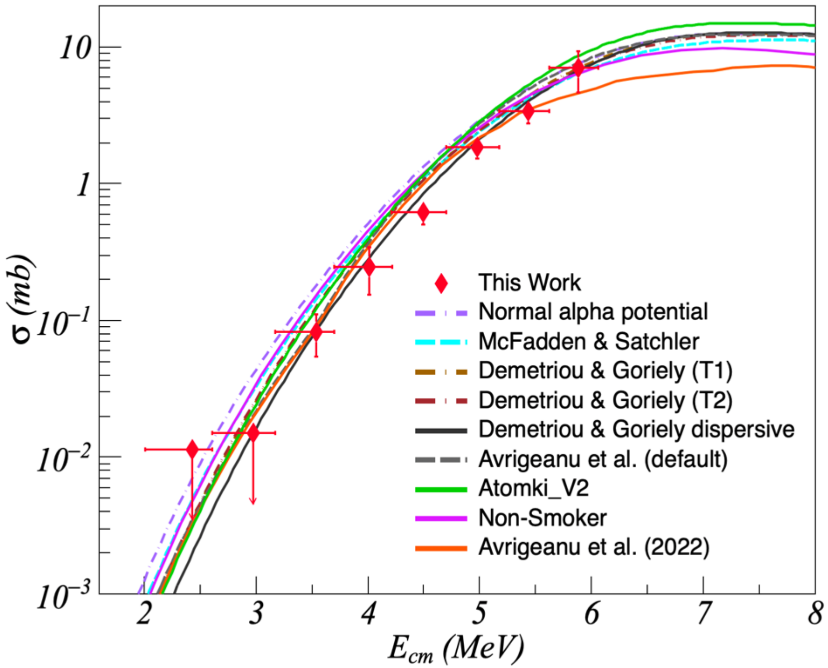


EXPERIMENTAL EXCITATION FUNCTION

Just Submitted to PRL + PRC!

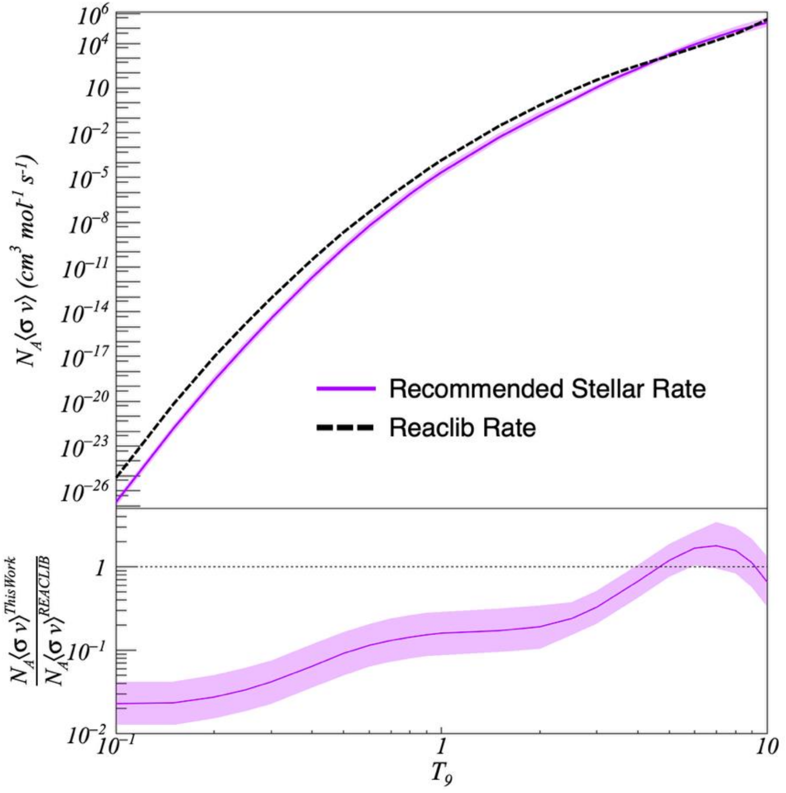
$$\sigma_{(p,\alpha)} \propto \frac{T_{p0}\,T_{\alpha}}{T_p + T_\gamma + T_\alpha} \approx \frac{T_{p0}\,T_{\alpha0}}{T_p}$$

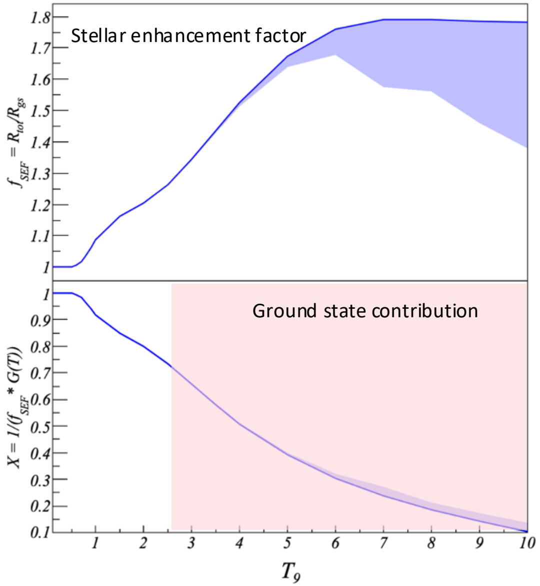




- Reaction follows compound-nucleus (Hauser–Feshbach) behavior
- Cross section dominated by α transmission (α-OMP sensitivity)
- Data directly constrain statistical-model extrapolations

NEW REACTION RATE





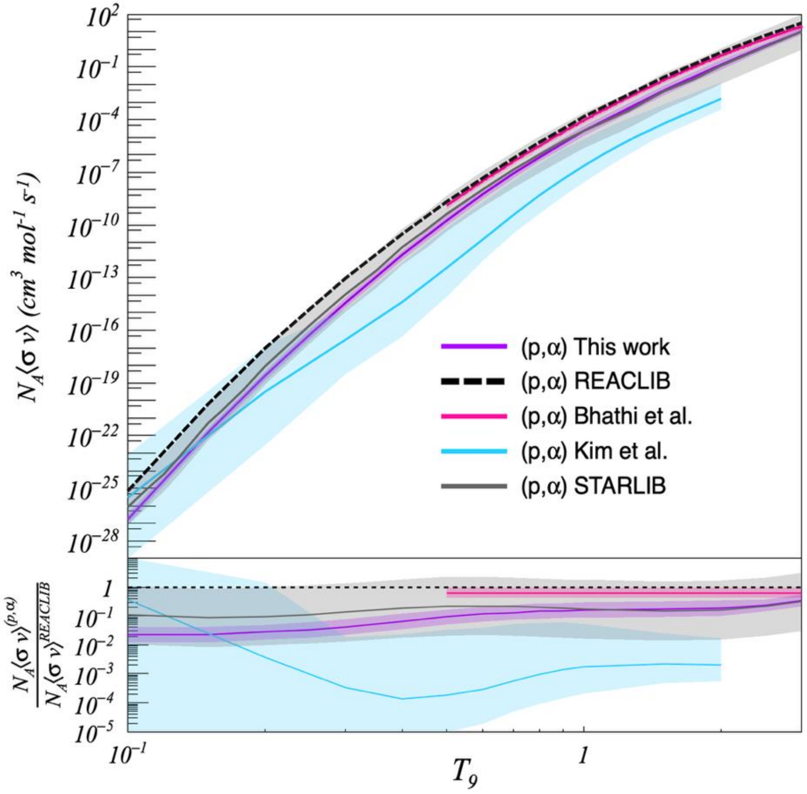
$$f_{\rm SEF}(T) = \frac{R^*(T)}{R_0(T)}$$

$$X(T) = \frac{1}{f_{\rm SEF}(T)G_0(T)}$$

Our experiment directly constrains approximately 10–75% of the stellar reaction rate

- **Experimental constraint:** Ground-state contribution to the stellar rate is experimentally constrained for T_9~2.6 –10.5.
- **Low-temperature extension:** Measured cross sections were combined with TALYS extrapolations using the DEM-3 a-OMP (uncertainty factor 1.5).
- **Final normalization:** TALYS rates were scaled by 0.86 to reproduce the experimental cross sections.

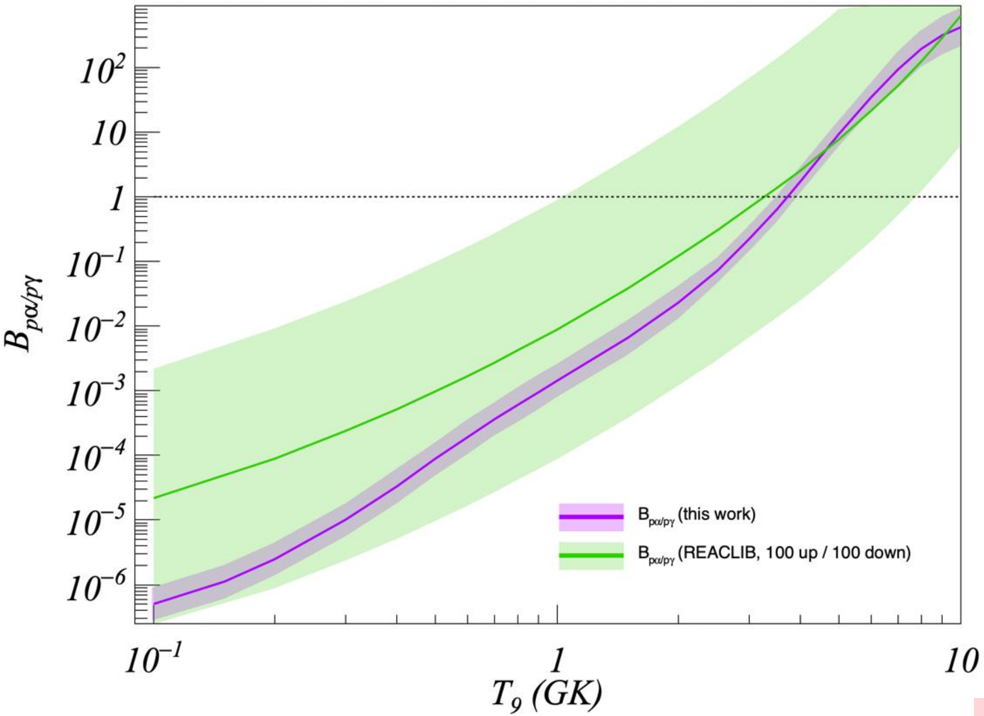
Constraining the (p,α) Rate: Community Efforts



- **Kim et al.:** Indirect constraint using known 60Zn resonance information combined with shell-model calculations and Porter–Thomas sampling of alpha widths.
- **Bhathi et al.:** Direct measurement of the 59Cu(p,a)56Ni cross section at higher energies, used to constrain the reaction rate. ((REACLIB) rate scaled by a factor of 0.49 to derive the stellar rate.)

- **Lower than REACLIB:** Up to 100× lower at low T9, converging toward STARLIB for T9 ≥ 1.
- **Between literature results:** Lies between Bhathi and Kim rates, matching Bhathi at high T9 while avoiding NON-SMOKER low-T9 overestimation.
- **Most reliable constraint:** Eliminates Porter–Thomas–driven discrepancies and provides the strongest experimental basis to date.

IMPACT ON THE X-RAY BURTS AND THE vp-PROCESS



- **Tighter constraint:** Experimental (p,a) data strongly reduce the branching-ratio uncertainty and constrain the Ni–Cu cycle strength.

- **XRBs :** For XRBs (T_9<= 1), $B_{(p,a/p,g)}$ <= 10^{-3}, implying negligible recycling (<= 0.1%).

- **vp-process** : (T_9 = 1–3), recycling rises to ~22% but most flow still proceeds to heavier nuclei.

- **Higher crossover temperature:** The (p,a/p,g) crossover shifts to T_9 ~ 3.7 (vs. T_9 ~ 3.2 in REACLIB), favoring more efficient vp-process conditions.

For **XRB** conditions, the Ni–Cu cycle is likely to be negligible

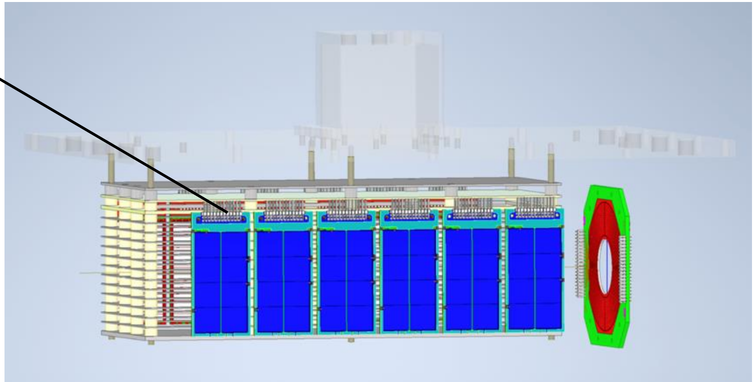
New rate keeps the flow out of the Ni–Cu cycle until higher temperatures and higher neutrino fluxes, which directly boosts **vp-process** efficiency.

THE FUTURE OF MUSIC: THE AMENA DETECTOR

THE AMENA DETECTOR:

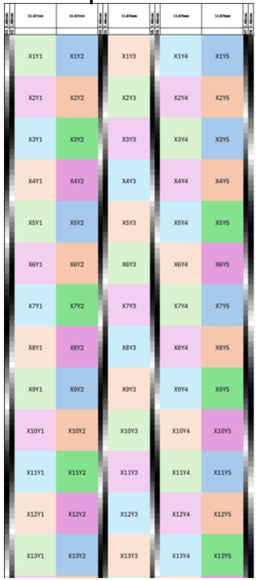
Field cage surrounded by position sensitive Silicon detectors

Now the light recoils are measured in coincidence with the heavy. New kinematic information can be extracted.



Better Position Resolution
Increased Data Granularity

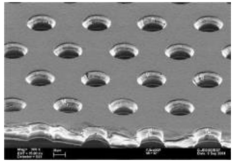
Higher Anode segmentation:
34 Ch -> 142 Ch

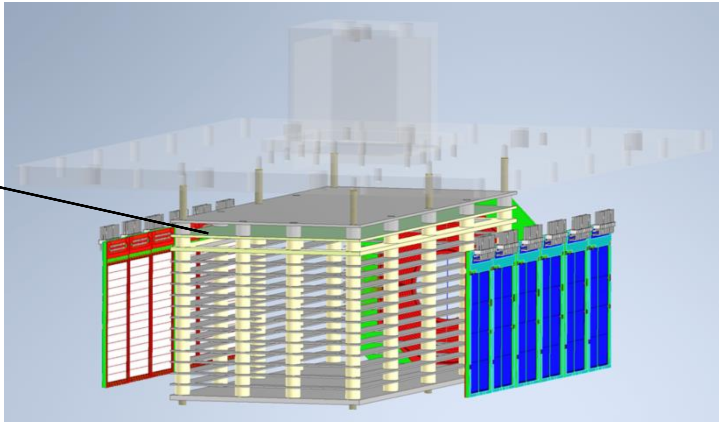


11.67mm	11.67mm	11.67mm	11.67mm	11.67mm
X1Y1	X1Y2	X1Y3	X1Y4	X1Y5
X2Y1	X2Y2	X2Y3	X2Y4	X2Y5
X3Y1	X3Y2	X3Y3	X3Y4	X3Y5
X4Y1	X4Y2	X4Y3	X4Y4	X4Y5
X5Y1	X5Y2	X5Y3	X5Y4	X5Y5
X6Y1	X6Y2	X6Y3	X6Y4	X6Y5
X7Y1	X7Y2	X7Y3	X7Y4	X7Y5
X8Y1	X8Y2	X8Y3	X8Y4	X8Y5
X9Y1	X9Y2	X9Y3	X9Y4	X9Y5
X10Y1	X10Y2	X10Y3	X10Y4	X10Y5
X11Y1	X11Y2	X11Y3	X11Y4	X11Y5
X12Y1	X12Y2	X12Y3	X12Y4	X12Y5
X13Y1	X13Y2	X13Y3	X13Y4	X13Y5

Signal Gains: $10^4 – 10^5$

More precise measurements of low-intensity reactions.





Frisch Grid replaced by THGEMS (Gas Electron Multipliers)

SUMMARY:

- The high efficient MUSIC detector offers great possibilities of study for direct measurements with radioactive beams.
- Exciting opportunities at FRIB and ATLAS!
- First excitation-function measurement of the $^{59}Cu(p,\alpha)^{56}Ni$ reaction over the relevant energy range.
- Ni–Cu cycle is likely to be negligible for X-ray bursts.
- Shift of the (p,α)/(p,γ) crossover to higher temperature favors more efficient νp-process nucleosynthesis.
- The AMENA detector expands MUSIC's sensitivities and open new exciting research possibilities!

Join our Collaboration!

Argonne
NATIONAL LABORATORY

U.S. DEPARTMENT
of ENERGY

Collaboration:

Lawrence Livermore National Laboratory

FRIB

1804 OHIO UNIVERSITY

Los Alamos NATIONAL LABORATORY EST. 1943

atomki DEBRECEN

PHYSICS FLORIDA STATE UNIVERSITY

cea

LSU

TUNL
Triangle Universities Nuclear Laboratory

CENS
CENTER FOR EXOTIC NUCLEAR STUDIES

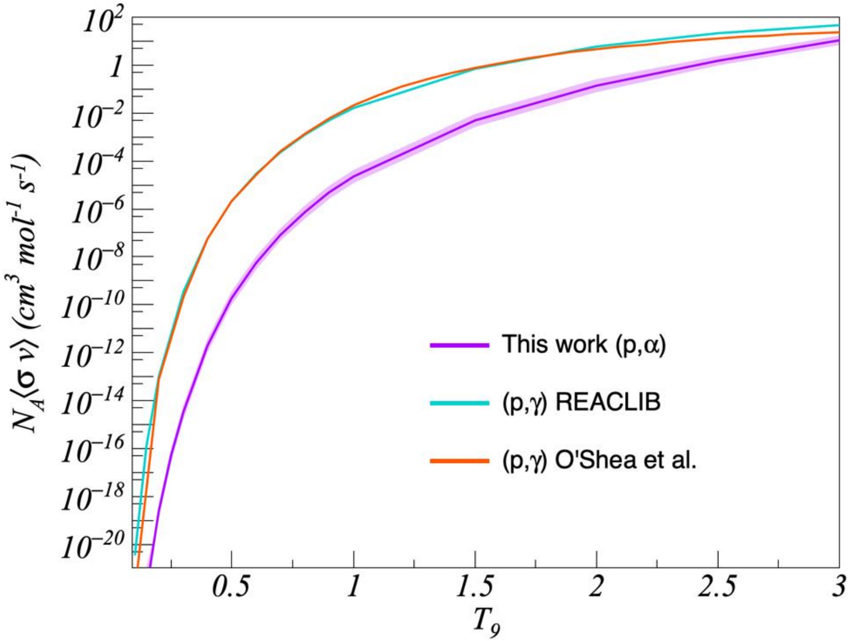
THE UNIVERSITY OF CHICAGO 1890

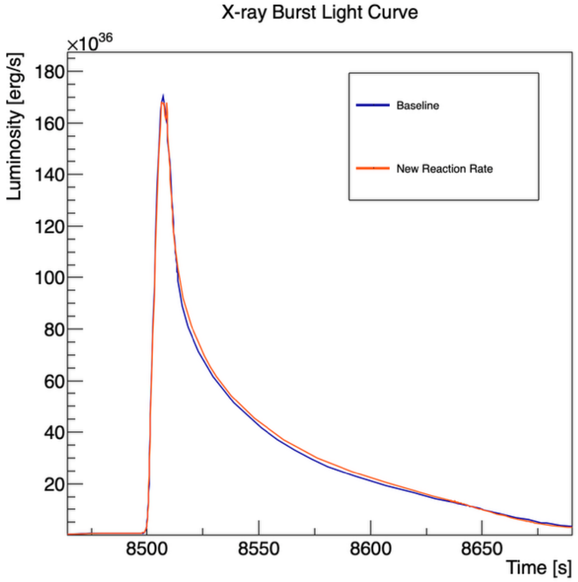
UIC

Saint Mary's University

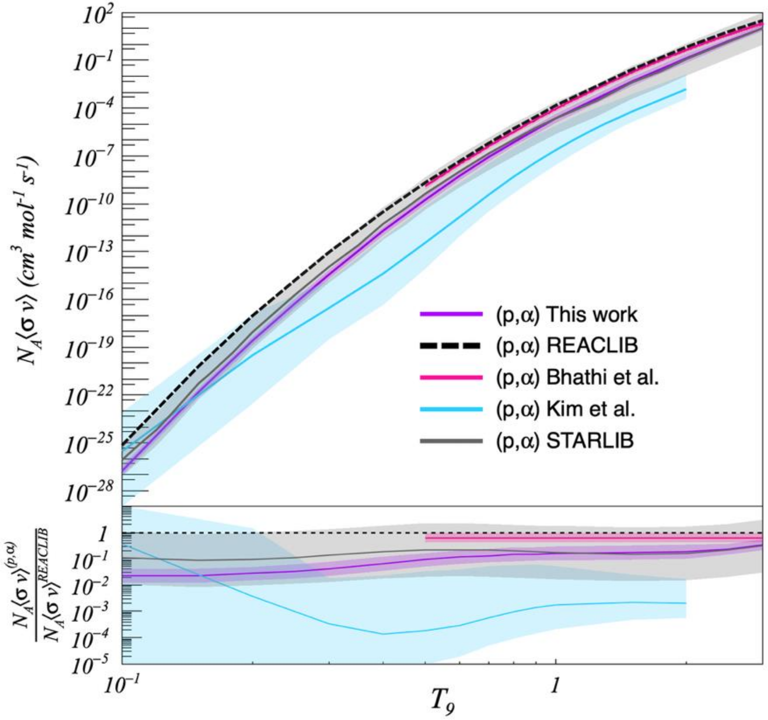
THANK YOU!

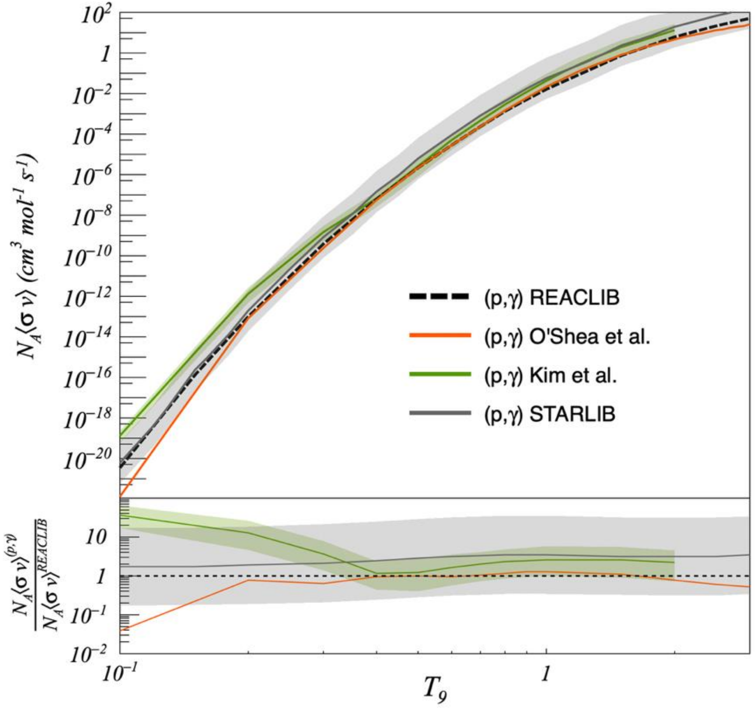
IMPACT ON X-RAY BURTS



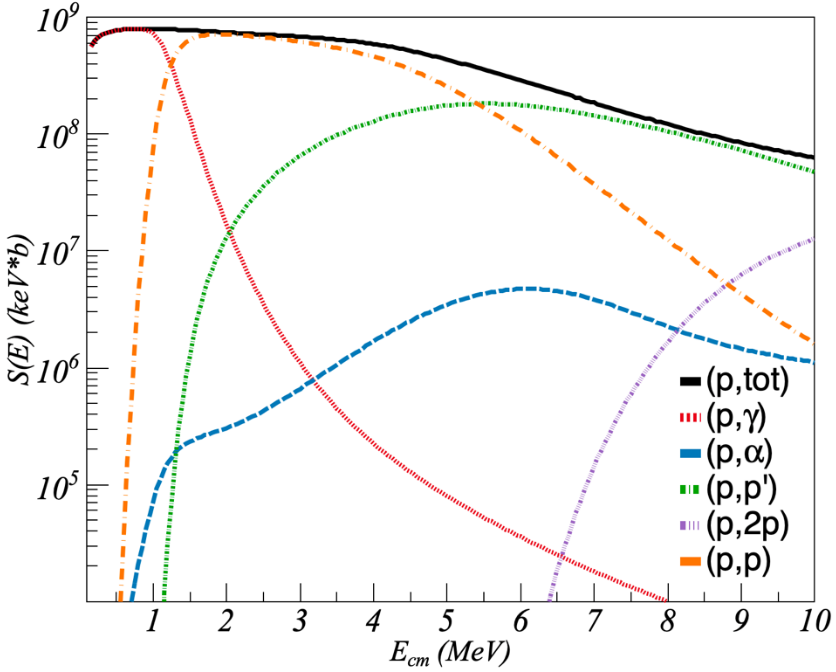


RATES COMPARISON

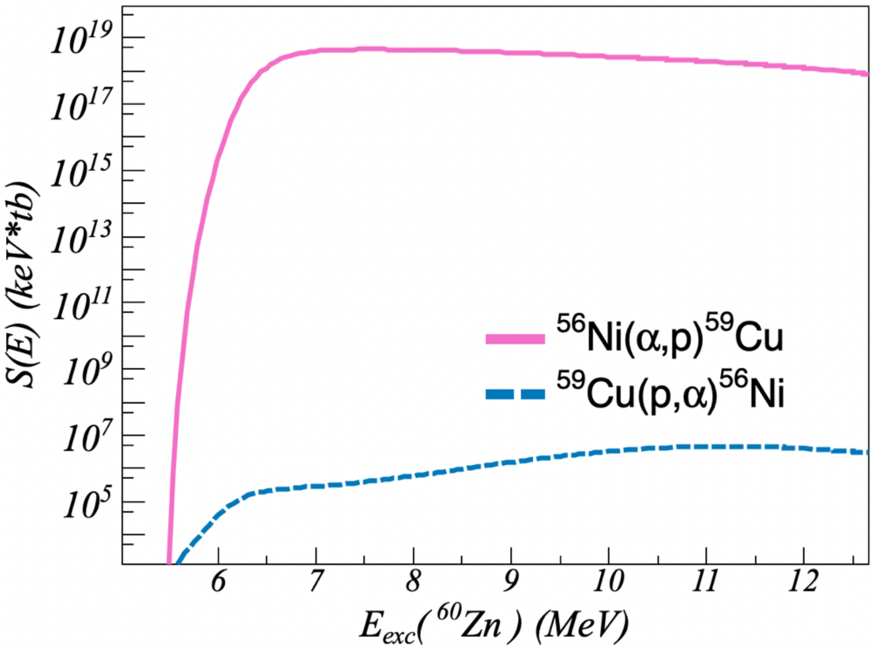




S-FACTOR



S(E) (keV*b)
10^9
10^8
10^7
10^6
10^5
1
2
3
4
5
6
7
8
9
10
E_cm (MeV)
(p,tot)
(p,γ)
(p,α)
(p,p')
(p,2p)
(p,p)



S(E) (keV*tb)
10^19
10^17
10^15
10^13
10^11
10^9
10^7
10^5
6
7
8
9
10
11
12
E_exc(60Zn) (MeV)
56Ni(α,p)59Cu
59Cu(p,α)56Ni