Experimental studies of key resonances for explosive hydrogen and helium burning

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Michigan State University and Facility for Rare Isotope Beams

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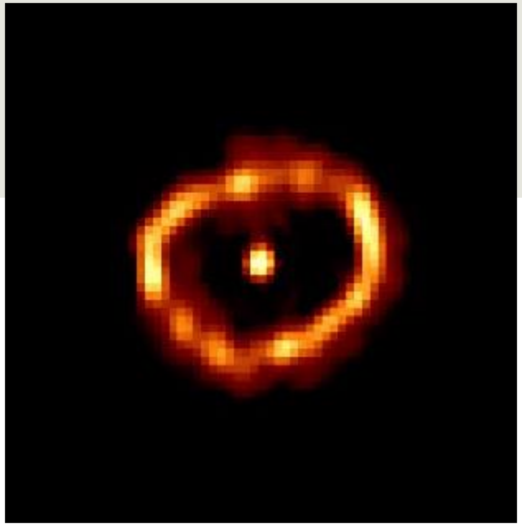
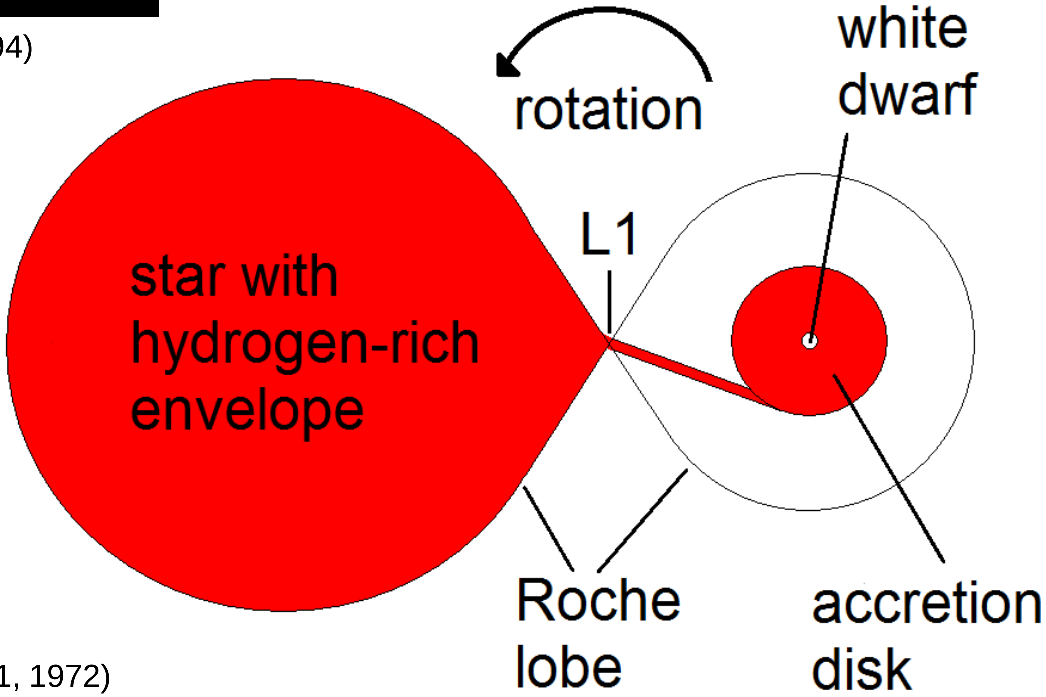
Outline

- **Thermonuclear charged particle reaction rates in novae and X-ray bursts**
- **Branching ratios for novae with the GADGET I system**
  - Experiment 17023 at NSCL: ^{22}Na(p,γ)^{23}Mg reaction using ^{23}Al β^+ decay
  - Experiment 17024 at NSCL: ^{30}P(p,γ)^{31}S reaction using ^{31}Cl β^+ decay
- **Lifetimes for novae with the Doppler Shift Lifetimes 1 and 2 systems**
  - Experiment S2193 at TRIUMF: ^{22}Na(p,γ)^{23}Mg reaction using ^{24}Mg(^{3}He,α)^{23}Mg reaction
  - Experiment S2373 at TRIUMF: ^{30}P(p,γ)^{31}S reaction using ^{32}S(^{3}He,α)^{31}S reaction
- **Branching ratios for X-ray bursts with the GADGET II systems**
  - Experiment 21072 at FRIB: ^{15}O(α,γ)^{19}Ne reaction using ^{20}Mg β^+p decay
  - Experiment 23035 at FRIB: ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reactions using ^{60}Ga β^+ decay
- **Lifetimes and branching ratios for X-ray bursts with a new PXCT system (to be named)**
  - Experiment to be proposed at FRIB: ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reactions using ^{60}Ga β^+ decay

Classical novae



Nova Cygni 1992 (in 1994)
NASA, ESA, HST




ABC NEWS

Nova explosion 3,000 light-years away will be seen from Earth with the naked eye

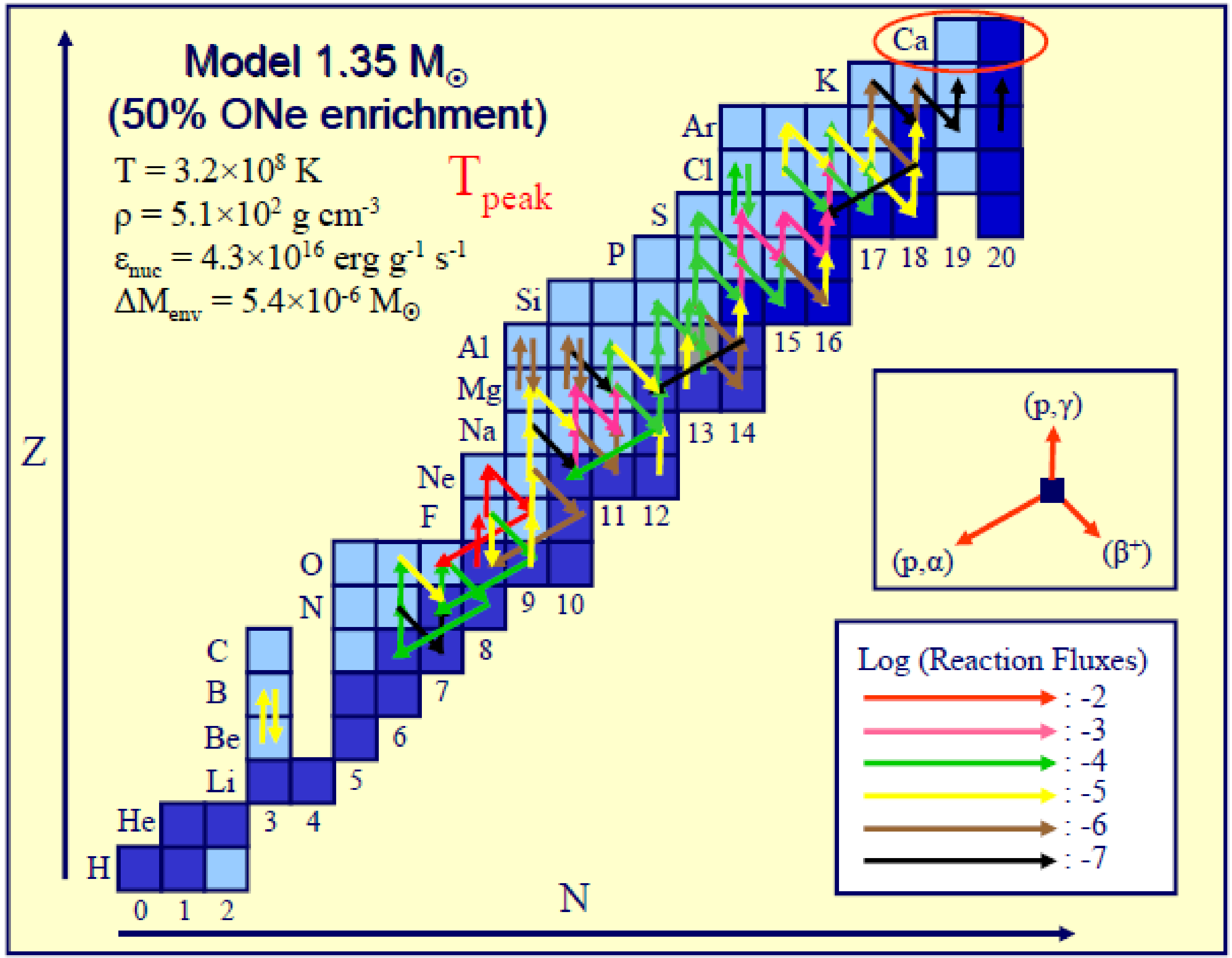
LEAH SARNOFF
July 31, 2024 · 4 min read

The last recorded outburst from T Coronae Borealis — which includes a hot, red giant star and a cool, white dwarf star — was in 1946, according to the space agency, which forecasts it will do so again before September 2024.

https://ca.news.yahoo.com/earth-soon-naked-eye-view-222113219.html

S. Starrfield *et al*., (1971, 1972)
J. Jose *et al*., Nucl. Phys **A777**, 550 (2006)

Nucleosynthesis in novae & nuclear uncertainties

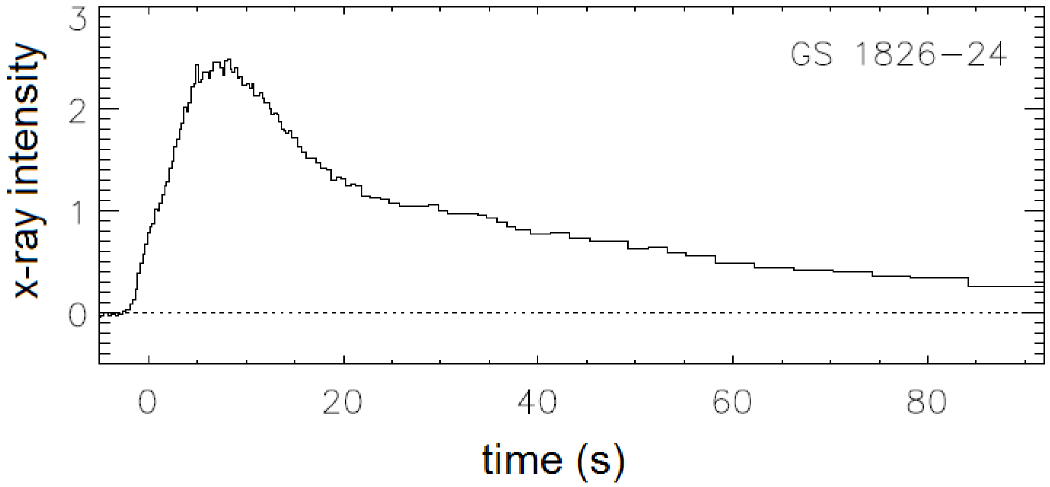


Handful of impactful reaction rate uncertainties remaining, including:

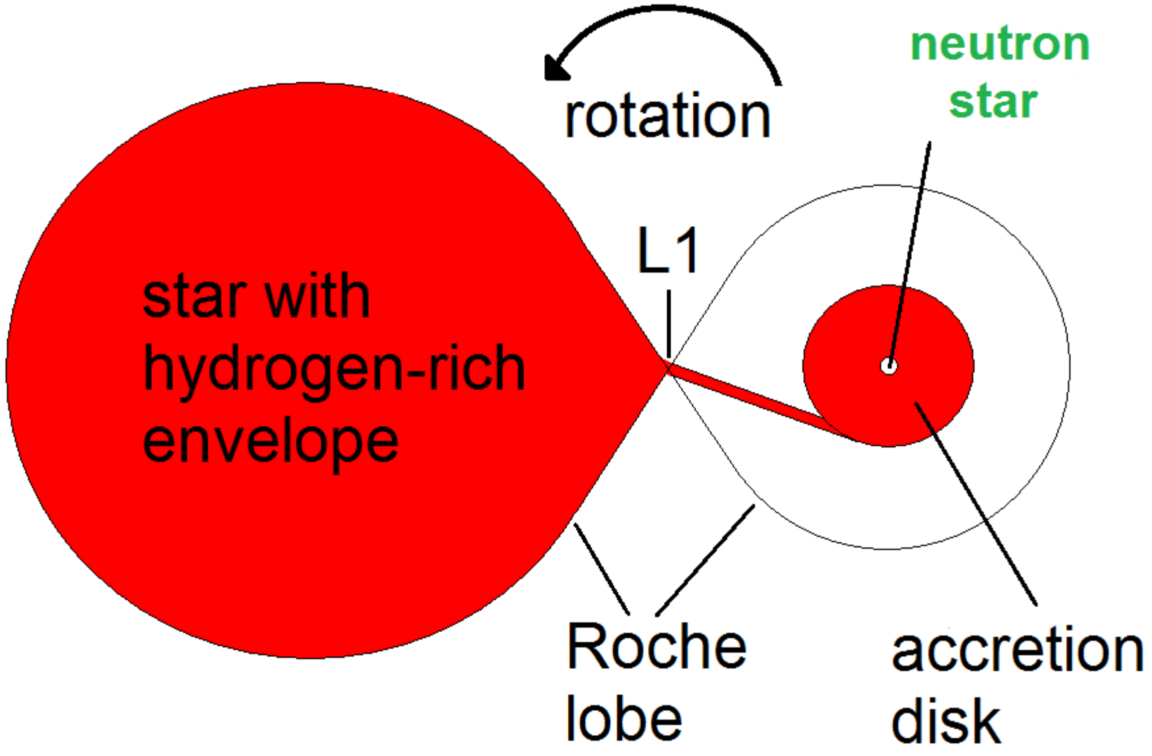
- Rate of $^{22}Na(p,\gamma)^{23}Mg$ affects modeling of ^{22}Na production in novae of interest to γ-ray line astronomy and Ne isotopic ratios in pre-solar nova grains
- Rate of $^{30}P(p,\gamma)^{31}S$ affects modeling of nucleosynthesis in the Si-Ca region: Si isotopic ratios in pre-solar nova grains; nova thermometers; nova mixing meters

J. Jose, Proceedings of Science, NIC XI 050 (2011)

X-ray burst

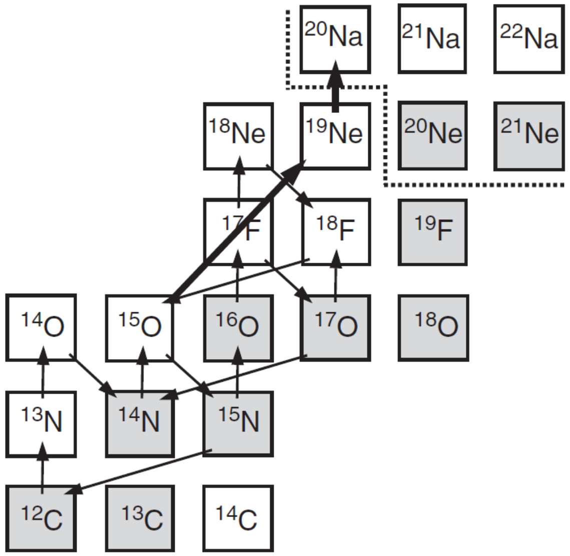


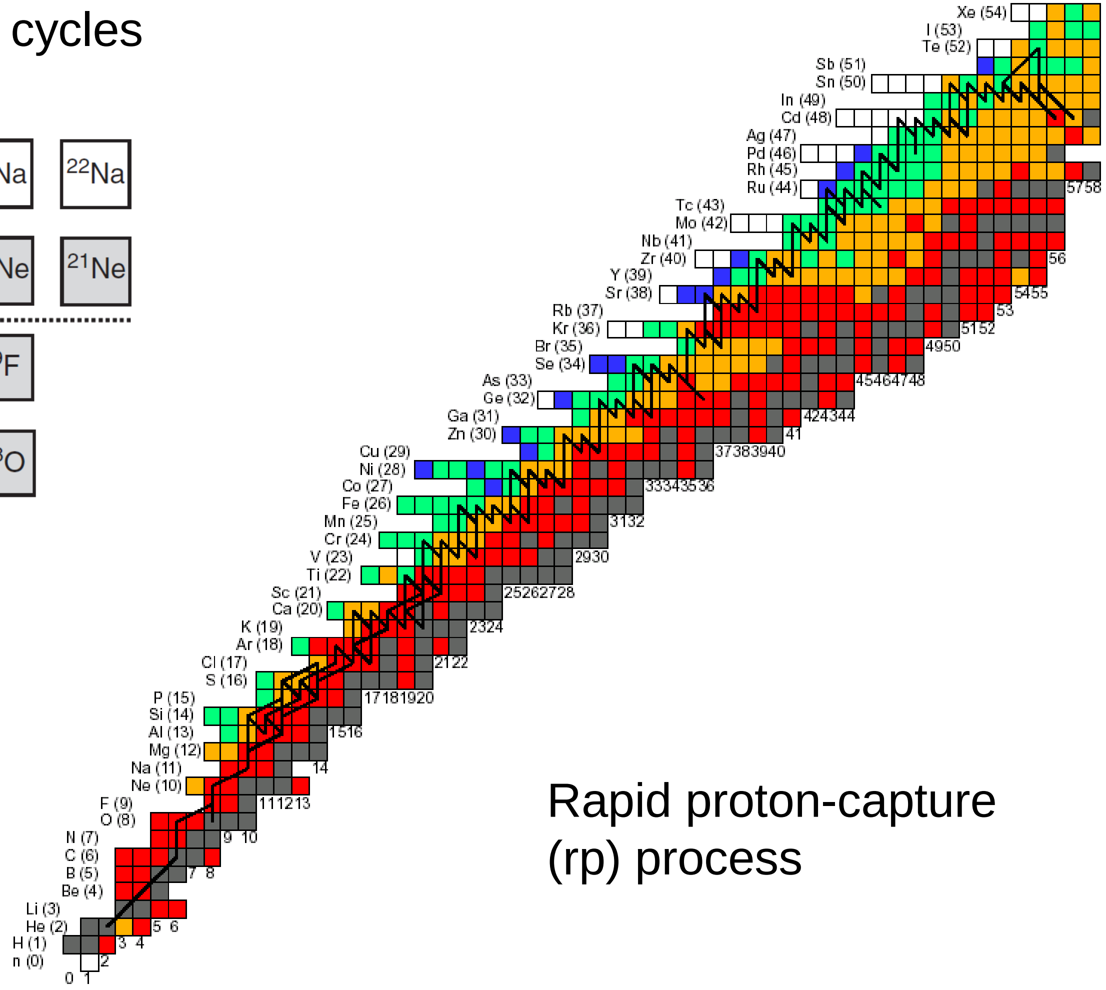
RXTE; Galloway *et al*., Astrophys. J. 179, 360 (2008)



Nucleosynthesis path in X-ray bursts

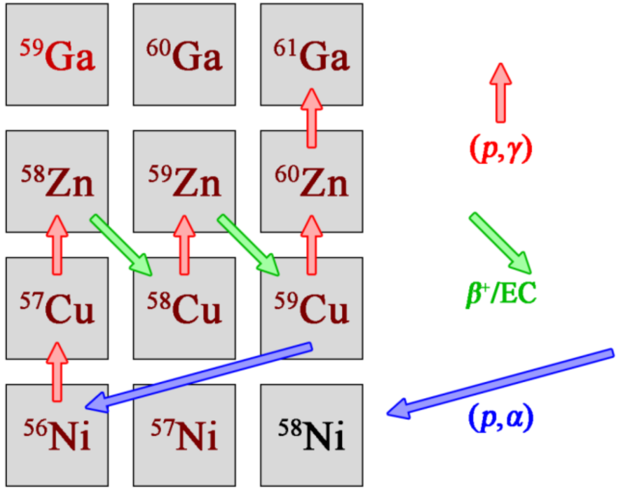
Break out from Hot CNO cycles





Rapid proton-capture (rp) process

NiCu cycle

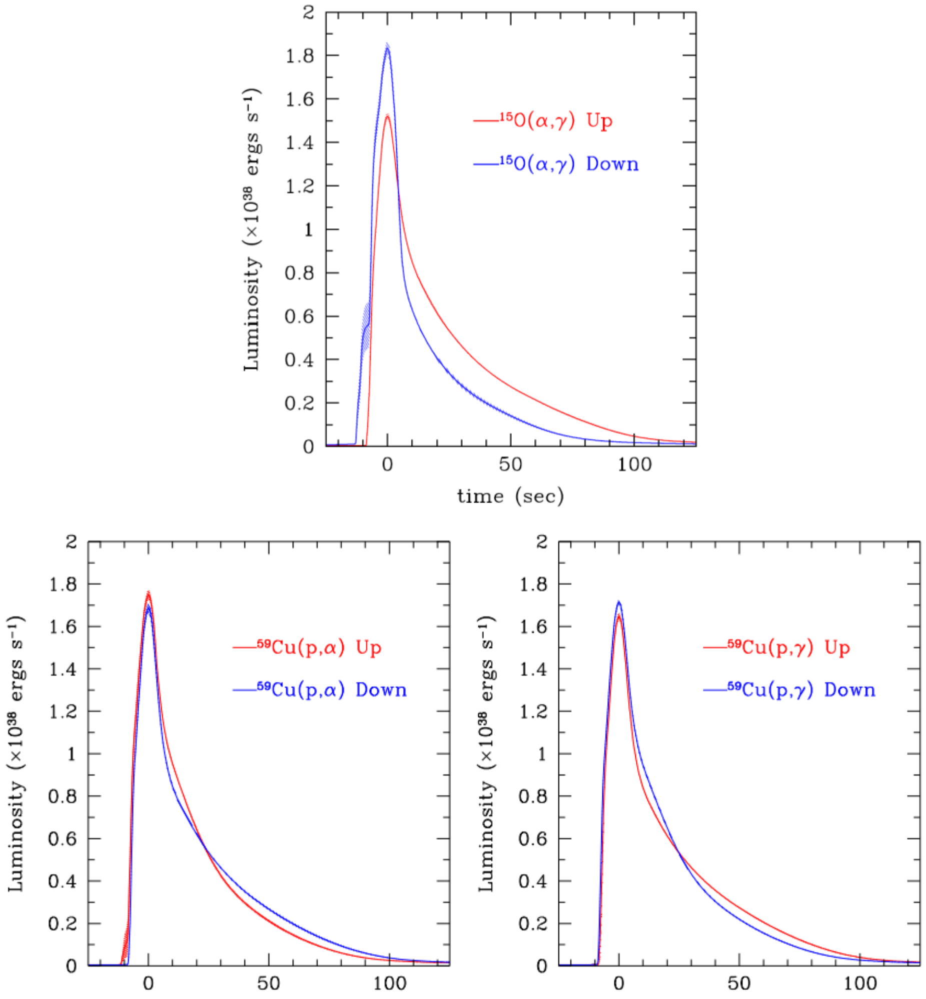


Figures: C. Iliadis, H. Schatz, L. Sun

Which reactions impact the X-ray burst light curve?

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

Rank	Reaction
1	$^{15}O(\alpha, \gamma)^{19}Ne$
2	$^{56}Ni(\alpha, p)^{59}Cu$
3	$^{59}Cu(p, \gamma)^{60}Zn$
4	$^{61}Ga(p, \gamma)^{62}Ge$
5	$^{22}Mg(\alpha, p)^{25}Al$
6	$^{14}O(\alpha, p)^{17}F$
7	$^{23}Al(p, \gamma)^{24}Si$
8	$^{18}Ne(\alpha, p)^{21}Na$
9	$^{63}Ga(p, \gamma)^{64}Ge$
10	$^{19}F(p, \alpha)^{16}O$
11	$^{12}C(\alpha, \gamma)^{16}O$
12	$^{26}Si(\alpha, p)^{29}P$
13	$^{17}F(\alpha, p)^{20}Ne$
14	$^{24}Mg(\alpha, \gamma)^{28}Si$
15	$^{57}Cu(p, \gamma)^{58}Zn$
16	$^{60}Zn(\alpha, p)^{63}Ga$
17	$^{17}F(p, \gamma)^{18}Ne$
18	$^{40}Sc(p, \gamma)^{41}Ti$
19	$^{48}Cr(p, \gamma)^{49}Mn$



Our experimental program focuses on the top three:

1. $^{15}O(\alpha,\gamma)^{19}Ne$
2. $^{59}Cu(p,\alpha)^{56}Ni$
3. $^{59}Cu(p,\gamma)^{60}Zn$

The same reactions also affect the ash composition

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

Thermonuclear resonant charged particle reaction rates

Thermonuclear reaction rate for narrow, isolated (p,γ) resonance:

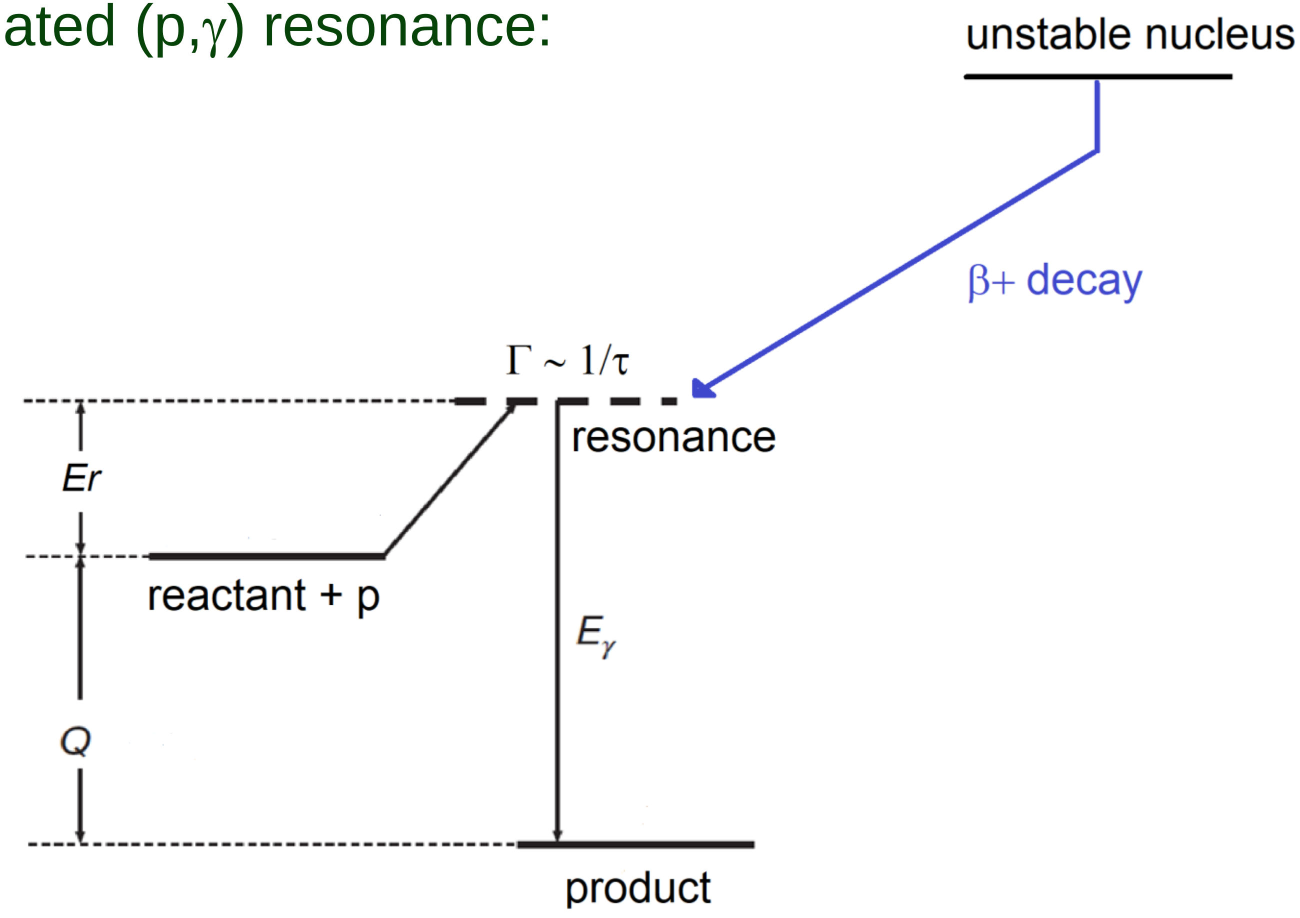
$$N_A\langle\sigma v\rangle \sim \omega\gamma e^{-E_r/kT}$$

Resonance strength:

$$\omega\gamma = \frac{(2J_{res}+1)}{(2J_{reac}+1)(2J_p+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma}$$

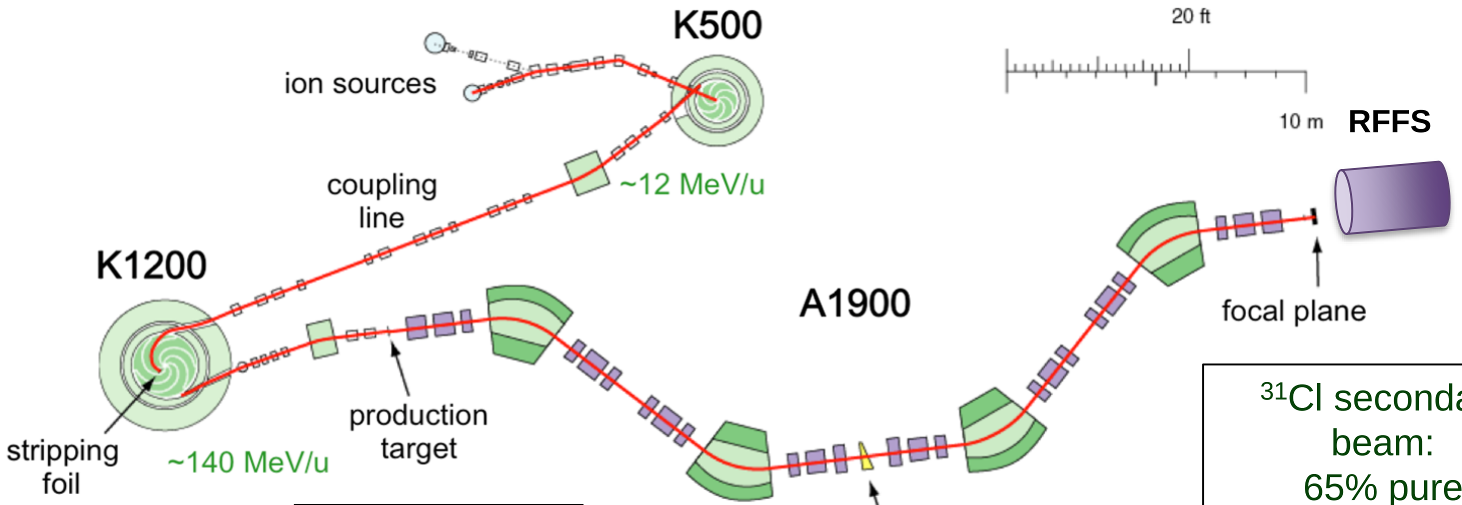
If $\Gamma_\gamma \gg \Gamma_p$, then $\omega\gamma \sim \frac{\Gamma_p}{\Gamma}\cdot\Gamma$

Need branching ratios and lifetimes



RIB production at NSCL and delivery to Gaseous Detector with Germanium Tagging (GADGET)

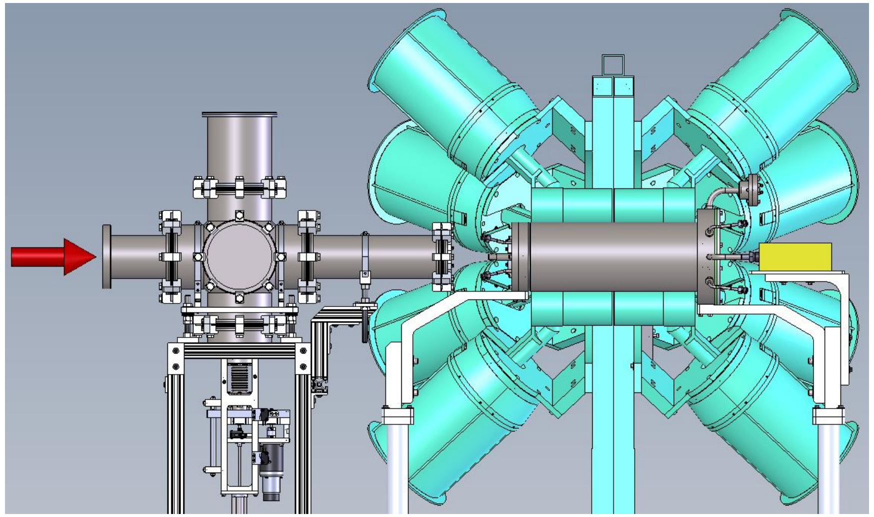
^{36}Ar primary beam:
150 MeV/u
75 *pnA*



^{9}Be target:
1645 mg/cm^2

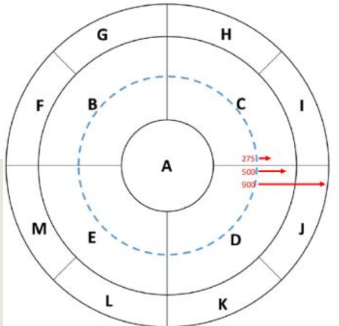
Al wedge: 300 mg/cm^2

^{31}Cl secondary
beam:
65% pure
6400 pps



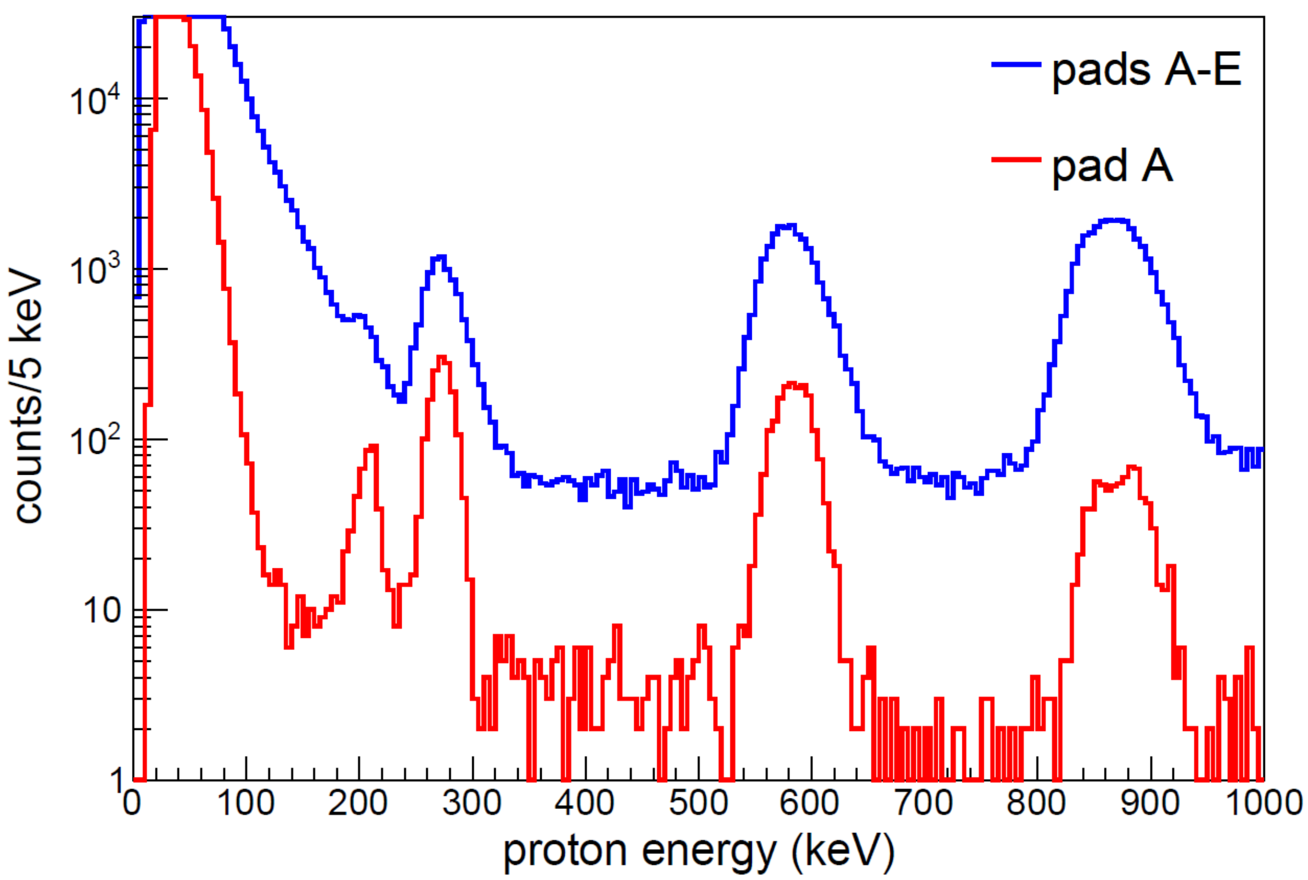
GADGET Main components:

1. Beam-energy degrader
2. Custom-designed and built gaseous “Proton Detector”
3. Existing Segmented Germanium Array (SeGA)



M. Friedman *et al*. NIM A 940, 93 (2019)

$^{23}Al(\beta p)^{22}Na$ GADGET spectrum and results



- GADGET value for 204-keV resonance is $I_p = (2.57 \pm 0.17) \times 10^{-4}$

→ First scientific measurement with GADGET

- GADGET value for 204-keV resonance is $\Gamma_p / \Gamma = (6.5 \pm 0.8) \times 10^{-3}$

→ Factor of 5 lower than most recent literature value

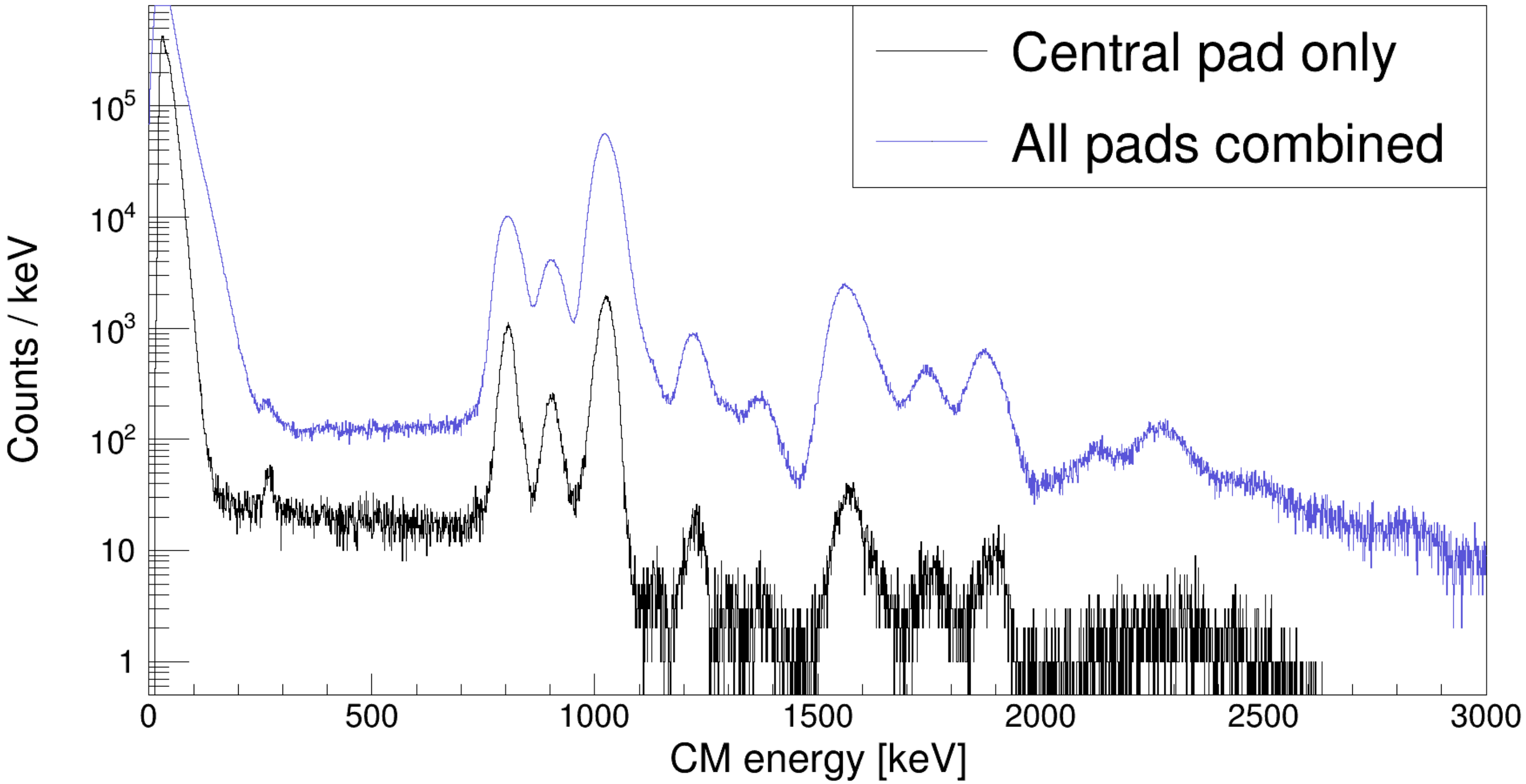
- Astrophysical impact

→ Inconsistencies between various direct and indirect measurements *increase* the uncertainty

→ Variation in predicted ^{22}Na yield increases to a factor of 3.8 corresponding to a factor of 2 in detectability distance

M. Friedman *et al.*, Phys. Rev. C 101, 052802(R) (2020)

$^{31}Cl(\beta p)^{30}P$ GADGET spectrum and results



- GADGET value for 260-keV resonance is $I_p = (8.3 \pm 1.0) \times 10^{-6}$

→ Lowest β-p intensity ever measured below 400 keV

- GADGET value for 260-keV resonance is $\Gamma_p / \Gamma = (2.9 \pm 0.6) \times 10^{-4}$

→ First measurement of tiny branching ratio for key resonance

- Astrophysical impact

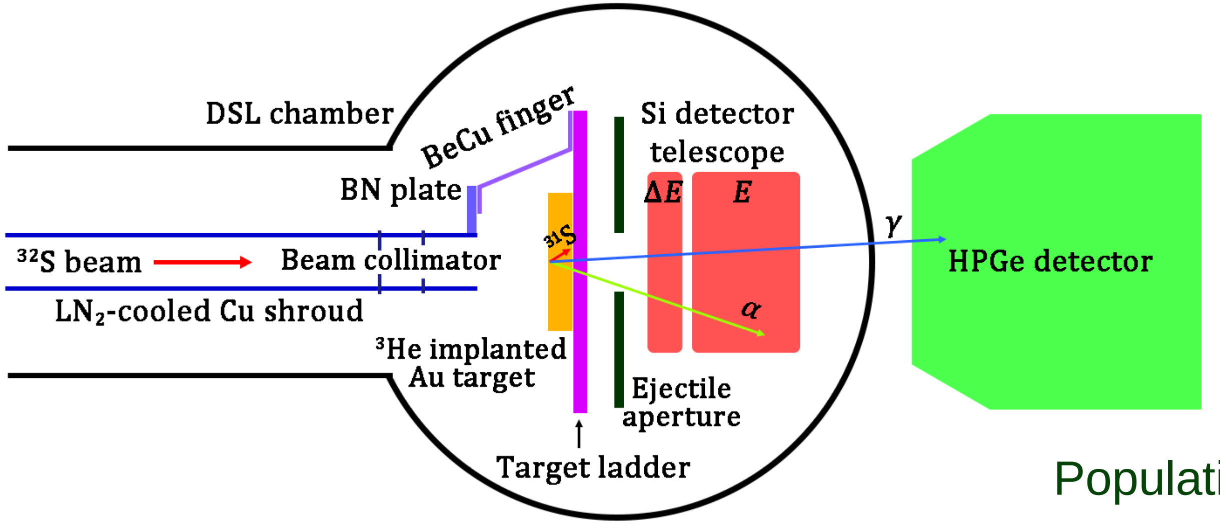
→ Calibrates nuclear thermometers for novae using elemental abundance ratios in ejecta

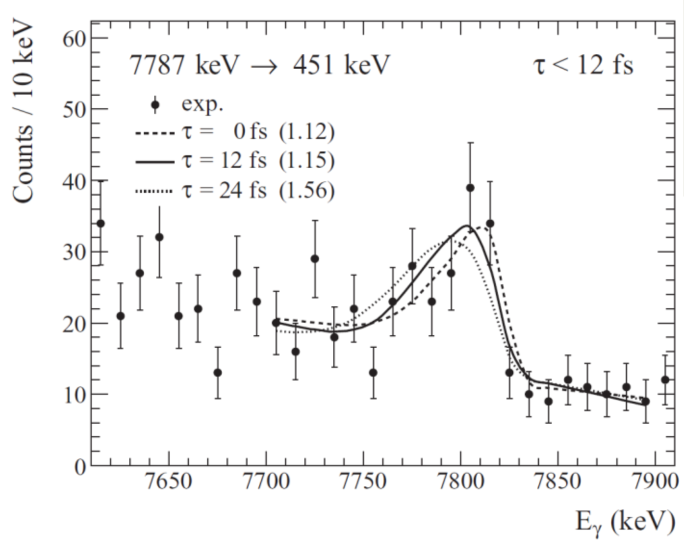
→ Identification of presolar nova grains in primitive meteorites by silicon isotopic ratios

T. Budner *et al.*, Phys. Rev. Lett. 128, 182701 (2022)
T. Budner, Ph.D. thesis (MSU, 2022)

Doppler Shift Lifetimes (DSL) @ TRIUMF ISAC-II

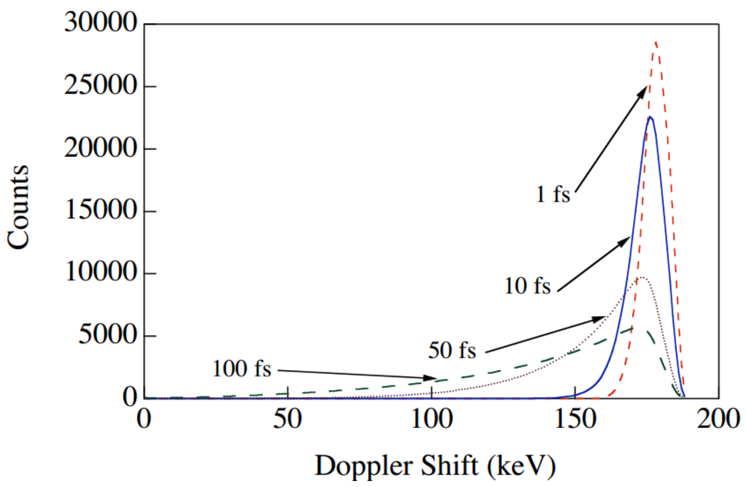
B. Davids, Hyperfine Interact. 225, 215 (2014)



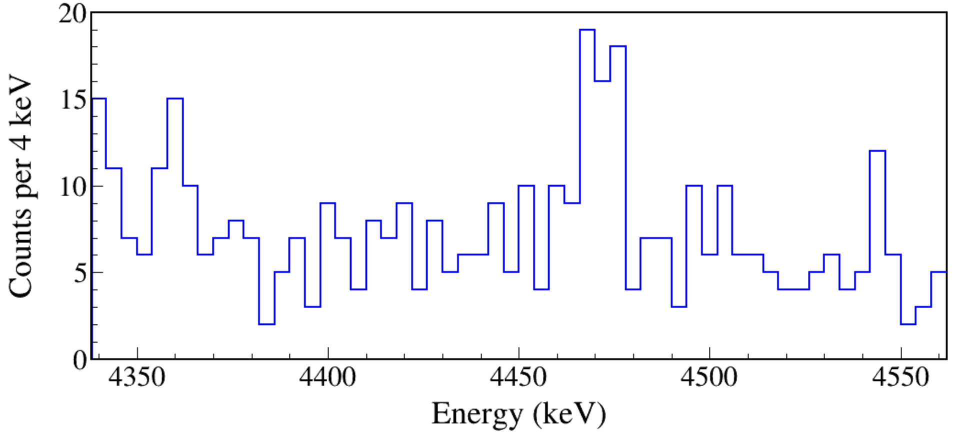


O. Kirsebom *et al.*, Phys. Rev. C 93, 025802(R) (2016)

12 fs lifetime upper limit for key $^{22}Na(p,\gamma)^{23}Mg$ resonance using $^{24}Mg(^3He,\alpha)^{23}Mg$

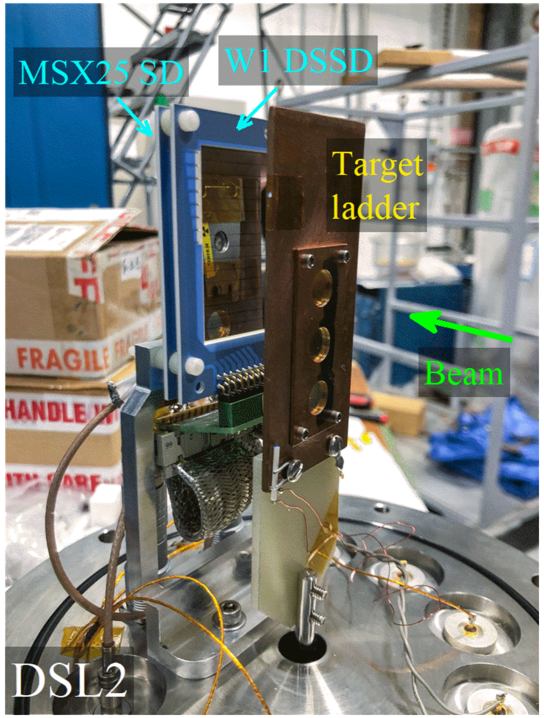


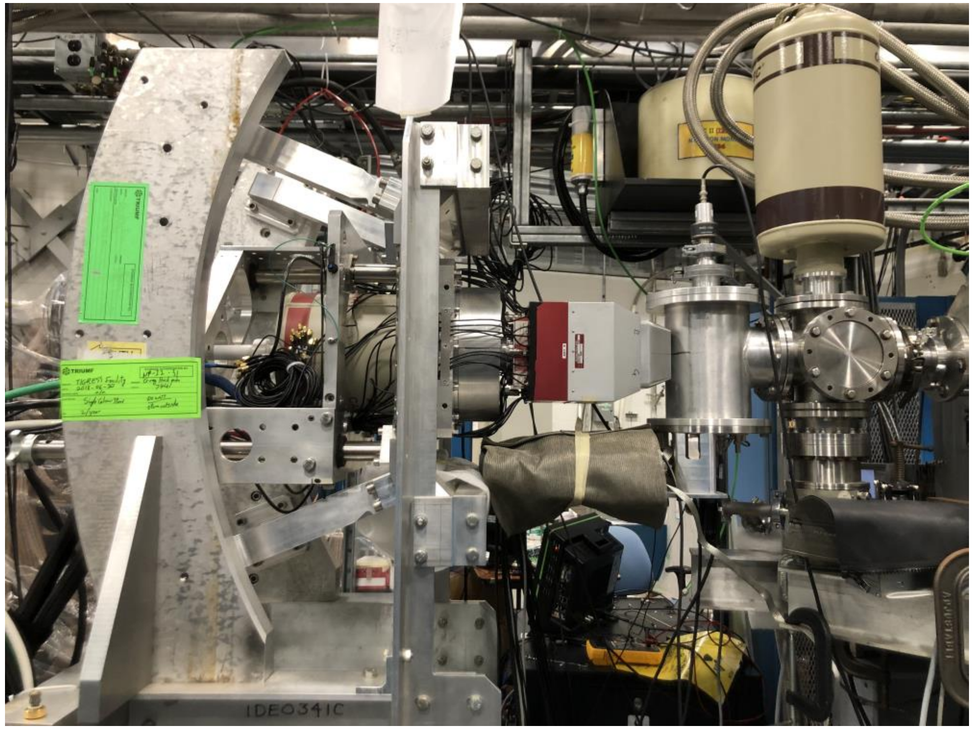
Population of key $^{22}Na(p,\gamma)^{23}Mg$ resonance using $^{31}S(^3He,\alpha\gamma)^{31}S$



L. Sun *et al.*, Phys. Lett. B 839, 137801 (2023)
C. Fry, PhD thesis (MSU, 2018)

Upgrade: DSL2 @ TRIUMF ISAC-II





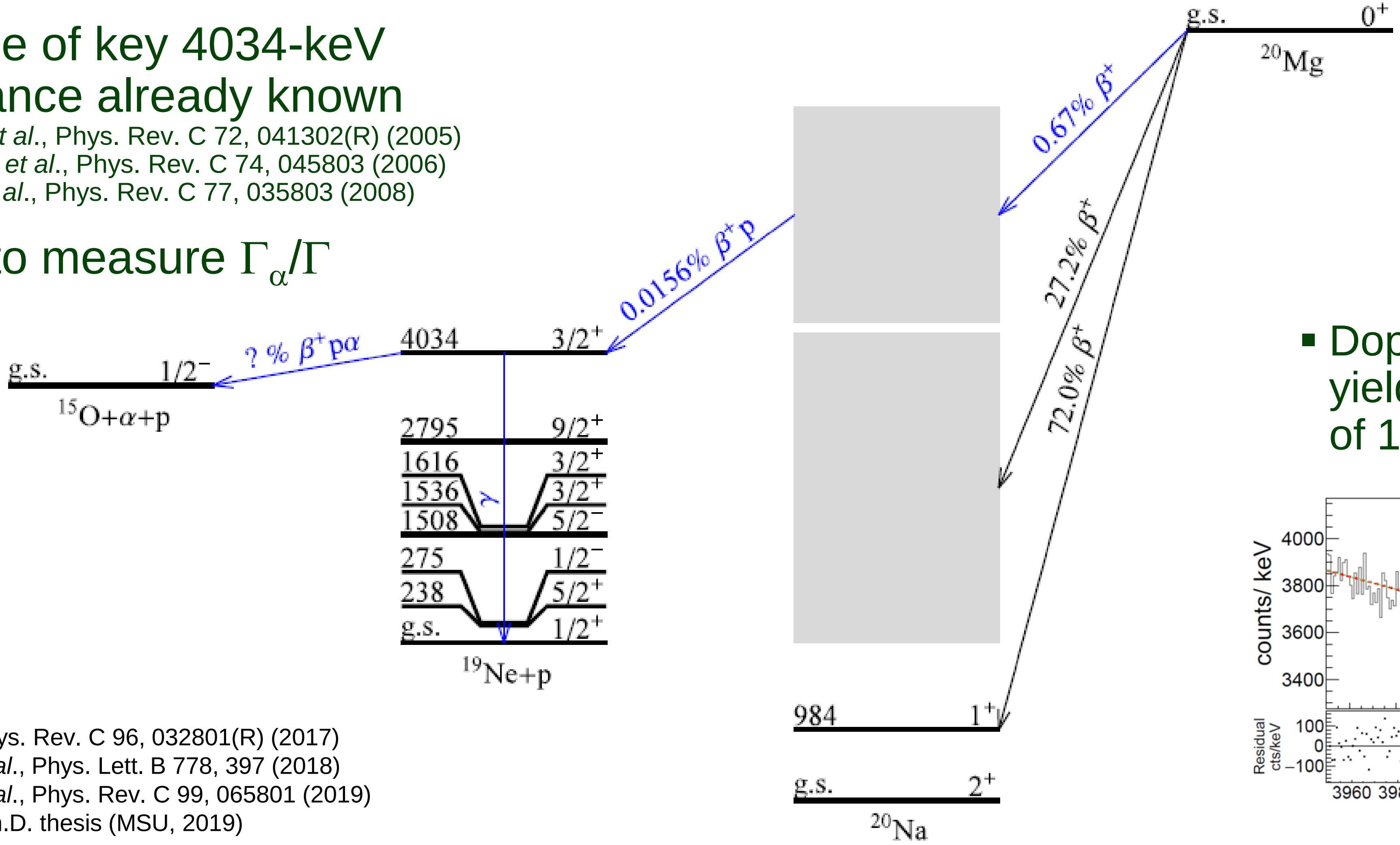
α detection efficiency ×11

γ detection efficiency ×1.3

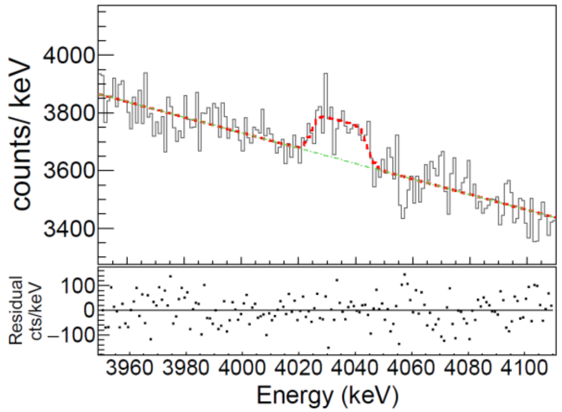
- 1st run of TRIUMF S2193 in 2022 to measure lifetime of key ^{23}Mg resonance demonstrated successful DSL2 operation; 2nd run soon
- TRIUMF S2373 approved to measure key ^{31}S resonance using DSL2; hoping for scheduling in 2025

β decay of ^{20}Mg to probe key ^{15}O(α,γ)^{19}Ne resonance

- Lifetime of key 4034-keV resonance already known
  W. P. Tan *et al.*, Phys. Rev. C 72, 041302(R) (2005)
  R. Kanungo *et al.*, Phys. Rev. C 74, 045803 (2006)
  S. Mythili *et al.*, Phys. Rev. C 77, 035803 (2008)
- Need to measure Γ_α/Γ

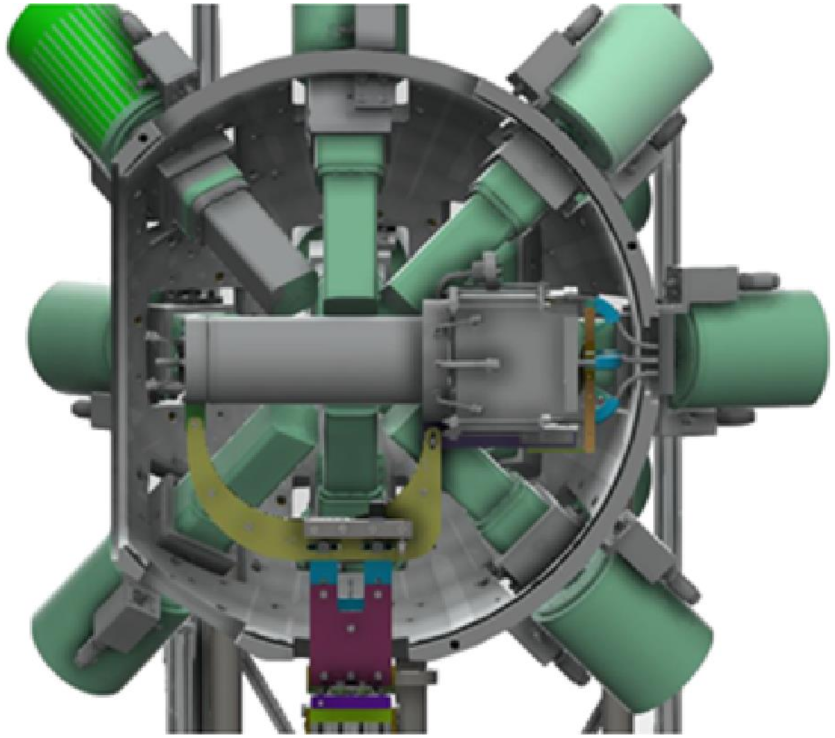


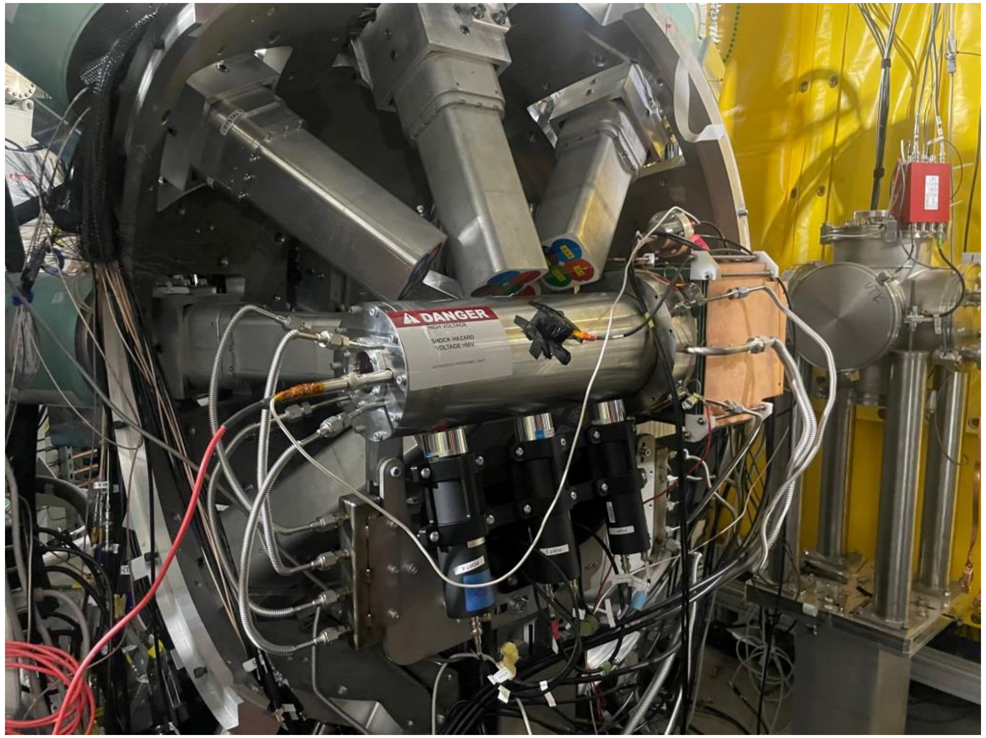
- Doppler technique yields proton energy of 1.2 ± 0.2 MeV



C. Wrede *et al.*, Phys. Rev. C 96, 032801(R) (2017)
B. E. Glassman *et al.*, Phys. Lett. B 778, 397 (2018)
B. E. Glassman *et al.*, Phys. Rev. C 99, 065801 (2019)
B. E. Glassman, Ph.D. thesis (MSU, 2019)

Gaseous Detector with Germanium Tagging II (GADGET II)



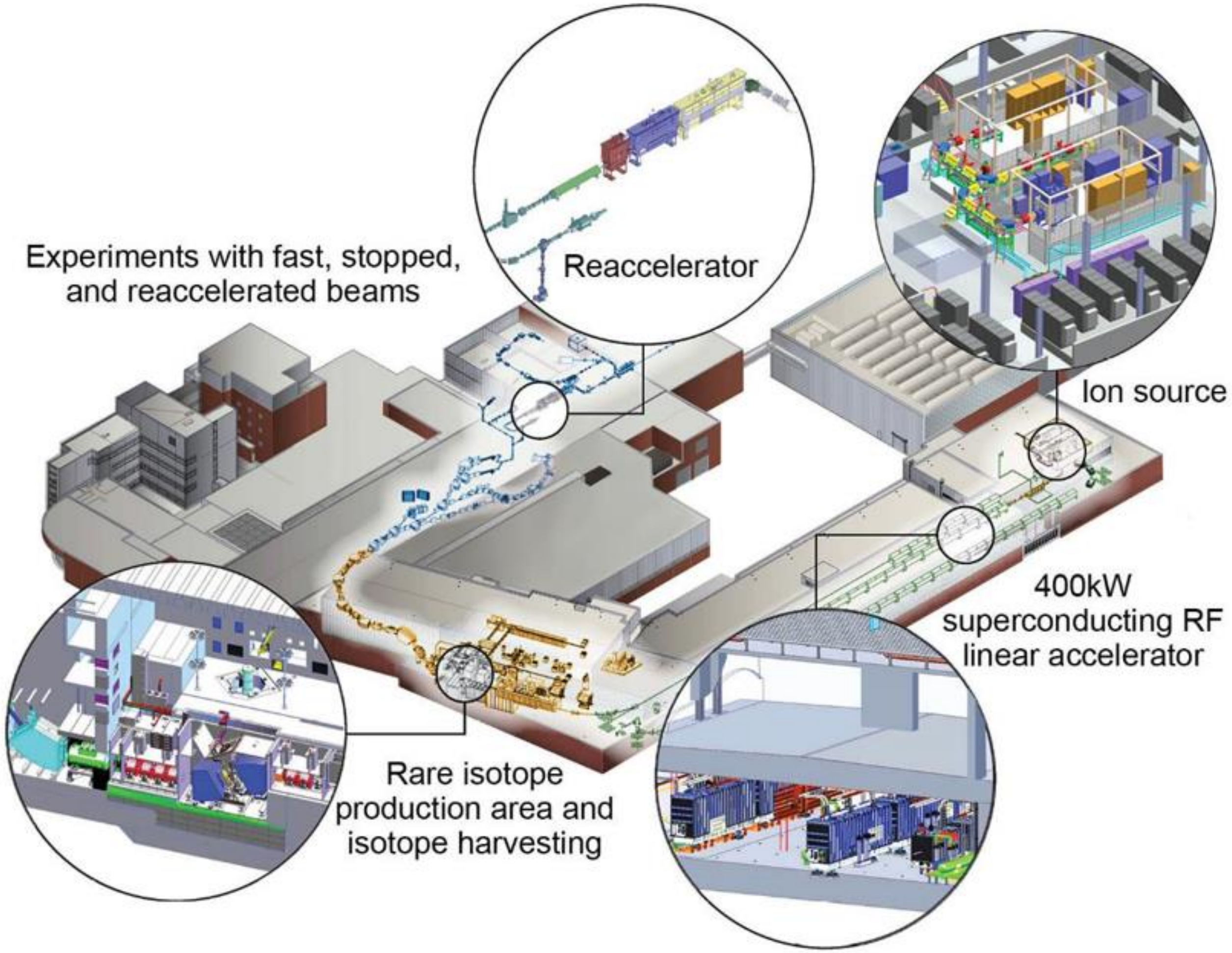


- Compact time projection chamber (TPC) surrounded by HPGe array (SeGA, DeGAi, PXCT, …)
- TPC can measure β^+ delayed charged particle tracks to identify particles and measure multi-particle emissions
- Operates at Facility for Rare Isotope Beams (FRIB)

R. Mahajan, T. Wheeler *et al.*, accepted in PRC, arXiv:2401.01904

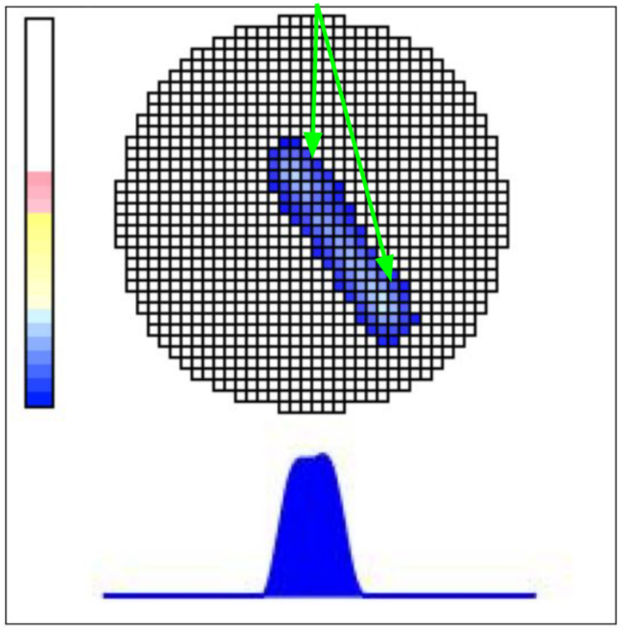
Facility for Rare Isotope Beams (FRIB)
A User Facility at Michigan State University

- Funded by U.S. Department of Energy with contributions and cost share from Michigan State University
- Serving over 1,400 users
- Key feature is 400 kW beam power for all ions (e.g. 5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Rapid development time for of any isotope
  - All elements and short half-half lives
  - Fast, stopped, and reaccelerated beams

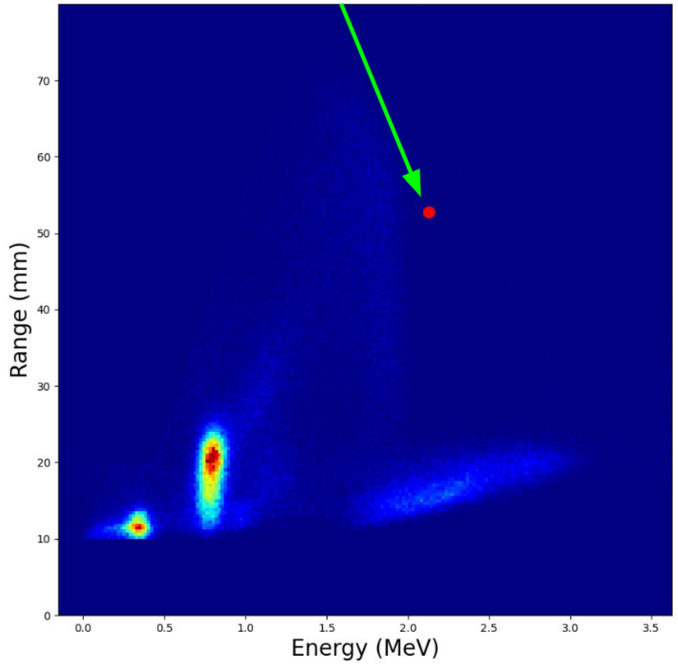


Example $^{20}Mg(\beta^{+}p\alpha)^{15}O$ Candidate Event of Interest (FRIB E21072, ran Nov. 2022)

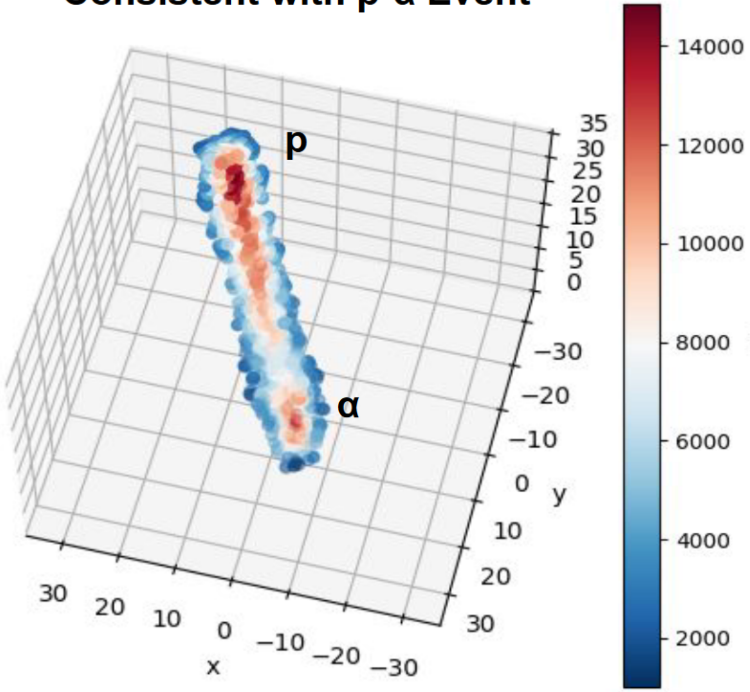
Double Bragg Peak



Event Lies in Region of Interest



3D Point Cloud Consistent with p-α Event

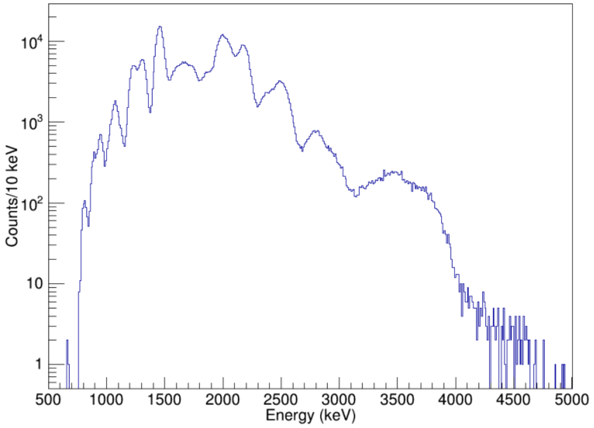


- Analysis is ongoing; search for candidates aided by machine learning
- Statistics 17 times lower than proposed to FRIB PAC1; impure beam with $^{21}Mg(\beta^{+}p\alpha)$ background
- Current effort is to quantify energy balance between p and α

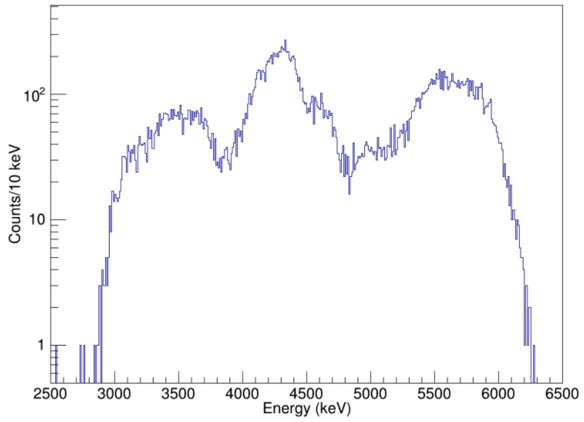
T. Wheeler, R. Mahajan *et al.*
T. Wheeler, PhD thesis (MSU, 2024)

Addressing ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reactions with GADGET II: FRIB Experiment 23035

- β^+ decay of ^{60}Ga to ^{60}Zn
- Goals: discover resonances in the competing ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reactions and determine their properties (*E*, and *p*, α, γ branches) for X-ray bursts
- Identical setup to E21072
- Approved by FRIB PAC2; likely to run in 2025



^{60}Ga(β^+p) simulation



^{60}Ga($\beta^+\alpha$) simulation

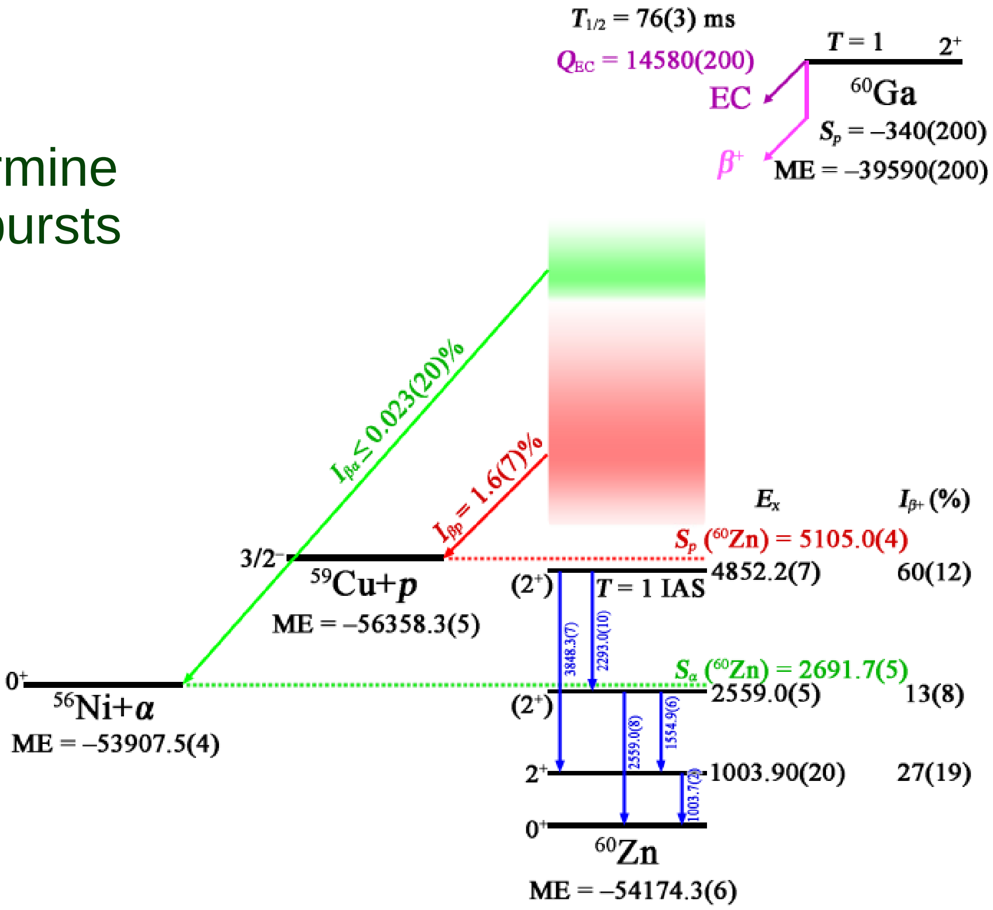
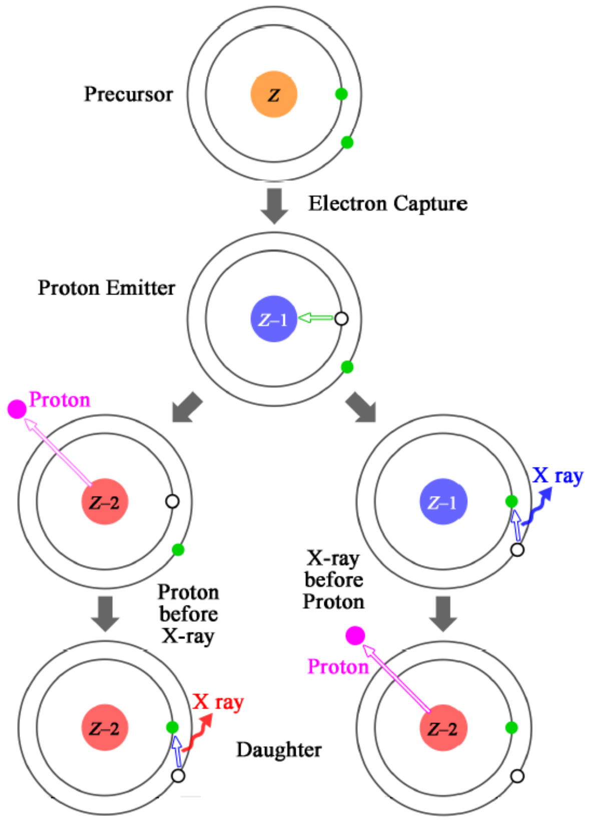


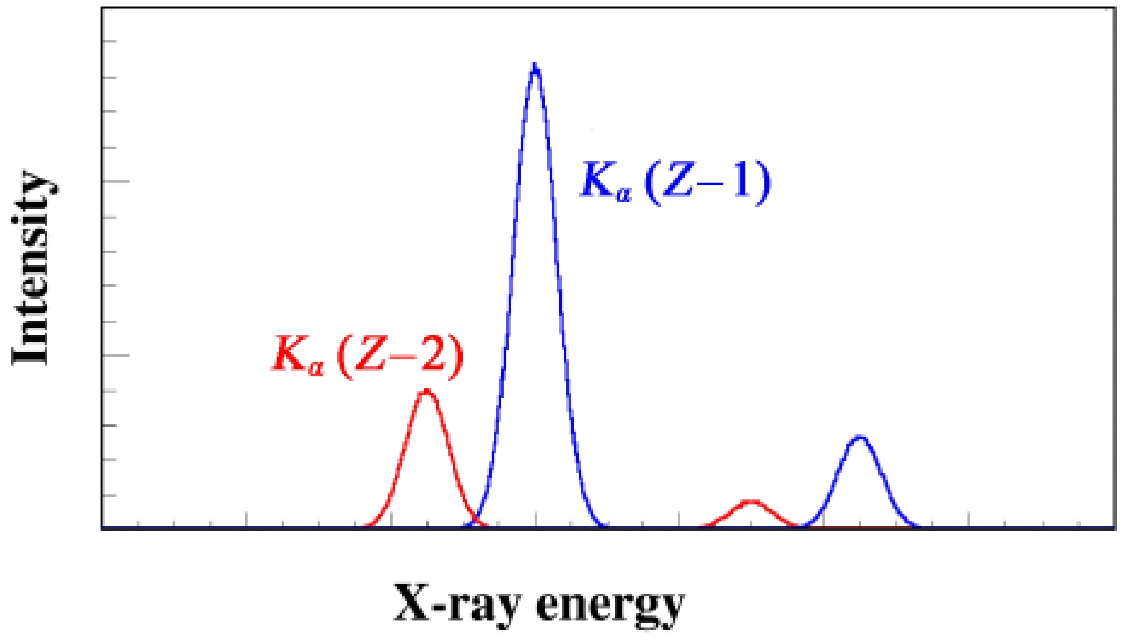
Image Credit: Lijie Sun
Simulations by A. Adams

Outlook for ^{59}Cu+p reactions: Particle X-ray Coincidence Technique (PXCT)

- PXCT was introduced in 1976 and is the only experimental technique available to measure nuclear excited state lifetimes in the 0.01-1.0 fs range



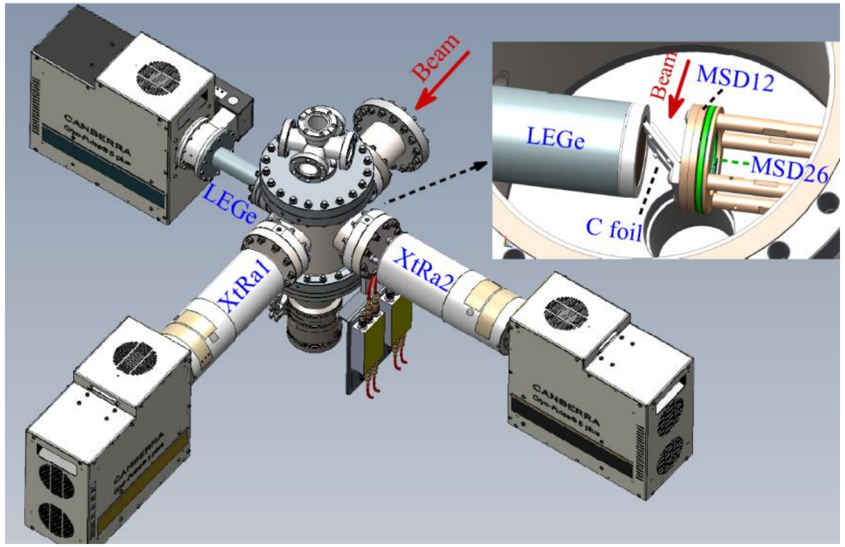
X-ray spectrum observed in coincidence with all delayed protons.

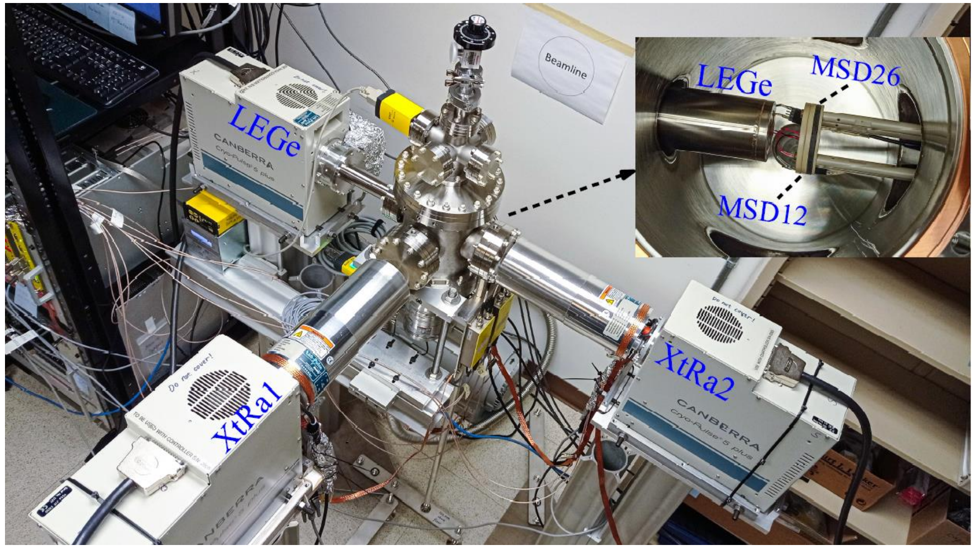


J. C. Hardy *et al.*, Phys. Rev. Lett. 37, 133 (1976)
Figures: L. Sun

Revival and extension of PXCT method at FRIB

- **Revival**: design and build PXCT setup at FRIB
- **Extension**: Measure lifetimes of *isolated* resonances using PXCT
- **Extension**: Measure p/α/γ branching ratios simultaneously
- **Extension**: Use information to calculate resonance strengths for nuclear astrophysics
- Flagship science case to be proposed to FRIB PAC: ^{60}Ga EC(β^+)$\rightarrow$ ^{60}Zn $\rightarrow$ ^{59}Cu + p (or ^{56}Ni + α)

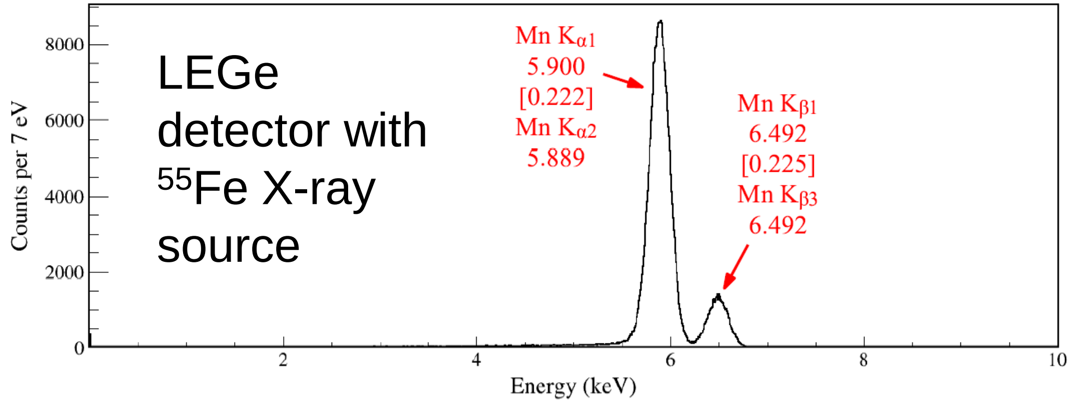


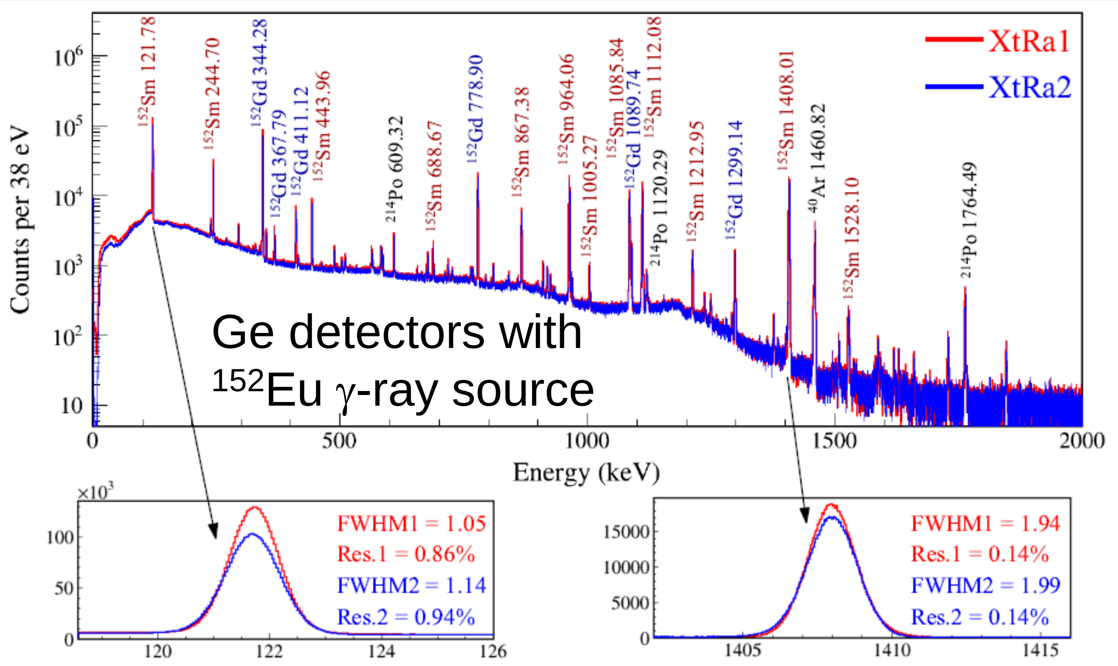


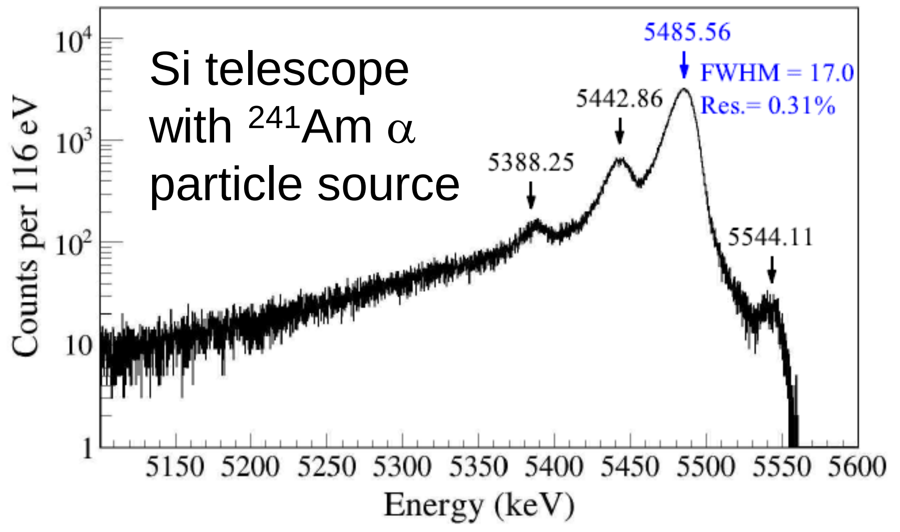
Figures: L. Sun

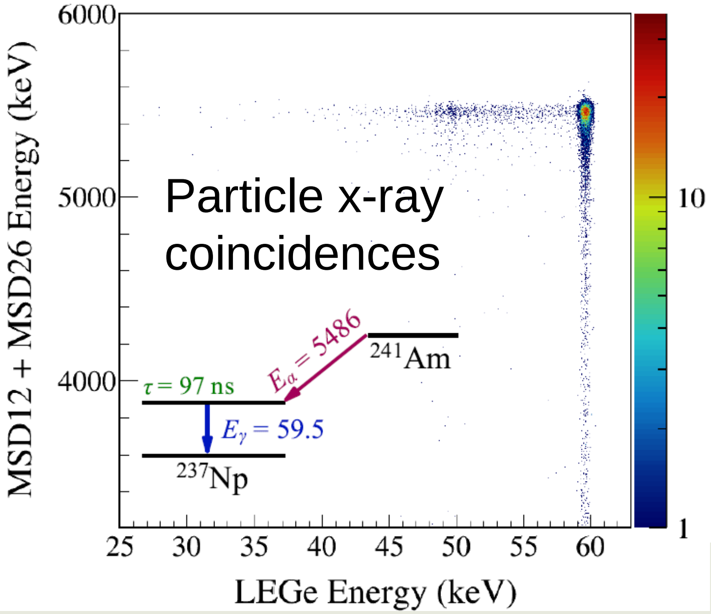
L. Sun, J. Dopfer *et al.*, to be submitted

PXCT system thoroughly tested with sources









L. Sun, J. Dopfer *et al.*, to be submitted

Summary and Outlook

- NSCL E17023 and E17024 with GADGET I: determined small proton branching ratio of key ^{22}Na(p,γ)^{23}Mg and ^{30}P(p,γ)^{31}S resonances using ^{23}Al and ^{31}Cl beta decay for novae
  [M. Friedman *et al*., Phys. Rev. C 101, 052802(R) (2020); T. Budner *et al*., PRL 128, 182701 (2022); T. Budner PhD thesis (MSU, 2022)]
- TRIUMF Experiments S2193 and S2373 with DSL2: Doppler Shift Attenuation Method to measure lifetimes of key ^{22}Na(p,γ)^{23}Mg and ^{30}P(p,γ)^{31}S resonances
  [L. Sun *et al*., Phys. Lett. B 839, 137801 (2023); C. Fry PhD thesis (MSU, 2018); L. Weghorn PhD in progress (MSU)]
- FRIB E21072 with GADGET II: β decay of ^{20}Mg to measure alpha branching ratio of key ^{15}O(α,γ)^{19}Ne resonance for X-ray bursts
  [Ran successfully in November 2022; data analysis approaching completion; T. Wheeler PhD thesis (MSU, 2024)]
- FRIB E23035 with GADGET II: β decay of ^{60}Ga to discover resonances in the competing ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reactions and determine their properties (E, and p, α, γ branches) for X-ray bursts
  [PAC2 approved and to be scheduled for 2025; A. Adams PhD in progress (MSU)]
- Development of PXCT system at FRIB: Lifetimes and branching ratios using electron capture and beta decay in one experiment: ^{60}Ga decay for ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reactions
  [System built and tested; technical manuscript L. Sun, J. Dopfer *et al*., to be submitted]

Thank you for your attention!