Hydrogen and Helium Burning in Type I X-ray Bursts: Experimental Results and Future Prospects

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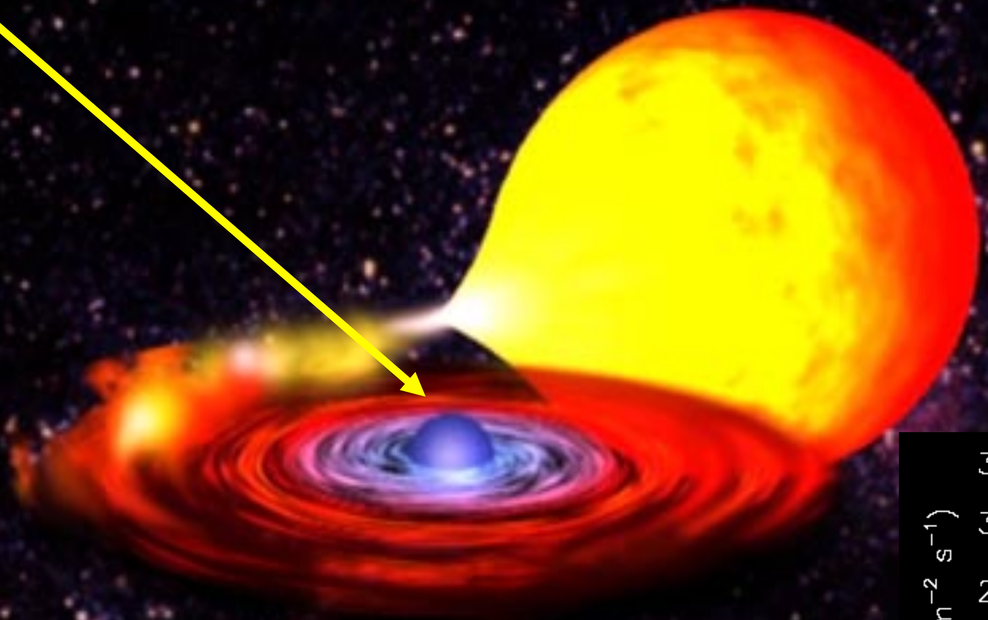
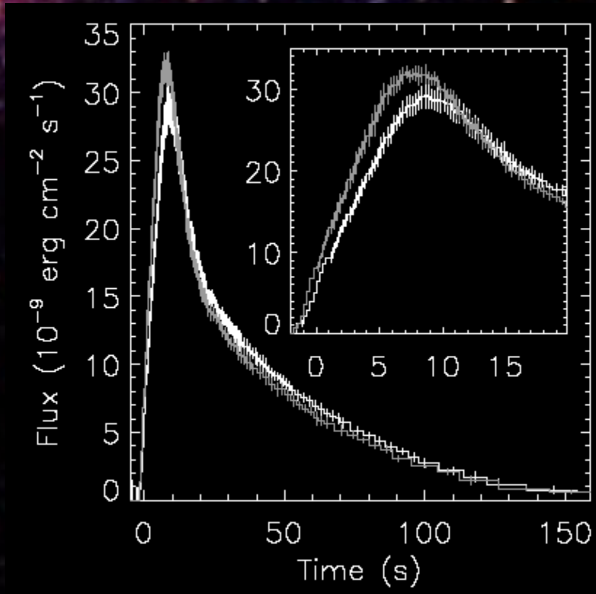
Type I X-Ray Bursts (XRBs)

Neutron stars:
1.4 M_o, 10 km radius

Normal star



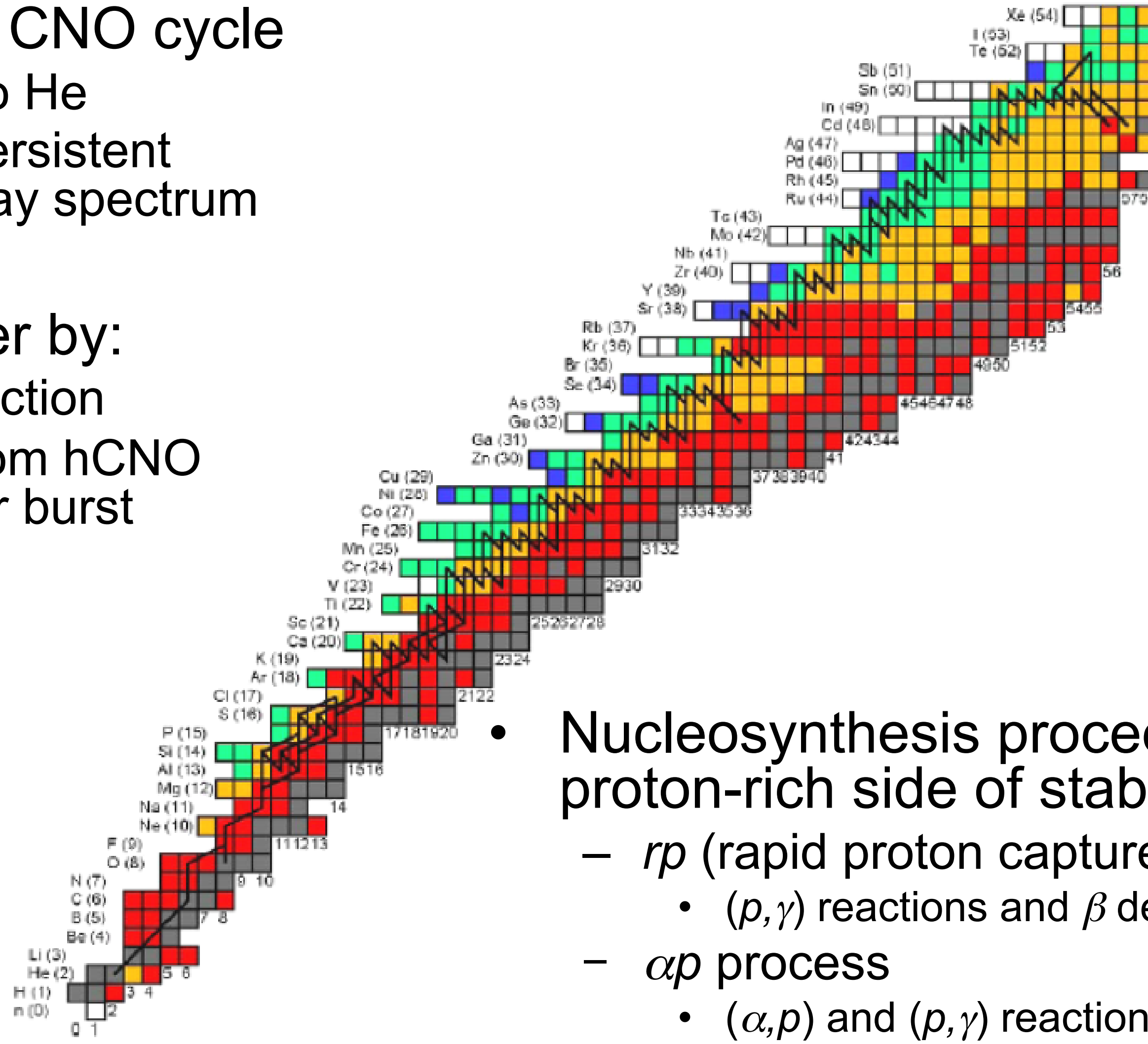
- Accretion rate ~ $10^{-8}/10^{-10}$ M_o/year
- Peak x-ray burst temperature ~ 1.5 GK
- Recurrence rate ~ hours to days
- Burst duration of 10 – 100 s
- Observed x-ray outburst ~10^{39} – 10^{40} ergs



D.K. Galloway et al., ApJ 601 466 (2004).

X-Ray Burst Nucleosynthesis

- Pre-burst hot CNO cycle
  - burns H into He
  - results in persistent thermal X-ray spectrum
- Burst is trigger by:
  - Triple-α reaction
  - breakout from hCNO cycle trigger burst
  - T ~10^8 K



H. Schatz, K. E. Rehm, NPA **777**, 601 (2006)

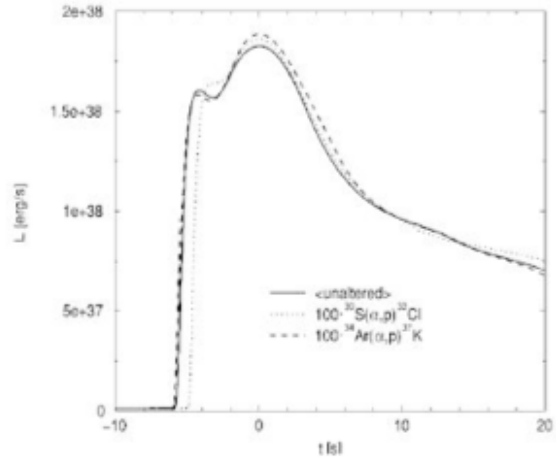
- Nucleosynthesis proceeds up proton-rich side of stability:
  - *rp* (rapid proton capture) process
    - (p,γ) reactions and β decays
  - αp process
    - (α,p) and (p,γ) reactions
  - peak temperatures of 1 – 2 GK

Modeling XRBs

- Reaction rates are crucial
  - determine flow of burst
  - effect energy output
  - influence final elemental abundances

- Theoretical rates used in models for almost all reactions
  - based on Hauser-Feshbach theory
  - level densities may be low for many resonant reactions

- Not all reactions are created equally!
  - thousands of reactions involving radioactive nuclei . . . where to focus efforts?
  - sensitivity studies give some direction, but may not be the full story



J.L. Fisker, *et al.*, ApJ (2004).

Table 19. Summary of the most influential nuclear processes, as collected from Tables 1–10. These reactions affect the yields of, at least, 3 isotopes when their nominal rates are varied by a factor of 10 up and/or down. See text for details.

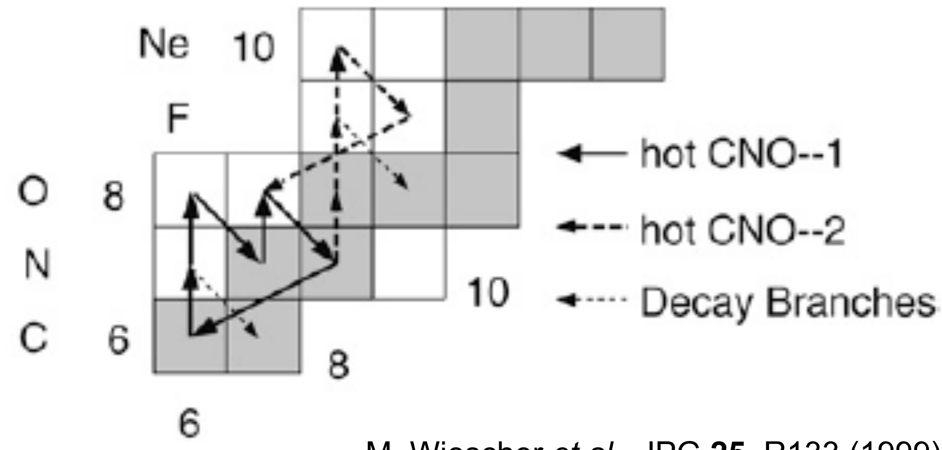
Reaction	Models affected
^{12}C(α, γ)^{16}O^{a}	F08, K04-B2, K04-B4, K04-B5
^{18}Ne(α, p)^{21}Na^{a}	K04-B1^{b}
^{25}Si(α, p)^{28}P	K04-B5
^{26g}Al(α, p)^{29}Si	F08
^{29}S(α, p)^{32}Cl	K04-B5
^{30}P(α, p)^{33}S	K04-B4
^{30}S(α, p)^{33}Cl	K04-B4^{b}, K04-B5^{b}
^{31}Cl(p, γ)^{32}Ar	K04-B1
^{32}S(α, γ)^{36}Ar	K04-B2
^{56}Ni(α, p)^{59}Cu	S01^{b}, K04-B5
^{57}Cu(p, γ)^{58}Zn	F08
^{59}Cu(p, γ)^{60}Zn	S01^{b}, K04-B5
^{61}Ga(p, γ)^{62}Ge	F08, K04-B1, K04-B2, K04-B5, K04-B6
^{65}As(p, γ)^{66}Se	K04^{b}, K04-B1, K04-B2^{b}, K04-B3^{b}, K04-B4, K04-B5, K04-B6
^{69}Br(p, γ)^{70}Kr	K04-B7
^{75}Rb(p, γ)^{76}Sr	K04-B2
^{82}Zr(p, γ)^{83}Nb	K04-B6
^{84}Zr(p, γ)^{85}Nb	K04-B2
^{84}Nb(p, γ)^{85}Mo	K04-B6
^{85}Mo(p, γ)^{86}Tc	F08
^{86}Mo(p, γ)^{87}Tc	F08, K04-B6
^{87}Mo(p, γ)^{88}Tc	K04-B6
^{92}Ru(p, γ)^{93}Rh	K04-B2, K04-B6
^{93}Rh(p, γ)^{94}Pd	K04-B2
^{96}Ag(p, γ)^{97}Cd	K04, K04-B2, K04-B3, K04-B7
^{102}In(p, γ)^{103}Sn	K04, K04-B3
^{103}In(p, γ)^{104}Sn	K04-B3, K04-B7
^{103}Sn(α, p)^{106}Sb	S01^{b}

A. Parikh *et al.*, ApJ SS (2008)

hCNO Breakout

- Interplay between triple-α reaction and breakout from hCNO trigger burst
  - $^{15}O(\alpha,\gamma)^{19}Ne$
  - $^{18}Ne(\alpha,p)^{21}Na$

- Multiple direct and indirect measurements of $^{18}Ne(\alpha,p)^{21}Na$, but large discrepancies exist

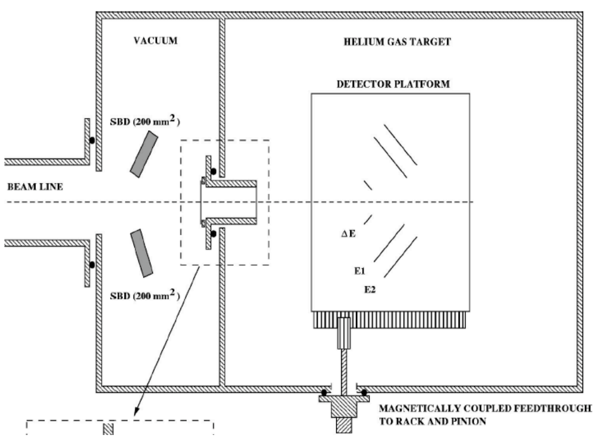


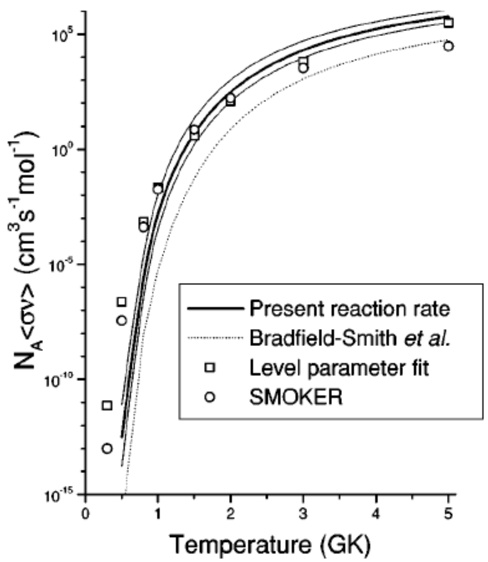
M. Wiescher *et al.*, JPG **25**, R133 (1999)

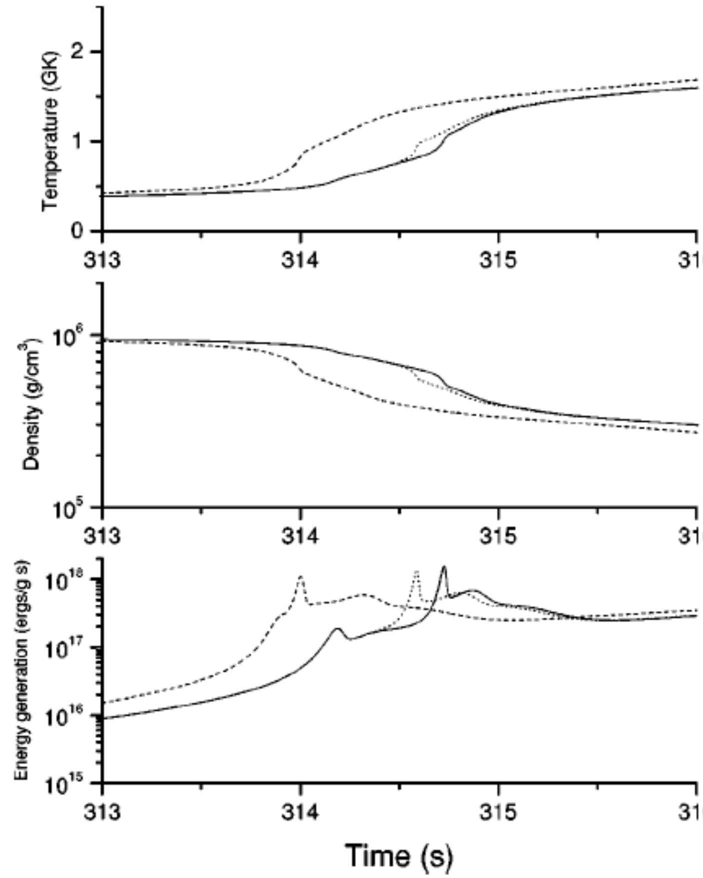
Direct Study of ^{18}Ne(α,p)^{21}Na

- Few direct measurements exist
  - lack of high intensity RIBs along path
  - difficulty with gas targets

- Direct ^{18}Ne(α,p)^{21}Na reaction measurement at Louvain-la-Neuve between E_{cm} = 1.7 - 2.6 MeV
  - shows delay of hCNO breakout



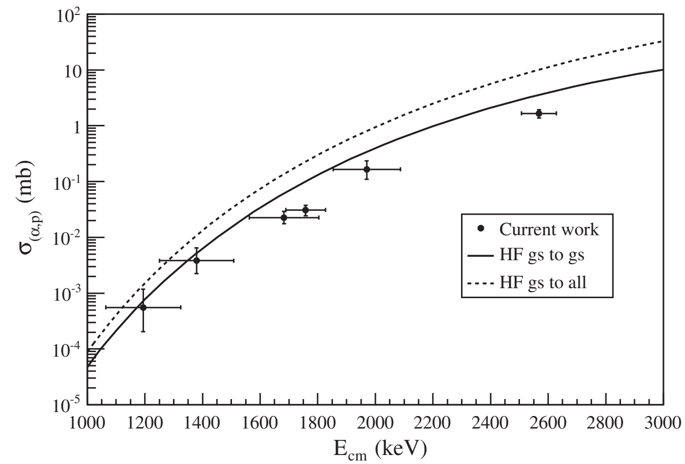




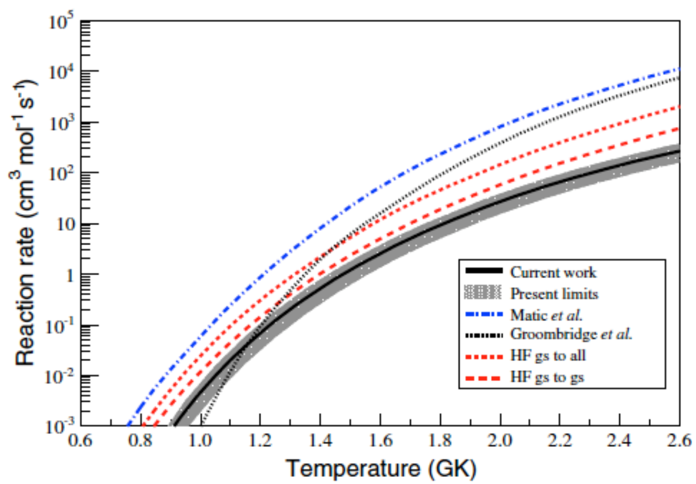
Groombridge *et al.*, PRC **66**, 055802 (2002)

Indirect ^{18}Ne(α,p)^{21}Na measurement

- Time inverse ^{21}Na(p,α)^{18}Ne reaction performed at TRIUMF laboratory
  - ^{21}Na beam at six energies
  - CH_2 target
  - $E_{cm}(\alpha,p)$ = 1.17 – 2.57 MeV



- Results:
  - cross sections lower than theoretical calculations
  - lower rate leads to delay of breakout and higher temperatures at breakout point



P. J. C. Salter *et al*, PRL**108**, 242701 (2012)

hCNO Breakout

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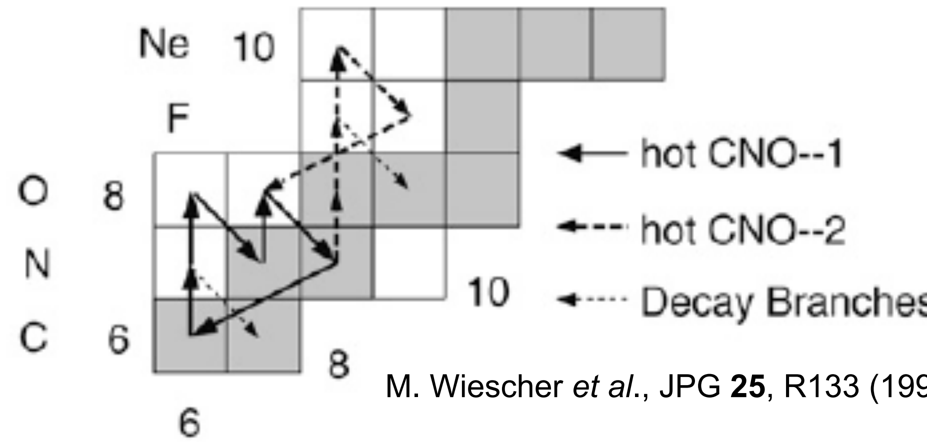
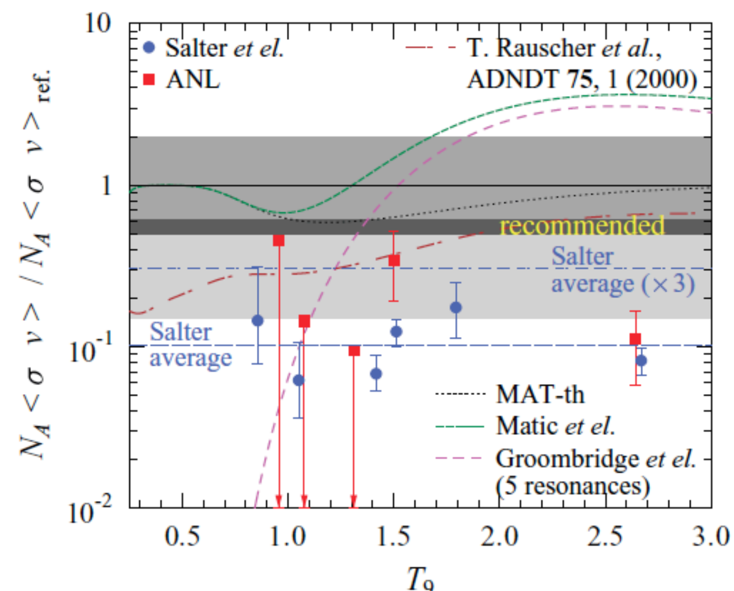


M. Wiescher *et al.*, JPG **25**, R133 (1999)

$E_{\text{eff}}(\alpha,p)$ (MeV)	Exponent for σ (mb)	σ_{exp}	Ref.	$\bar{\sigma}_{\text{ref.}}$	$\sigma_{\text{exp}}/\bar{\sigma}_{\text{ref.}}$
1.194 ± 0.130	10^{-4}	$5.5^{+6.2}_{-3.5}$	SAL	37.8	$0.145^{+0.164}_{-0.067}$
1.379 ± 0.129	10^{-3}	$3.8^{+2.7}_{-1.6}$	SAL	61.6	$0.062^{+0.044}_{-0.026}$
1.683 ± 0.121	10^{-2}	$2.3^{+0.7}_{-0.5}$	SAL	33.7	$0.068^{+0.021}_{-0.015}$
1.758 ± 0.069	10^{-2}	3.1 ± 0.6	SAL	25.1	0.124 ± 0.024
1.970 ± 0.117	10^{-1}	$1.7^{+0.7}_{-0.6}$	SAL	9.7	$0.175^{+0.073}_{-0.062}$
2.568 ± 0.061	10^{0}	1.7 ± 0.3	SAL	20.7	0.082 ± 0.015
1.748 ± 0.077	10^{-2}	$7.5^{+3.8}_{-3.3}$	ANL	22.0	$0.341^{+0.173}_{-0.150}$
2.551 ± 0.077	10^{0}	$2.0^{+1.0}_{-0.9}$	ANL	17.8	$0.111^{+0.056}_{-0.053}$

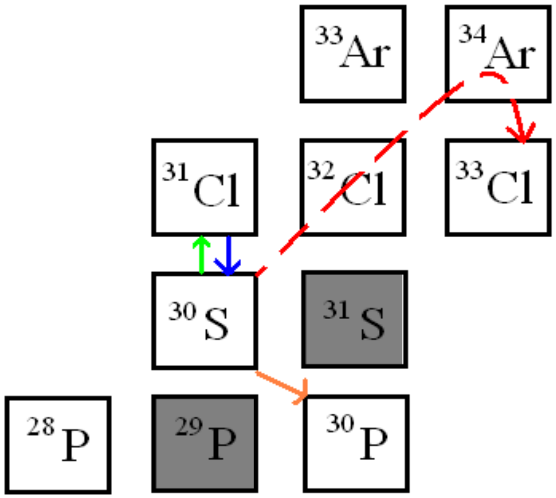


P. Mohr and A. Matic, PRC **87**, 035801 (2013)

Waiting point in XRBs

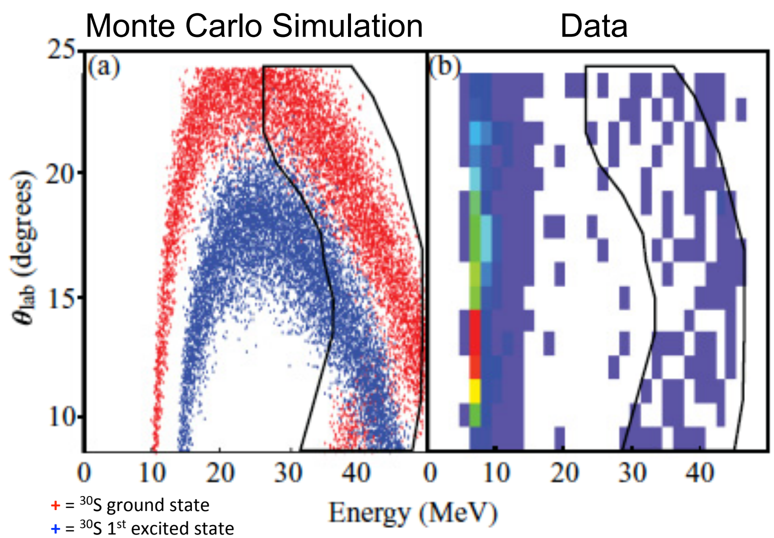
- (α,p) process waiting points affect energy generation near the beginning of XRB nucleosynthesis final elemental abundances luminosity profile

- Possible (α,p) process waiting points
  - ^{22}Mg
  - ^{26}Si
  - ^{30}S
  - ^{34}Ar

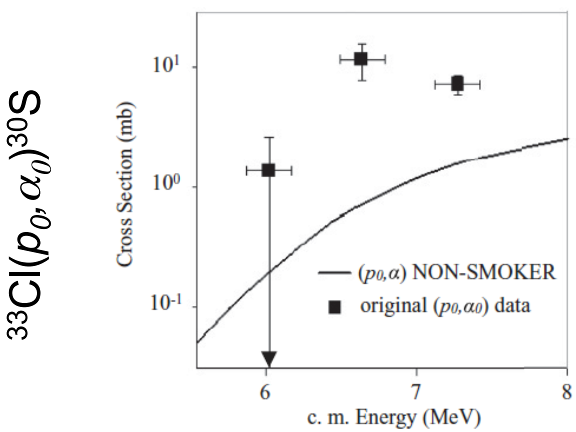


Time-Inverse Studies of αp process waiting points

- Studies of the reverse time (p,α) reactions:
  - RIBs closer to stability
  - solid CH_2 targets
  - ground state → ground state measurement only



- Studies of αp process waiting points at ATLAS
  - $^{25}Al(p,\alpha)^{22}Mg$
  - $^{29}P(p,\alpha)^{26}Si$
  - $^{33}Cl(p,\alpha)^{30}S$
  - $^{37}K(p,\alpha)^{34}Ar$



C.M. Deibel *et al*, PRC **84**, 045802 (2011).

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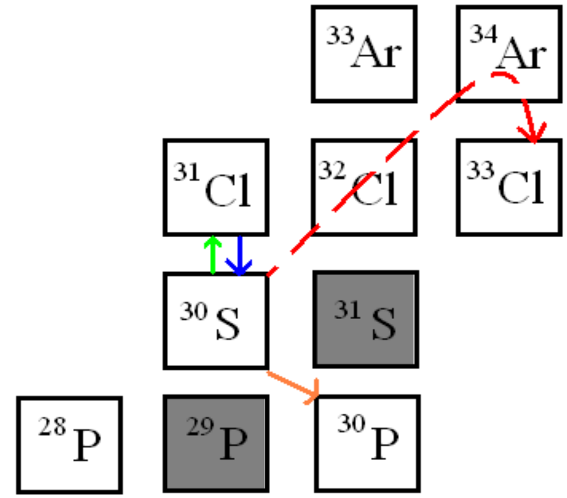

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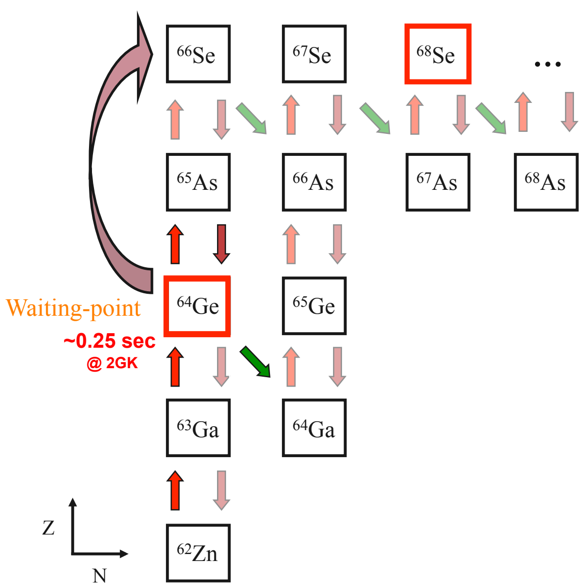
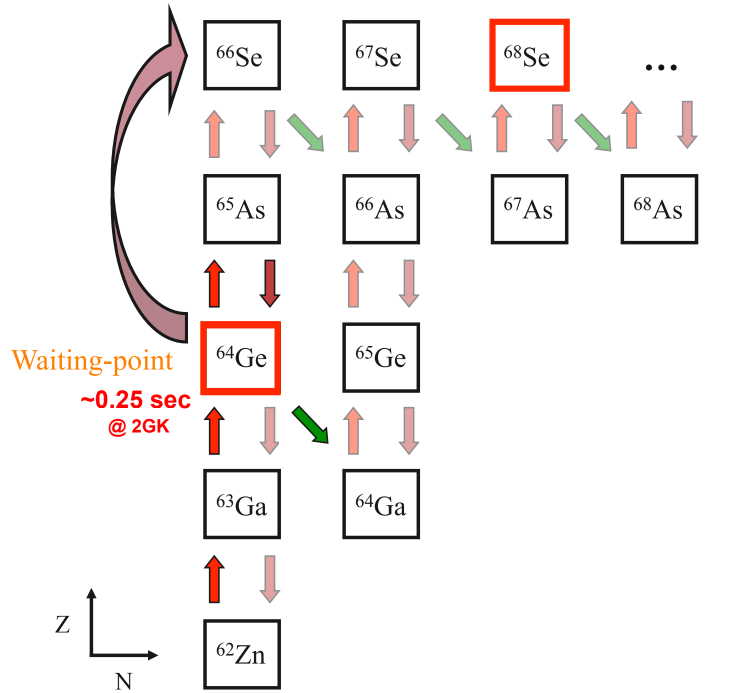
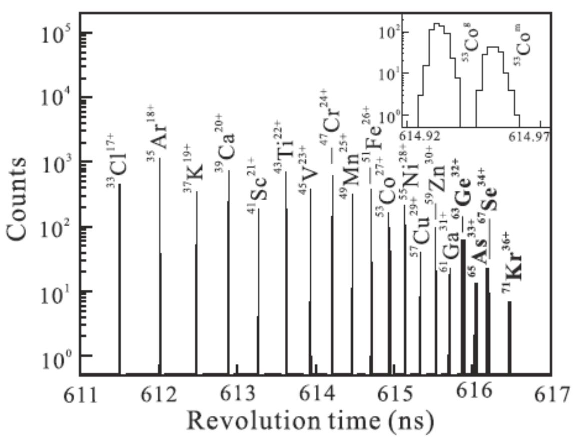


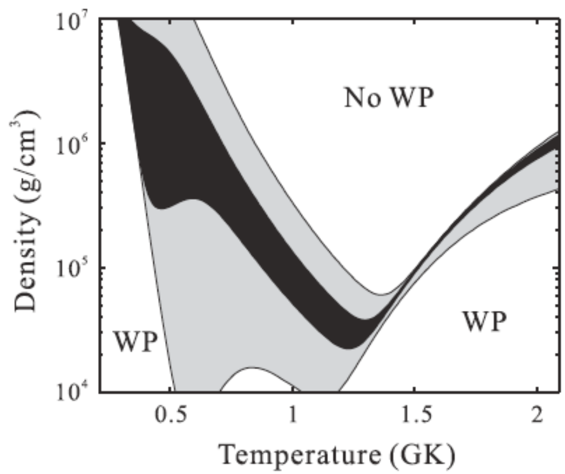
- High-mass waiting points in XRBs determine shape of light-curve tail
- Main waiting points: ^{64}Ge, ^{68}Se, ^{72}Kr
- Lifetimes well known, but not S_p's of Z+1 nuclei
- ^{69}Br and ^{73}Rb both experimentally known to have negative S_p, supporting ^{68}Se and ^{72}Kr as waiting points, respectively

^{64}Ge waiting point

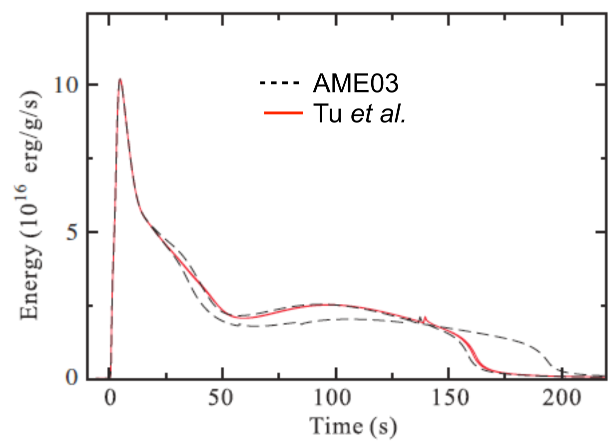
- Mass measurement of ^{65}As done at Lanzhou with the HIRFL-CSR (Cooler-Storage Ring)
- Projectile fragmentation of ^{78}Kr
- $S_p(^{65}As)$ = -90(85) keV: confirms ^{65}As is proton-unbound at 68.3% C.L.
- Coulomb Displacement Energy (CDE) calculations defines when ^{64}Ge is a w. p.





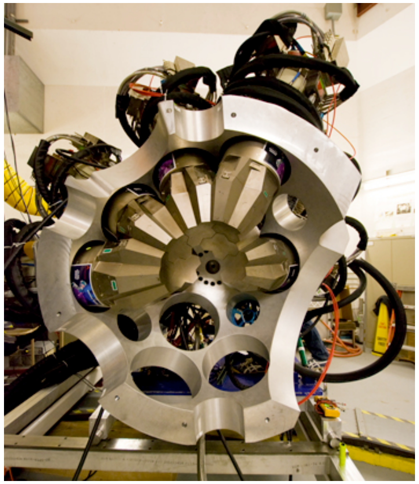


Effect of new ^{65}As mass on XRB light curve

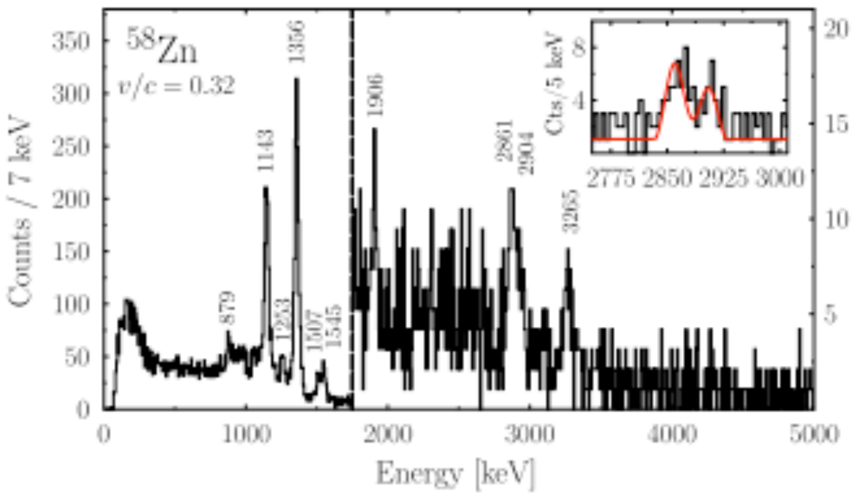


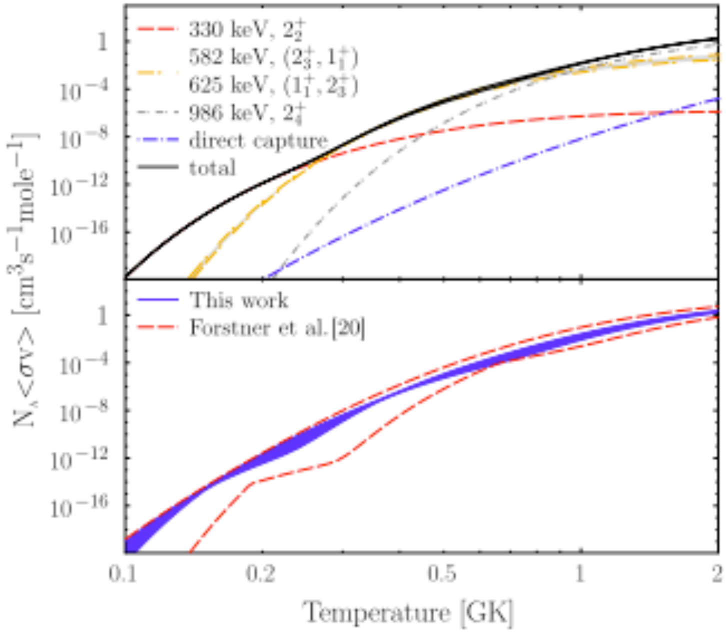
X. L. Tu *et al.*, PRL **106**, 112501 (2011).

Indirect *rp* process measurements



- ^{57}Cu(p,γ)^{58}Zn largest, unmeasured uncertainty in XRB nucleosynthesis around ^{56}Ni waiting point
- Studied d(^{57}Cu,^{58}Zn)n at NSCL
  - ^{58}Zn identified with S800
  - γ rays from ^{57}Cu* detected with GRETINA
- Measurements of resonance energies and tentative spins reduce reaction rate uncertainties by 3 orders of magnitude



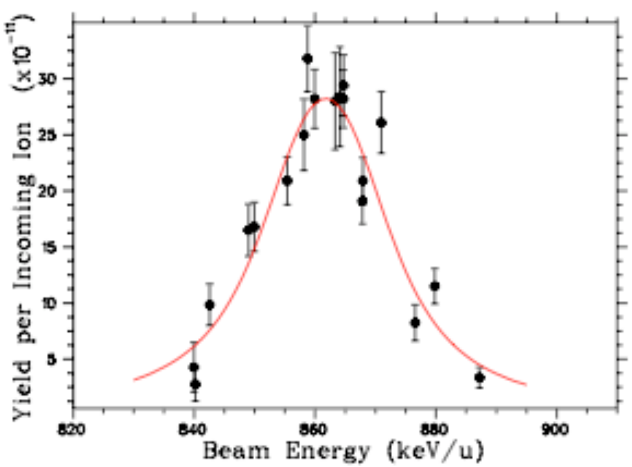


C. Langer *et al.*, PRL **113,** 032502 (2014)

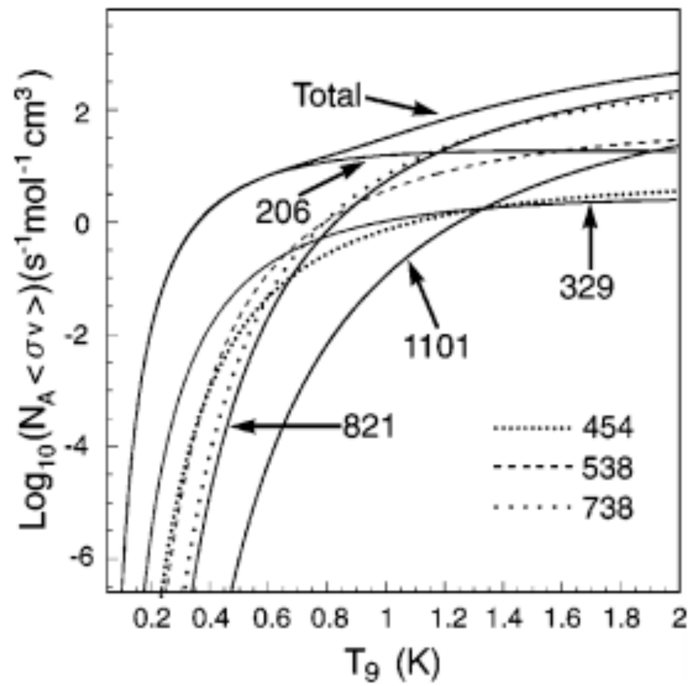
Direct *rp* process measurements

- ^{21}Na(p,γ)^{22}Mg direct measurement with DRAGON at TRIUMF
  - ^{21}Na ISOL produced beam
  - extended H_2 target
  - coincidence measurement

- Inclusion of directly measured rate shows small differences in XRB peak timing and total luminosity



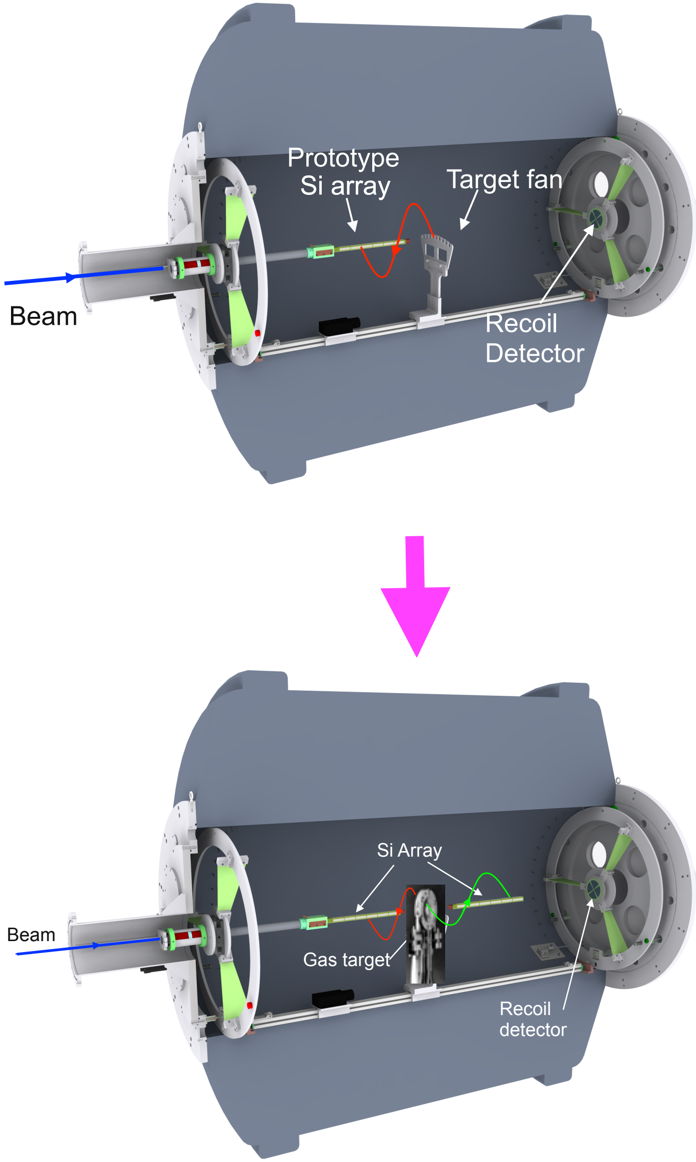
A. A. Chen *et al.*, NPA **A752**, 510 (2005)



J. M. D'Auria *et al.*, PRC **69**, 065803 (2004).

Future: Direct (α,p) Studies with HELIOS

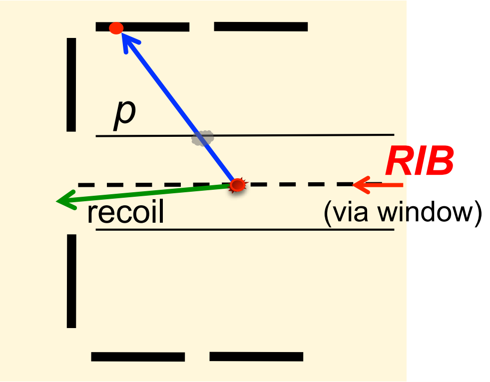
- HELIcal Orbit Spectrometer (HELIOS)
  - 2.85 T repurposed MRI magnet
  - allows improved inverse kinematics studies:
    - high geometrical efficiency
    - better resolution (alleviates kinematic compression)
    - unique particle ID via time-of-flight



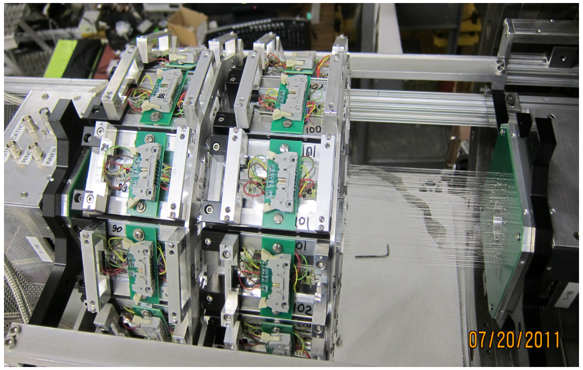
- Upgrades to HELIOS for (α,p) studies:
  - cryogenic gas target
    - commissioned Spring 2013
  - high-rate ionization chamber
    - commissioned Spring 2013
  - new Si array
    - under construction

- Beam development underway at ANL
  - AIRIS upgrade for future high intensity RIBs

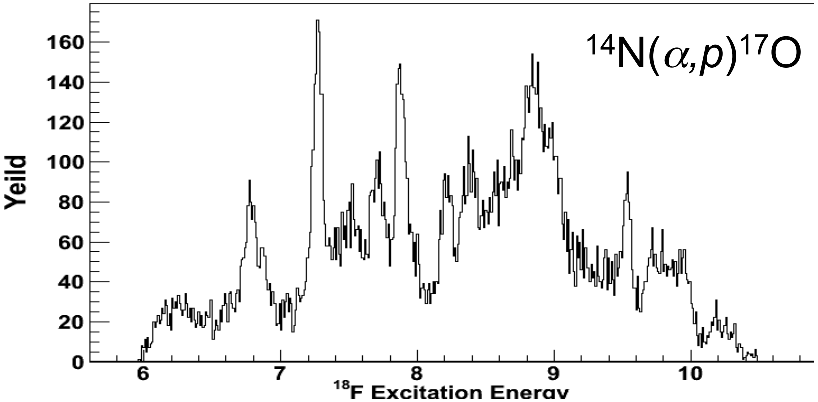
Current Developments: ANASEN

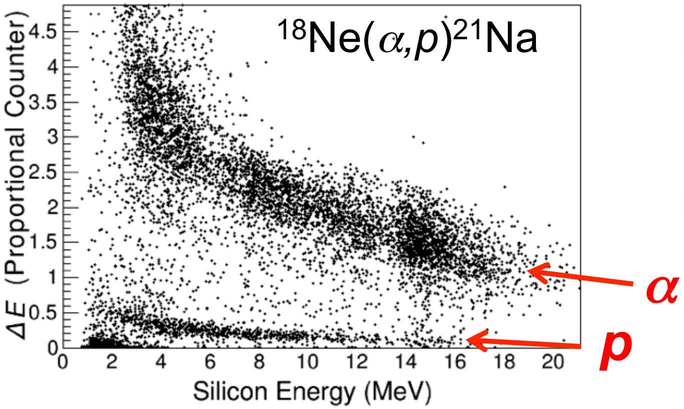


- Array for Nuclear Astrophysics and Structure with Exotic Nuclei
  - designed for direct (α,*p*) reaction studies
    - extended, active gas target
    - proportional counter
    - Si detector array



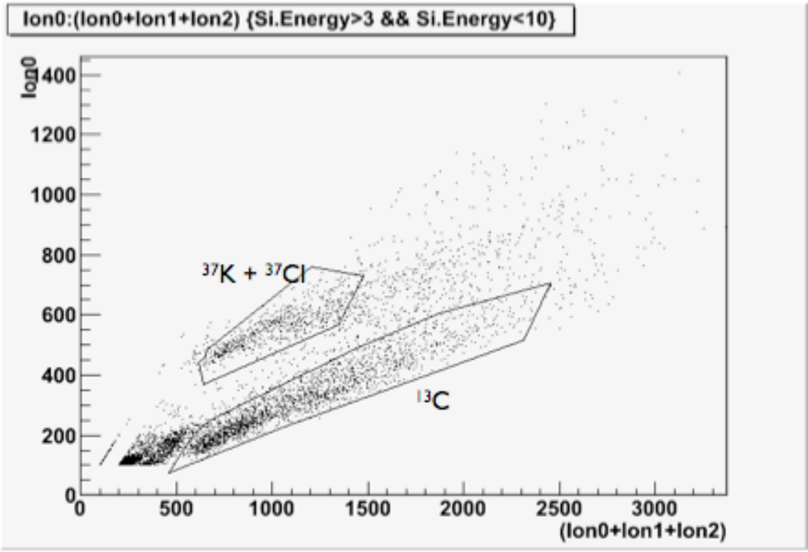
- Nuclear Astrophysics measurements:
  - ^{14}N(α,*p*)^{17}O (stable beam FSU)
  - ^{18}Ne(α,*p*)^{21}Na (RIB from RESOLUT @ FSU)
  - ^{37}K(*p*,*p*)^{37}K (first RIB measurement @ ReA3)



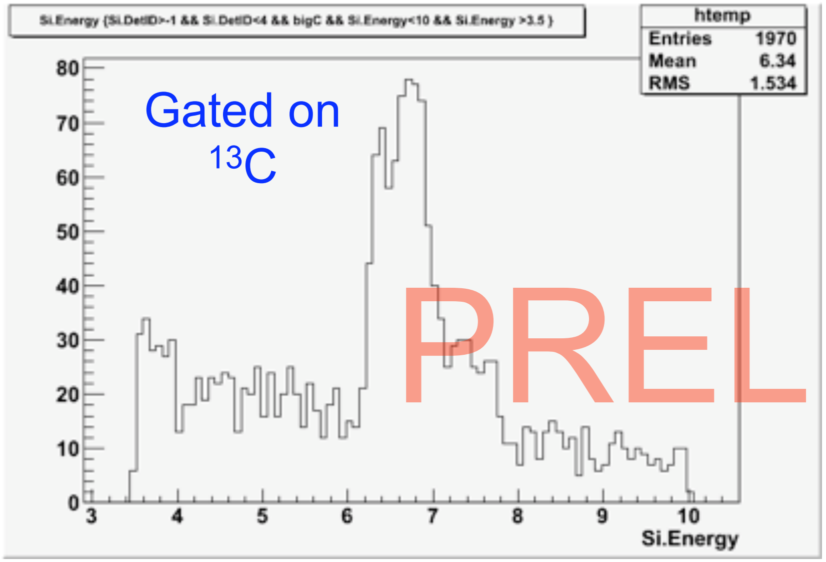


19 Anode PC

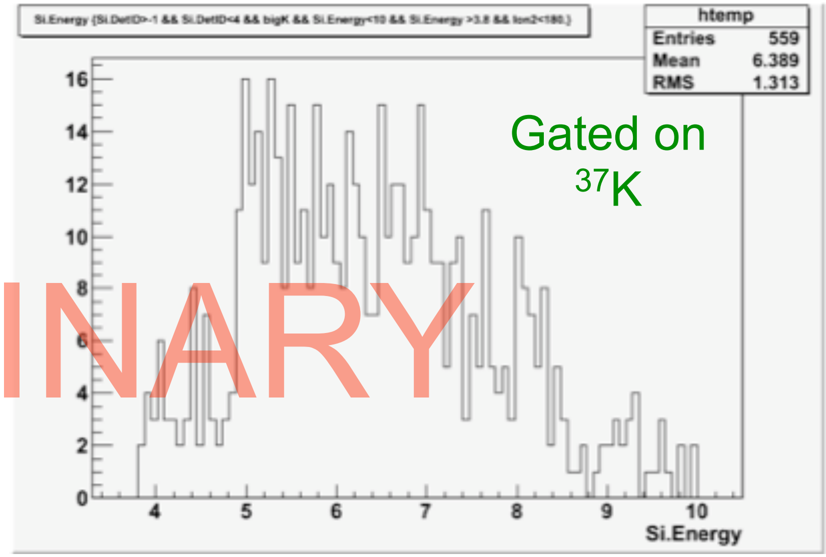
ANASEN at ReA3: $^{37}K(p,p)^{37}K$



- First measurement with reaccelerated beams at ReA3 @ Michigan State University:
  - reaccelerated ^{37}K beam
  - CH_2 target
- Coincidence measurement
  - scattered protons detected in ANASEN Si array
  - Heavy recoils detected in ionization chamber



PRELIMINARY

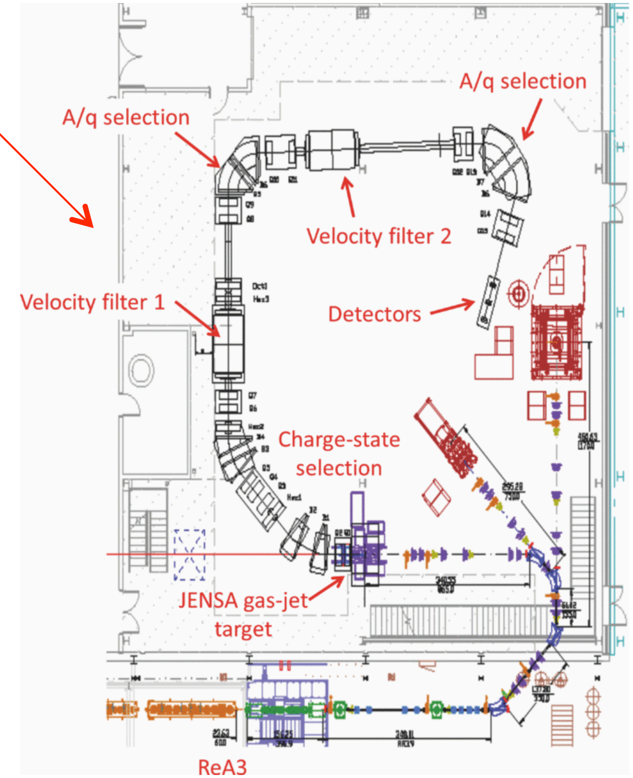


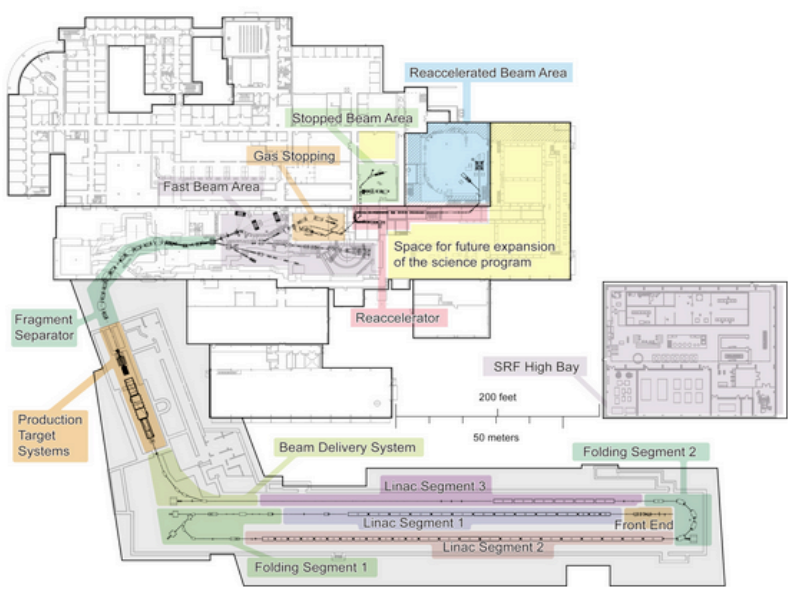
Future Direct Studies: SECAR

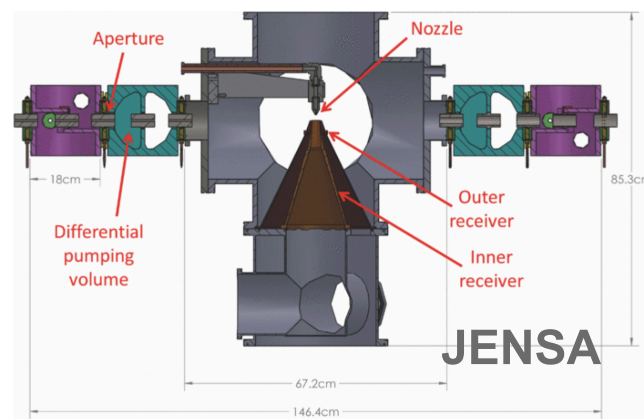
- Recoil separator planned for ReA/FRIB at Michigan State University

- Targets:
  - windowless gas target JENSA already installed at ReA
  - extended gas target to be developed

- Direct measurements of (p,γ) and (α,γ) reactions
  - capture on nuclei up to A = 65
  - 1×10^{-17} rejection







S. D. Pain, AIP **4**, 041015 (2014)

Summary

- Most work on XRB reaction rates consists of indirect measurements:
  - transfer reactions with stable beams
  - time-inverse reaction studies with RIBs
- Needs for direct reaction measurements:
  - high-intensity, low energy radioactive beams
  - high density gas targets
  - recoil separators
  - other novel experimental techniques (e.g. active gas targets)
- Other needs:
  - *rp* process mass measurements
  - indirect measurements of relevant nuclear structure information
  - specific observations data (e.g. isotopic measurements)
  - more realistic modeling

Thank you!