Studies of X-Ray Burst αp-process Waiting Points using Radioactive Ion Beams at ATLAS

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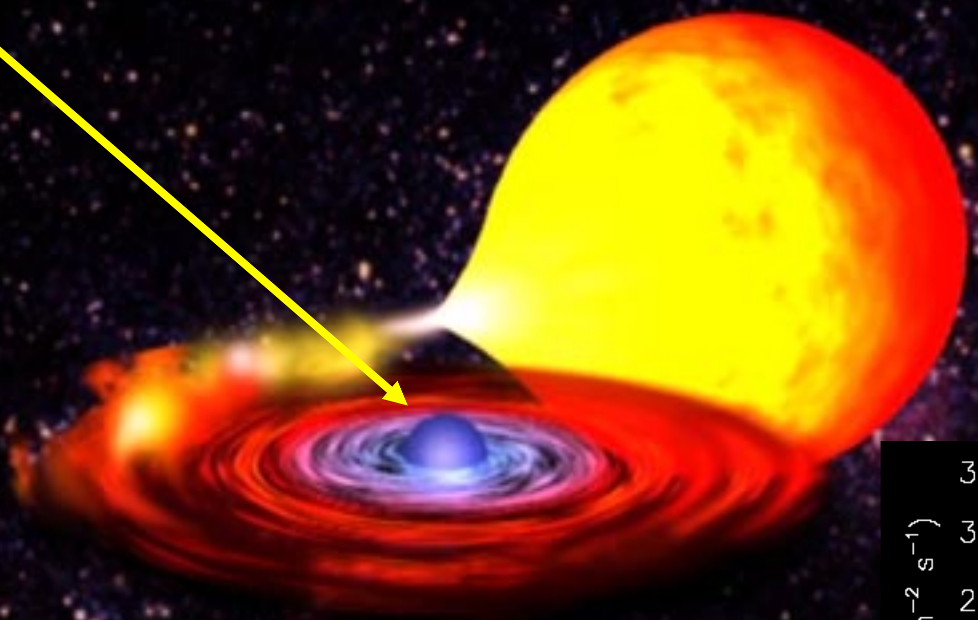
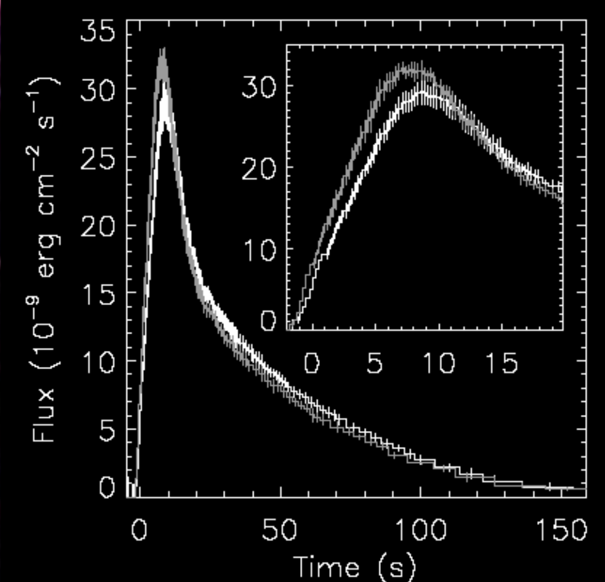
Type I X-Ray Bursts (XRBs)

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

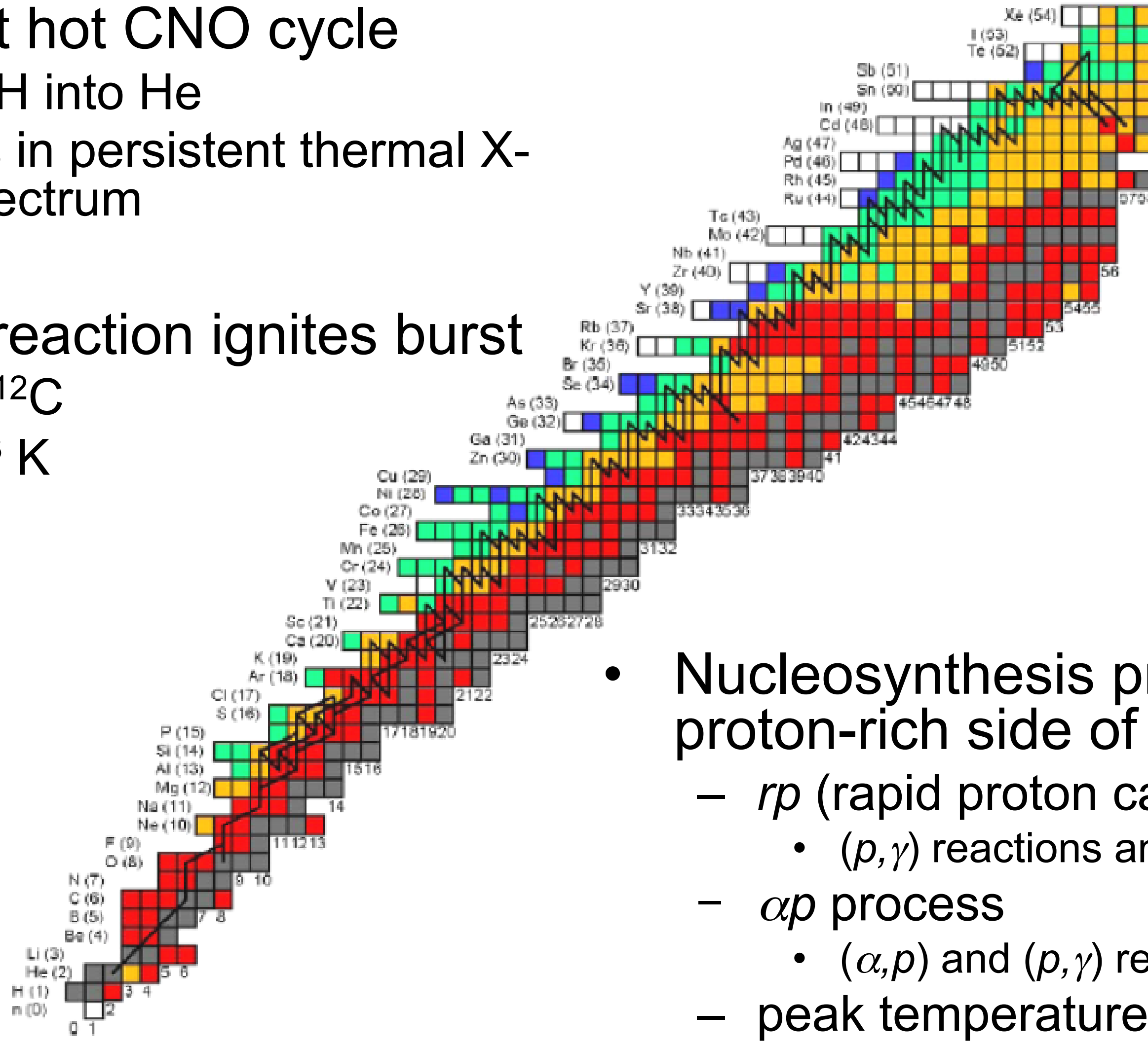


D.K. Galloway et al., ApJ 601 466 (2004).

X-Ray Burst Nucleosynthesis

- Pre-burst hot CNO cycle
  - burns H into He
  - results in persistent thermal X-ray spectrum

- Triple-α reaction ignites burst
  - $3\alpha \rightarrow {}^{12}C$
  - $T \sim 10^8$ K

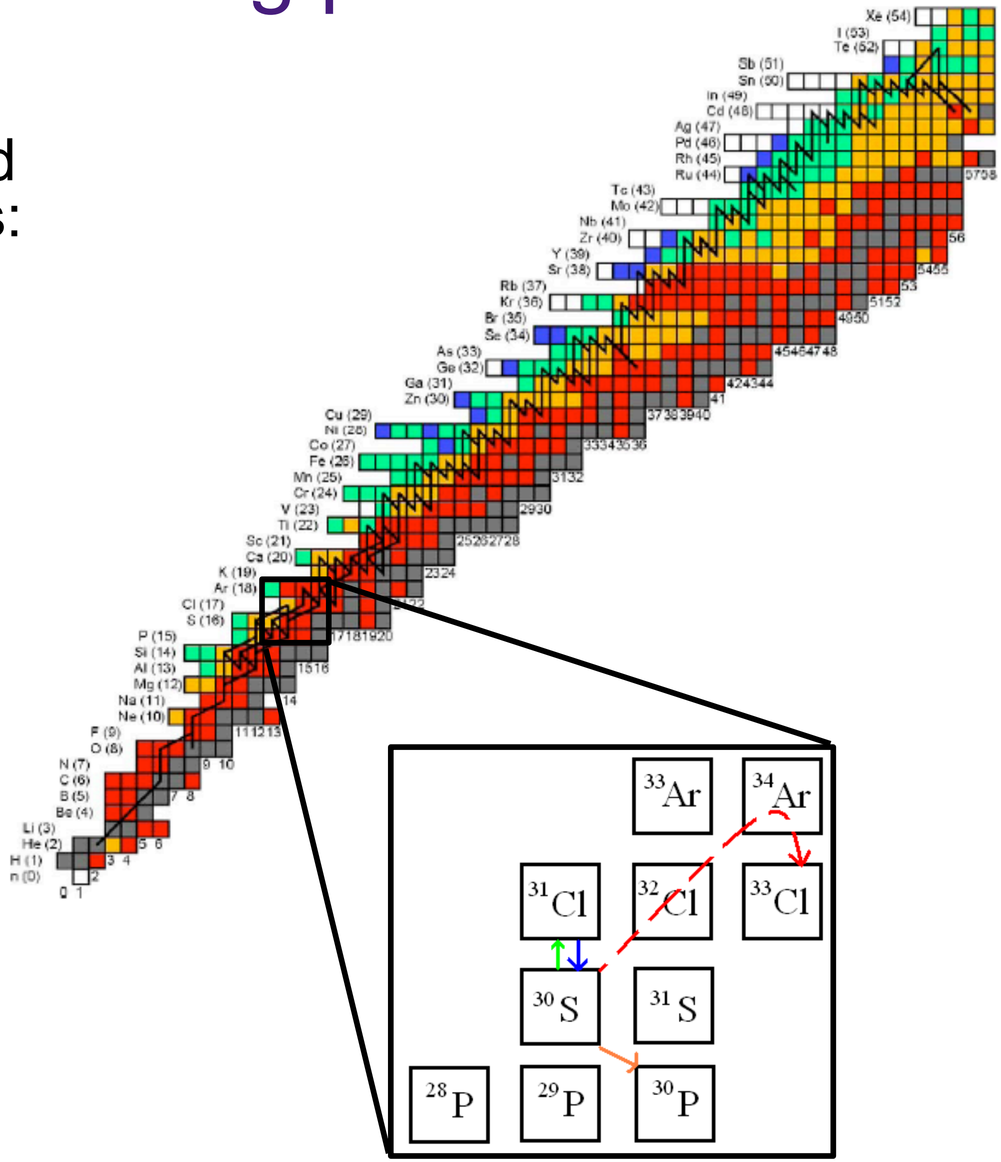


H. Schatz, K. E. Rehm, NPA **777**, 601 (2006)

- 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

αp-process waiting points

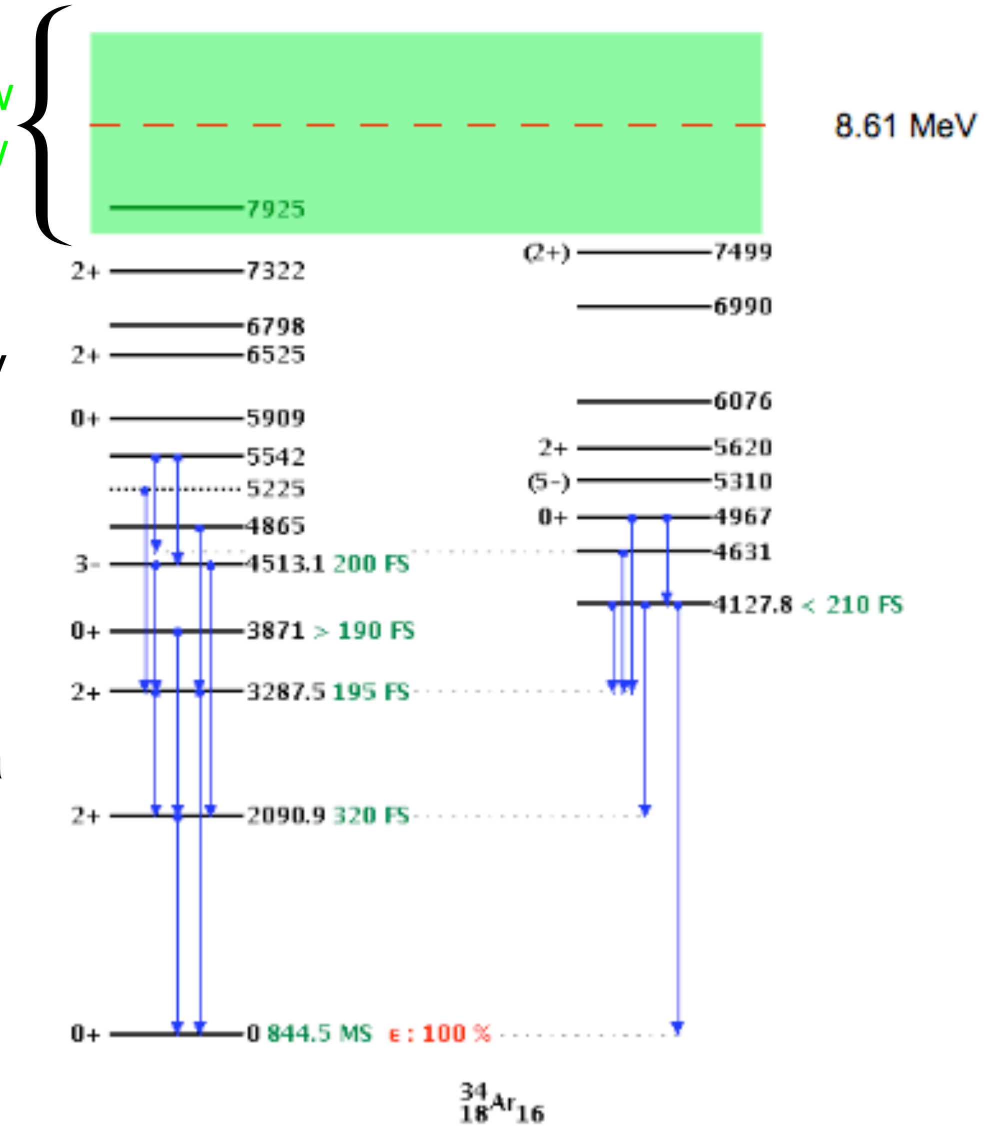
- Nuclei with low $Q_{p\gamma}$ values and long (~ 1 s) β–decay half lives:
  - ^{22}Mg, ^{26}Si, ^{30}S and ^{34}Ar
- **(p,γ)-(γ,p)** equilibrium is reached and nucleosynthesis stalls awaiting **β decay** or breaks out via **(α,p)** reaction
- Effects of waiting points:
  - final elemental abundances
  - energy output of XRB
  - luminosity profiles (multi-peaked structure)



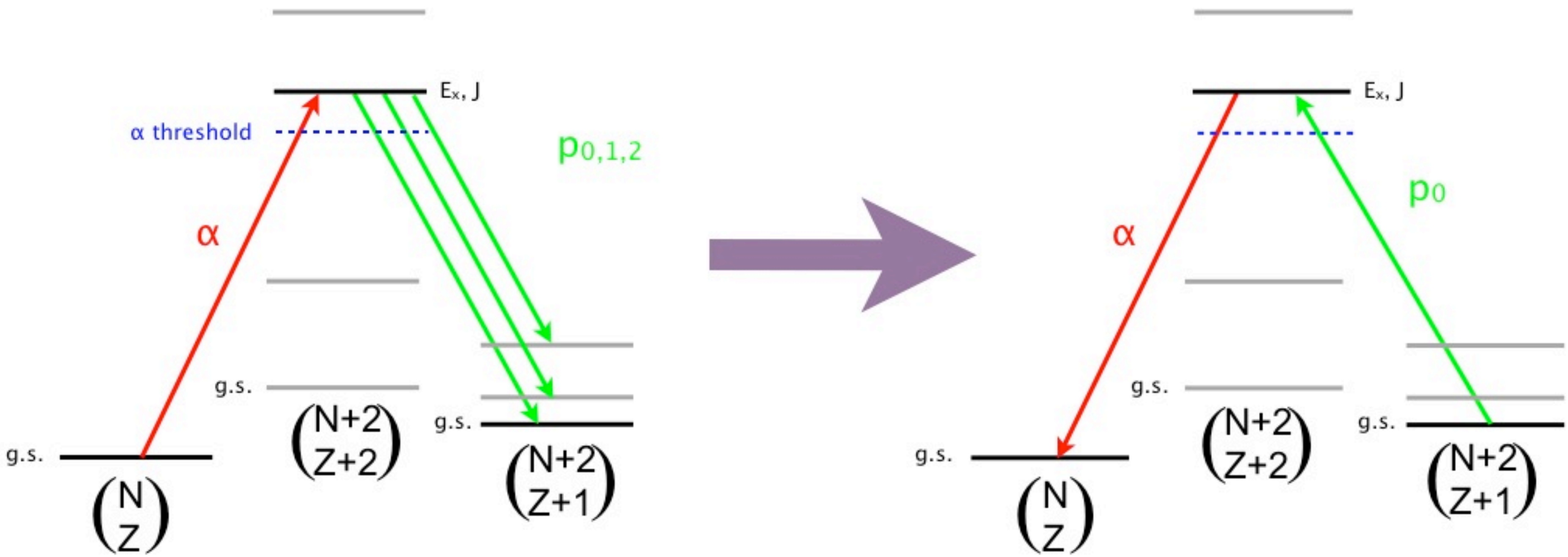
Nuclear Structure Information

- $^{30}S + \alpha \rightarrow {}^{34}Ar$ compound nucleus
- At T ~ 1 GK (peak temperature)
  - Gamow peak located at 8.61 MeV
  - only one known level in window
- Similar situations for other waiting point nuclei
- Indirect studies at RCNP, Osaka and Notre Dame have been completed to determine level structure

  [e.g. O'Brien AIP Conf. Proc. **101** 288 (2009), S. Almaraz-Calderon PRC **86** 065805 (2012)]



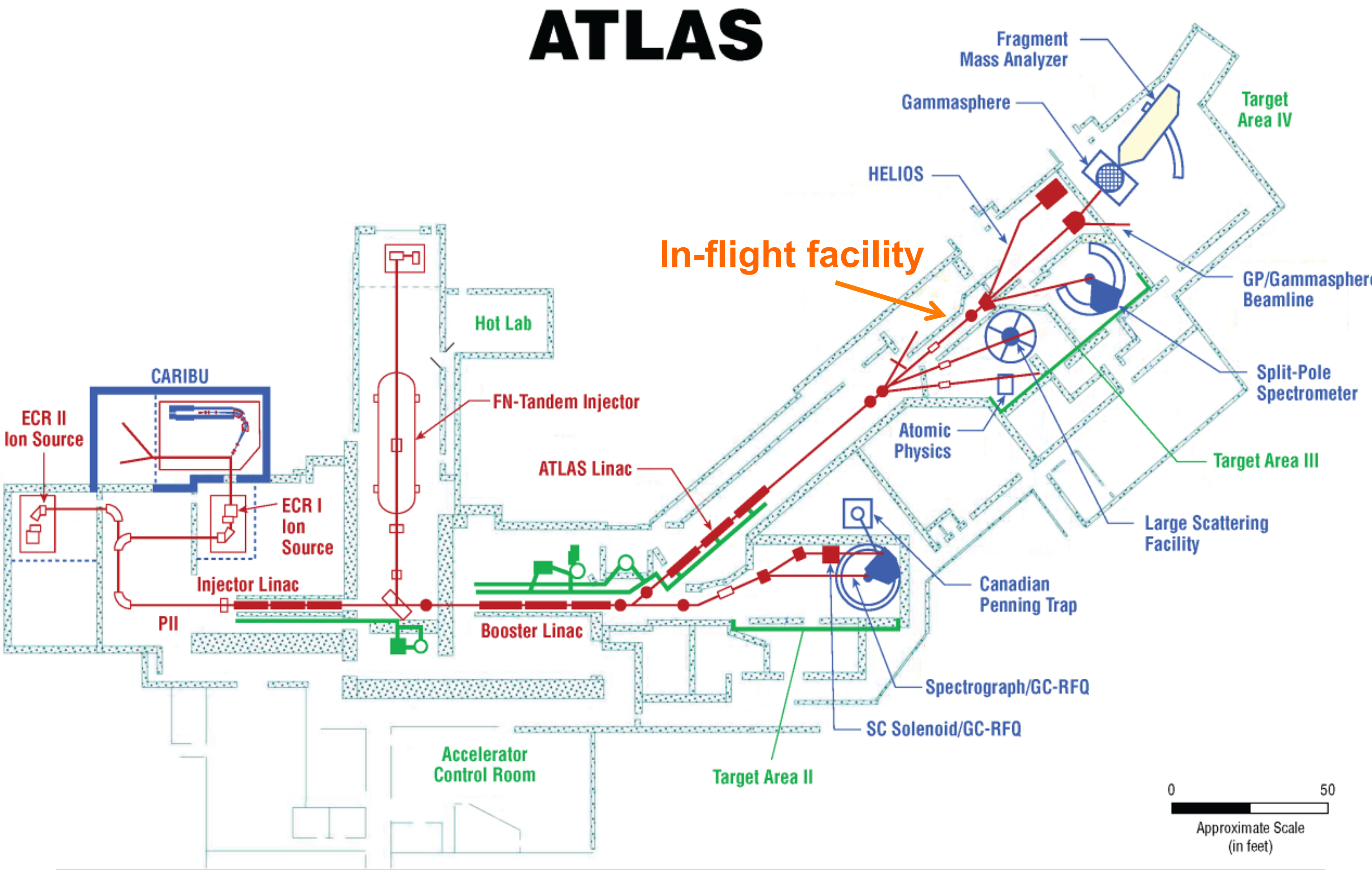
Studying (α,*p*) Waiting Points via (*p*,α) Reactions



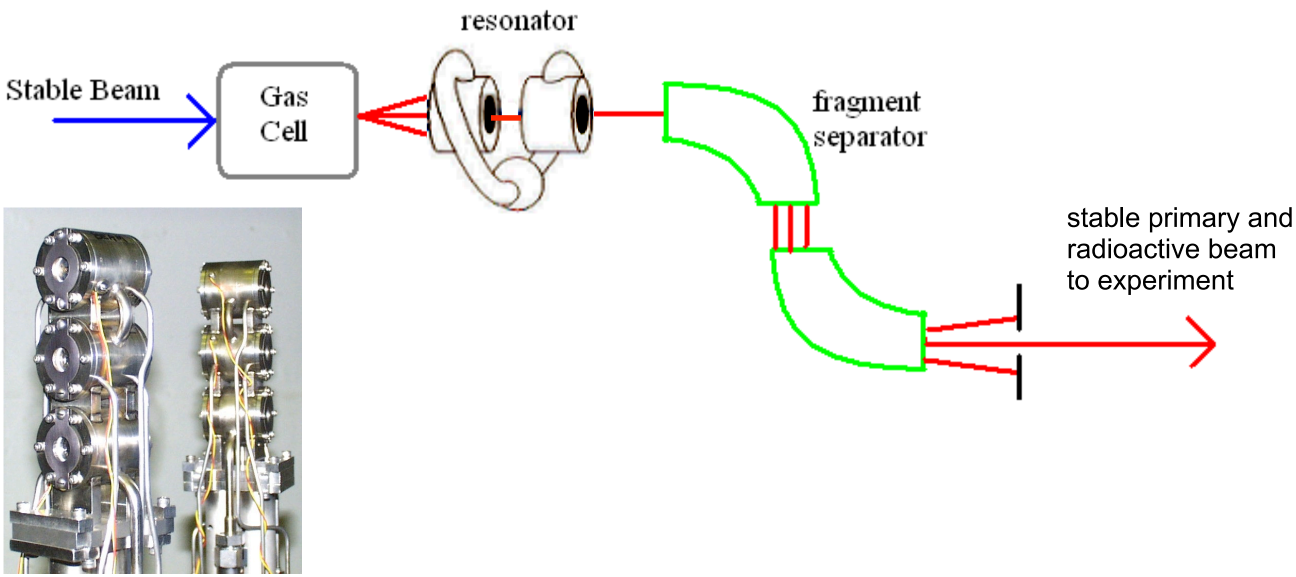
^{22}Mg(α,*p*)^{25}Al	^{25}Al(*p*,α)^{22}Mg
^{26}Si(α,*p*)^{29}P	^{29}P(*p*,α)^{26}Si
^{30}S(α,*p*)^{33}Cl	^{33}Cl(*p*,α)^{30}S
^{34}Ar(α,*p*)^{37}K	^{37}K(*p*,α)^{34}Ar

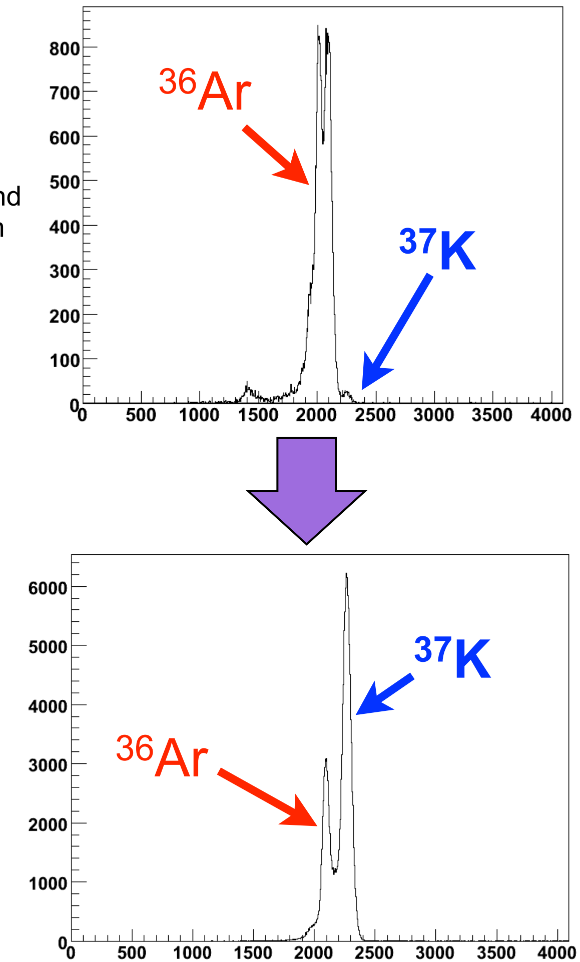
Study reaction cross sections by measuring time-inverse reactions in inverse kinematics

Radioactive Ion Beams at ATLAS



Radioactive Ion Beams (RIBs) at ATLAS





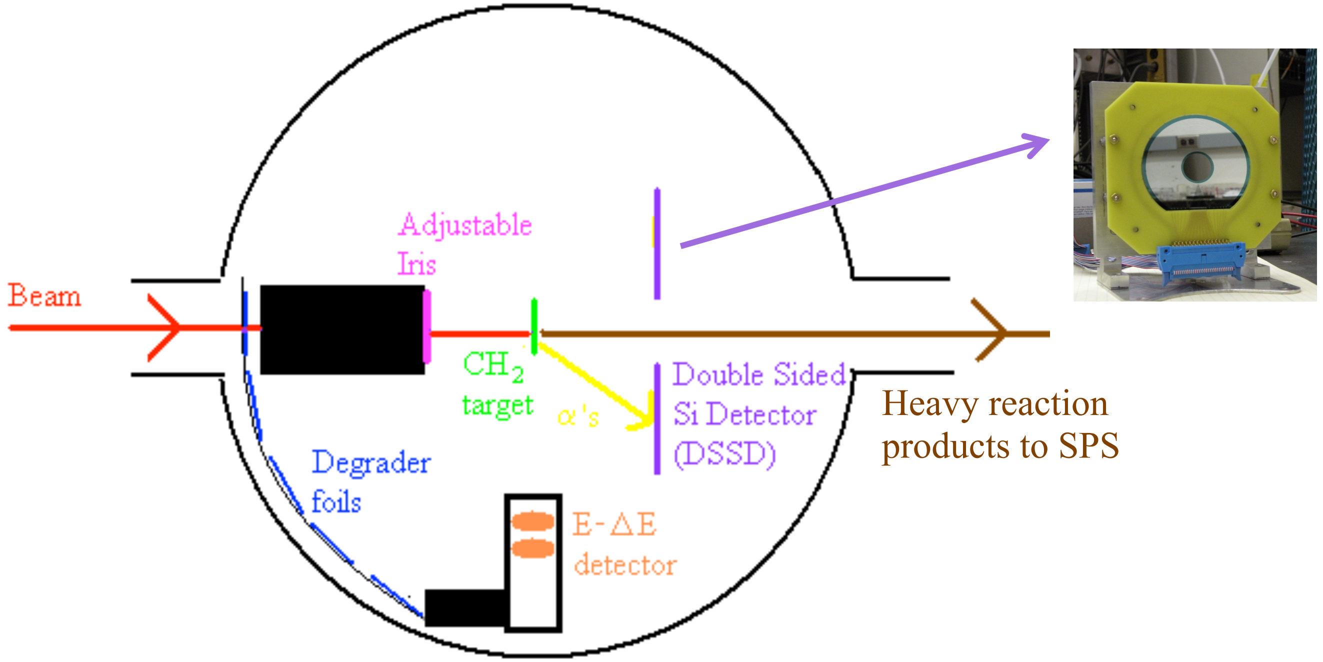
- RIBs produced via 1 or 2 nucleon transfer reactions:

$$\begin{matrix} ^{24}\mathrm{Mg} \\ ^{28}\mathrm{Si} \\ ^{32}\mathrm{S} \\ ^{36}\mathrm{Ar} \end{matrix} \quad (d,n) \quad \begin{matrix} ^{25}\mathrm{Al} \\ ^{29}\mathrm{P} \\ ^{33}\mathrm{Cl} \\ ^{37}\mathrm{K} \end{matrix}$$

- Result is cocktail beam of RIB and primary beam
- RF sweeper reduced background from stable beam component

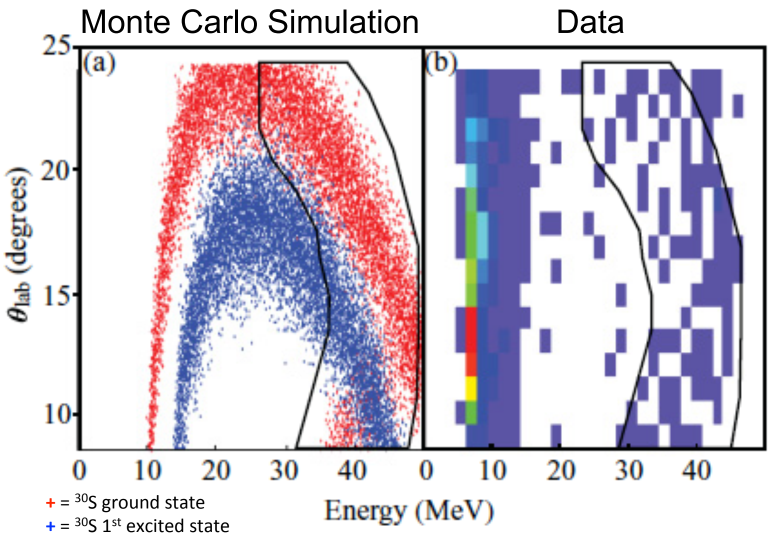
Experimental Setup

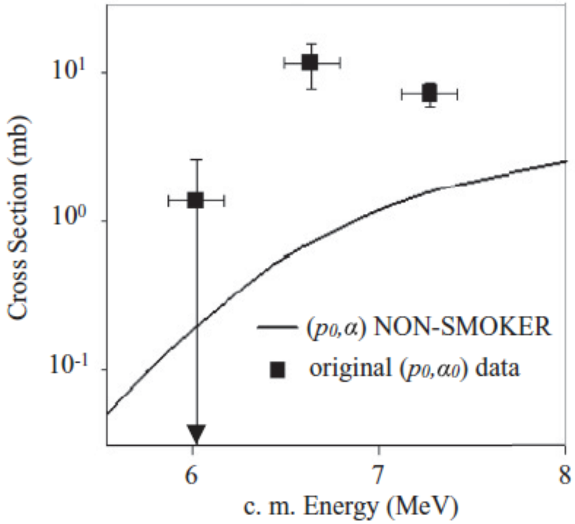
- RIB produced via in-flight method enters target chamber
  - energy degraded by Au foils
  - impinges on 650 $\mu g/cm^2$ CH_2 target
- α-particles detected in double-sided Si strip detector (DSSD) segmented in θ_{lab}
- Heavy reaction products separated from beam by Enge Split-Pole Spectrograph SPS):
  - SPS run in gas-filled mode
  - detected at focal plane by Parallel Grid Avalanche (PGAC) counter and Ionization Chamber (IC)



Results: $^{33}Cl(p,\alpha)^{30}S$

- Coincidence detection between ^{30}S heavy recoils and α's
- Yield normalized to beam current and target thickness
- Normalized yield corrected for efficiencies determined via Monte Carlo simulations
- Resulting cross sections up to a factor of four greater than NON-SMOKER calculations
  - theoretical calculations valid for these reactions?
  - experimental determination necessary





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

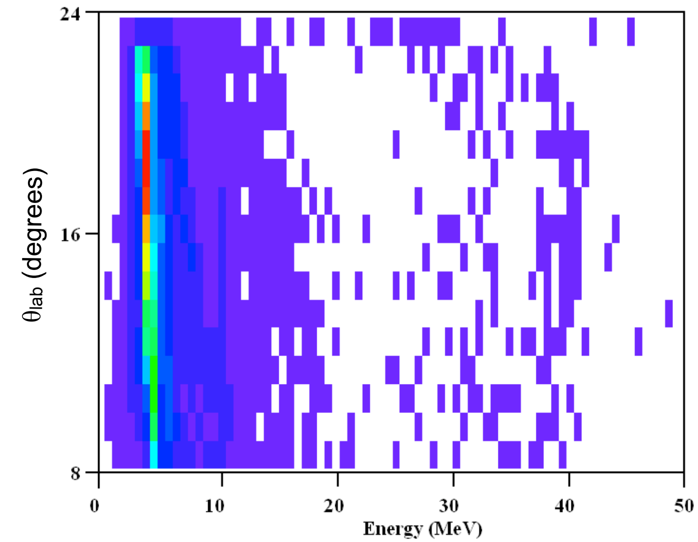
Results: $^{37}K(p,\alpha)^{34}Ar$

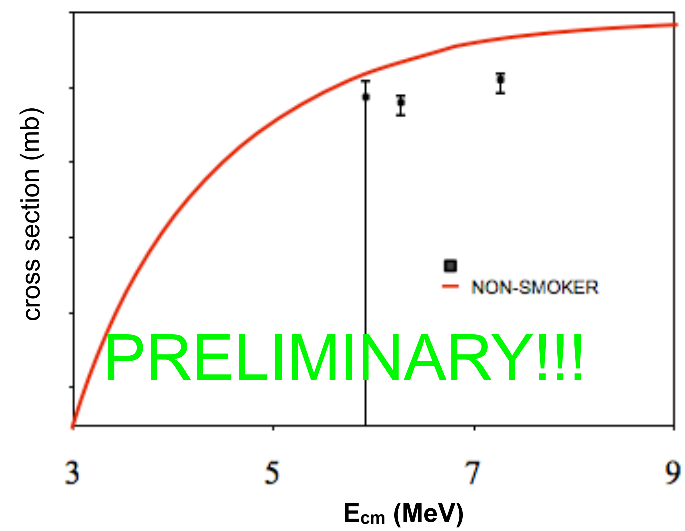
- Similar setup to $^{33}Cl(p,\alpha)^{30}S$ study

- SSB monitor added for third method of normalization

- Preliminary results show cross sections lower than NON-SMOKER calculations

- Publication to be submitted Summer 2014





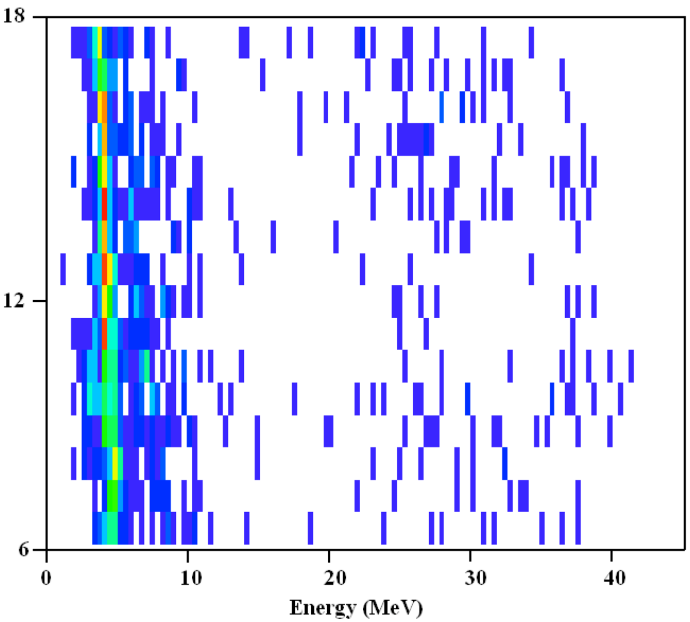
Results: $^{29}P(p,\alpha)^{26}Si$ and $^{25}Al(p,\alpha)^{22}Mg$

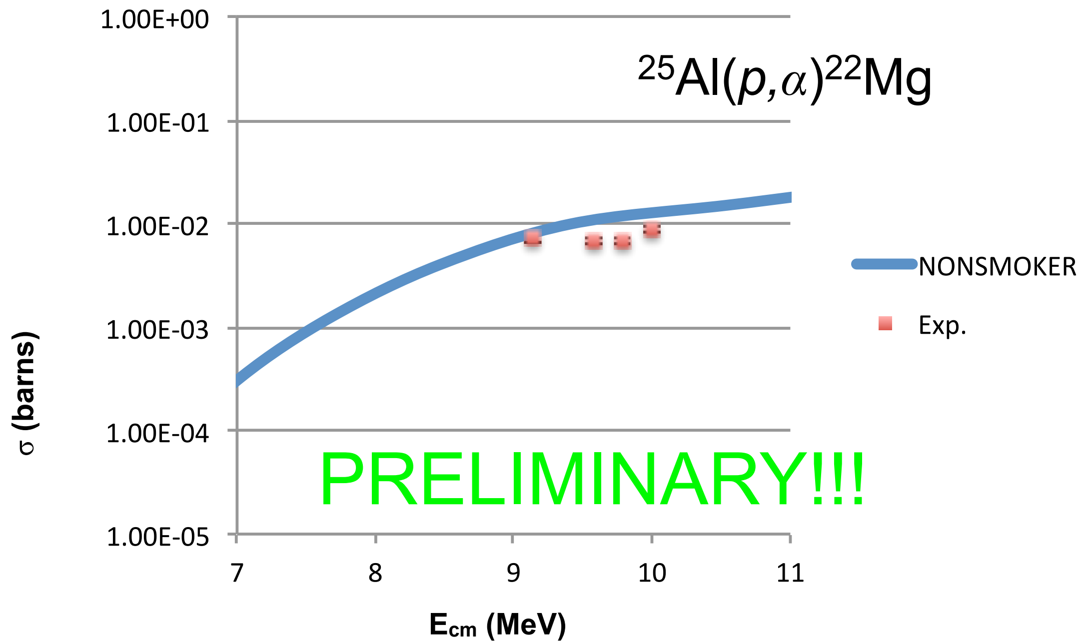
- Similar setup to $^{33}Cl(p,\alpha)^{30}S$ and $^{37}K(p,\alpha)^{34}Ar$ studies

- Analysis in progress for both experimental runs

PRELIMINARY!!!

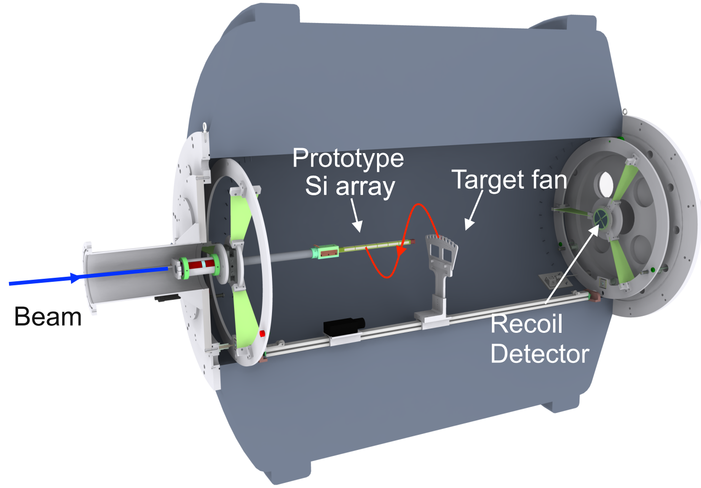
$^{29}P(p,\alpha)^{26}Si$



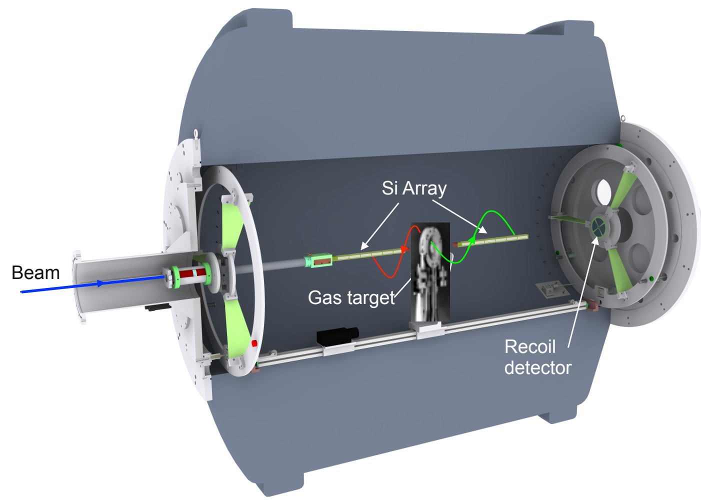


Future . . . Direct (α,*p*) Studies with HELIOS

- 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

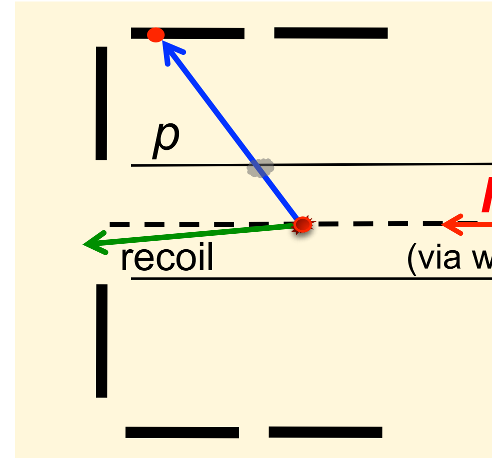


- Upgrades to HELIOS for (α,*p*) studies:
  - cryogenic gas target
    - commissioned Spring 2013
  - high-rate ionization chamber
    - commissioned Spring 2013
  - new Si array
    - under construction



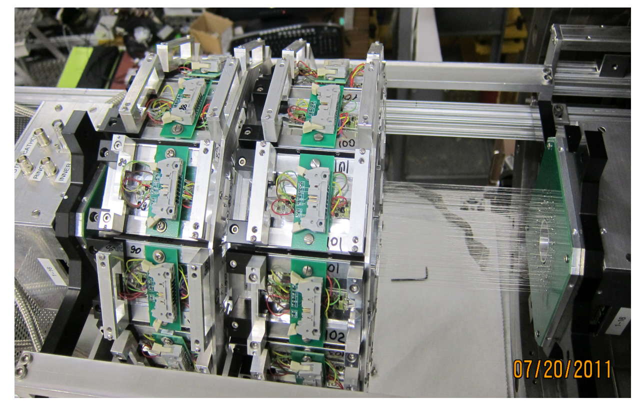
- ^{30}S beam development underway

Studying (α,*p*) reactions with ANASEN

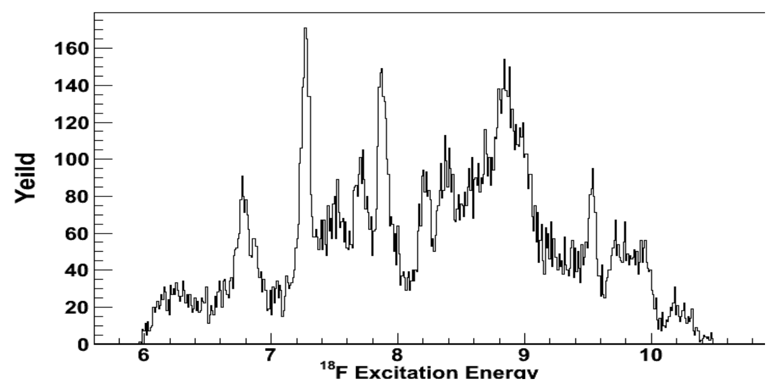


- Array for Nuclear Astrophysics and Structure with Exotic Nuclei (ANASEN)
  - posters: PS1-A059 J. Blackmon; PS1-A056 G. Rogachev

- Extended active gas target/detector
  - Proportional Counter (PC) gas acts as target
  - PC plus Si detector coverage allow for event by event reconstruction
  - active gas target allows maximum efficiency with low intensity RIBs



- Successful runs with both stable and radioactive beams at Florida State University
  - ^{14}N(α,*p*)^{17}O
  - ^{18}Ne(α,*p*)^{21}Na



- First experimental run with reaccelerated RIB from ReA3 at NSCL: ^{37}K(*p*,*p*) ^{37}K

Summary

- Time-inverse (p,α) measurements have been completed for all four candidate αp process waiting-point nuclei
  - $^{25}Al(p,\alpha)^{22}Mg$
  - $^{29}P(p,\alpha)^{26}Si$
  - $^{33}Cl(p,\alpha)^{30}S$
  - $^{37}K(p,\alpha)^{34}Ar$
- Significant deviations from theoretical calculations have been found
- Next steps:
  - examining effects of new cross sections on XRBs
  - direct (α,p) measurements with devices such as HELIOS and ANASEN

Thank You!!

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