Nuclear Astrophysics: the need for Indirect Techniques and Nuclear Data

Robert Tribble
Texas A&M University

November 6, 2008

Key questions in nuclear astrophysics:

- **How do Stars evolve?***
  (from first generation stars to our Sun)
- **What is the Origin of the elements in the Universe?****

*Focus of TAMU work

**For next generation RIB facilities

Stellar Evolution:

Nuclear Reactions (+ gravity):

the energy source that *drives* the cosmos

Energy production (and nucleosynthesis) via:

- **pp** chain
- α-α-α reaction
- **CNO** cycle
- **NeNa** cycle, …
- **rapid α-p** chain in first generation stars
- . . .

Have **vast** amount of data
on this from astronomy!

Explosive Processes:

Nucleo-synthesis (and energy production) via:

- **HCNO** cycle
- **rp** process
- **r** process
- rapid α **capture**
- . . .

Involve reactions on radioactive nuclei

Nuclear Physics Input

- **Reaction Rates**
  - (p,γ), (p,α), (α,p), (α,γ), (n,γ), (n,α), (α,n) . . . *at stellar energies*

    (for resonance reactions need excitation energies, spin/parities, decay widths)

- **β decay lifetimes**, **nuclear masses**
  - needed for nuclei *very* far from stability

Why use **Indirect Techniques**?

Get cross sections difficult for direct studies!
Including:

- Reaction rates on **radioactive nuclei**
- Capture through **subthreshold states**
- **Direct capture** to add to resonant capture
- **Screening** and low-energy extrapolations

Indirect Techniques
for Reaction Rates

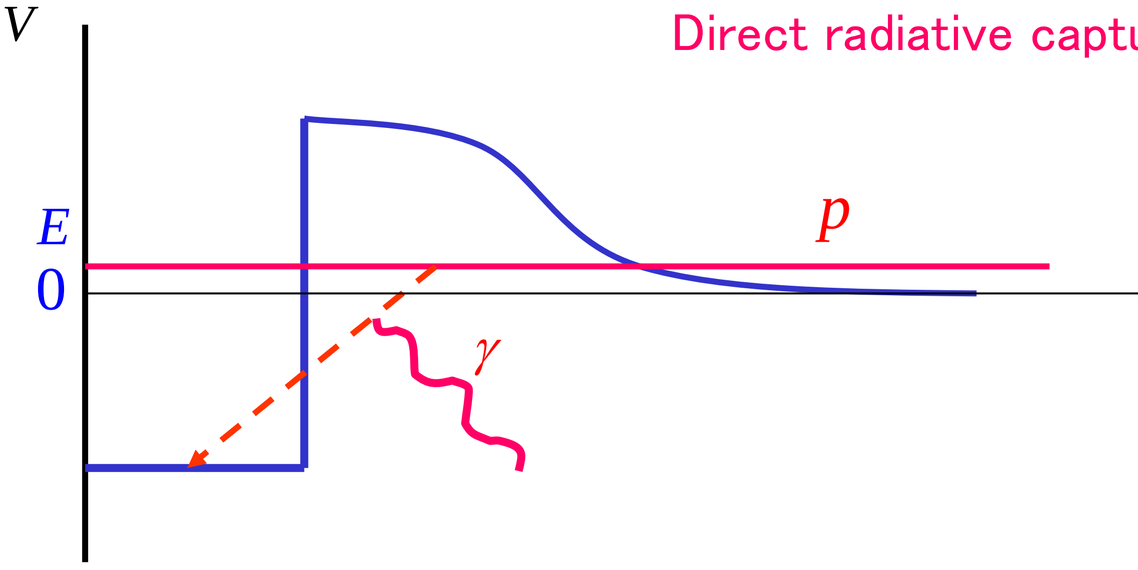
- **Widths** (γ and 'p') of resonance rates
  - populate resonance state and measure decay
- **Resonance energies** – determine E_R

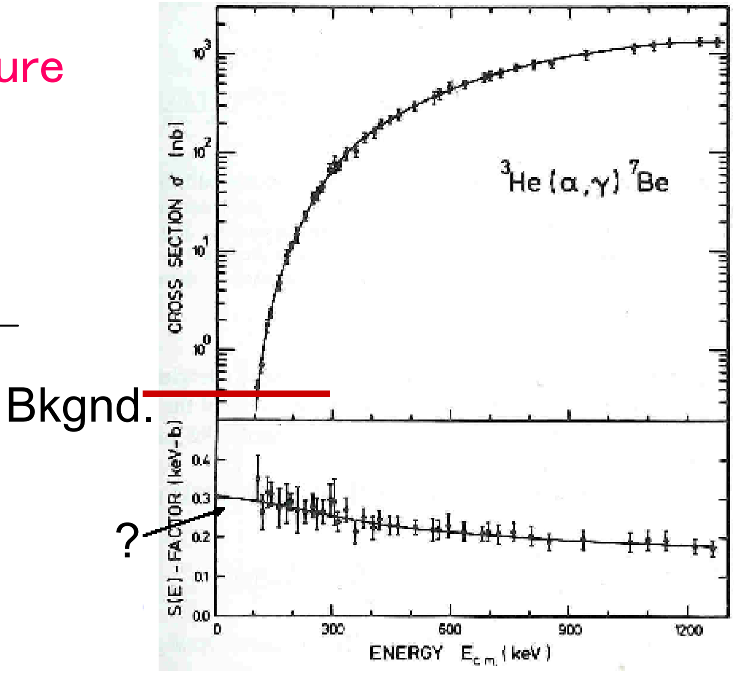
} **resonant capture**

- **Coulomb dissociation**
- **Trojan Horse Method**
  - unique way to understand screening
- **Asymptotic Normalization Coefficients**
  - use with stable and radioactive beams

Radiative *p* (α) capture at stellar energies

- Classical **barrier penetration** problem





- **low energies** ⇒ capture at large radii
- **very small** cross sections
- define astrophysical **S** factor:

$$\sigma(E) = \frac{S(E)}{E}\exp\{-2\pi\eta(E)\} \qquad \eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v}$$

Direct Radiative proton capture

$$\sigma \propto |M|^2$$

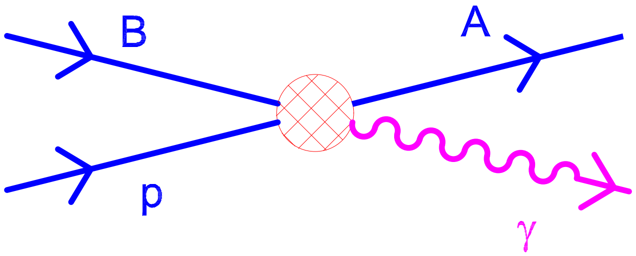
M is: $$M = \left\langle \phi_A(\xi_B, \xi_p, \xi_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \phi_B(\xi_B)\phi_p(\xi_p)\psi_i^{(+)}(r_{Bp}) \right\rangle$$

Integrate over ξ: $$M = \left\langle I_{Bp}^{A}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

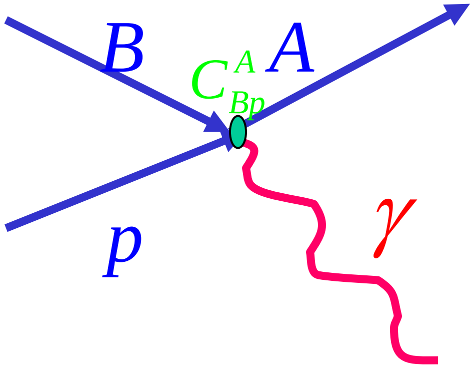
Low B.E.: $$I_{Bp}^{A}(r_{Bp}) \overset{r_B > R_N}{\approx} C_{Bp}^{A} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

ANC ⇒ amplitude for tail of overlap function

Find: $$\sigma_{capture} \propto (C_{Bp}^{A})^2$$

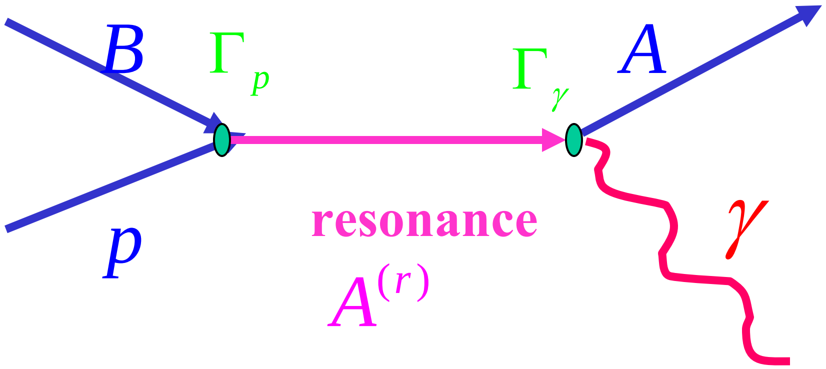


ANCs in astrophysics



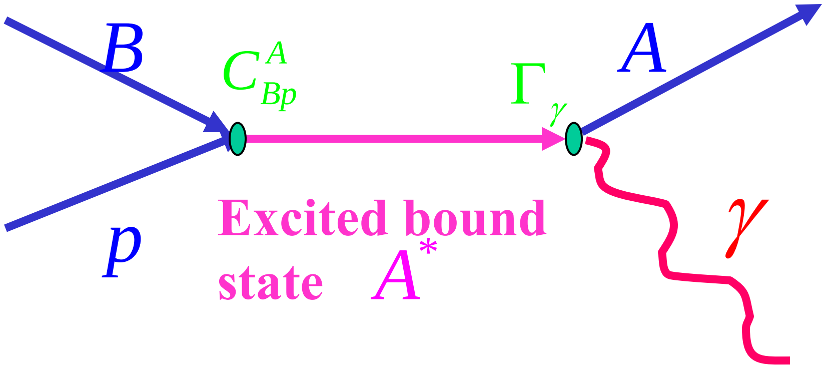
Direct Capture

$$M \propto C_{Bp}^{A}$$



Resonant Capture

$$M \propto \frac{\Gamma_p^{1/2}\,\Gamma_\gamma^{1/2}}{E - E_0 + \frac{i\Gamma}{2}}$$



Capture through subthreshold state

$$M \propto \frac{C_{Bp}^{A}\,\Gamma_\gamma^{1/2}}{E + \varepsilon^* + \frac{i\Gamma}{2}}$$

Measure ANCs?

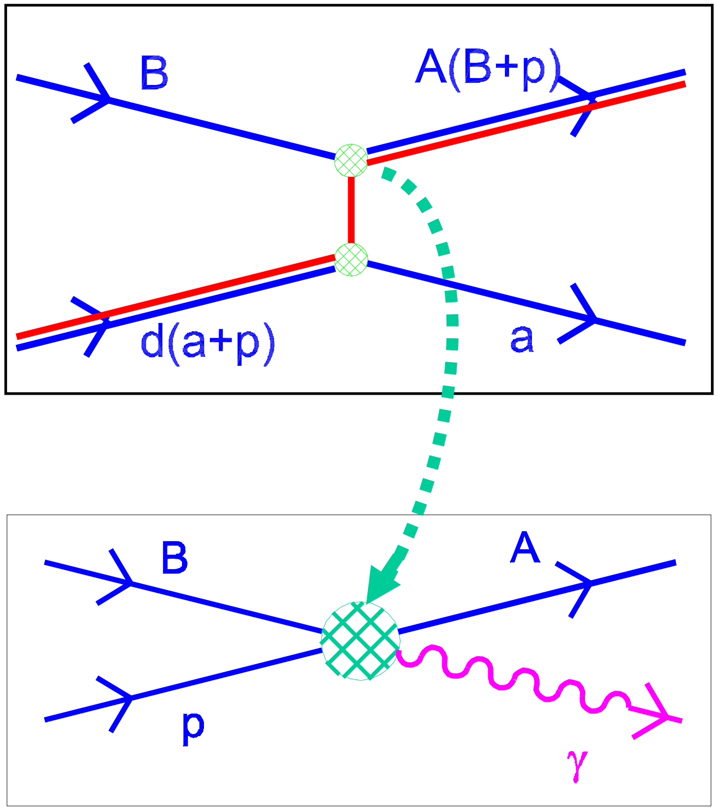
Extracting spectroscopic factors

Transfer reaction B+d→A+a

$$\frac{d\sigma}{d\Omega} = \sum S_{Bpl_A j_A} S_{apl_d j_d} \sigma^{DW}_{l_A j_A l_d j_d}$$

Peripheral Transfer:

$$\frac{d\sigma}{d\Omega} = (C^A_{Bpl_A j_A})^2 (C^d_{apl_d j_d})^2 \frac{\sigma^{DW}_{l_A j_A l_d j_d}}{b^2_{Bpl_A j_A} b^2_{apl_d j_d}}$$



Direct *p* capture

$$\sigma_{(p,\gamma)} \propto (C^A_{Bp})^2$$

Direct *n* capture

$$\sigma_{(n,\gamma)} =$$ more complicated!

$$I^A_{Bp} \overset{r_{Bp}>R_N}{\approx} C^A_{Bp} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

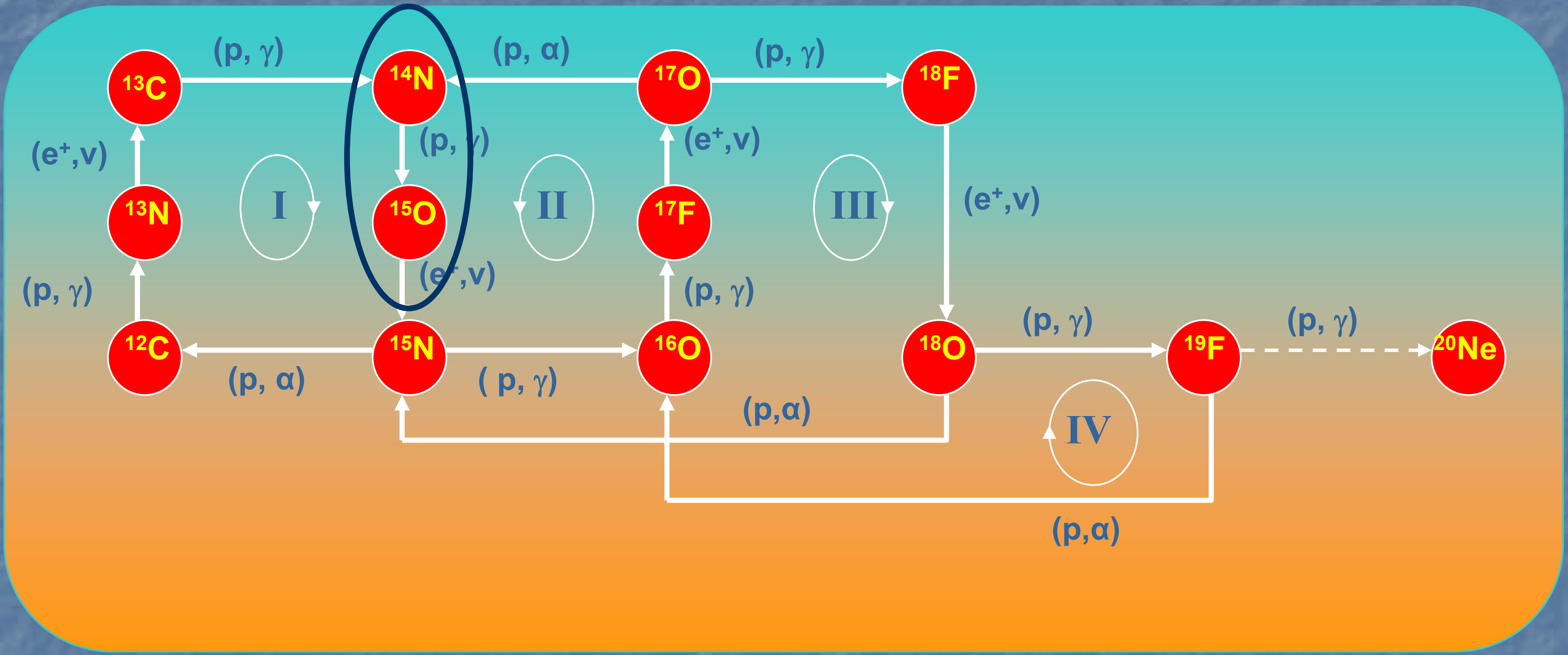
Proton ANCs measured using stable beams

$^{9}\text{Be} + \text{p} \leftrightarrow {}^{10}\text{B}^*$	$[^{9}\text{Be}(^{3}\text{He},d)^{10}\text{B};{}^{9}\text{Be}(^{10}\text{B},{}^{9}\text{Be})^{10}\text{B}]$	$^{9}\text{Be}(\text{p},\gamma)^{10}\text{B}$
$^{12}\text{C} + \text{p} \leftrightarrow {}^{13}\text{N}$	$[^{12}\text{C}(^{3}\text{He},d)^{13}\text{N}]$	$^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$
$^{13}\text{C} + \text{p} \leftrightarrow {}^{14}\text{N}$	$[^{13}\text{C}(^{3}\text{He},d)^{14}\text{N};{}^{13}\text{C}(^{14}\text{N},{}^{13}\text{C})^{14}\text{N}]$	$^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$
$^{14}\text{N} + \text{p} \leftrightarrow {}^{15}\text{O}$	$[^{14}\text{N}(^{3}\text{He},d)^{15}\text{O}]$	$^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$
$^{15}\text{N} + \text{p} \leftrightarrow {}^{16}\text{O}$	$[^{15}\text{N}(^{3}\text{He},d)^{16}\text{O}]$	$^{15}\text{N}(\text{p},\gamma)^{16}\text{O}$
$^{16}\text{O} + \text{p} \leftrightarrow {}^{17}\text{F}^*$	$[^{16}\text{O}(^{3}\text{He},d)^{17}\text{F}]$	$^{16}\text{O}(\text{p},\gamma)^{17}\text{F}$
$^{20}\text{Ne} + \text{p} \leftrightarrow {}^{21}\text{Na}$	$[^{20}\text{Ne}(^{3}\text{He},d)^{21}\text{Na}]$	$^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$

beams ≈ 10 MeV/u

* Test cases

CNO Cycles


^{13}C
(p, γ)
^{14}N
(p, α)
^{17}O
(p, γ)
^{18}F
(e^{+},v)
(p, γ)
(e^{+},v)
(e^{+},v)
^{13}N
I
^{15}O
II
^{17}F
III
(p, γ)
(e^{+},v)
(p, γ)
^{12}C
^{15}N
^{16}O
^{18}O
(p, γ)
^{19}F
(p, γ)
^{20}Ne
(p, α)
(p, γ)
(p,α)
IV
(p,α)

S factor for $^{14}N(p,\gamma)^{15}O$

- ANC's ⇐ $^{14}N(^{3}He,d)^{15}O$

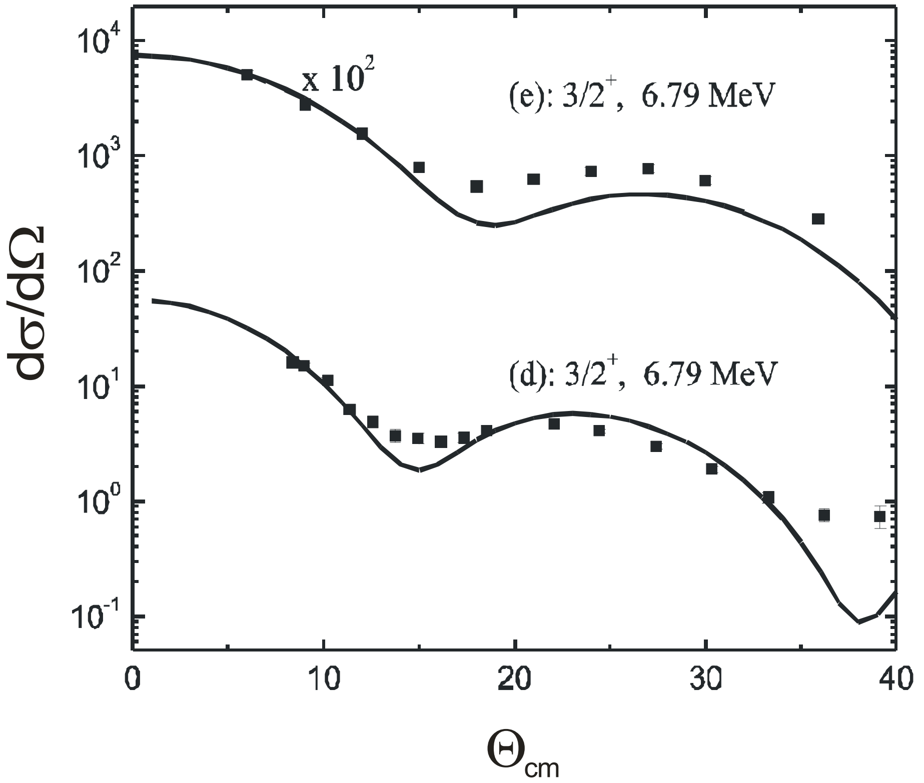
  (d) ⇒ Rez/TAMU (27 MeV)

  (e) ⇒ TUNL (20 MeV)

- NRC to subthreshold state at $E_x = 6.79$ MeV

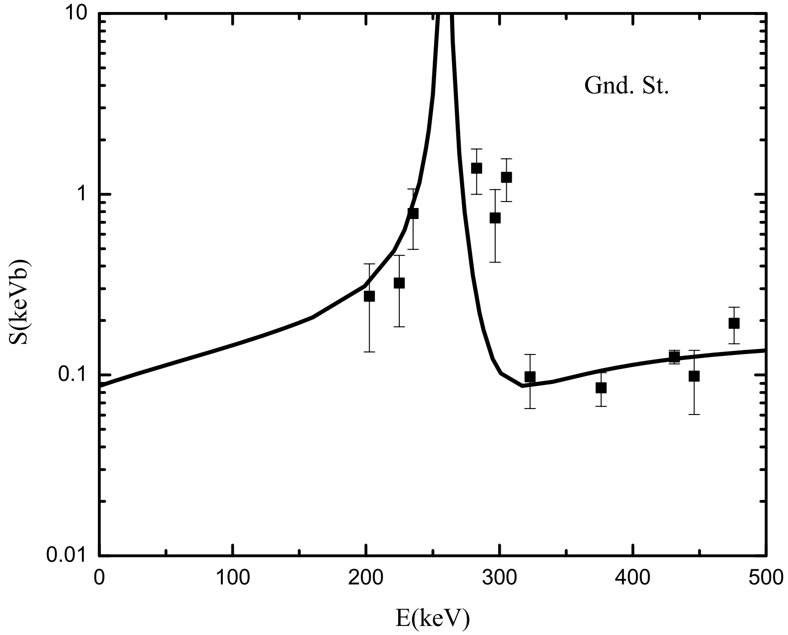
- Subthreshold resonance width from Bertone, *et al.*

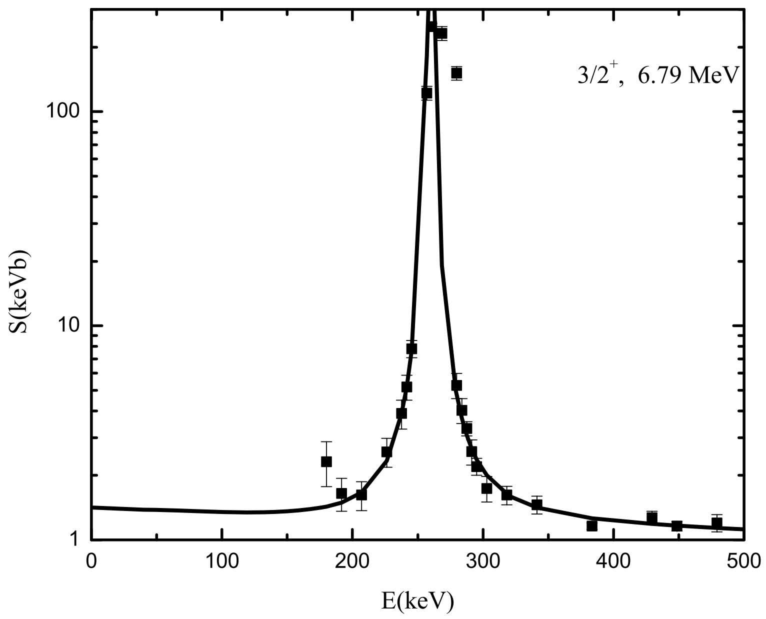
- R-Matrix fits to data from Schröder, *et al.*



DWBA analysis ⇒ need optical model parameters!

S factor for $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$





- $C^2(E_x=6.79\ \mathrm{MeV}) \approx 27\ \mathrm{fm}^{-1}$ [non-resonant capture to this state dominates S factor]
- $S(0) = 1.40 \pm 0.20$ keV·b for $E_x = 6.79$ MeV
- $S_{tot}(0) = 1.70 \pm 0.22$ keV·b

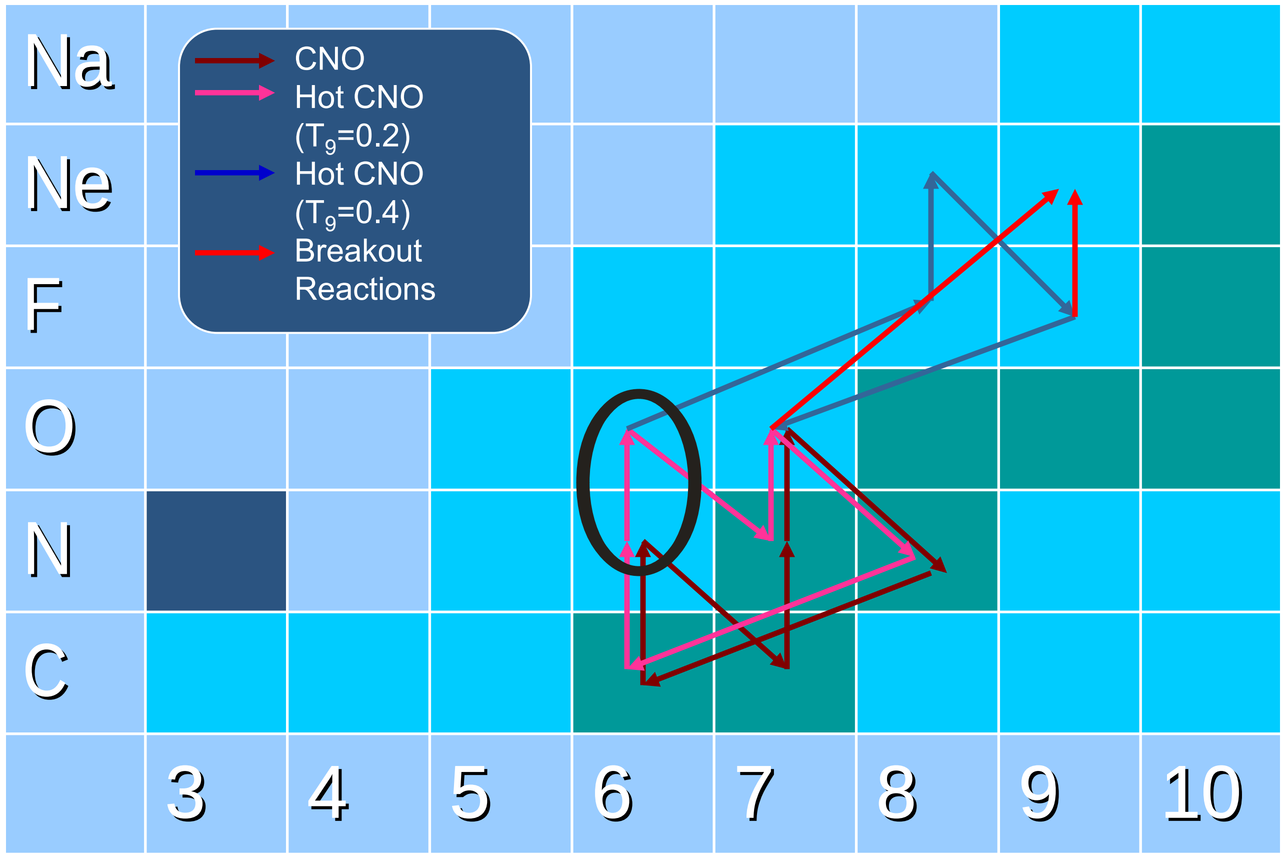
ANCs measured by our group with **radioactive** (rare isotope) **beams**

- **^{7}Be + p** ↔ **^{8}B** [^{10}B(^{7}Be,^{8}B)^{9}Be] **^{7}Be(p,γ)^{8}B**
  [^{14}N(^{7}Be,^{8}B)^{13}C]
- **^{11}C + p** ↔ **^{12}N** [^{14}N(^{11}C,^{12}N)^{13}C] **^{11}C(p,γ)^{12}N**
- **^{12}N + p** ↔ **^{13}O** [^{14}N(^{12}N,^{13}O)^{13}C] **^{12}N(p,γ)^{13}O**
- **^{13}N + p** ↔ **^{14}O** [^{14}N(^{13}N,^{14}O)^{13}C] **^{13}N(p,γ)^{14}O**
- **^{17}F + p** ↔ **^{18}Ne** [^{14}N(^{17}F,^{18}Ne)^{13}C] **^{17}F(p,γ)^{18}Ne**

{ORNL (TAMU collaborator)}

beams ≈ 10 - 12 MeV/u

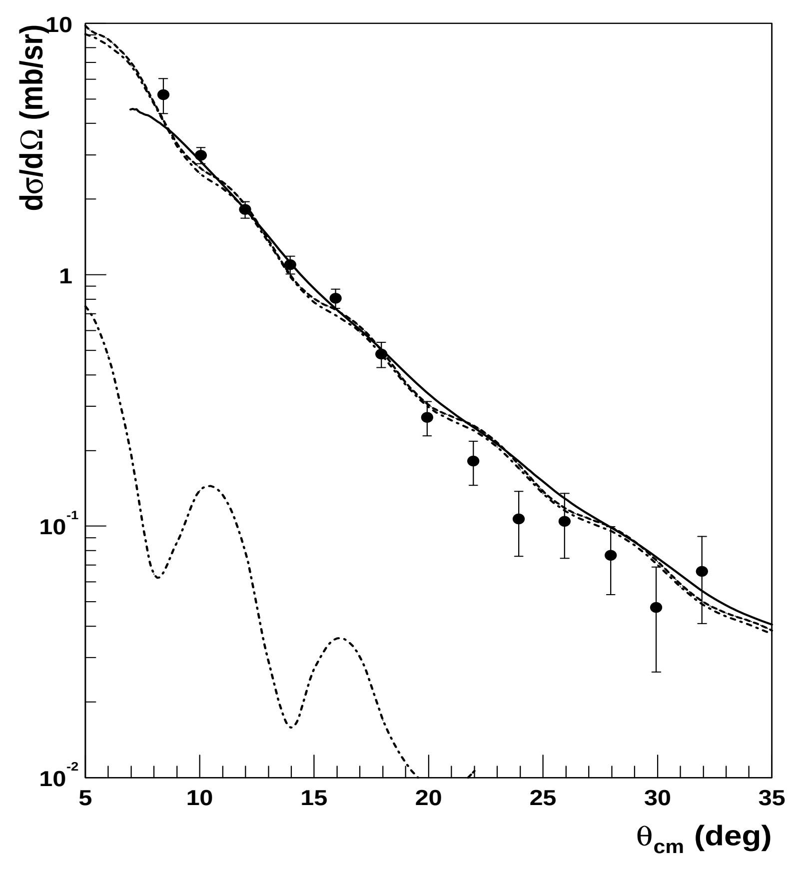
Hot CNO Cycle and $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$



http://csep10.phys.utk.edu/guidry/NC-State-html/cno.html

$^{14}N(^{13}N,^{14}O)^{13}C$

(ANC for $^{14}N \rightarrow ^{13}C + p$)

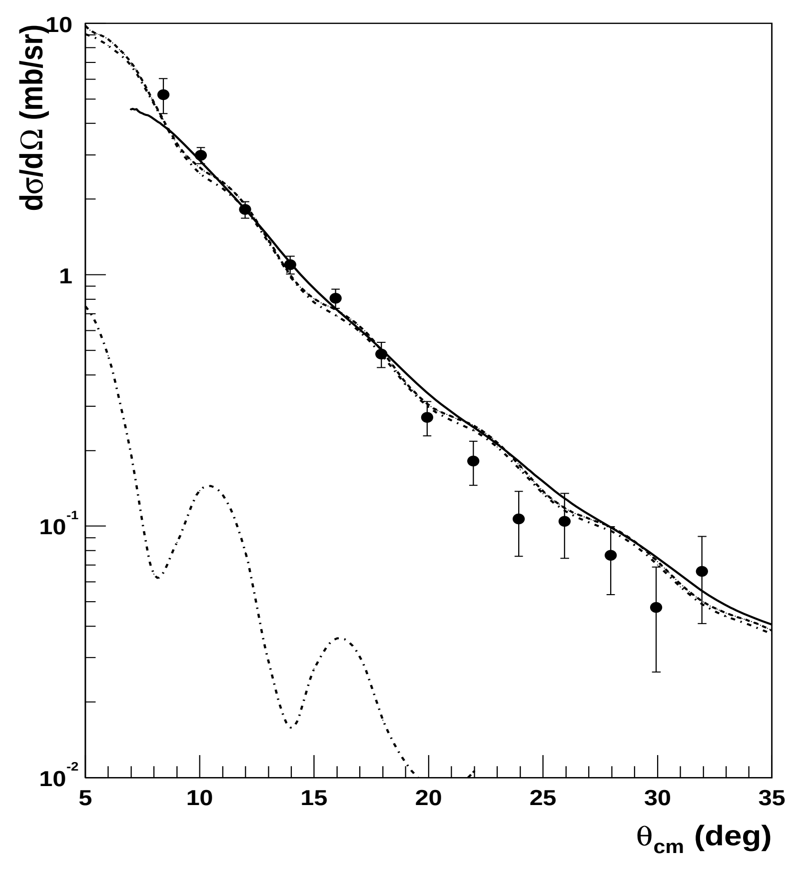


DWBA by FRESCO

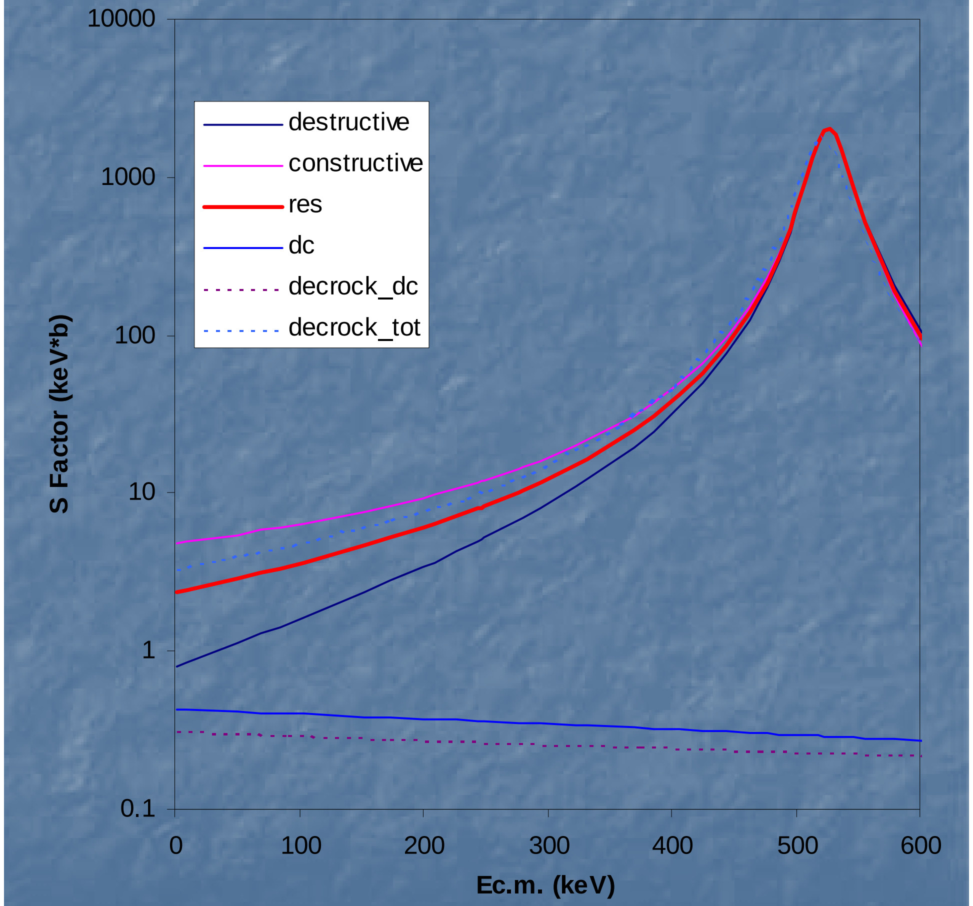
$$\sigma_{\exp} = \left(C^{^{14}O}_{^{13}N1\frac{1}{2}}\right)^2 \left(\left(\frac{C^{^{14}N}_{^{13}C1\frac{3}{2}}}{b^{^{14}N}_{^{13}C1\frac{3}{2}}\, b^{^{14}O}_{^{13}N1\frac{1}{2}}} \right)^2 \sigma^{DW}_{1\frac{1}{2}1\frac{3}{2}} + \left(\frac{C^{^{14}N}_{^{13}C1\frac{1}{2}}}{b^{^{14}N}_{^{13}C1\frac{1}{2}}\, b^{^{14}O}_{^{13}N1\frac{1}{2}}} \right)^2 \sigma^{DW}_{1\frac{1}{2}1\frac{1}{2}} \right)$$

$C^2 = 29.0 \pm 4.3\ \mathrm{fm}^{-1}$

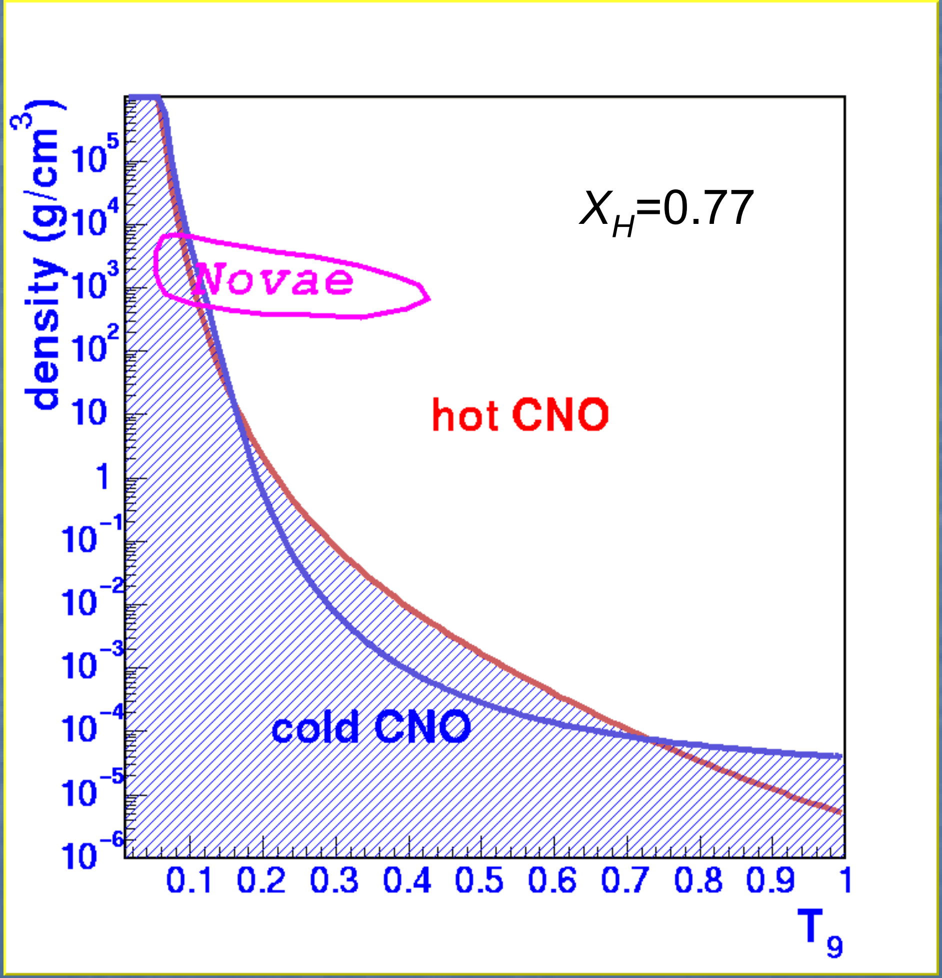
S Factor for $^{13}N(p,\gamma)^{14}O$



DWBA by FRESCO



Transition from CNO to HCNO



Crossover at $T_9 \approx 0.2$

- $^{13}N(p,\gamma)^{14}O$ vs β decay
- $^{14}N(p,\gamma)^{15}O$ vs β decay

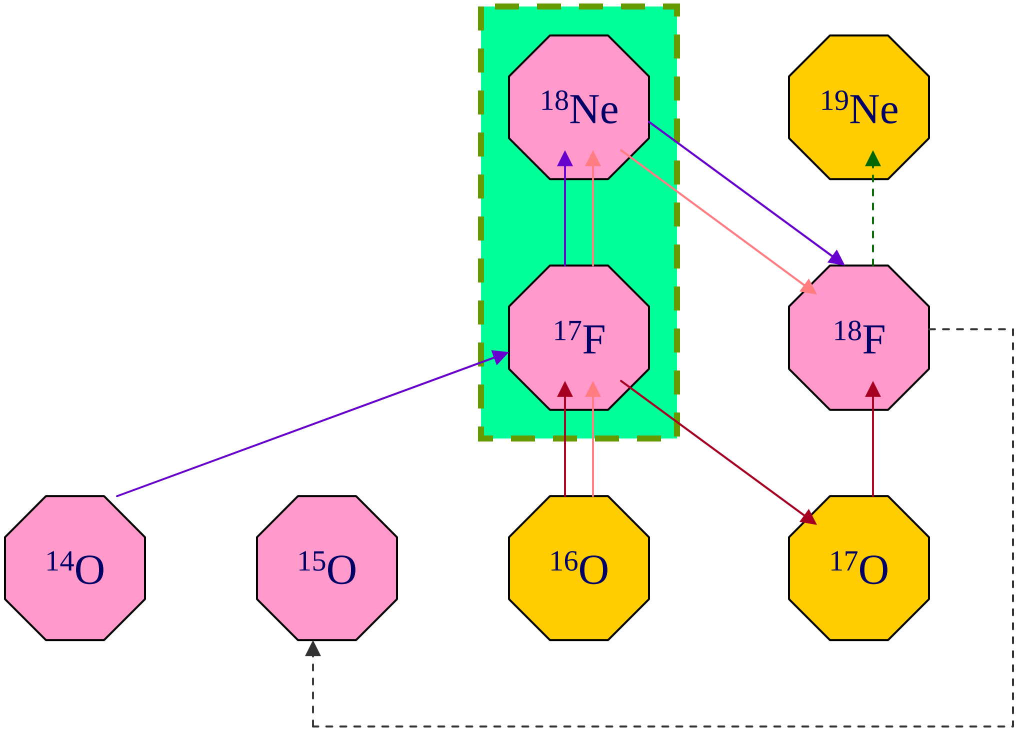
For novae find that $^{14}N(p,\gamma)^{15}O$ slower than $^{13}N(p,\gamma)^{14}O$; $\therefore$ $^{14}N(p,\gamma)^{15}O$ dictates energy production

ANCs (n) measured using stable beams [**Charge Symmetry**]

• **^{7}Li + n ↔ ^{8}Li**	[^{13}C(^{7}Li,^{8}Li)^{12}C]	**^{7}Be(p,γ)^{8}B**
• **^{12}C + n ↔ ^{13}C**	[^{12}C(^{13}C,^{12}C)^{13}C]	
• **^{22}Ne + n ↔ ^{23}Ne**	[^{13}C(^{22}Ne,^{23}Ne)^{12}C]	**^{22}Mg(p,γ)^{23}Al**
• **^{16}O + n ↔ ^{17}O**	[^{13}C(^{16}O,^{17}O)^{12}C]	**^{16}O(p,γ)^{17}F**
• **^{17}O + n ↔ ^{18}O**	[^{13}C(^{17}O,^{18}O)^{12}C]	**^{17}F(p,γ)^{18}Ne**

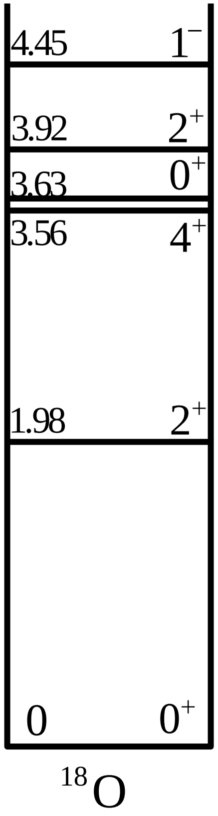
beams ≈ 10 MeV/u

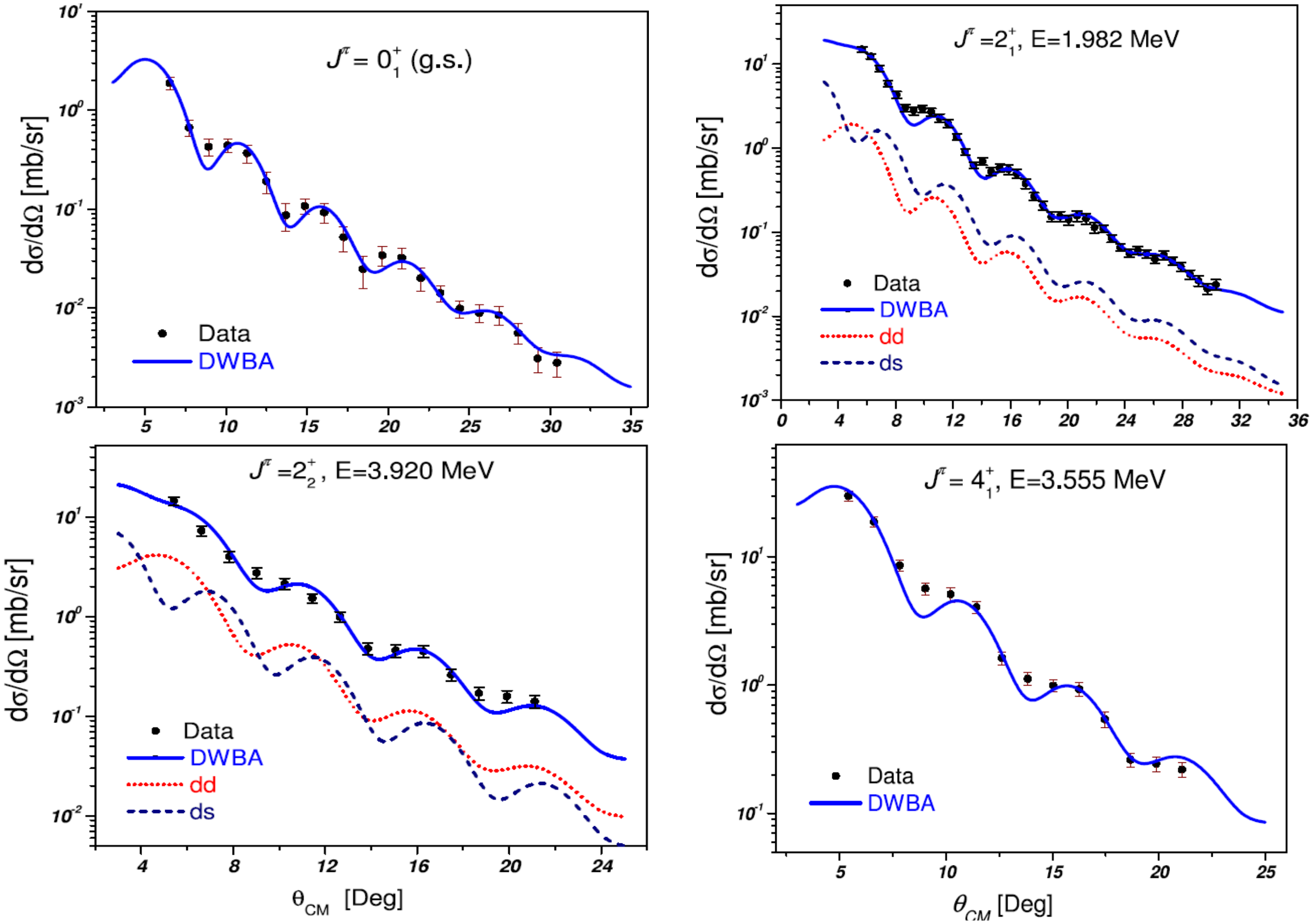
Why ^{18}F?



- **^{18}F** is a **major target for γ-ray observations** from novae
- The **^{17}F(p,γ)^{18}Ne** reaction:
  - Influences the abundances of ^{15}O, ^{17}F, **^{18}F**, ^{18}Ne
  - Determines the ^{17}O/^{18}O ratio
  - Provides a path from the HCNO cycle into the rp-process

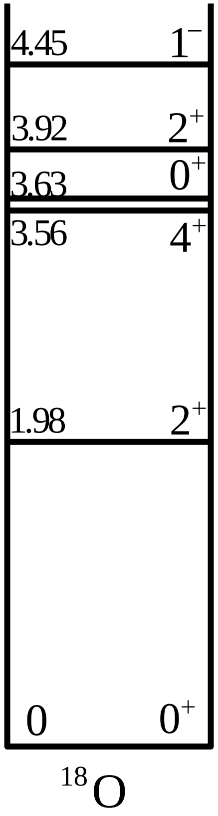
$^{13}C(^{17}O,^{18}O)^{12}C$

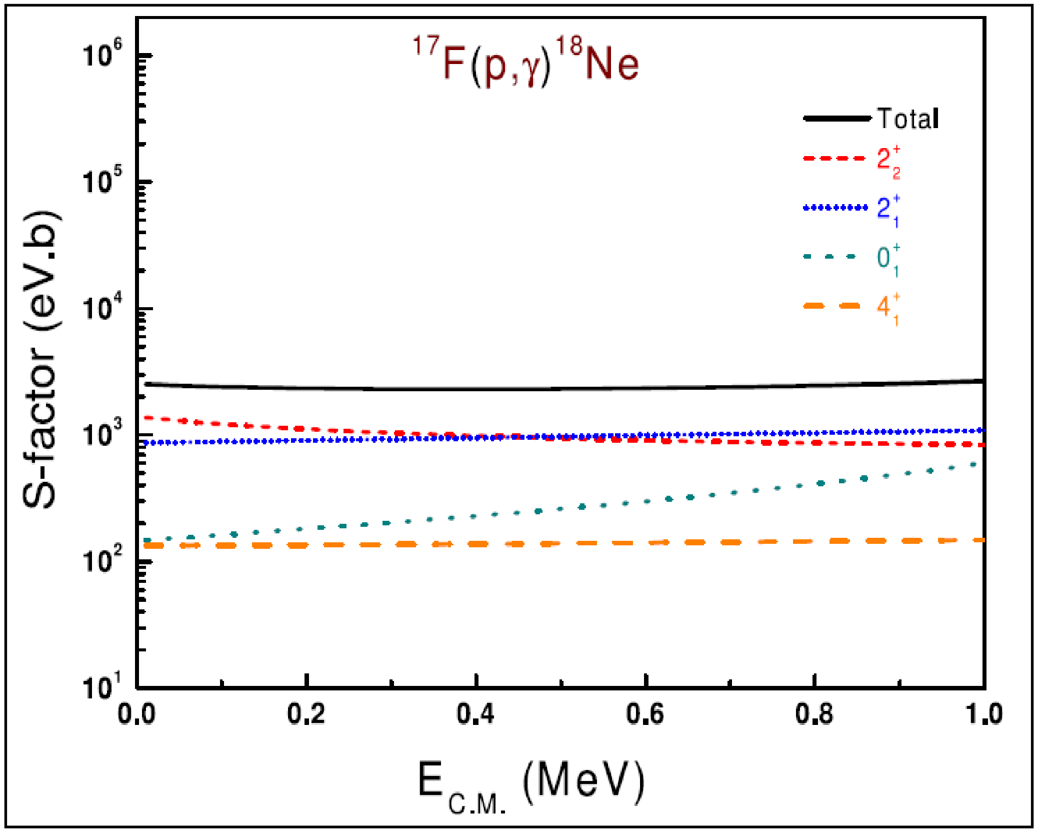




- Measured ANCs for ground state, 2^+_1, 2^+_2, 4^+
- The 2^+ states dominate the S factor
- **S(0) = 2.5 ± 0.4 keV b**
  - If nova M = 1.25 $M_\odot$, more ^{18}F & ^{18}O
  - If M ≥ 1.35 $M_\odot$, less ^{18}F but more ^{17}F & ^{17}O

$^{13}C(^{17}O,^{18}O)^{12}C$





- Measured ANCs for ground state, 2^+_1, 2^+_2, 4^+
- The 2^+ states dominate the S factor
- **S(0) = 2.5 ± 0.4 keV b**
  - If nova M = 1.25 $M_\odot$, more ^{18}F & ^{18}O
  - If M ≥ 1.35 $M_\odot$, less ^{18}F but more ^{17}F & ^{17}O

Reactions studied relevant to:

p-p chain

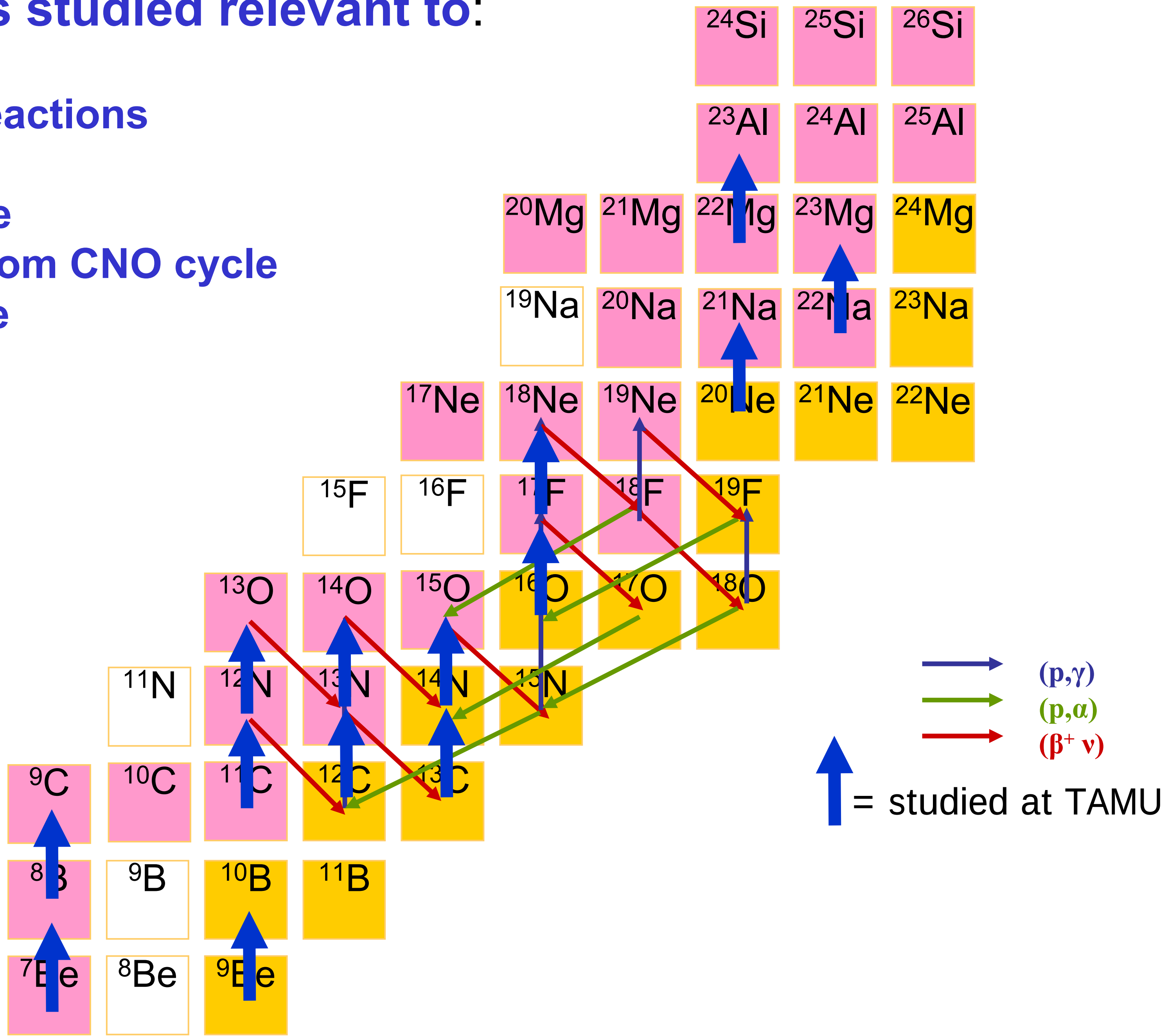
rapid α-p reactions

CNO cycle

HCNO cycle

Breakout from CNO cycle

Ne-Na cycle



Future direction:

reliable determination of spectroscopic factors and an extension to

(n,γ) direct capture

Obtaining reliable Spectroscopic Factors

- Direct reactions (even (d,p)!) have strong peripheral component
- Do not really ‘sample’ nuclear interior—which determines spectroscopic factor
- s-wave neutron capture DOES depend on nuclear interior—need spectroscopic information
- Our method to get this:
  - Measure ANC to fix exterior
  - Use reaction that is not too peripheral, analyze with ANC fixed and extract spectroscopic factor
  - Effectively removes dependence on single particle properties

Test case: $^{14}C(n,\gamma)^{15}C$

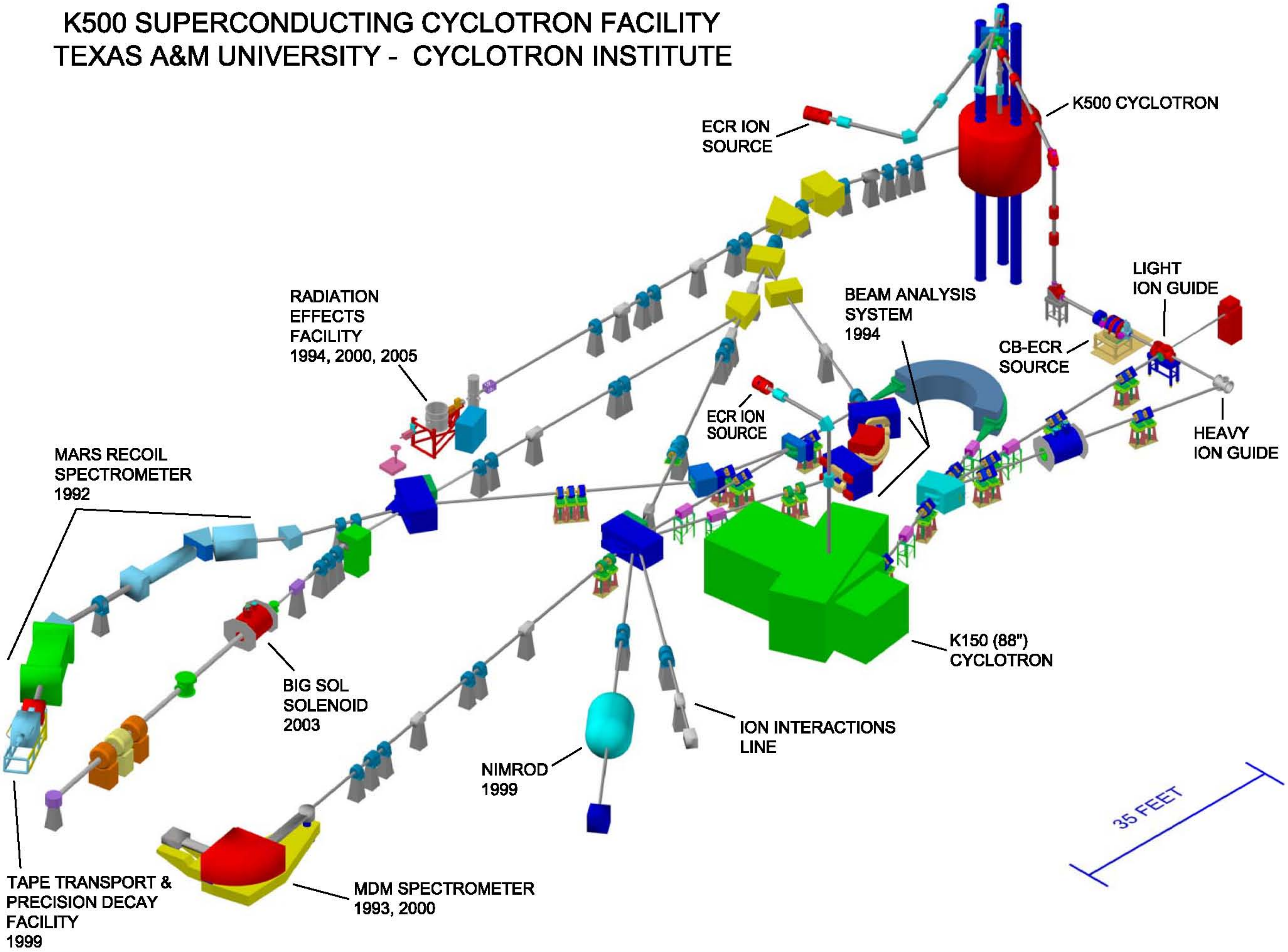
- **ANC** from breakup of $^{15}C \rightarrow {}^{14}C + n$
- Compare to $^{13}C(^{14}C,^{15}C)^{12}C$ at TAMU
- Determine **spectroscopic factor**
  - from $^{14}C(d,p)^{15}C$ – 60 Mev
- Use **ANC** to fix exterior part of cross section
- With **S**, determine $^{14}C(n,\gamma)^{15}C$ direct capture
- Compare **spectroscopic factor** to expectations
- **Extend to other systems**!

A Future Direction for Nuclear Astrophysics ⇒ RIBs

A focus of the next generation **RIB Facility** in the US!

One step: Upgrade at **TAMU** to produce reaccelerated **Rare Isotope Beams**

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE



Future Outlook at TAMU

- Goal: maintain K500 operation during project
- After 4th year project is on schedule
- Budget is about $5 M capital
- Look forward to **reaccelerated RIBs** by end of 2010!

Collaborators

- **TAMU:** T. Abdulla, A. Banu, C. Fu, C. Gagliardi, Y.-W. Lui, M. McClesky, A. Sattarov, E. Simmons, G. Tabacaru, X. Tang, L. Trache, Y. Zhai, A. Zhanov
- **INP** (Czech Republic): P. Bem, V. Burjan, V. Kroha, E. Simeckova, J. Vincour
- **IAP** (Romania): F. Carstoiu