Indirect Techniques (I):
Asymptotic Normalization Coefficients
and the
Trojan Horse Method

NIC IX

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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

Some Indirect Techniques
[focus on reaction rates]

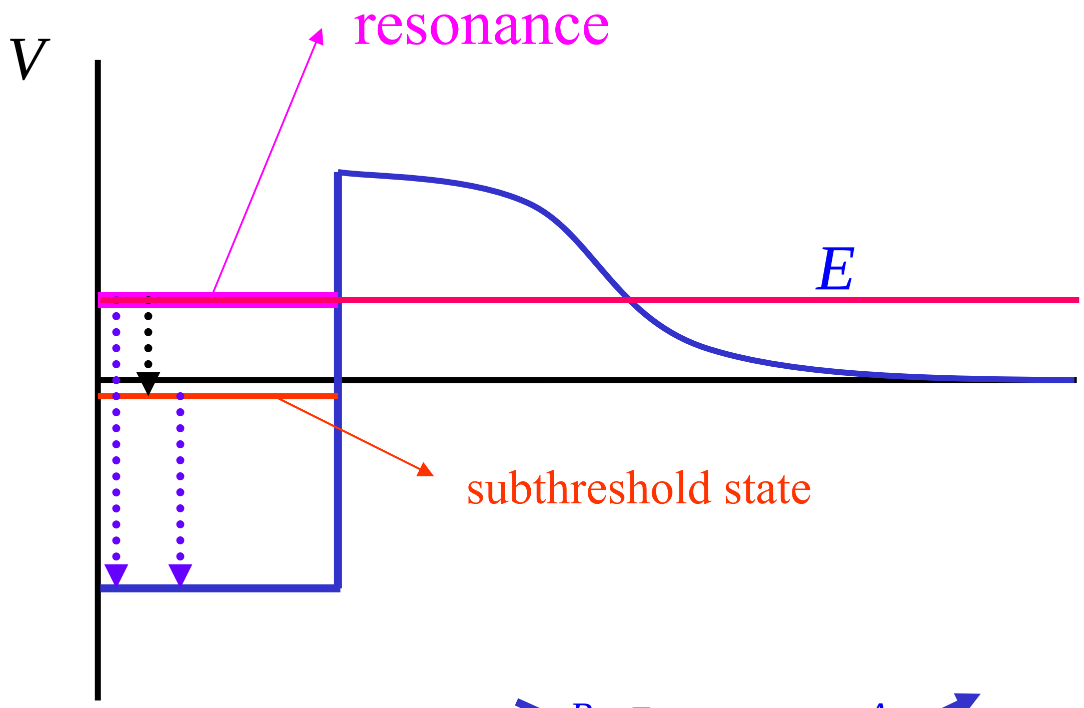
- **Widths** (γ and ‘p’) of resonance rates
  - populate resonance state and measure decay
- **Resonance energies** – determine E_R

} **resonant capture**

- **Coulomb dissociation** (T. Motobayashi)
- **Trojan Horse Method** ✓**
  - unique way to understand screening
- **Asymptotic Normalization Coefficients** ✓
  - use with stable and radioactive beams

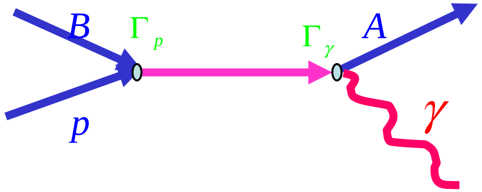
**Experts in audience for detailed questions!

Radiative [p(α)] **Capture** with **resonant** and **subthreshold** states: **ANCs**



Capture **through resonance**

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



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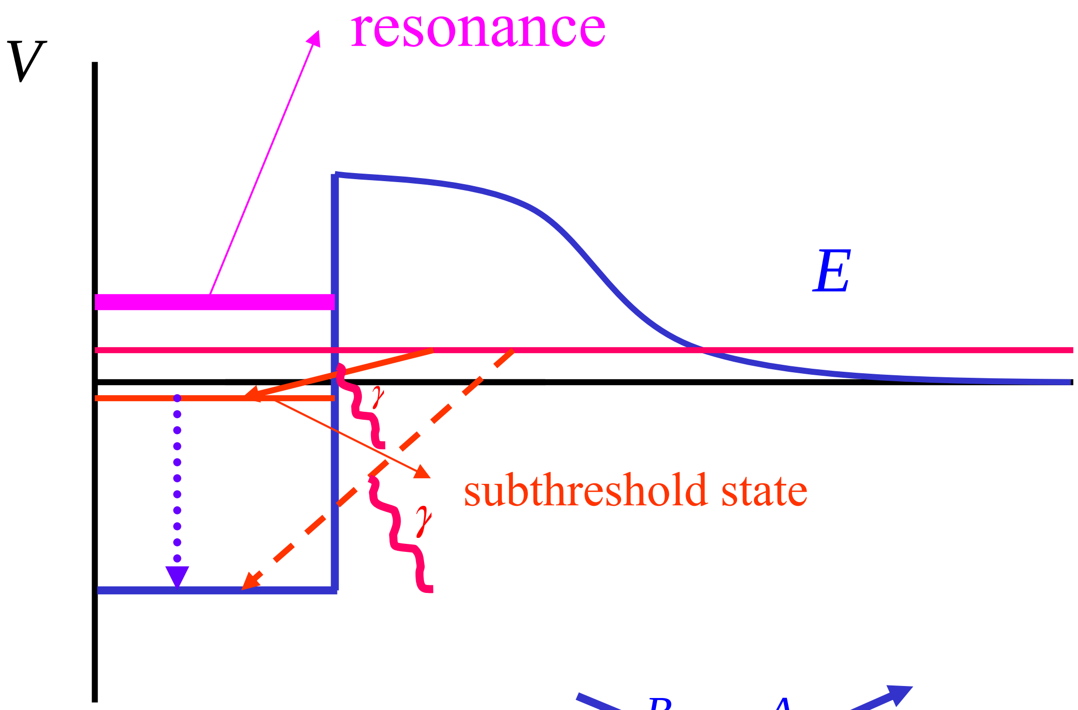
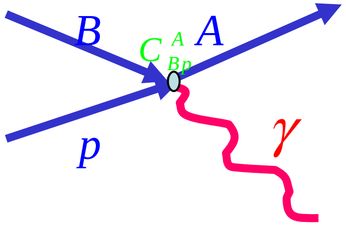
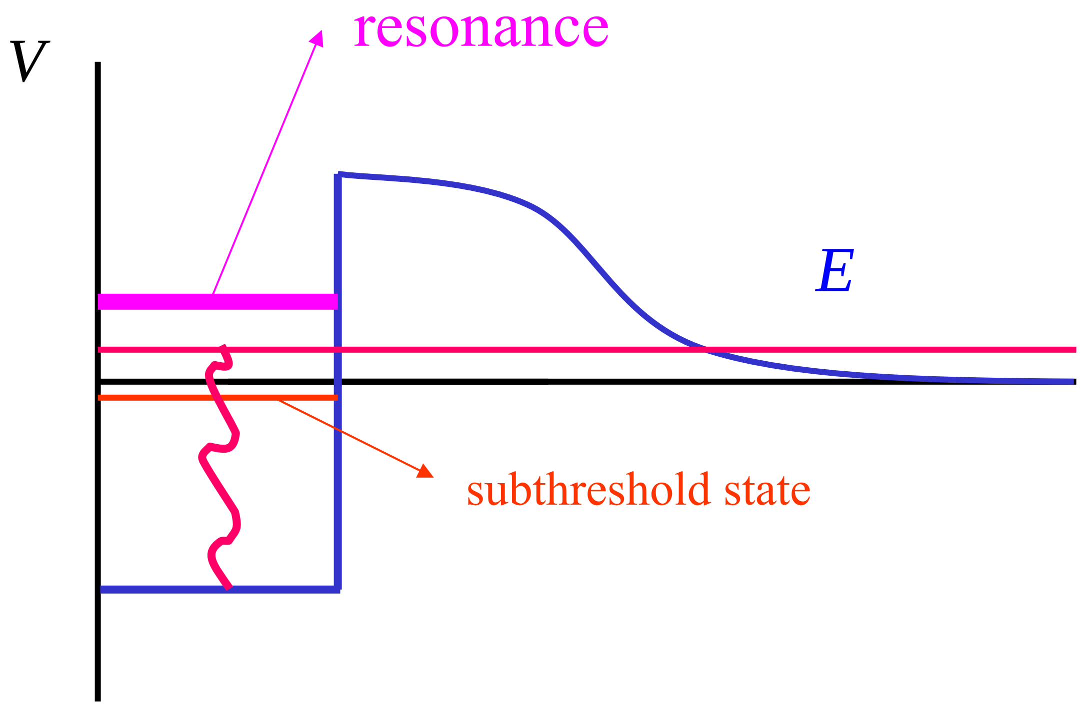


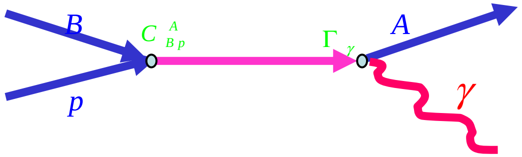
Direct capture

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



Radiative [p(α)] **Capture** with **resonant** and **subthreshold** states: **ANCs**

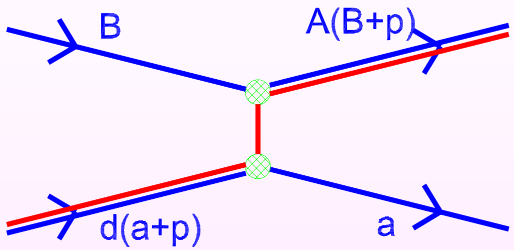




Capture **to ground state**
through subthreshold state

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

Measuring ANCs:
Transfer Reactions



Transition amplitude:

$$M = \sum \left\langle \chi_f^{(-)} I_{Bp}^{A} \middle| \Delta V \middle| I_{ap}^{d} \chi_i^{(+)} \right\rangle$$

Peripheral transfer:

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

$$\frac{d\sigma}{d\Omega} = (C_{Bpl_A j_A}^{A})^2 (C_{apl_d j_d}^{d})^2 \frac{\sigma_{l_A j_A l_d j_d}^{DW}}{b_{Bpl_A j_A}^2 b_{apl_d j_d}^2}$$

[$S = C^2/b^2$]

ANC Examples:
capture at stellar energies

DC:

- ^{7}Be(p,γ)^{8}B and ^{7}Be + p $\leftrightarrow$ ^{8}B
- ^{22}Mg(p,γ)^{23}Al and ^{22}Ne + n $\leftrightarrow$ ^{23}Ne

DC through subthreshold state:

- ^{14}N(p,γ)^{15}O and ^{14}N + p $\leftrightarrow$ ^{15}O
- ^{13}C(α,n)^{16}O and ^{13}C + α $\leftrightarrow$ ^{17}O (2 posters)

DC and resonance interference:

- ^{13}N(p,γ)^{14}O and ^{13}N + p $\leftrightarrow$ ^{14}O

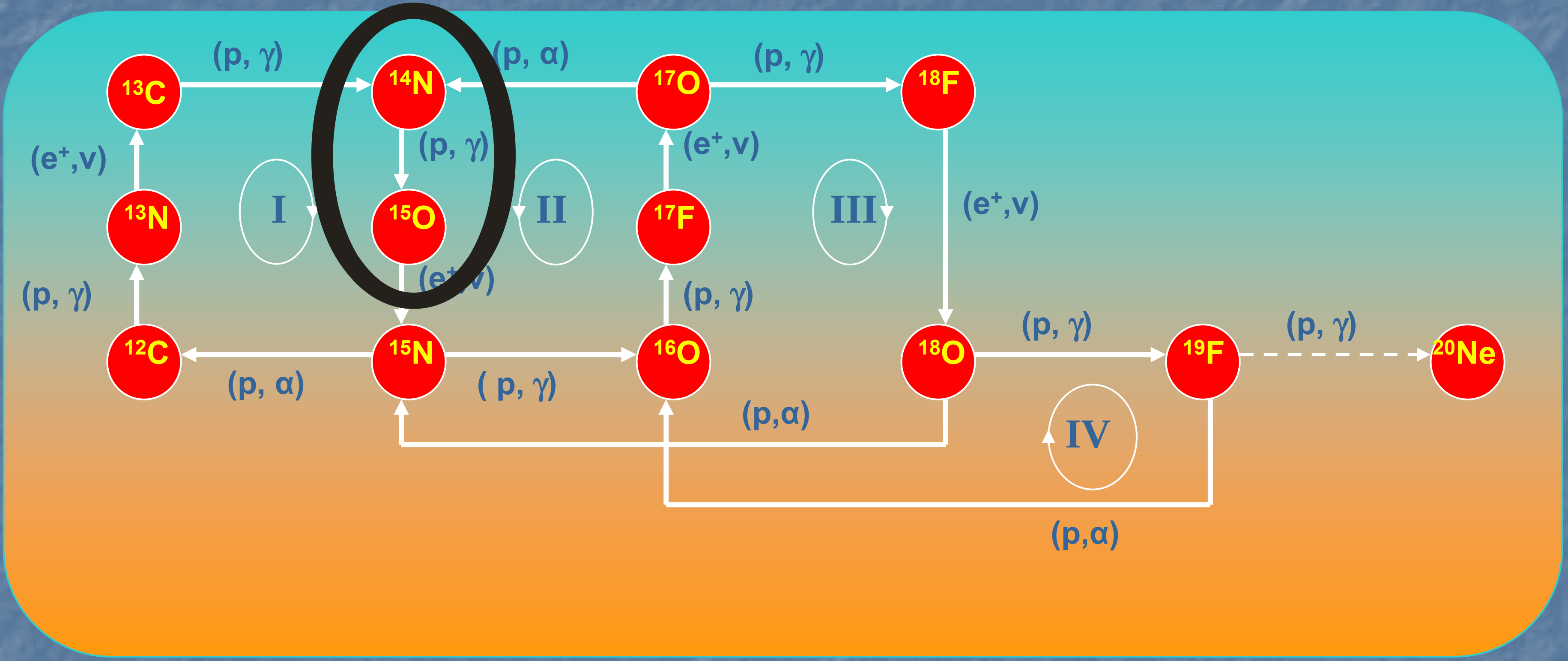
S factor for ^{7}Be(p,γ)^{8}B

- **S** factor dominated by direct capture—our published value via **ANCs** from two (^{7}Be,^{8}B) transfer reaction studies:

$$S(0) = 18.0 \pm 1.9 \text{ eV}\cdot\text{b}$$

- ➢ Result low by about 2 σ compared to most recent direct measurement (?)
- ➢ Details about ^{7}Be(p,γ)^{8}B from C.D. in later talk

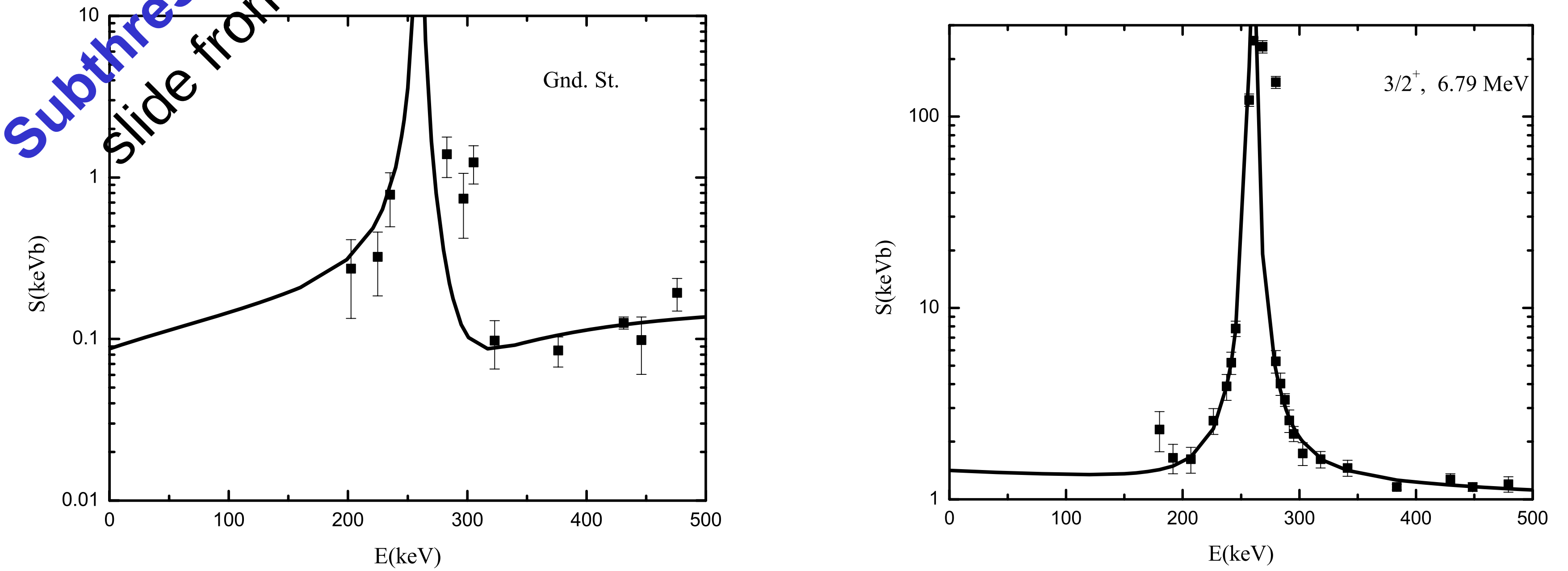
CNO Cycles



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

Subthreshold state: slide from **NIC VII**

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



- $C^2(E_x=6.79\ \text{MeV}) \approx 27\ \text{fm}^{-1}$ [non-resonant capture to this state dominates S factor]
- $S(0) \approx 1.41 \pm 0.24$ keV·b for $E_x=6.79$ MeV
- $S_{tot}(0) \approx 1.62 \pm 0.25$ keV·b

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

- **S** factor dominated by direct capture to the subthreshold state—our published value

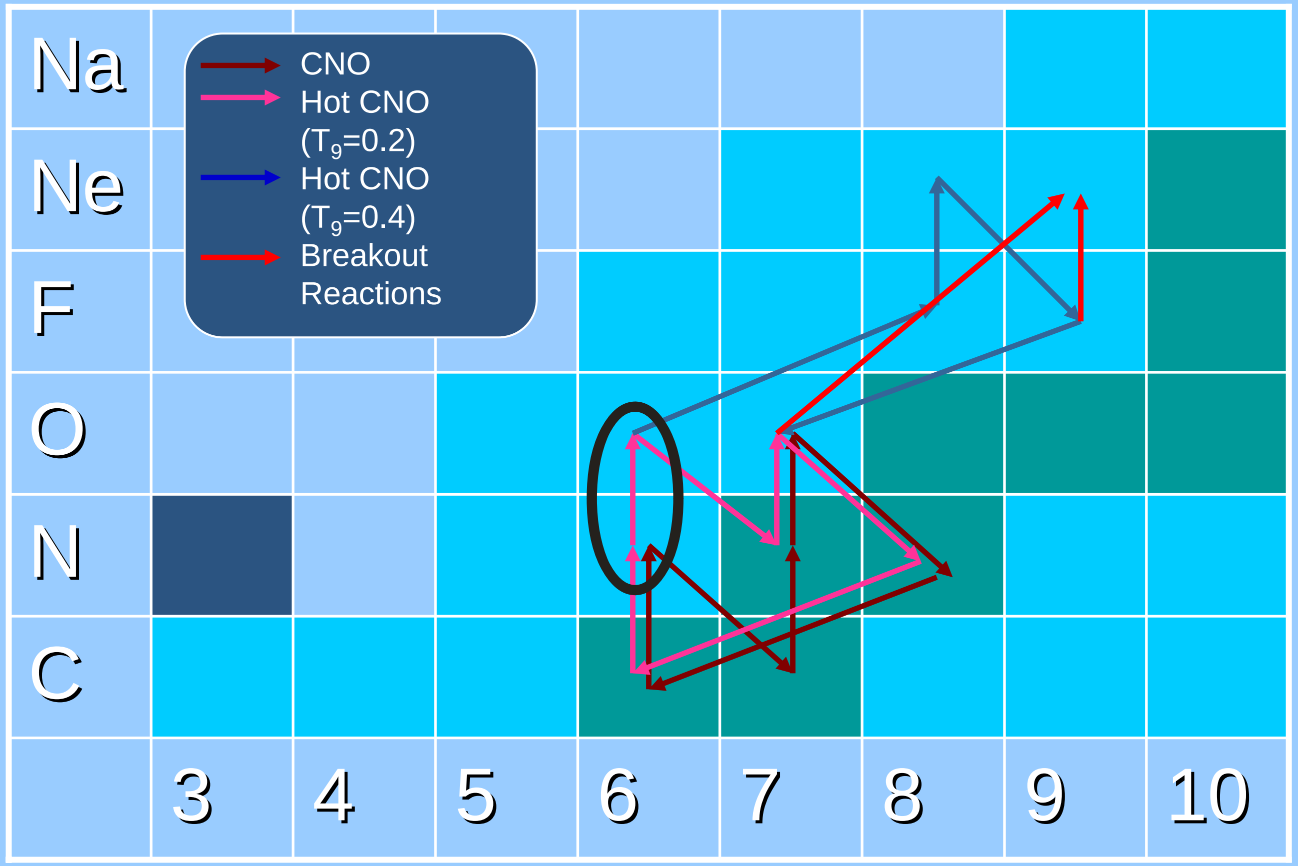
  $S(0) = 1.62 \pm 0.25$ keV·b

  reduces previous results by ≈ 2

- New direct measurements from LUNA (1.7±0.2) and LENA (1.68±0.09±0.16) in ***excellent agreement*** with this
- Impacts stellar luminosity at transition period to red giants and ages of globular clusters by about 1 Gyr

PC1

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



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

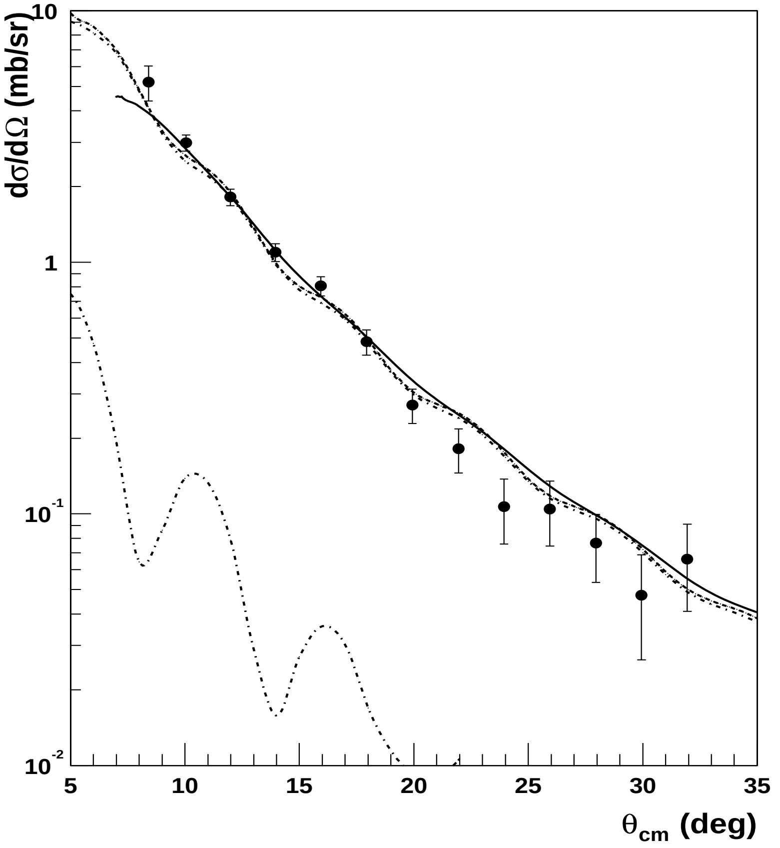
Slide 13

PC1 After star runs out of pp chain fuel, CNO cycle would take over. When T9>0.1, the p capture rate on 13N could become of the same order or faster than its beta decay. As a result, hot CNO cycle will replace the normal CNO cycle to operate. So 13N(p,g)14O is a important reaction which determine the transition condition from CNO to hotCNO.

Preferred Customer, 1/15/2003

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

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

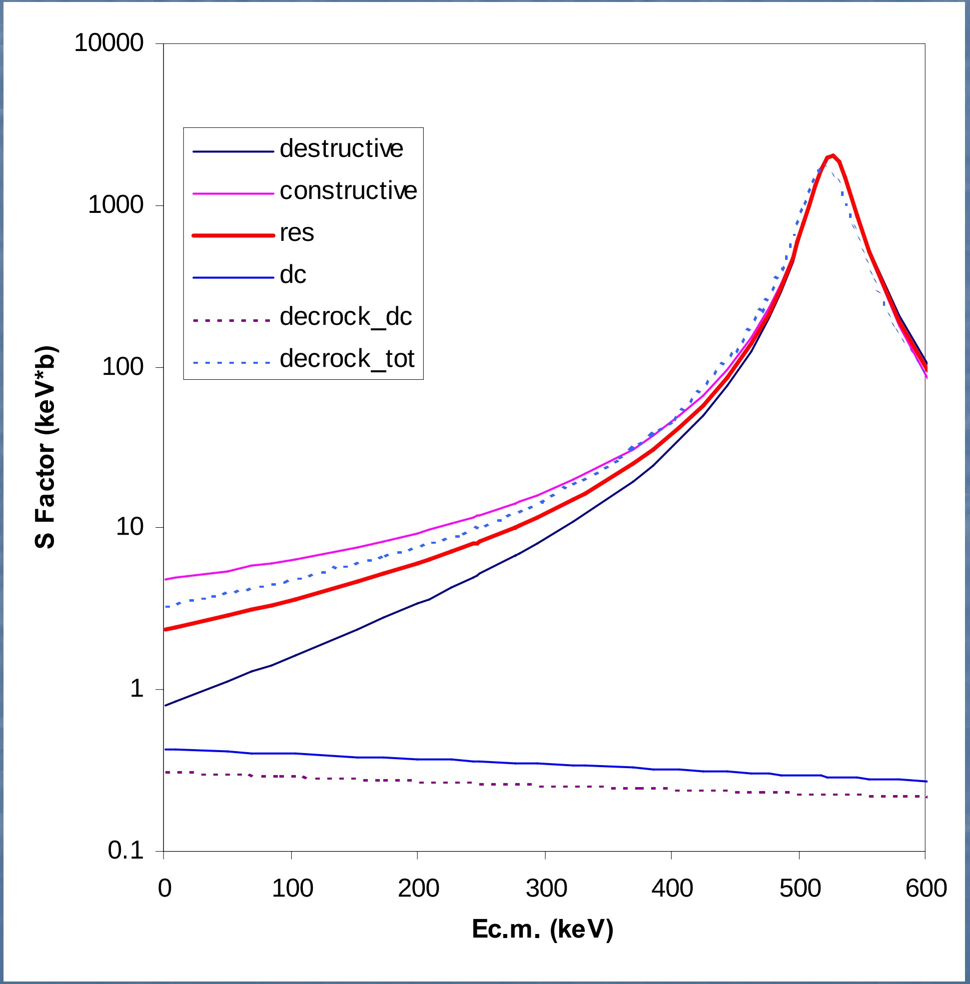


DWBA by FRESCO

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

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

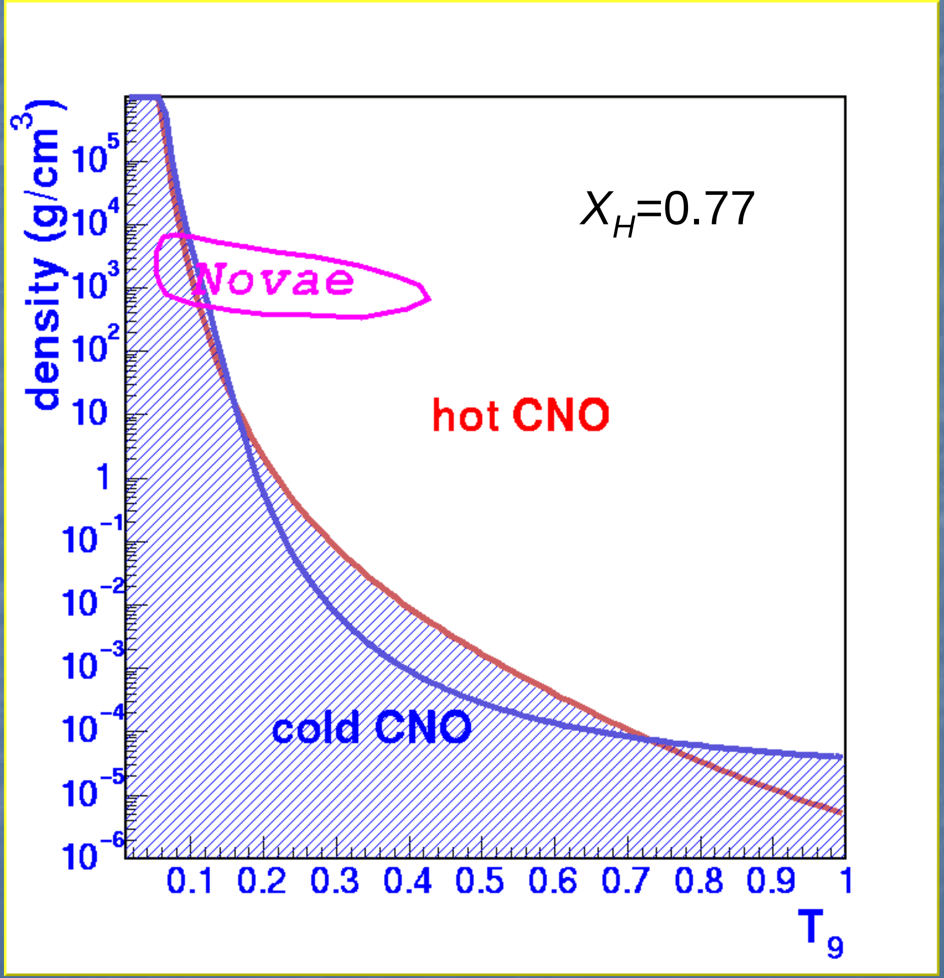
S Factor for $^{13}N(p,\gamma)^{14}O$



For Gamow peak at T_9=0.1,

- DC/Decrock_dc = 1.4
- Constructive/Decrock_tot =1.4
- Constructive/Destructive =4.0
  (expected constructive interference for lower energy tail, useful to check)

Transition from CNO to HCNO



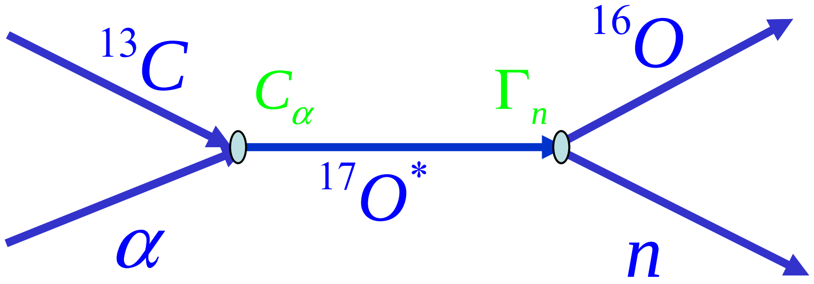
Crossover at $T_9 \approx 0.2$

- $^{13}N(p,\gamma)^{14}O$ 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

S factor for $^{13}C(\alpha,n)^{16}O$ and s-process neutrons

S factor dominated by subthreshold state (E_x=6.356 MeV)



$$\Gamma_n = 124\,\text{keV};\quad E_R = 2.22\,\text{Mev};$$

$$J^\pi = 1/2^+;\quad l_i = 1;\; l_f = 0;$$

ANC from $^6Li(^{13}C,d)^{17}O$ – sub Coulomb transfer

(recent result from Florida State University and TAMU, earlier result - Kubono)

ANC + Γ_n gives $S(0) = 2.36 \pm 0.52 \times 10^6$ Mev·b

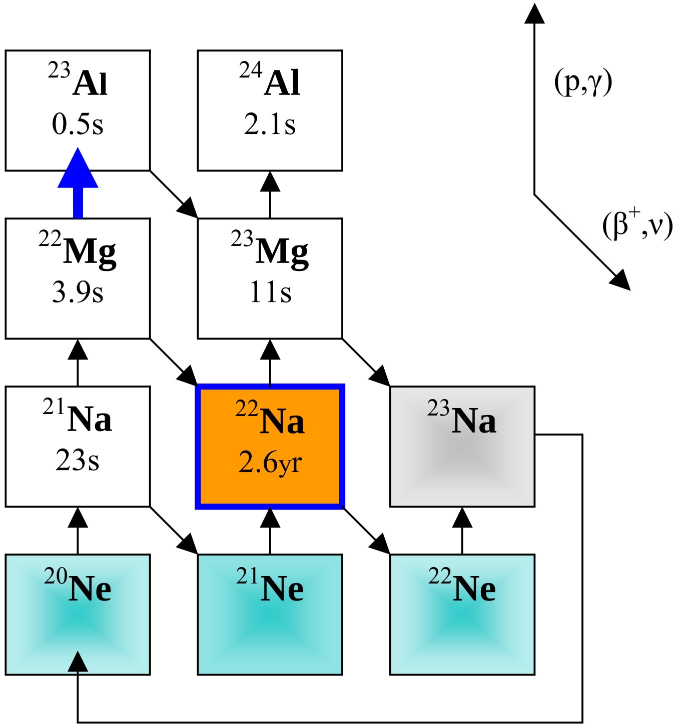
Factor of ≈ 10 below present NACRE value

[posters on this topic!]

S factor for ^{22}Mg(p,γ)^{23}Al

S factor dominated by direct capture up to $T_9 \approx 0.2$

^{22}Mg produced in ONe novae in Ne-Na cycle ⇒ source of ^{22}Na



β decay or p capture dominate?

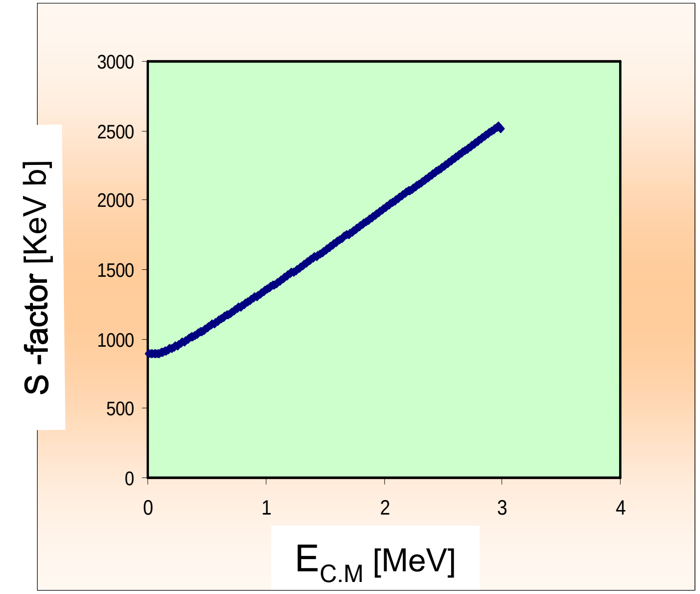
Use charge symmetry for **ANC**:

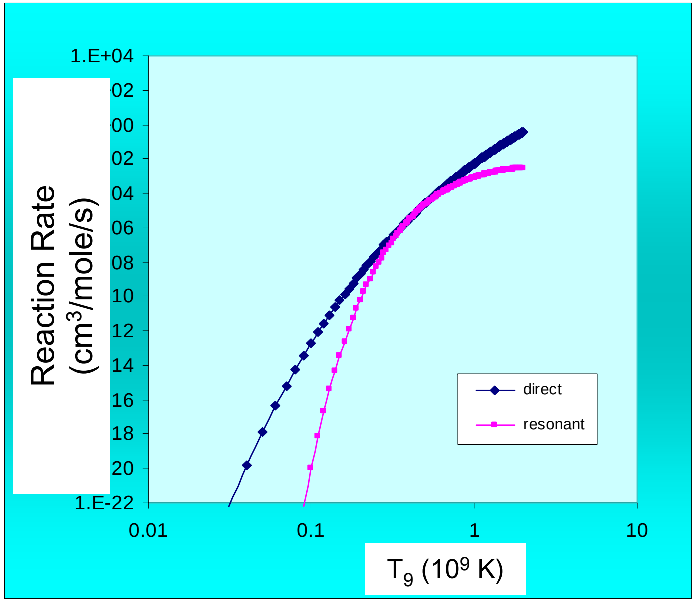
$$C^2_{d_{5/2}}(^{23}Al) = C^2_{d_{5/2}}(^{23}Ne)\frac{b^2_{d_{5/2}}(^{23}Al)}{b^2_{d_{5/2}}(^{23}Ne)}$$

β-decay of ^{23}Al ⇒ gnd. state is $5/2^+$

^{22}Mg (p,γ)^{23}Al Reaction Rate

$$C^2(^{23}Al) = (1.22 \pm 0.12) * 10^4\ fm^{-1}$$





S(E) – Direct Capture reaction rate

ρ=10^6 gm/cm^3, T$_9$=0.4

^{22}Mg(p,γ)^{23}Al competes with β$^+$ rate

but photodisintegration is issue

Charged Particle Capture: the **Trojan Horse Method** I

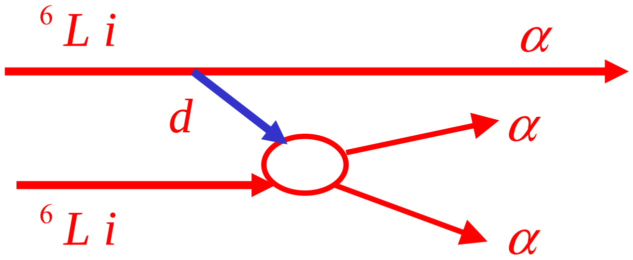
- Many charged-particle reaction rates important in stellar evolution
- Laboratory measurements ⇒ **Coulomb barrier** issues (e.g. electron screening) making extrapolation difficult
- **THM** (Baur – 1986) uses surrogate to remove Coulomb effects

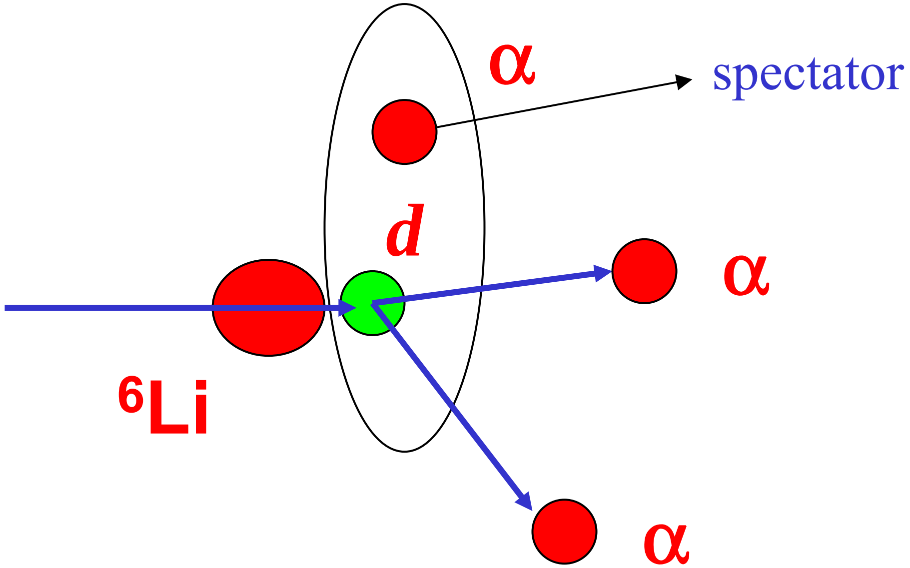
THM - Example

Consider a reaction $^{6}Li(d,\alpha)^{4}He$

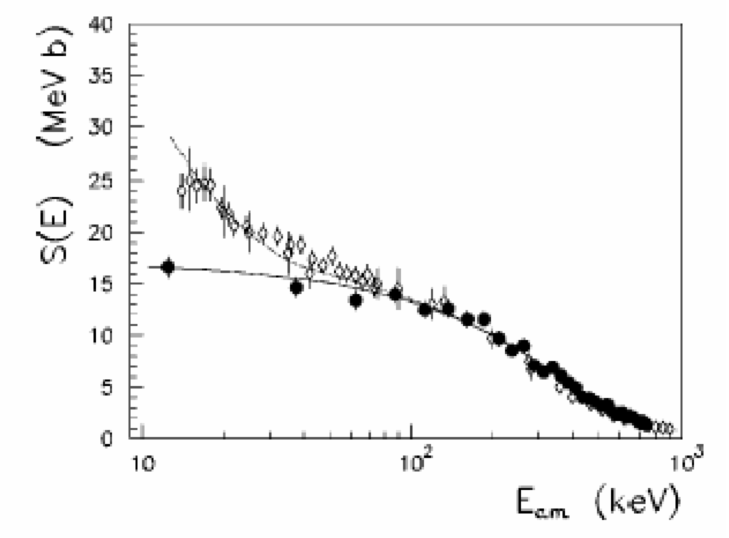
THM ⇒ use $^{6}Li(^{6}Li,\alpha\alpha)^{4}He$

$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$ for $^{6}Li(d,\alpha)^{4}He$





THM - Spitaleri et al.
Direct data Englster et al.



Charged Particle Capture: the **Trojan Horse Method** II

- Issues:
    - transferred particle is off energy shell
    - initial and final state effects important
    - no absolute normalization
    - must have quasi-free kinematics
    - analysis with PWIA and MPWIA

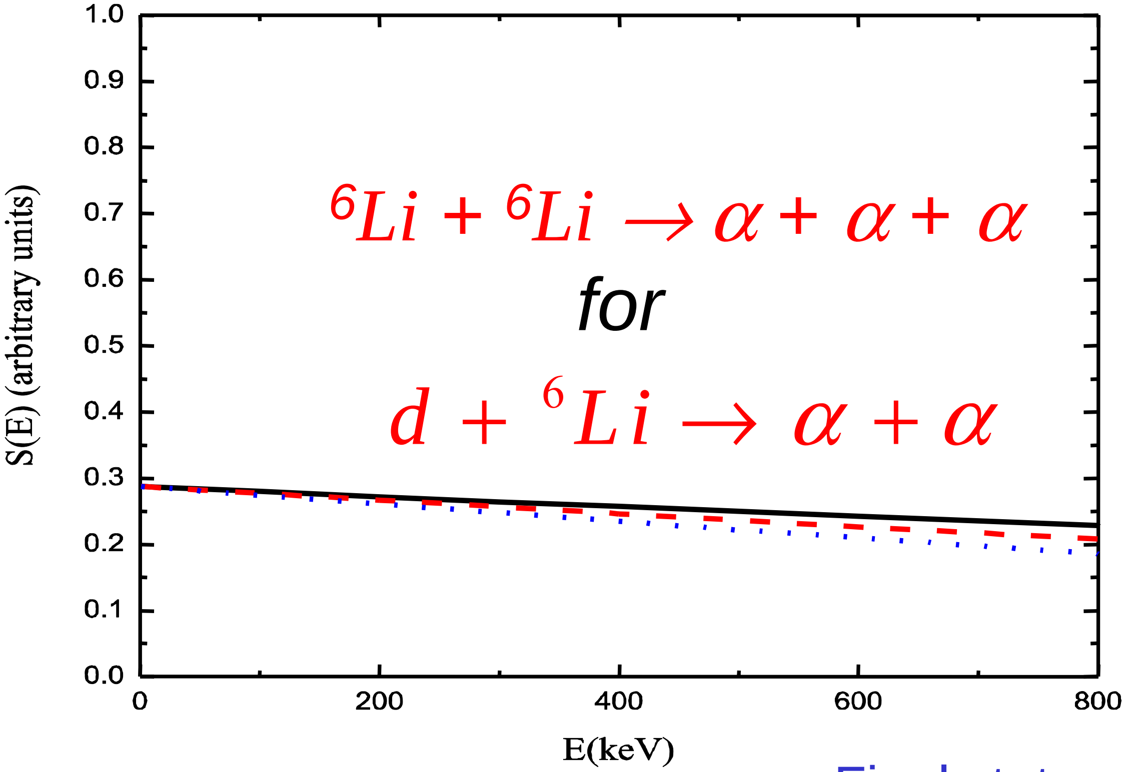
Some Reaction Mechanism Issues

Three calculations (spectator α ignored) as a function of $\Delta=(p_{\alpha d})^2/(\mu_{\alpha d})^2$

‘**on shell**’ transfer $\Rightarrow$ $\Delta=0$ (black)

‘**half off shell**’ with QF kinematics $\Rightarrow$ $\Delta=m_\alpha+m_d-m_{Li}=$ BE (red)

‘**half off shell**’ with $\Rightarrow$ $\Delta=1.5\times$BE (blue)



Coulomb effects included

Final state effects also not important!

[Mukhamedzhanov et al., nucl/th-0602001]

THM Applications

- Direct Capture:
  - extrapolation to S(0) without e-screening
  - extraction of screening potential
- Resonant capture:
  - extrapolation to S(0) with small uncertainty
- Subthreshold Capture:
  - observe effects at very low relative energy

Direct Capture

$^6Li + d \rightarrow \alpha + \alpha$ S_0= 16.9 MeV b

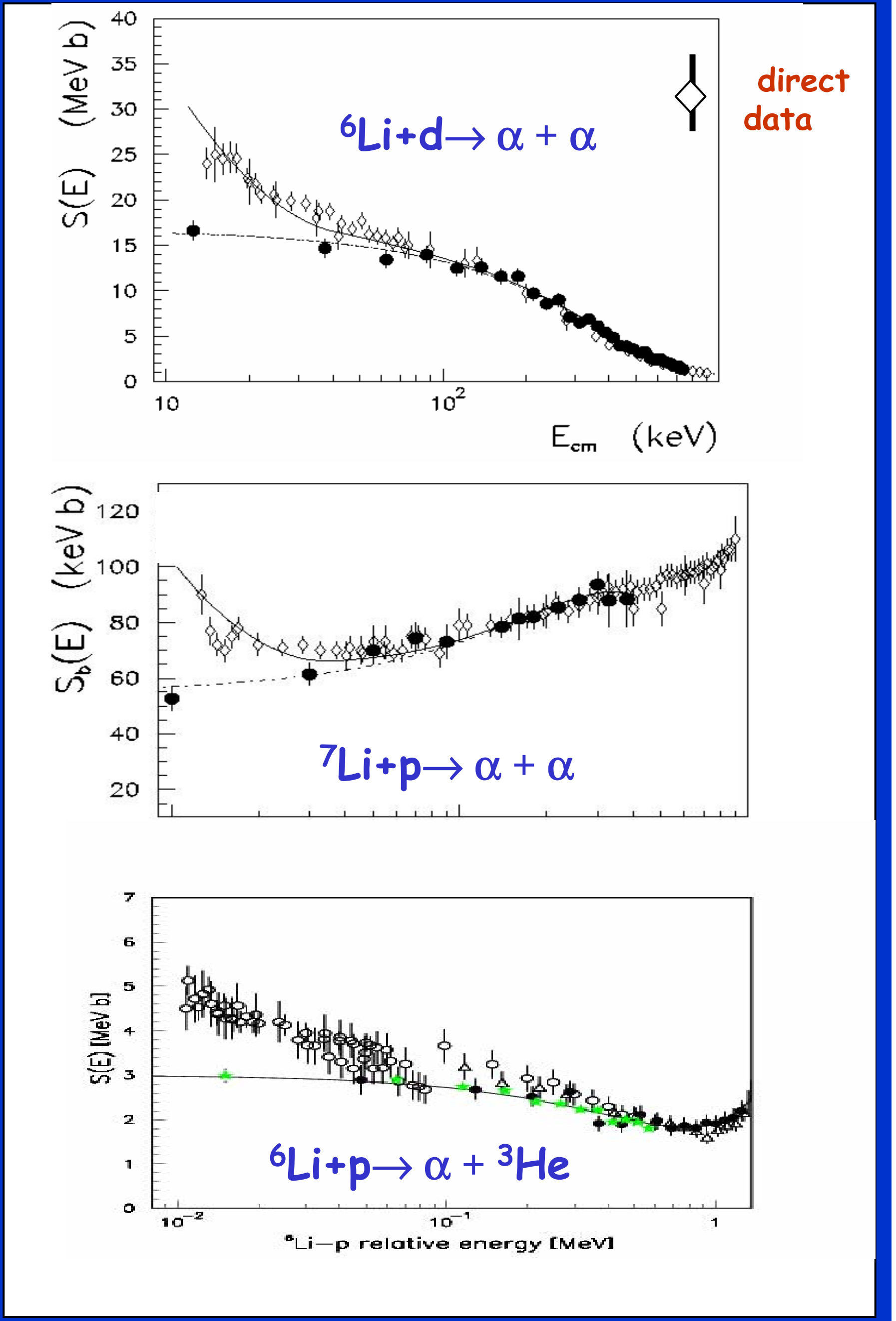
U_e (ad)		U_e (Dir) ^6Li+d
186 eV		330 ± 120 eV

$^7Li + p \rightarrow \alpha + \alpha$ S_0=55 ± 3 keV b

U_e (ad)		U_e (Dir) ^7Li+p
186 eV		300 ± 160 eV

^6Li+p α+^3He So = 3 ± 0.9 MeVb

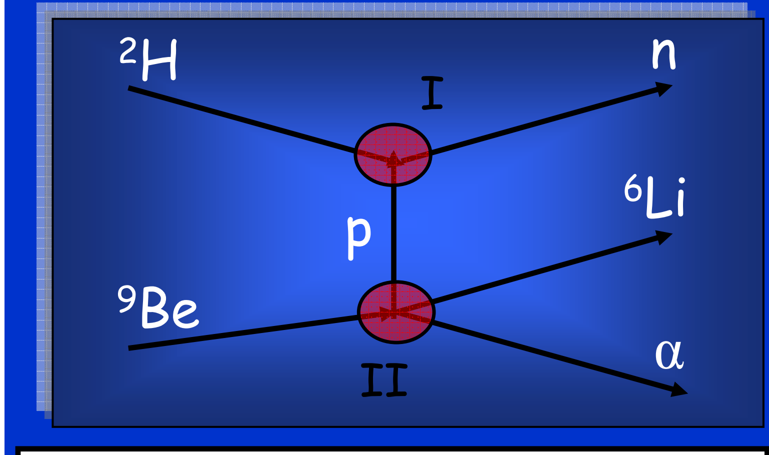
U_e (ad)		U_e (Dir) ^6Li+p
186 eV		440 ± 80 eV

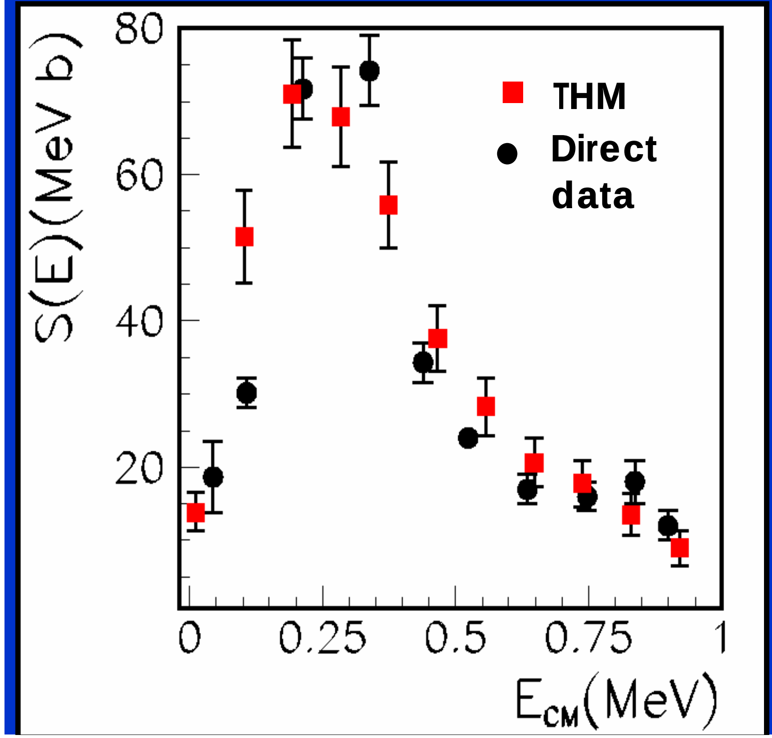


From C.S.

Resonant Capture

The $^{9}Be(p,\alpha)^{6}Li$ reaction via $^{2}H(^{9}Be,\alpha^{6}Li)n$





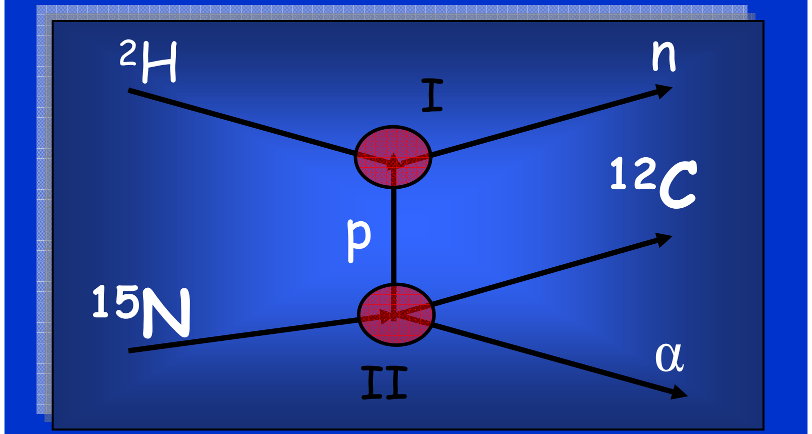
Laboratory: Tandem: LNS INFN-Catania

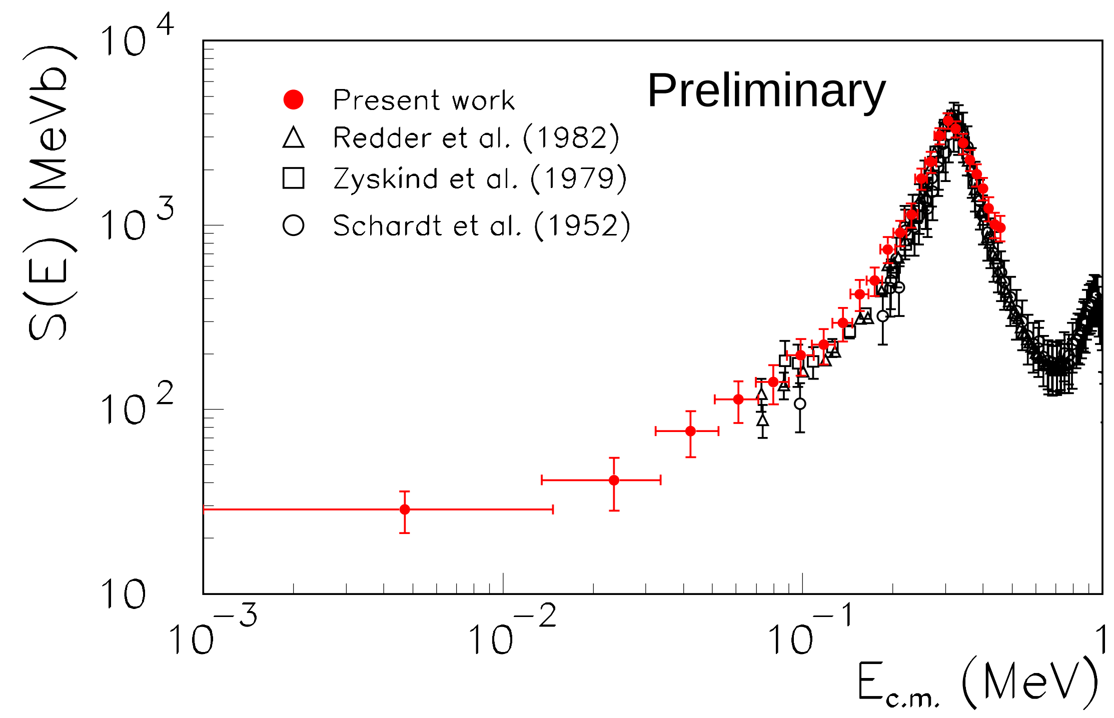
Energy: $E_{9Be} = 22$ MeV

Reaction important for depletion of light nuclei

From C.S.

The $^{15}N(p,\alpha)^{12}C$ reaction via $d(^{15}N,\alpha^{12}C)n$





Destroys $^{15}N \Rightarrow$ reduces ^{19}F production in AGB stars

Laboratory:

TAMU (K500 cyclotron)

$^{2}H(^{15}N,\alpha^{12}C)n$

E_{beam} = 60 MeV

S(0) ≈ 37 MeVb [about 1/2 NACRE value]

From C.S.

Summary

- Indirect techniques ⇒ valuable tools in N.A.
- Useful for range of reaction types
- S(0) with different extrapolation systematics
- Can provide auxiliary information
- Yield cross sections difficult to get otherwise!

Challenge for the future:
find new techniques to understand (n,γ) rates

Collaborators

- **ANCs**:

  T. Al-Abdullah, A. Azhari, A. Banu, P. Bem, V. Burjan, F. Carstoiu, C. Fu, C. Gagliardi, V. Kroha, J. Piskor, A. Sattarov, E. Simeckova, G. Tabacaru, X. Tang, L. Trache, J. Vincour, Y. Zhai, A. Mukhamedzhanov

- **THM** (TAMU experiment):

  C. Spitaleri,S. Cherubini, V. Crucilla, M. La Cognata, L. Lamia, R.G. Pizzone, S. Romano, A. Tumino