EM Capture as a Fundamental Process in Nuclear Astrophysics

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Capture Reactions in Astrophysics

$$\text{Maxwell-Boltzmann} \rightarrow \langle \sigma v \rangle \propto \int_0^\infty E\, \sigma \exp(-E/kT)\, dE$$

- Big-Bang Nucleosynthesis
- Stellar Hydrogen Burning
- Stellar Helium Burning
- Slow Neutron Capture Process (s-process)
- Rapid Neutron Capture Process (r-process)

Electromagnetic Capture Mechanism

$$\sigma \propto |\langle \Psi_{\rm f} | \vec{J} \cdot \vec{A} | \Psi_{\rm scat} \rangle|^2$$

We are therefore consider:

- The initial scattering state $\Psi_{\rm scat}$ (partial wave decomposition)
- The EM operator: multipole decomposition (E1, M1, ...)
- The final bound-state wavefunction $\Psi_{\rm f}$

Classification of Capture Reactions

$$\mathrm{A}(b, \gamma)\mathrm{C}$$

- Non-resonant (direct) capture:
  - Little sensitivity to Ψ_{scat} ($\sim$Coulomb wave)
  - Little sensitivity to interior part of Ψ_{f}
  - Asymptotic normalization of $\mathrm{A} + b$ in Ψ_{f} is crucial

- Isolated resonances:
  - Ψ_{scat} is resonant
  - Need E_x, partial widths, J^π
  - Energy relative to $\mathrm{A} + b$ threshold particularly important

- Many Resonances (statistical model):
  - Average cross section is determined statistically
  - Need optical potentials, level densities, γ-ray strength functions

α captures into $A = 7$: $^{3}\mathrm{H}(\alpha, \gamma)^{7}\mathrm{Li}$ and $^{3}\mathrm{He}(\alpha, \gamma)^{7}\mathrm{Be}$

- Both reactions are important for Big-Bang Nucleosynthesis

- $^{3}\mathrm{He}(\alpha, \gamma)^{7}\mathrm{Be}$ impacts solar neutrino generation

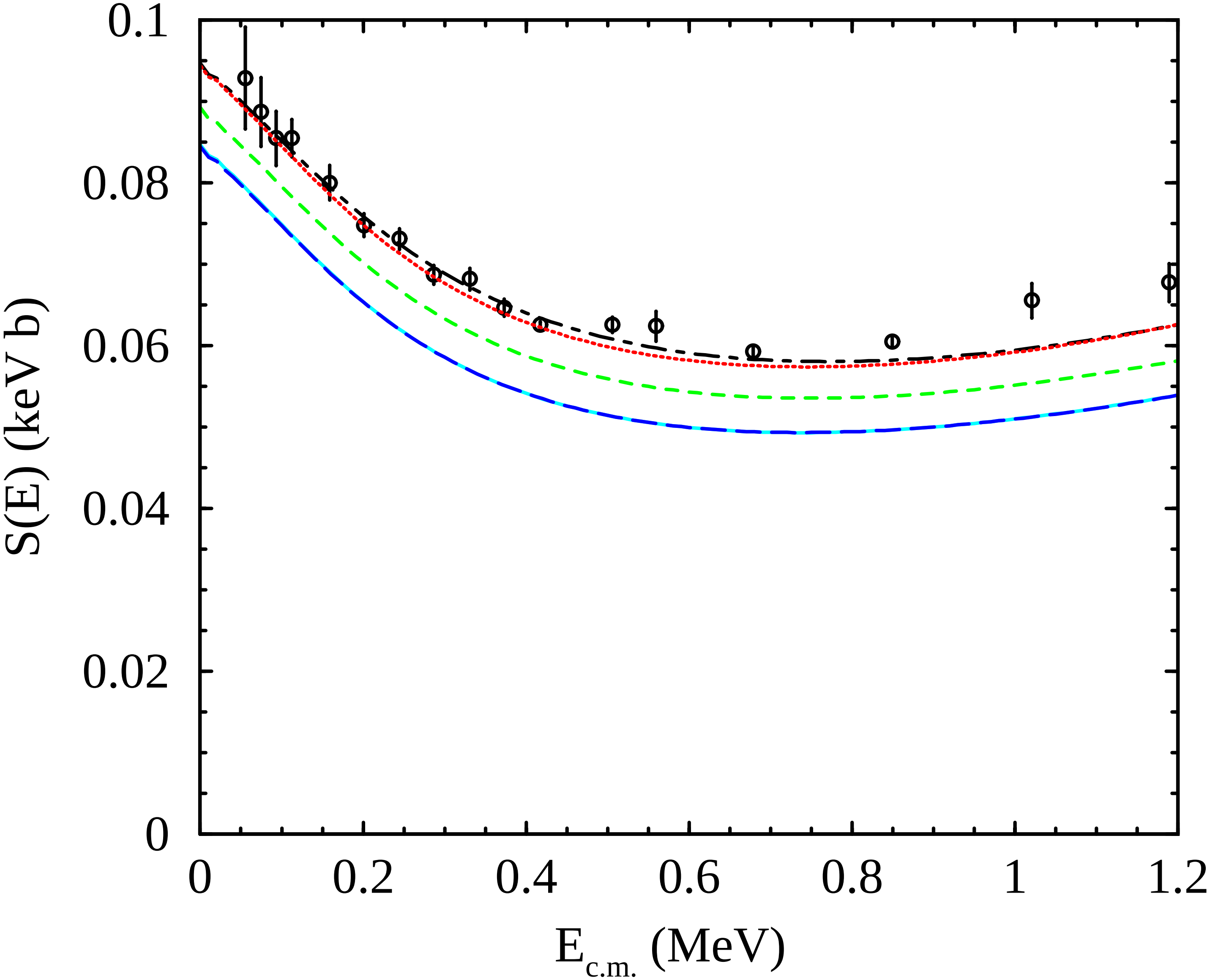
- Numerous experiments have been carried out on both reactions

- Recent theoretical progress:
  K.M. Nolllett, R.B. Wiringa, R. Schiavilla

- Astrophysical S-factor: $S = \sigma\, E \exp(2\pi\eta)$

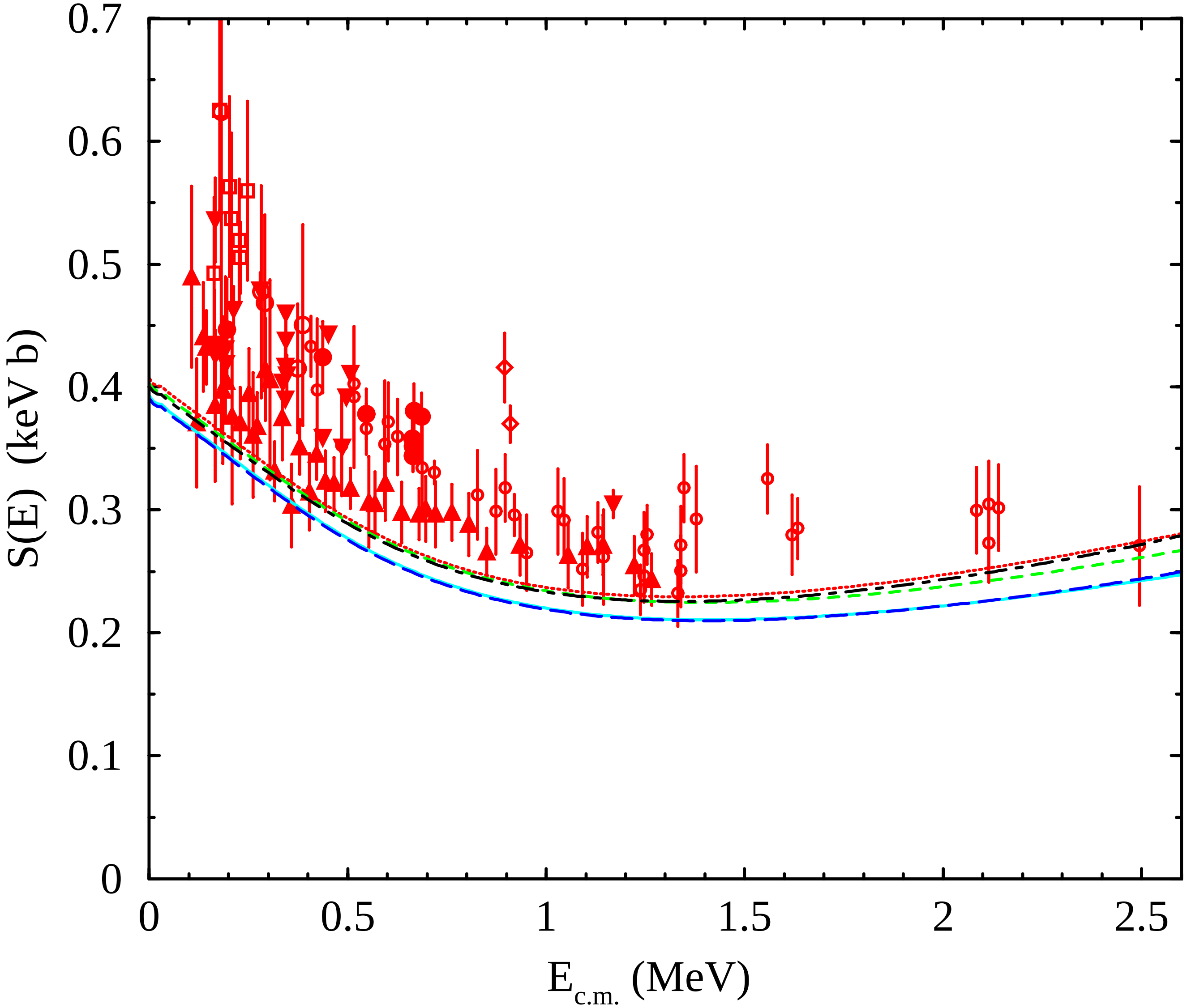
$^3H(\alpha,\gamma)^7Li$

calculation: K.M. Nollett



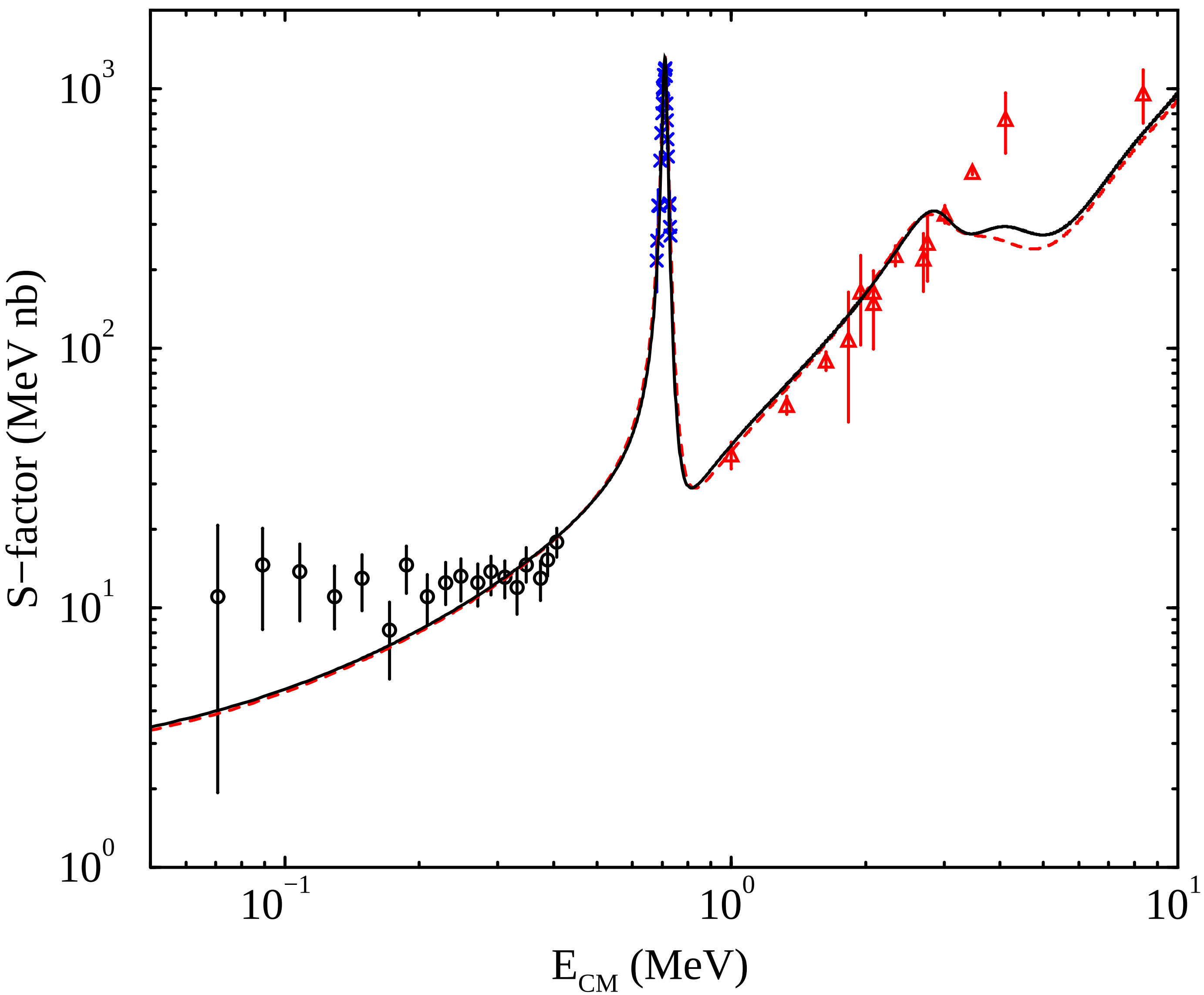
$^{3}He(\alpha,\gamma)^{7}Be$

calculation: K.M. Nollett

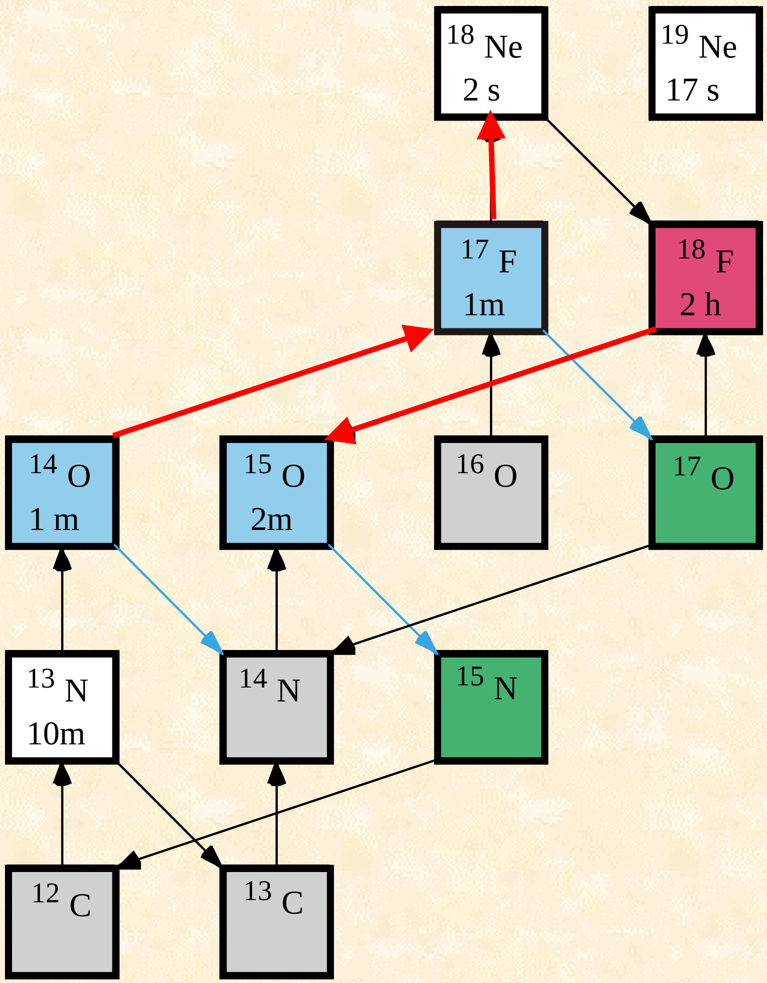


$^2H(\alpha,\gamma)^6Li$

calculation: K.M. Nollett



The hot CNO cycle



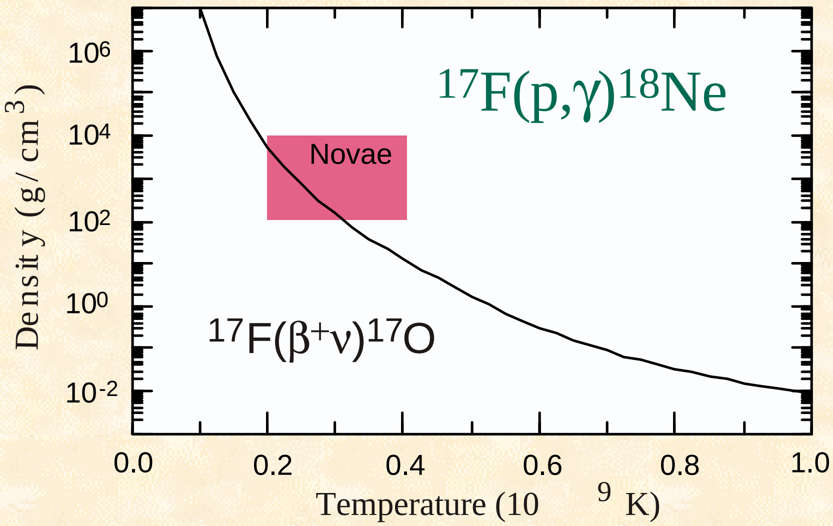
- Powers nova explosions
- Hydrogen → Helium
- Large uncertainties in some reactions

* $^{17}F(p,\gamma)^{18}Ne$
^{17}O, ^{18}F production

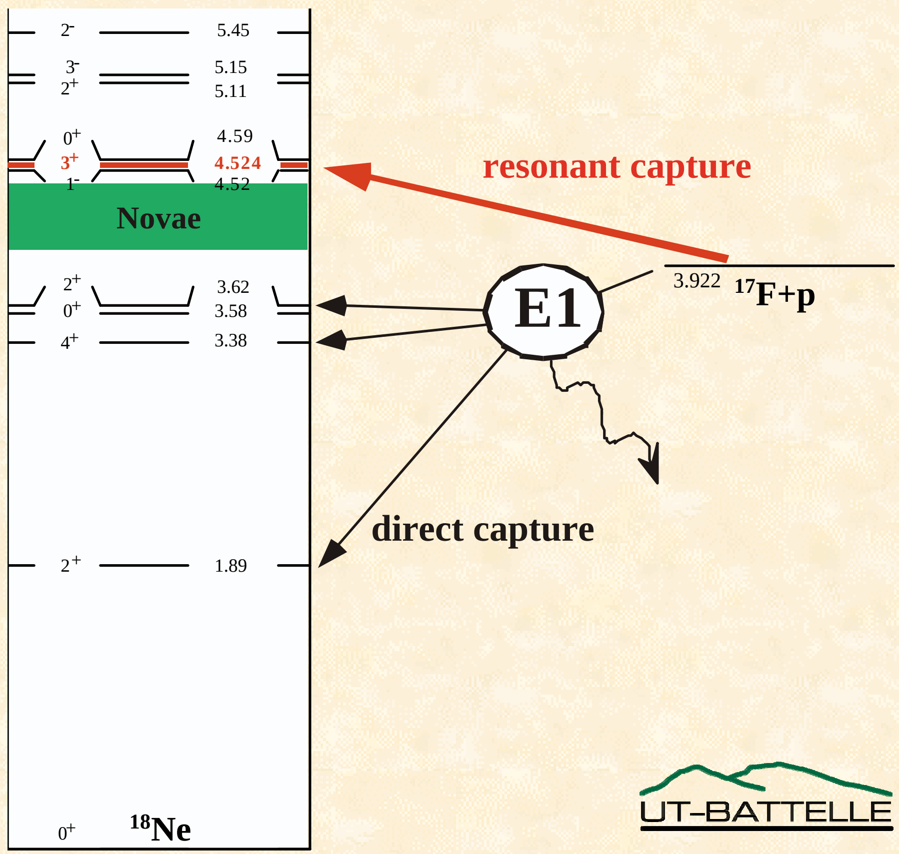
- $^{18}F(p,\alpha)^{15}N$ and $^{18}F(p,\gamma)^{19}Ne$
^{15}N, ^{18}F production
$^{17}O/^{18}O$ ratios

- $^{14}O(\alpha,p)^{17}F$
only way to burn ^{14}O

The $^{17}F(p,\gamma)^{18}Ne$ reaction rate



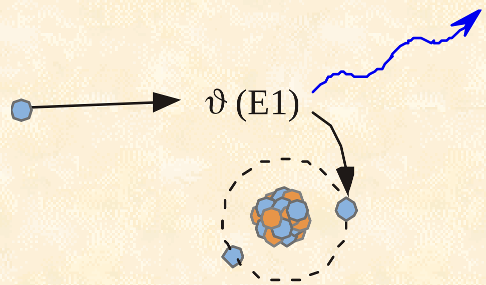
- Capture rate is comparable to the beta decay rate in novae.



- Two contributions to the rate:
  - Direct capture
  - 3+ resonance

Direct capture cross section can be determined by measuring ANC's from proton transfer reactions.

- Direct capture occurs via an electromagnetic transition at large radii.
- The cross section can be accurately calculated from the Asymptotic Normalization Coefficients (ANC's) with little model dependence.
- The ANC's can be determined by measuring the cross section for peripheral proton transfer reactions.

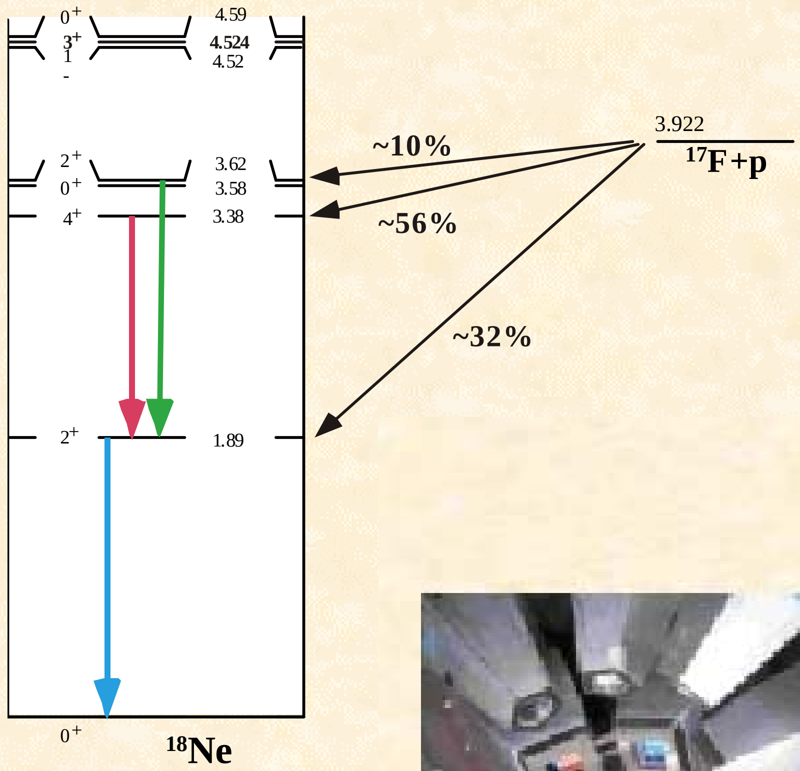


$$\sigma_{DWBA} \sim \left| \langle \chi_\beta \psi_\beta | \vartheta | \chi_\alpha \psi_\alpha \rangle \right|^2$$

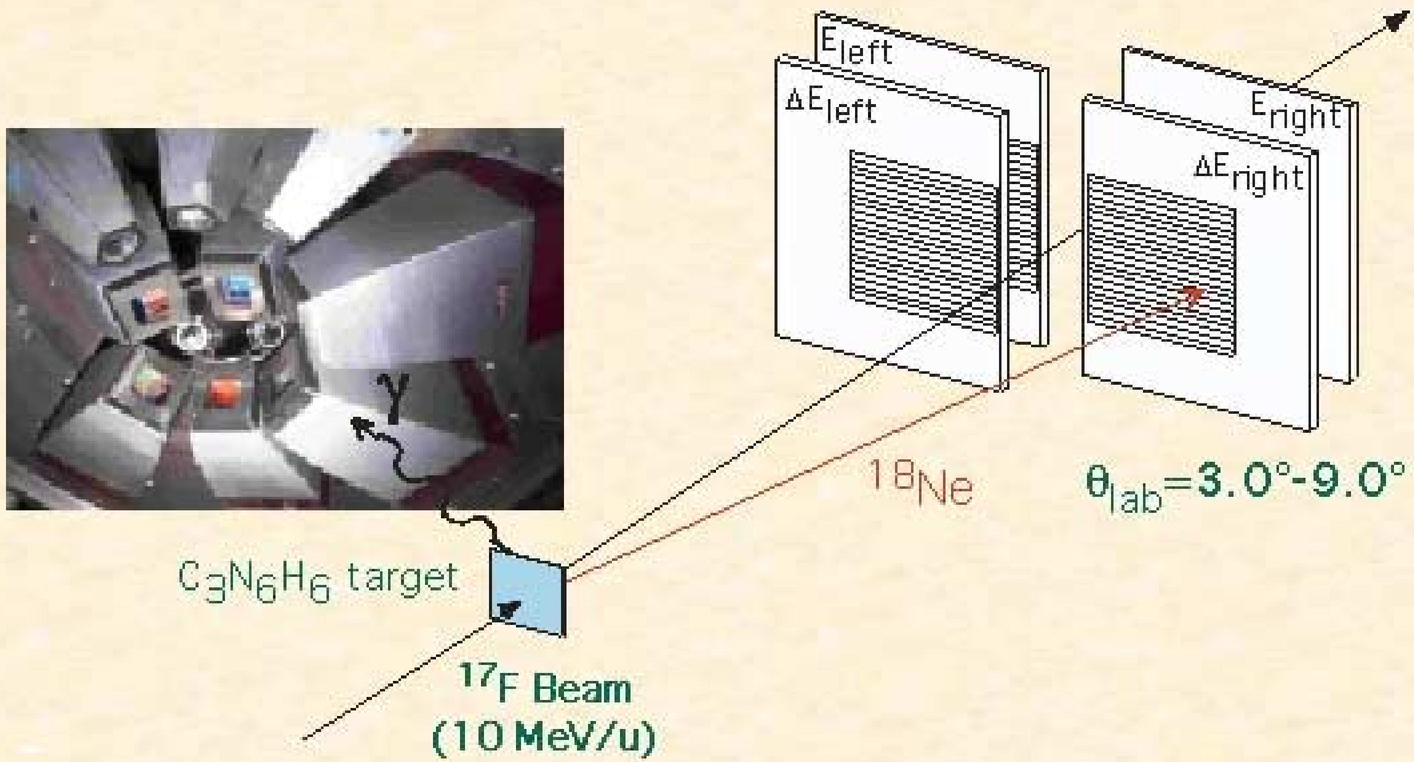
$$\psi \sim \left(\frac{C}{b}\right)\varphi \quad \text{and} \quad \varphi \xrightarrow[r \gg R_A]{} b\,\frac{W}{r}$$

$$\frac{d\sigma}{d\Omega} = \frac{C_{Z+p}}{b_{Z+p}}\,\frac{C_{17F+p}}{b_{17F+p}}\,\sigma_{DWBA}$$

$^{14}N(^{17}F,^{18}Ne^*)^{13}C$ at the HRIBF



- The direct capture cross section is dominated by capture to excited states in ^{18}Ne.
- Gamma rays were detected by the CLARION array in coincidence with ^{18}Ne to resolve the states of interest.



THE ^{17}F$(p,\gamma)^{18}$Ne DIRECT CAPTURE CROSS SECTION

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Conclusions

- EM Capture Reactions play a crucial role in Nuclear Astrophysics
  - see talk later by Moshe Gai
- Both experimental and theoretical approaches are useful