Radiative Capture Reactions

(involving charged particles)

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Why Radiative Capture Reactions?

- Cross section are small...
  (electromagnetic versus strong interaction)

- Often (p, γ) and/or (α, γ) are the only possible reactions with positive Q value
- Due to their small cross sections these reactions are often the rate-limiting factor

Outline

- Astrophysical Scenarios:
  - Quiescent H and He burning
  - Novae and X-ray Bursts
  - Supernovae
- Experimental Methods:
  - Regular (forward) kinematics
  - Inverse kinematics
- Examples
- Physics relevant to recoil separators

Hydrostatic Fusion Stages

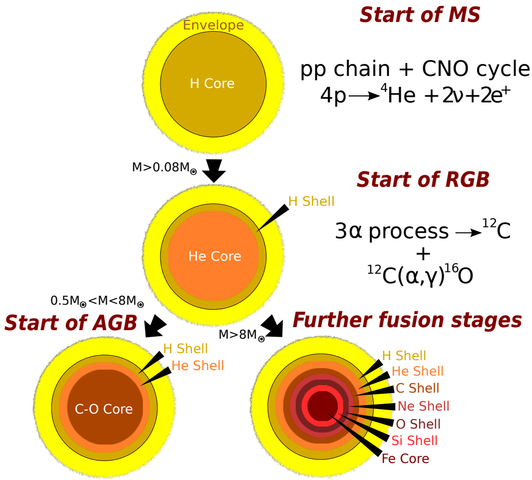
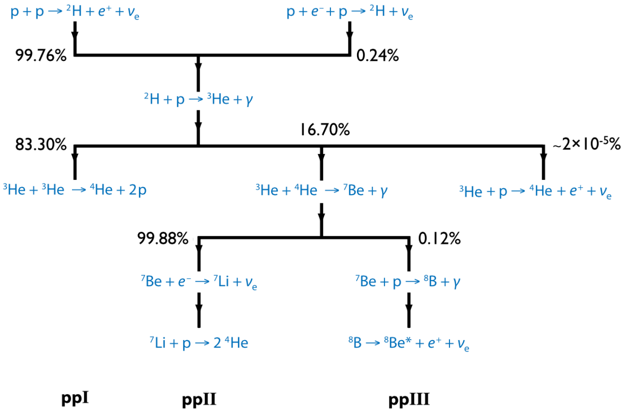


Figure courtesy of Dan Sayre.

PP Chains



Branching ratios are for our sun [Adelberger *et al.*, RMP **83**, 195 (2011)].

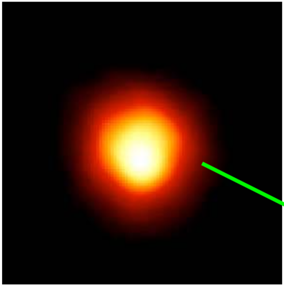
The CNO Cycles

CNO-I	CNO-II	CNO-III	CNO-IV
$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$	$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$	$^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$	$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$
$^{13}\mathrm{N}(\beta^+\nu)^{13}\mathrm{C}$	$^{15}\mathrm{O}(\beta^+\nu)^{15}\mathrm{N}$	$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$	$^{17}\mathrm{F}(\beta^+\nu)^{17}\mathrm{O}$
$^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$	$^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$	$^{17}\mathrm{F}(\beta^+\nu)^{17}\mathrm{O}$	$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$
$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$	$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$	$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$	$^{18}\mathrm{F}(\beta^+\nu)^{18}\mathrm{O}$
$^{15}\mathrm{O}(\beta^+\nu)^{15}\mathrm{N}$	$^{17}\mathrm{F}(\beta^+\nu)^{17}\mathrm{O}$	$^{18}\mathrm{F}(\beta^+\nu)^{18}\mathrm{O}$	$^{18}\mathrm{O}(p,\gamma)^{19}\mathrm{F}$
$^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$	$^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$	$^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$	$^{19}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$

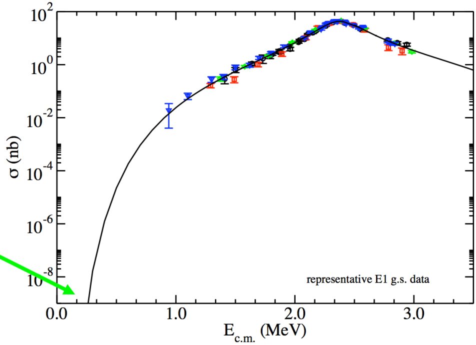
Similar cycles continue to some extent up to $A \approx 40$.

He Burning: $^{12}C(\alpha,\gamma)^{16}O$

Red Giant



The Lab



$T=(1\text{-}3)\times10^8$ K

- Extrapolation to low energies is required. More challenging than the typical data evaluation problem.
- Experimental challenges: small cross sections, even above the Coulomb barrier (rather generic to α capture).

Explosive Nucleosynthesis

- Novae
- X-ray Bursts
- Supernovae

- Temperatures are higher!
- Radioactive nuclei are involved!
- Higher masses are reached!

Nuclear Physics Aspects

- Non-resonant cross sections (especially for $A < 20$)
- Narrow versus broad resonances
- Many resonances $\rightarrow$ statistical (especially for $A > 40$)

- $\langle \sigma v \rangle \propto \int_0^\infty E\sigma(E) \exp[-E/(k_B T)] \mathrm{d}E$
- Gamow Window
- Breit-Wigner Formula: $\sigma(E) = \omega \frac{\pi}{k^2} \frac{\Gamma_a \Gamma_b}{(E-E_R)^2 + \Gamma^2/4}$
- Information on the location (E_R) of possible resonances is very helpful.

Experimental Approaches

- p or α beams on stable (or nearly stable) targets
  - – detect γ rays
  - – or detect activation,...
- inverse kinematics: heavy ion beam on a gas target
  - – separate and detect recoils (very efficient)
  - – can detect γ rays in coincidence

- stable nuclei: we are often interested in high precision
- radioactive nuclei: inverse kinematics essential

Hall and Fowler (1950): Motivation for Experiments

Phys. Rev **77**, 197

$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N} \quad 88 \leq E_p \leq 128$ keV

"The essential point of Bethe's argument cannot be questioned in spite of the fact that nuclear reaction rates at stellar temperatures can be only roughly estimated from existing experimental data at laboratory energies. However, it was felt that additional and more accurate experimental evidence should be obtained on these reactions, in particular at energies as close as possible to the effective stellar energies. It is the purpose of this paper to present such evidence on the first reaction given above, namely $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$."

$^7Be(p,\gamma)^8B$

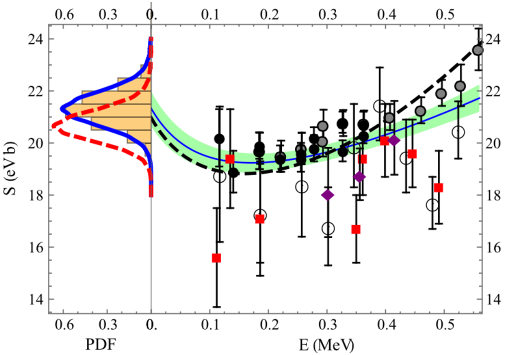


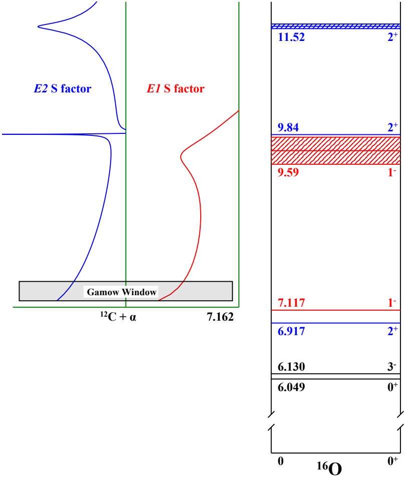
Fig. 3. (Color online.) The right panel shows the NLO S-factor (y-axis) at different energies (x-axis), including the median values (solid blue curve). Shading indicates the 68% interval. The dashed line is the LO result. The data used for parameter determination together with a few above 0.5 MeV are shown, but have not been rescaled in accord with our fitted $\{\xi_i\}$. They are: Junghans et al., BE1 and BE3 [48] (filled black circle and filled grey circle), Filippone et al. [49] (open circle), Baby et al. [50,51] (filled purple diamond), and Hammache et al. [52,53] (filled red box). The left panel shows 1d PDFs for $S(0)$ (blue line and histogram) and $S(20\text{ keV})$ (red-dashed line). In this case the y-axis is $S(0)$ or $S(20\text{ keV})$, while the PDFs shown along the x-axis are normalized to unit total probability.

Zhang, Nollett, and Phillips, Phys. Lett. B **751**, 535 (2015).

$^{12}C(\alpha,\gamma)^{16}O$: Important Energy Levels

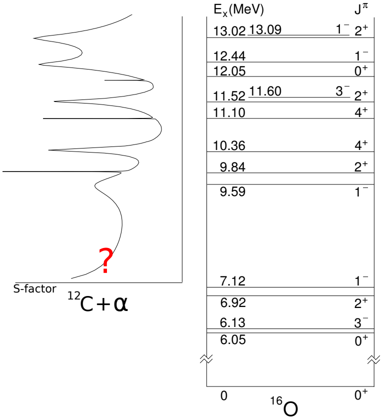
Physics: Subthreshold resonances and interference

Note: Combination of experiment and theory required to obtain $S(300)$. Subthreshold resonances along with their interference must be considered in the theory.



A partial level diagram

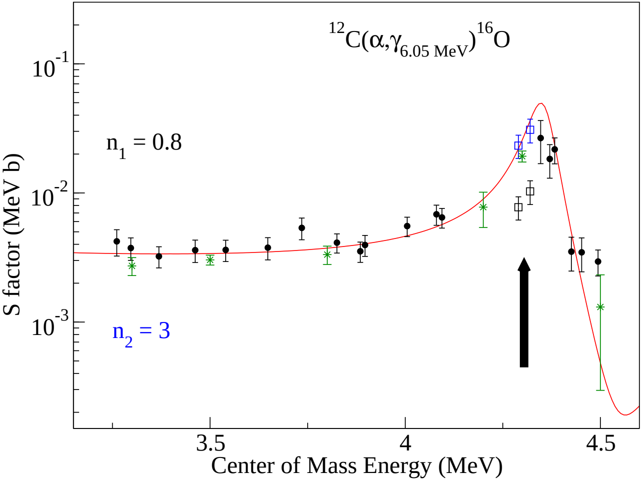
The Motivation to Extend Analysis to Higher Energies



- $R_{cc'} = \sum_\lambda \frac{\gamma_c \gamma_{c'}}{E_\lambda - E}$ + background pole(s)
- By explicitly including higher-energy levels, the strength of the remaining background is diminished. This is advantageous if the higher-energy levels can be constrained by data.
- There is also a need for precision data.

Transition to the 6.05-MeV State of ^{16}O

Recoil Separators are Key for this Transition

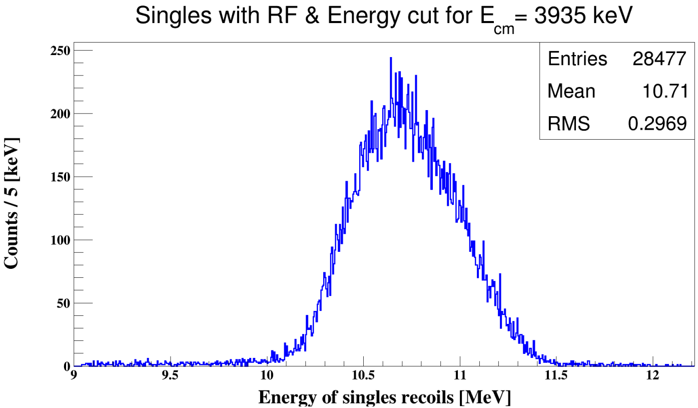


Matei *et al.* (TRIUMF, 2006, black/blue, normalized by 0.8); Schuürmann *et al.* (Bochum, 2011, green stars).
Figure by James deBoer.

New measurements have been performed with DRAGON at TRIUMF

for $E_{c.m.} = 3.7$, 4.0, and 4.2 MeV

Rekam Giri, C.R. Brune, S.N. Paneru, D.S. Connolly, B. Davids, D.A. Hutcheon, A. Lennarz, L. Martin, C. Ruiz, U. Greife, U. Hager, G. Christian, and A. Hussein



12 shifts of running, >10,000 γ-recoil coincidences for each energy.

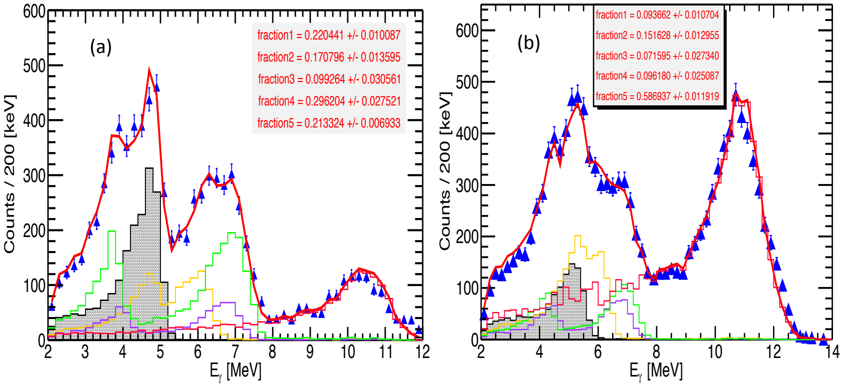
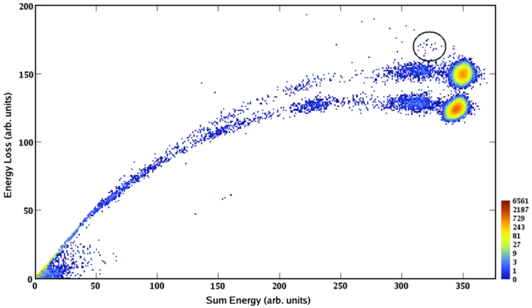


Fig. Comparison of the γ-ray spectra, (a) at E_{cm} = 3.7 MeV and (b) at E_{cm} = 4.2 MeV, (filled blue triangles) with the results of the fit for the different contributions: total = red line, 6.05 MeV transition = light gray shaded area, 6.13 MeV = orange line, 6.92 MeV = violet, 7.12 MeV = green line, and ground state = pink line.

$^{17}F(p,\gamma)^{18}Ne$ with DRS at HRIBF

3^+ resonance at $E_{c.m.} = 600$ keV



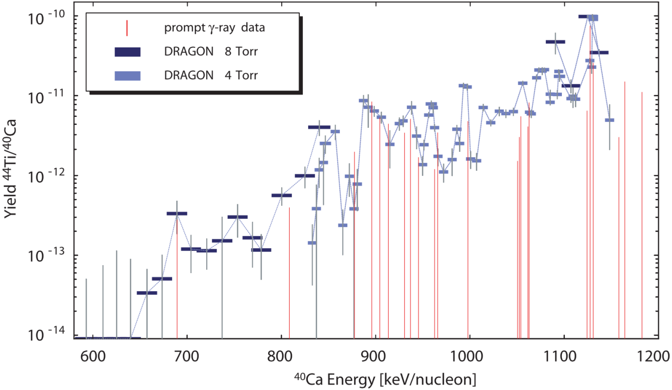
Chipps *et al.*, PRL **102**, 152502 (2009).

No γ-ray detection. Resonance width comparable to target thickness.

Additional Considerations for Heavier Nuclei

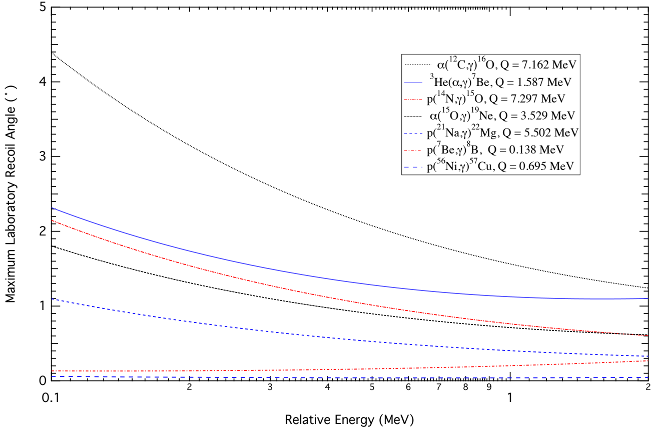
- Transition from “Narrow Resonances” to “Statistical”
- Occurs at $A \approx 40$
- The actual cross section is chaotic
- One needs to think carefully about energy averaging
- Particularly with thin gas targets

$^{40}Ca(\alpha,\gamma)^{44}Ti$ with DRAGON at TRIUMF



Vockenhuber *et al.*, Phys. Rev. C **76** 035801 (2007).

Recoil Cone Angle



$$\tan\theta \approx \frac{Q+E}{\sqrt{2m_b c^2\left(\frac{m_b+m_t}{m_t}\right)E}}$$

(Figure by Barry Davids)

similar considerations apply to the energy spread of the recoils

Transitions through excited states: considerations for recoil separators

- Effects on recoil cone angle
- Effects on γ-ray detection efficiency
- γ-ray angular distributions
- γ-ray angular correlations

Thinking outside the box:

The combination of energy loss (dE/dx) and narrow resonances makes life difficult. . .

- Can some kind of re-acceleration scheme be used in gas targets?
- Photon beams? (ELI-NP, HIGS)
- Electron beams? $^{16}\mathrm{O}(e, e')\alpha^{12}\mathrm{C}$?
- Crossed beam experiments?
- Inertial Confinement Fusion?

To Summarize:

- Radiative capture is essential in nuclear astrophysics
- Recoil separators are very useful for measuring such reactions
- Physics aspects are varied: resonant versus non-resonant
- Goals also are variable: high-precision versus pioneering experiments

Thank you for your attention.