The importance of $\alpha$-clustering in nuclear astrophysics

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What kind of reactions am I talking about?

- Low mass nuclei (A<30)
  - Capture reactions
    - $(\alpha, \gamma)$ but also $(p, \gamma)$
    - $(p, \alpha)$
  
- Low level densities

- Individual state(s) near threshold are critical (Ikeda)
Reaction Rates

\[ N_A \langle \sigma v \rangle = N_A \frac{(8/\pi)^{1/2}}{\mu^{1/2} (k_B T)^{3/2}} \int_0^\infty \sigma E \exp(-E/k_B T) dE, \]

Ex. $^{20}$Ne(p,\(\gamma\))

- **Sharp resonance**
- **Broad resonance**
- **Direct or “non-resonant”**
Reaction Components

External Capture?
Subthreshold State?
Tail of broad high energy resonance?
Charged particle cross section extrapolations

\[ T \approx 0.2 \text{ GK} \]
S-factor

\[ S(E) = \sigma(E)Ee^{2\eta} \]

\( R \rightarrow \text{total} \)

\( 300 \text{ keV} \)

S-factor (MeV b)

\( E_{\text{cm}} \) (MeV)
Phenomenological $R$-matrix

- Provides basic framework to calculate cross sections
- Resonances and direct contribution strengths are put in *ad hoc*
- NEED!
  - Good understanding of the nuclear structure
    - Level structure
    - Reaction mechanisms
    - Accurate cross section data
What do you need to do an R-matrix fit?

- $J^\pi$'s
- Energies
- Partial widths
- Asymptotic Normalization Coefficients for subthreshold states
- Data for every decay path
What kinds of nucleosynthesis processes?

- Big Bang (BBN)
- Carbon-Nitrogen-Oxygen (CNO) cycles
- Helium Burning
BBN

Fields (2011)
$^3\text{He}(\alpha,\gamma)^7\text{Be}$
Observed Cross Section: External Capture? Subthreshold State? Tail of broad high energy resonance?
Level structure
Observed Cross Section

Tails of higher energy states
Broad cluster states demand measurements on similar energy scales.
Level structure
Two bound states in $^7$Be

- Cross section is external capture dominated (since the 1960’s)
- Nollet (2001) and Neff (2011), internal contributions are significant
  - $\alpha$ asymptotic normalization coefficients of both of these states have not been measured
  - Largest sources of uncertainty

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

Neff (2011)
CNO cycle

Fig. 5.8 Representation of the four CNO cycles in the chart of the nuclides. Stable nuclides are shown as shaded squares. Each reaction cycle fuses effectively four protons to one $^4$He nucleus.

Christian Iliadis, Nuclear Physics of Stars
CNO cycles

- Direct reaction or broad resonance?
  - $^{15}\text{N}(p,\alpha)^{12}\text{C},\ ^{16}\text{O}$ CN
  - $^{19}\text{F}(p,\alpha)^{16}\text{O},\ ^{20}\text{Ne}$ CN
$\alpha$ separation energy $<\text{proton separation energy}$

$^{15}\text{N}(p,\alpha)^{12}\text{C}$

Same for $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction that populates the $^{20}\text{Ne}$ compound nucleus.
$^{15}\text{N}(p, \alpha)^{12}\text{C}$

$J^\pi = 1^-$

Part of $1^-$ band
$^{15}\text{N}(p,\gamma)^{16}\text{O}$
$^{19}\text{F}(p,\alpha)^{16}\text{O}$

$^{19}\text{F}(p,\alpha)^{16}\text{O}$

Lombardo et al. (2015)
Helium Burning

- $3\alpha \rightarrow ^{12}\text{C}$
- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
- $^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}$

In the absence...
Helium Burning

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
Different Transitions for $^{12}C(\alpha,\gamma)^{16}O$

Schürmann et al. (2012)
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
Ground State
Subthreshold state ANCs

- Determined by
  - $^{12}\text{C}(\alpha,\alpha)^{12}\text{C}$ Scattering --- large uncertainty
  - $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ Capture --- large uncertainty
  - Beta delayed $\alpha$ emission of $^{16}\text{N}$ --- inconsistent data
  - Sub-Coulomb $\alpha$ transfer $^{12}\text{C}(^6\text{Li,d})^{16}\text{O}$ and $^{12}\text{C}(^7\text{Li,t})^{16}\text{O}$

- Theory calculations of ANCs are highly desired
$^{12}\text{C}(\alpha,\gamma_{6.05\text{ MeV}})^{16}\text{O}$ transition

ANC = $44^{+270}_{-44}$ fm$^{-1/2}$

6.05 MeV transition

Schürmann et al. (2011)
6.05 MeV transition

Avila et al. (2015)

ANC = 1560(100) fm^{-1/2}
Scattering is important too!

Feng et al. (1996)
Higher energy data is very important too!
Conclusion

- Phenomenological fits + theory calculations yield the very accurate cross section descriptions
  - Theory calculations
    - Level structure
    - Underlying reaction mechanisms
    - Accurate data for all open reaction channels

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