Uncertainties in Helium Burning Rates and Nucleosynthesis

The helium burning reaction rates are not well known experimentally.

- Triple Alpha—Rate $R_{3\alpha}$ ±12% Few studies
- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ –Rate $R_{\alpha12}$ ±25% Significant attention

Investigated sensitivity of nucleosynthesis to variations of $\pm 2\sigma$ in $R_{3\alpha}$ and $R_{\alpha12}$

For low mass ($2 \, M_{\odot}$, $Z=0.01$) AGB stars

For massive (15, 20, 25 $M_{\odot}$) stars undergoing core collapse and a SN explosion

The SN sensitivities are the main subject for today.
Results for Low-Mass AGB Stars

**Motivation:** Do low mass AGB stars become Carbon Stars?

Use code EVOL

Changes in $^{12}\text{C}(\alpha,\gamma)$ have weak effects

Rates: 2 (recommended), 5, 6, 8, 9

Higher $R_{3a}$ (by +1σ) increases C/O by a factor of two over NACRE rates.

High $R_{3a} \rightarrow$ Carbon Star
Calculations for Massive Stars

For 15, 20, 25 $M_{\text{sun}}$ stars
Evolve to core collapse-KEPLER
Simulate ensuing explosion by a piston at the base of the O-burning shell ($S=4k/Byon$) that imparted 1.2 Bethe to the explosion products

Reaction rates (Vary by ± 2$\sigma$)

Calculate for both Ander-Grevasse (89) and Lodders(03 abundances.

Major difference: Lodders has $\approx 30\%$ lower CNONe abundances—most other abundances are roughly 15% higher
Nucleosynthesis for Massive Stars

Significant variation of Production Factors for changes in either rate —factors of 5 to 10 occur.

Different for AA89 and LOD03 abundances.
More nucleosynthesis—S-Only Nuclei

Note Log scale. Again significant variations for different abundances and for $R_{3\alpha}$ and $R_{\alpha12}$

Side remark—still larger differences for the gamma emitters $^{26}$Al, $^{60}$Fe

Roughly factor 2 differences for neutrino production of $^{11}$B, $^{19}$F, $^{138}$La, $^{180}$Ta
The Radioactive Nuclei

60Fe/26Al ratio is uncertain at the x10 level
Central Carbon Mass Fraction at C ignition

Significant variations of central C mass fraction with both $R_{3\alpha}$ and $R_{\alpha 12}$
Similar for AA89 and LOD03 abundances—shown for LOD 03

Smaller but significant variation if the ratio of $R_{3\alpha}$ and $R_{\alpha 12}$ is kept at its central value, but both rates are increased or decreased.
Significant non-monotonic changes in remnant mass (corrected for gravitational binding) for changes in $R_{3\alpha}$ or $R_{\alpha12}$

Note: Takes 1 Bethe to dissociate 0.1 $M_{\odot}$
Improving the The Triple Alpha Reaction Rate

Step I: $\alpha + \alpha \leftrightarrow ^8\text{Be}$

- Resonant process
- Form equilibrium abundance of $^8\text{Be}$

Step II: $^8\text{Be} + \alpha \leftrightarrow ^{12}\text{C}(7.65)$

If resonant as in core helium burning:

$$r_{3\alpha} \propto \Gamma_{\text{rad}}(7.65)e^{-Q/kt}$$

$$\Gamma_{\text{rad}} = \Gamma_\gamma + \Gamma_\pi, \quad Q = Q_1 + Q_2$$

If non-resonant:

- At very low or high $T$
- Much more complex
Prospects for Improved Resonant $R_{3\alpha}$

$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \left(\frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma}\right) \frac{\Gamma}{\Gamma_\pi}$$

$$Q_{3\alpha} = E_r - 3M_\alpha^2$$

Each arrow a measurement

Experiments
- $\approx 8$
- 3
- 2
- 6

Excluded results
- 1
- 0
- 0
- 0

Precision
- 2.7%
- 9.2%
- 6.4%
- 1.2%

Improvements possible?
- 4%
- 3.2%

WMU+MSU+ANL (to do)  Darmstadt (in press)

If the improvements happen (likely?) then the uncertainty will be reduced from about 12% to about 6%. Certainly there will be some improvement.
Triple-alpha At Low T

Triple alpha is non-resonant process at sufficiently low T


CDCC calculations include non-resonant effects

At $T = 10^7$ $R_{3\alpha}$ is $10^{26}$ x NACRE

$T = 10^8$, $1.5 \times 10^6$ x NACRE

$T = 2 \times 10^8$, $1.9$ x NACRE

At higher $T > 2.5 \times 10^8$, same as NACRE

Ogata rate results in stellar behavior that deviates from the observation of extended red giant branches for helium burning stars in old systems.

Is the rate calculation right?

Is screening dealt with appropriately?

An unresolved issue
Is there a $J^\pi=2^+$ resonance near 10 MeV in $^{12}$C?

Predicted by cluster models

Not seen in $\beta$ decay, claimed in (p,p$'$) and ($\alpha$,\alpha$'$)


Evidence for $2^+$ (inconclusive?):


(p,p$'$): M. Freer, PRC 80, 041303 (2009)

Detailed discussion: S. Hyldegaard, PRC 81, 024303 (2020)

Another unresolved issue
Triple Alpha at High T, Density

**An old/new issue:** In matter the de-excitation of the Hoyle state can be enhanced by interaction with particles or electrons.

Shaw and Clayton (1967); Truran and Kozlovsky (1969); Morgan and Wisser (1970); Davids and Bonner (1971)

This will affect (increase) any reaction rate that depends on $\Gamma_{\text{rad}}$

The enhancement shown here is an underestimate. Doesn’t include:
- De-excitation to the 4.44 MeV state
- Alpha particle scattering
- Neutron scattering

Important in x-ray bursters?

Important for $(n,\gamma)$ reactions?

![Graph of enhancement of radiative decay of $^{12}$C*(7.653) by proton inelastic scattering](image)
Prospects for Improved $R_{\alpha 12}$

To quote Woosley, et al. 2003: The major nuclear uncertainty afflicting modern studies of massive stellar evolution and nucleosynthesis continues to be $R_{\alpha 12}$

Similar statements have motivated MANY experiments and continue to do so. Yet the rate uncertainty remains large and there is no assurance that it will significantly decrease in the near future.

The great majority of model studies use a specific rate, unpublished, but quoted, for example, by Woosley, et al. 2003.

Next we discuss how this determination was made.
The Boyes Determination

Evolve 15, 20, 25 $M_{\text{sun}}$ stars, average

KEPLER

Anders & Grevesse (1989) abundances

Range of $R_{\alpha,12}$

No explosive processing

Find value of $R_{\alpha,12}$ that minimizes spread in Production Factors = $1.1 \pm 0.1 \times$ Buchmann,
Widely used as standard rate

Need to check. Why?
Explosive processing changes abundances

20 $M_{\text{sun}}$ stars have anomalous nucleosynthesis—average over more stars

Come back to other issues
Check on Boyes

Large star set: 13, 15, 17, 19, 21, 23, 25, 27 \( M_{\odot} \)

AG89 abundances

Include explosive processing

Reasonable agreement in minimum (1.3 vs 1.2) and rms scatter at minimum. ± 0.1 seems too accurate

Somewhat surprising, since explosion changes abundances by >x2 for \( A>30 \)
Issues Not Resolved

PROBLEM: Rate derived for a specific case, but used in many situations

Does not always work
  For LOD03 RMS minimum is poorly defined

Other things not considered in detail
  Different models, convection, etc.
  $R_{3\alpha}$ uncertain
  Changes with metallicity
  Changes with mass
An Effective Reaction Rate

A safer point of view: Define an “Effective Reaction Rate” with application limited to a specific code.

Determine dependence of interaction on
  Metallicity
  Mass
  Range of nuclei described
  $R_{3\alpha}$ --When $R_{3\alpha}$ is better known, can avoid latter dependence—until then it’s an uncertainty.

Parameterize dependence of these quantities

Compare results for different codes.

A lot of work
Some Directions

Need to understand the uncertainties in the simulation codes so we can understand the reliability of our simulations and whether any discrepancies with observation are real.

Specific needs for SNII:

Compare the results of extant codes for some benchmark cases.

Develop an open source SN code, with open source rates.

Incorporate insights from multi-D calculations: convection issues, explosion issues

Evaluate of effects of uncertainties in input abundances and reaction rates
Well predicted abundances

Some abundances are more sensitive to uncertainties than others.

Perhaps one should concentrate, as far as possible, on those isotopes/elements that are less sensitive to the nuclear physics uncertainties.