The importance of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction in Asymptotic Giant Branch stars

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$s$-process

$\tau_\beta \ll \tau_n$

$N_n \sim 10^7 \text{ n/cm}^3$

$r$-process

$\tau_\beta \gg \tau_n$

$N_n > 10^{22} \text{ n/cm}^3$

FROM CLAYTON 1968
s-process

Easy to be reproduced with an exponential distribution of neutron exposures.

Moreover, since neutron flow reaches equilibrium between nuclei with magic neutron numbers, the product of the Maxwellian averaged stellar $(n,\gamma)$ cross section of a nuclide, $\langle \sigma \rangle$, and its corresponding abundance, $N_s$, remains almost constant (the difference in the two product is much smaller than the magnitude of either one of them):

$$\langle \sigma \rangle_A N_A \approx \langle \sigma \rangle_{A+1} N_{A+1}$$

LOCAL APPROXIMATION
s-process

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Moreover, since neutron flow reaches equilibrium between nuclei with magic neutron numbers, the product of the Maxwellian averaged stellar \((n,\gamma)\) cross section of a nuclide, \(<\sigma>\), and its corresponding abundance, \(N_s\), remains almost constant (the difference in the two product is much smaller than the magnitude of either one of them):

\[
<\sigma>_A N_A \approx <\sigma>_{A+1} N_{A+1}
\]
s-process

Easy to be reproduced with an exponential distribution of neutron exposures.

r-process
**s-process**

Easy to be reproduced with an exponential distribution of neutron exposures.

**r-process**

\[ r = 1 - s \]
r-process residuals from s-process studies

C.A.: Classical Analysis
S.M.: Stellar Model
G.C.E.: Galactic Chemical Evolution
AGB structure

CO Core
He-shell
H-shell

Earth radius ($\sim 10^{-2} R_{\text{SUN}}$)

Earth-Sun ($\sim 200 R_{\text{SUN}}$)

Convective Envelope

Straniero, Gallino & Cristallo 2006
The s-process in AGB stars

Busso et al. 1999
The s-process in AGB stars

\[ ^{13}\text{C}(\alpha, n)^{16}\text{O} \] reaction

\[ ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \] reaction

Busso et al. 1999
The formation of the $^{13}$C pocket

$^{13}$C-pocket

$^{14}$N-pocket

$^{14}$N strong neutron poison via $^{14}$N(n,p)$^{14}$C reaction

$\Delta M \sim 10^{-3} \, M_\odot$

Cristallo+ 2009
Measurements of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction

- Trippella+ 2017
- Avila+ 2015
- La Cognata+ 2013
- Xu+ 2013
- La Cognata+ 2012
- Guo+ 2012
- Heil+ 2008
- Kubono+ 2003
- Angulo+ 1999
- Drotleff+ 1993
- ...
Reference rate (most recent direct measure): Heil+ 2008

Upper case: *1.5 - *2
Lower case: *0.67 - *0.5

Substantial scatter of existing data, showing a broad (up to a factor of 2) range of absolute values for the astrophysical S-factor

Explored stellar models

- M=1.5 M_{SUN} [Fe/H]=-0.15 Convective $^{13}$C burning
- M=3.0 M_{SUN} [Fe/H]=-0.15 s-process main component
- M=4.0 M_{SUN} [Fe/H]=-2.15 Intermediate AGBs in GCs
- M=1.3 M_{SUN} [Fe/H]=-2.85 Proton ingestions at low Z

$$[A/B]=\log(N_A/N_B)_{\text{STAR}}-\log(N_A/N_B)_{\text{SUN}}$$
The Importance of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ Reaction in Asymptotic Giant Branch Stars

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$[A/B]=\log(N_A/N_B)_{\text{STAR}}-\log(N_A/N_B)_{\text{SUN}}$
$M = 1.5 \, M_{\odot}$

$[Fe/H] = -0.15$

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Cristallo+ 2015
$M=1.5 \ M_{\odot}$

$[\text{Fe/H}]=-0.15$

$M=3.0 \ M_{\odot}$

$[\text{Fe/H}]=-0.15$

Cristallo+ 2015
M=1.5 M\textsubscript{SUN}  
[Fe/H]=-0.15

M=3.0 M\textsubscript{SUN}  
[Fe/H]=-0.15

Same results with NEWTON code @ Perugia

Cristallo+ 2015

96\textsuperscript{Zr}  
86\textsuperscript{Kr}, 87\textsuperscript{Rb}  
152\textsuperscript{Gd}
We confirm the results by Guo+ 2012 and Trippella & La Cognata 2017.

Same results with NEWTON code @ Perugia.

$M = 1.5 \, M_{\odot}$

$[Fe/H] = -0.15$

$M = 3.0 \, M_{\odot}$

$[Fe/H] = -0.15$
Isotopic anomalies in pre-solar SiC grains

\[ \delta(X_i/X_j) = \left( \frac{X_i}{X_j} \right)_{\text{MEASURED}} / \left( \frac{X_i}{X_j} \right)_{\text{SUN}} - 1 \times 1000 \]

Schonbachler TALK
Davis TALK
s-rich Globular Clusters: the importance of intermediate AGBs

Straniero+ 2014 (Shingles+ 2014)
s-rich Globular Clusters: the importance of intermediate AGBs

\[ M = 4.0 \, M_{\text{SUN}} \, [\text{Fe/H}] = -2.15 \]

Straniero+ 2014 (Shingles+ 2014)
Low-metallicity low-mass AGB stars

Hollowell+ 1990
Fujimoto+ 2000
Iwamoto+ 2004
Suda+ 2004
Campbell+ 2007
Cristallo+ 2009
Herwig+ 2014
Dardelet+ 2015
Hampel+ 2016
Cristallo+ 2016
$M = 1.3 \, \text{Msun}$

$[\text{Fe/H}] = -2.85$

Diagram showing:
- CO core
- Convective envelope
- H-shell
- He-shell
M = 1.3 M_{\odot}
$M = 1.3\ M_{\odot}$

$[\text{Fe/H}] = -2.85$

**SPLITTING**

**He**

**CO core**

![Graph showing arbitrary age versus mass](image)
$M = 1.3 \ M_{\text{Sun}}$ 

$\[ \text{Fe/H} = -2.85 \]$

CO core
Convective envelope

HUGE TDU
SPLITTING

Arbitrary Age (yrs)
The importance of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction (energetic point of view)

**NECESSARY CONDITION:**
Full network coupled to physical evolution, due to neutron captures energetics!!!
Cristallo+ 2009
M = 1.3 \, M_{\text{SUN}} \quad [\text{Fe/H}] = -2.85
$M=1.3 \, M_{\text{SUN}} \quad [\text{Fe/H}]=-2.85$

Threshold effect: not enough $^{13}\text{C}$ mixed before shell splitting
M = 1.3 M$_{\odot}$ [Fe/H] = -2.85

Threshold effect: not enough $^{13}$C mixed before shell splitting

Warning: treatment of mixing is a key point!!!
CONCLUSIONS

- The $^{13}$C($\alpha$,n)$^{16}$O reaction rate is **important** in low mass AGBs ($M< 3.0$ $M_{\text{SUN}}$) at close-to-solar metallicities, because it determines how much $^{13}$C burns in a convective environment;

- A variation of the $^{13}$C($\alpha$,n)$^{16}$O reaction rate **does not change** s-process abundances in more massive AGBs ($M> 3$ $M_{\text{SUN}}$), as well as in all masses at low metallicities;

- The $^{13}$C($\alpha$,n)$^{16}$O reaction **could be important** for low mass AGBs at very low metallicities, because in that case the convective $^{13}$C burning (together with the subsequent neutron capture) affects the physical and chemical evolution of the model. **However**, the treatment of mixing is equally important.