Sezione d'urto della reazione $^{17}\text{O}(p, \alpha)^{14}\text{N}$ come chiave di lettura della composizione di grani meteoritici

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**$^{17}\text{O}(p, \alpha)^{14}\text{N}$ fusion reaction measured by THM**

\[ \omega \gamma (\text{eV}) \quad \text{Sergi et al. 2010} \quad \text{THM} \quad \text{Chafa et al. 2007} \quad \text{NACRE} \]

<table>
<thead>
<tr>
<th>$\omega \gamma (\text{eV})$</th>
<th>Sergi et al. 2010 THM \ ($10^{-6}$)</th>
<th>Chafa et al. 2007 \ ($10^{-9}$)</th>
<th>NACRE \ ($10^{-9}$)</th>
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<tr>
<td>65 keV</td>
<td>$3.4 \pm 0.6 \cdot 10^{-6}$</td>
<td>$4.7 \pm 0.8 \cdot 10^{-9}$</td>
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<td>183 keV</td>
<td>$1.16 \pm 0.1 \cdot 10^{-3}$</td>
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\[ {^{17}O(p, \alpha)^{14}N \text{ fusion reaction measured by THM}} \]

\[
\omega_{\gamma} (\text{eV}) & \quad \text{Sergi et al. 2010} & \quad \text{THM} & \quad \text{Chafa et al. 2007} & \quad \text{NACRE} \\
65 \text{ keV} & 3.4 \pm 0.6 \cdot 10^{-6} & 4.7 \pm 0.8 \cdot 10^{-9} & 5.5^{+1.8}_{-1.0} \cdot 10^{-9} \\
183 \text{ keV} & 1.16 \pm 0.1 \cdot 10^{-3} & 1.66 \pm 0.1 \cdot 10^{-3} & 5.8^{+5.2}_{-5.8} \cdot 10^{-5} 
\]
\( ^{17}\text{O}(p, \gamma)^{18}\text{F} \) Reaction rate determination ... from the strength definition:

\[
(\omega \gamma)_i = \frac{2J_{^{18}\text{F}} + 1}{(2J_{^{17}\text{O}} + 1)(2J_p + 1)} \frac{\Gamma(p^{^{17}\text{O}})_i(E_{R_i})\Gamma(\alpha^{^{14}\text{N}})_i(E_{R_i})}{\Gamma_i(E_{R_i})}
\]

\[
(\omega \gamma)_{p\gamma}^{THM} = (\omega \gamma)_{p\alpha}^{THM} \frac{\Gamma_\gamma}{\Gamma_\alpha}
\]

\[
(\omega \gamma)_{p\gamma}^{THM} = (1.18 \pm 0.22) \times 10^{-11} \text{ eV}
\]

\[
(\omega \gamma)_{p\gamma}^{THM} = (1.64 \pm 0.28) \times 10^{-11} \text{ eV}
\]

T=0.03-0.09 GK: the differences between the rate adopted in literature and the total rate calculated, if one considers the \( N_A < \sigma v >_{65}^{\text{THM}} \) extracted as explained before, is \(~25\%\).
\[ ^{17}\text{O}(p,\alpha)^{14}\text{N} \text{ } \& \text{ } ^{17}\text{O}(p,\gamma)^{18}\text{F} \]
in stellar H-burning

Chafa et al 2007
THM data

\[ ^{17}\text{O}(p,\alpha)^{14}\text{N} \text{ } \& \text{ } ^{17}\text{O}(p,\gamma)^{18}\text{F} \]
Chafa et al 2007
THM data

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$^{17}\text{O}/^{16}\text{O}$ as a stellar thermometer

Equilibrium conditions:

$\frac{dY_{^{17}\text{O}}}{dt} = Y_{^{16}\text{O}}Y_H N_A \langle \sigma v \rangle_{^{16}\text{O}(p,\gamma)^{17}\text{F}}} \rho$

$-Y_{^{17}\text{O}}Y_H N_A \left( \langle \sigma v \rangle_{^{16}\text{O}(p,\gamma)^{17}\text{F}}} + \langle \sigma v \rangle_{^{16}\text{O}(p,\alpha)^{14}\text{N}}} \right) \rho$

$0 = Y_{^{16}\text{O}}Y_H N_A \langle \sigma v \rangle_{^{16}\text{O}(p,\gamma)^{17}\text{F}}} \rho - Y_{^{17}\text{O}}Y_H N_A \left( \langle \sigma v \rangle_{^{17}\text{O}(p,\gamma)^{18}\text{F}}} + \langle \sigma v \rangle_{^{17}\text{O}(p,\alpha)^{14}\text{N}}} \right) \rho$

$Y_{^{16}\text{O}}Y_H N_A \langle \sigma v \rangle_{^{16}\text{O}(p,\gamma)^{17}\text{F}}} \rho = Y_{^{17}\text{O}}Y_H N_A \left( \langle \sigma v \rangle_{^{17}\text{O}(p,\gamma)^{18}\text{F}}} + \langle \sigma v \rangle_{^{17}\text{O}(p,\alpha)^{14}\text{N}}} \right) \rho$

$\frac{Y_{^{16}\text{O}}}{Y_{^{17}\text{O}}} = \frac{N_A \langle \sigma v \rangle_{^{17}\text{O}(p,\gamma)^{18}\text{F}}} + N_A \langle \sigma v \rangle_{^{17}\text{O}(p,\alpha)^{14}\text{N}}} \right)}{N_A \langle \sigma v \rangle_{^{16}\text{O}(p,\gamma)^{17}\text{F}}} \right)}$

$^{17}\text{O}/^{16}\text{O}$ equilibrium value depends on reaction rates and gives us information about the mixing depth.
Nuclear physics of H-burning

Stellar Energy Range -- Gamow Window
-- Resonance Width

\[ \sigma \propto \exp \left( -\frac{E}{kT} \right) \]

\[ \text{GAMOW PEAK} \quad \sigma \propto \exp \left( -\frac{b}{\sqrt{E}} \right) \]

\[ \text{RESONANCE} \quad \sigma \propto \frac{1}{(E - E_r)^2 + (\Gamma/2)^2} \]

Temperature:
8.3 \(10^7\) K \(\rightarrow\) 3 \(10^6\) K

Conversion Factors Between Units of Energy
3.45 keV \(\rightarrow\) 0.25 keV

Most effective energy \(^{17}\text{O} + p\) reactions
125 keV \(\rightarrow\) 36.5 keV

High uncertainties in nuclear physics input because of the low energies at which reactions take place.

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

\[ E_0 = \left( \frac{\mu}{2} \right)^{1/3} \left( \frac{\pi e^2 Z_1 Z_2 k_B T}{\hbar} \right)^{2/3} = 0.1220 (Z_1^2 Z_2^2 A)^{1/3} T_9^{2/3} \text{ MeV} \]

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Low mass star evolution: RGB and AGB phase

- The lower is the mass, the larger is the number of stars

- $M<3M_\odot$

IRC+10216 C-star is the brightest object on the sky at mid infrared.
Red giant stars contribution to the galactic chemical evolution

[Diagram showing the processes of molecule formation, dust condensation, and the flow of material to the interstellar medium (ISM).]

- Inert C/O core
- H/He burning & S-process
- Convective Envelope
- Pulsating Atmosphere
- Circumstellar Envelope

Molecular Cloud
Meteorite
Presolar grains

Nucleosynthesis + mixing
Molecule formation
Dust formation
Photochemical reactions

- $C/O < 1$
- Degenerate C/O core
- Convective stellar envelope
- $C/O > 1$
- He- and H-burning shell

Shock waves
Silicates, Mg/Al oxides
Dynamical atmosphere + gas ejection
Dust formation + wind acceleration
Amorphous carbon, SiC

- $H_2O$, $TiO$, $VO$
- $SiO$, $H_2$, CO
- $H_2$, CO, CN, $C_2$, $C_2H$, HCN
- 3-30 km/s
- 10^4 - 10^5 M_☉/yr

$OH \rightarrow O + H$
$H_2O \rightarrow OH + H$
HCN $\rightarrow$ CN + H
CN $\rightarrow$ C + N

Our Solar System

SIF2015
Types of presolar grains

which can be isolated from meteorites in almost pure form by chemical and physical processing

Table 1 Types of presolar grains in primitive meteorites and IDPs

<table>
<thead>
<tr>
<th>Grain type</th>
<th>Noble gas components</th>
<th>Size</th>
<th>Abundance&lt;sup&gt;a,b&lt;/sup&gt;</th>
<th>Stellar sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>Xe–HL</td>
<td>2 nm</td>
<td>1400 ppm</td>
<td>Supernovae?</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>Ne–E(H), Xe–S</td>
<td>0.1–20 μm</td>
<td>150 ppm</td>
<td>AGB, SNe, J stars, novae, born-again AGB</td>
</tr>
<tr>
<td>Graphite</td>
<td>Ne–E(L)</td>
<td>1–20 μm</td>
<td>&gt;1.5%</td>
<td>SNe, AGB, born-again AGB</td>
</tr>
<tr>
<td>Silicates in IDPs</td>
<td></td>
<td>0.2–1 μm</td>
<td>1–2 ppm</td>
<td>RG, AGB, SNe</td>
</tr>
<tr>
<td>Silicates in meteorites</td>
<td></td>
<td>0.2–0.9 μm</td>
<td>&gt;220 ppm</td>
<td>RG, AGB, SNe</td>
</tr>
<tr>
<td>Oxides</td>
<td></td>
<td>0.15–3 μm</td>
<td>&gt;80 ppm</td>
<td>RG, AGB, SNe, novae</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td></td>
<td>0.3–1 μm</td>
<td>~3 ppb</td>
<td>SNe</td>
</tr>
<tr>
<td>Ti, Fe, Zr, Mo carbides</td>
<td></td>
<td>10–200 nm</td>
<td>~4–5%</td>
<td>AGB, SNe</td>
</tr>
<tr>
<td>Kamacite, iron</td>
<td></td>
<td>~10–20 nm</td>
<td></td>
<td>SNe</td>
</tr>
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</table>

<sup>a</sup>Abundances refer to meteorite type AB grains. The values here are maximum values.

<sup>b</sup>Because detection efficiency for ion imaging identification are not included, given abundances are lower limits (see Nguyen et al., 2007).
Grains & challenges from RGB & AGB stars

C/O<1 Oxide grains
From stars with M<2.5M☉
Grains & challenges from RGB & AGB stars

C/O<1 Oxide grains
From stars with M<2.5M☉
Oxide grains of AGB origin: HBB or CBP?

In conclusion, the measured $^{17}$O/$^{16}$O ratio of grain OC2 ($= 1.25 \pm 0.07 \times 10^{-3}$) could be reproduced within the large error bars of the NACRE compilation ($2.44^{+1.54}_{-1.78} \times 10^{-3}$) in models of massive AGB stars; however, the much more precise $^{16}$O(p,γ)$^{17}$F rate of the present work leads to $2.52^{+0.88}_{-0.76} \times 10^{-3}$ for the $^{17}$O/$^{16}$O ratio and disagrees with the measured value. Consequently, there is not clear evidence to date for any stellar grain origin from massive AGB stars. Stellar model uncertain-

Iliadis et al. 2008

Nollett et al. 2003

Palmerini et al. 2011

Boothroyd, Sackmann & Wasserburg 1995
Variation of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction rate

Figure: $(p,\gamma)$ solid line, $(p,\alpha\gamma)$ bold and $\beta^+$ decay dashed line

Proton capture reactions on nitrogen and oxygen isotopes are of special importance in our context. In particular, the reaction rate for $^{14}\text{N}(p,\gamma)^{15}\text{O}$ by ADE10, reduced by 50% with respect to NACRE, leads to a reduction in the efficiency of the whole CNO cycling, moving the H-burning shell toward inner stellar regions, where temperature and density values are higher by about 10% and 25%, respectively, as compared to previous stellar models. We shall discuss at length the important

Angulo et al. 1999
Adelberger et al 2011
Variation of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction rate

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Figure: $(p,\gamma)$ solid line, $(p,\alpha\gamma)$ bold and $\beta^+$ decay dashed line
$^{17}\text{O}+\text{p}$ reaction rates and Oxide grains

- RGB stars with $1M_\odot < M_\star < 2M_\odot$ and solar composition
- AGB stars with $M_\star < 2M_\odot$ and solar composition

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$^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction rate variations

Adelbreger et al. 2011 (Chafa et al. 2007)

Nollet et al. 2004

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$^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction rate variations

Nollet et al. 2004

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$^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction rate variations

Nollet et al. 2004

THM (Sergi et al. 2010)

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\( ^{17}\text{O}(p,\alpha)^{14}\text{N} \) reaction rate variations

- NACRE
- Adelbreger et al. 2011 (Chafa et al. 2007)
- THM (Sergi et al. 2010)

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\[ ^{17}\text{O} + p \text{ reaction rates and Oxide grains} \]

- \[ ^{17}\text{O} + p \text{ from Chafa et al. 2007} \]

- Low mass RGB stars \((M_*<2M_\odot)\) are progenitor of group 1 grains

- Extra-mixing in AGB stars account for isotopic composition of Group 2 oxide grains

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$^{17}\text{O} + p$ reaction rates and Oxide grains

- Mass range of stellar progenitors of group 2 oxide grains is $1M_\odot < M_\star < 1.2M_\odot$

- Group 2 grains might be divided in 2 subgroups because of the progenitor mass

THM data
Aluminum isotopic ratio...a challenge

How to reach $^{26}\text{Al}/^{27}\text{Al}>0.02$ shown by part of group 2 grains?
Aluminum isotopic ratio: a possible stellar solution from nuclear physics

- The measurement of $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ excludes that a solution coming from nuclear data (Strieder et al. 2012)

- What about the mixing profile?

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Extra-mixing
Convective envelope
H-burning shell

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Palmerini et al. in prep
In nuclear astrophysics

- Sometimes solutions come from nuclei ($^{17}$O/$^{16}$O in grains)

- Sometimes solutions come from stars ($^{26}$Al/$^{27}$Al in grains)

- Other times we do not know yet ($^{14}$N/$^{15}$N in grains and the Li problem)

- In any case it is necessary to collaborate

GRAZIE!

THANK YOU!