The astrophysical lithium, beryllium and boron problem in astrophysics in view of the recent Trojan Horse burning reaction rate determination

Livio Lamia
Dipartimento di Fisica e Astronomia
Univ. di Catania
"Celebrating the past...": why studying Lithium, Beryllium and Boron (LiBeB)?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Cause</th>
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</thead>
<tbody>
<tr>
<td>Exponential decrease from hydrogen to $A \sim 100$</td>
<td>Increasing rarity of synthesis for increasing $A$, reflecting that stellar evolution to advanced stages necessary to build high $A$ is not common.</td>
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<tr>
<td>Fairly abrupt change to small slope for $A &gt; 100$</td>
<td>Constant $\sigma(n,\gamma)$ in $s$ process. Cycling in $r$ process.</td>
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<tr>
<td>Rarity of D, Li, Be, B as compared with their neighbors H, He, C, N, O</td>
<td>Inefficient production, also consumed in stellar interiors even at relatively low temperatures.</td>
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</tbody>
</table>

Rarity of proton-rich heavy nuclei | Not produced in main line of $r$ or $s$ process; produced in rare $p$ process. |

Advanced stage where maximum energy is released ($Fe^{56}$ lies near minimum of packing-fraction curve). 

Double peaks $A = 80, 130, 196$ 

Neutron capture in $r$ process (magic $N = 50, 82, 126$ for progenitors). 

Neutron capture in $s$ process (magic $N = 50, 82, 126$ for stable nuclei). 

Rarity of D, Li, Be, B as compared with their neighbors H, He, C, N, O | Inefficient production, also consumed in stellar interiors even at relatively low temperatures.
The observational LiBeB trend vs the metallicity [Fe/H]

Different features can be extracted by studying the abundance vs metallicity scatter plot:

1) it is evident that the number of observations for lithium are large compared with those of beryllium and, more evident, with boron → Region of Abs. Lines;

2) at lower metallicity, lithium abundances exhibit the so-called “Li-plateau” (Spite & Spite A&A, 1982) → Primordial Nucleosynthesis;

3) beryllium and boron abundances are strongly related with metallicity, thus suggesting their production mainly via a synthesis occurring in a continuously evolved ISM → GCR’s nucleosynthesis;

4) Beryllium and boron abundances do not exhibit (until today!) any plateau → very scarce contribution from primordial nucleosynthesis. (see Spite & Spite 2010 review for Light Elem.)
Big Bang Nucleosynthesis: the Li-problem and BeB predictions

- **SBBN**: description of primordial abundances as a function of the only free parameter $\eta = n_B/n_\gamma$ (e.g., Coc et al., ArX 2013 and ref.)

Primordial Lithium ($\text{Li/H}^{\text{Stellar}} \sim 1.6 \times 10^{-10}$)

Primordial Lithium ($\text{Li/H}^{\text{Planck}} \sim 4.9 \times 10^{-10}$)

- Very faint objects and very low abundances....

- Further, Be has been suggested as possible tracer of IBBN (Kajino & Boyd, Nature, 1998).

- $\nu$-process nucleosynthesis in SN can lead to a significant formation of $^7\text{Li}$ and $^{11}\text{B}$ (talk by Kajino, Yoshida-Kajino PRL2005 or JPG2013)
Stellar Nucleosynthesis: The Lithium-Beryllium dip

For MS F-G stars, standard stellar models do not predict depletion of the trio LiBeB, except during PMS (due to convection). Thus, for F-G stars, no depletion should be detected, with respect the meteoritic abundances (see details in Boesgaard et al., 2004, Pinsonneault 1997, Théado & Vauclair 2003 (I &II), do Nascimento 2000)

✓ Observational status: Depletion in Open Clusters for stars with 6400<Teff(K)<6800.

✓ Li & Be dip: the depth of the dip reflects the nuclear fate in the nuclear destruction zone (NDZ).

✓ Burning (p,α) channel as the main contribution to their destruction at $T_6=2.5$ (Li), $T_6=4$ (Be), $T_6=5$ (B)
Uncertainties affecting stellar models.....

- Uncertainties on some key input parameters such as \( g \), \( T_{\text{eff}} \), [Fe/H];
- Theoretical models for stellar atmosphere and stellar opacity;
- Understanding stellar plasma physics and mixing: standard convection and/or extra-mixing phenomena (slow-mixing processes);

“....while looking to the future”

Uncertainties on the nuclear cross section for the burning \((p,\alpha)\) reactions responsible for lithium, beryllium and boron destruction inside stars ⇒ Low-energy cross section measurements!

Reaction rate determination

\[ ^7\text{Li}(p,\alpha)^4\text{He} \& ^6\text{Li}(p,\alpha)^3\text{He} \]
\[ ^9\text{Be}(p,\alpha)^6\text{Li} \]
\[ ^{11}\text{B}(p,\alpha)^8\text{Be} \& ^{10}\text{B}(p,\alpha)^7\text{Be} \]
The THM allows one to extract a charged particles two-body cross section \( A+x \to c+d \) at astrophysical energies by selecting the quasi-free (QF) contribution of a suitable three body reaction \( a(A,dc)s \) performed at energies well above the Coulomb barrier (Spitaleri et al. PAN, 2011).

(I) 2-body data free of Coulomb suppression and electron screening effects;

(II) validity test, introduction of penetrability function and normalization to direct data are needed!!!

The explored energy region \( E_{\text{cm}} \) goes from \( 0 < E_{\text{cm}} < 1 \) MeV by using only one value for the energy beam!!!
THM for studying the $^{11}\text{B}(p,\alpha_0)^8\text{Be}$ reaction (JpG, 2012)

- Study of the $^{11}\text{B}(p,\alpha)^8\text{Be}$ reaction ($Q=8.59$ MeV) through the QF $^2\text{H}(^{11}\text{B},\alpha^{8}\text{Be})n$ reaction ($Q=6.36$ MeV);
- $E_{\text{beam}}(^{11}\text{B})=27$ MeV & $I_{\text{beam}}(^{11}\text{B})=2-5$ nA;
- Displacement of the detectors around the QF-angular range.
THM for studying the $^7\text{Li}(p,\alpha)^4\text{He}$ reaction (A&A, 2012)

$S(0)=53 \pm 5$ (keV b) and $U_e=425 \pm 60$ eV;

The THM reaction rate

\[
N_A \langle \sigma v \rangle^{\text{THM}} = N_A \langle \sigma v \rangle^{\text{NACRE}} f_{\text{corr}}
\]

\[
N_A < v > = \frac{8}{(kT)^{3/2}} \int_0^E S_b(E) e^{2 \frac{E}{kT}} dE
\]

(cm$^3$ mol$^{-1}$ s$^{-1}$)

In which $S_b(E)$ has been measured, overcoming the extrapolation procedures.
Impact on $^7$Li nucleosynthesis in RGB phase

- Standard STellar Models (SSTMs) predict a Li depletion at the beginning of the red giant branch (RGB) phase (Pinsonneault 1997; Sestito et al. 2005), when the deepening convective envelope mixes the external layers with hydrogen-processed material.

- The difficulty in understanding the Li abundance in giant stars is increased by the observation of both Li-rich and Li-poor, for which different mixing mechanism (with different mass transport rate) are still discussed (Sackmann & Boothroyd 1999; Guandalini et al. 2007; Palmerini et al. 2011).

- Thus, we evaluate the impact of the TH reaction rate on $^7$Li abundance evolution for a 1.5 $M$ and solar-metallicity RGB star, by means of the code discussed and developed by Palmerini et al. 2011.

- The uncertainties on THM reaction rate (red lines) doesn’t introduce any significant variation in the Li abundance. If any modification occurs, this is negligible compared to the other uncertainties.

THM for studying the $^6$Li(p,$\alpha$)$^3$He reaction (ApJ, 2013)

- TH reaction rate compared with the calculation of Cyburt et al., ApJ, 189, 2010 (REACLIB, website);
- Variation of about 15% at astrophysical temperatures relevant for Li-burning in stars!!!

$S(0)=3.44\pm0.35$ (MeV b) and $U_e=355\pm100$ eV

The THM reaction rate
Astrophysical implications in PMS via the updated FRANEC code

- The observation of $^6$Li in stars is affected by observational difficulties mainly due to the scarce $^6$Li abundances in stellar envelopes, thus requiring high-quality spectra and spectral analysis based on updated atmospheric models (see e.g. Asplund et al. (2006); Steen et al. (2012)).

- Present models have been computed with a version of the FRANEC evolutionary code (Degl'Innocenti et al. (2008); Dell'Omodarme et al. (2012)) recently updated with particular attention to the physical inputs relevant for the Pre Main Sequence (PMS) phase (see Tognelli et al. (2011) for details). We did model calculations for four different masses (0.6 M, 0.8 M, 1.0 M, 1.2 M) and three different metallicities, namely $[\text{Fe/H}] = -0.5$, -1.0, and -2.0.

- The higher the metallicity, or the lower the stellar mass, the deeper and hotter the base of the convective envelope. This qualitatively explains the different $^6$Li depletion for various masses and metallicities.

- Uncertainties on $^6$Li abundance observations (stellar masses, input parameters....) make difficult any comparison with the obtained results, thus leaving 6Li in PMS as an open problem.
The THM for studying the $^{10}\text{B}(p,\alpha)^7\text{Be}$ reaction (PRC, November 2013 submitted)

- Discrepancy at high energies and related problems for normalization purposes;
- Direct measurement in collaboration with LNL-Univ.Padova

- Dominant Resonant contribution in the Gamow energy region @ $\sim$10keV ($\sim$ 8.7 MeV $^{11}\text{C}$ ($J^\pi=5/2^+$), as in AzS);
- Direct measurement in collaboration with LNL-Univ.Padova
The ASFIN people


INFN, Laboratori Nazionali del Sud, & Università di Catania, Italy

Thank you and see you in Catania...