Light element LiBeB depletion in astrophysics and related \((p,\alpha)\) cross section measurements via the THM

Livio Lamia
Outlook

Some astrophysics......

- Introduction to the problem of the “relatively low” abundances of lithium, beryllium and boron (LiBeB);
- Abundances vs. Metallicity: key formulas and the observational status;
- Lithium and primordial nucleosynthesis (BBN): stellar observations vs. WMAP;
- LiBeB as probes for stellar structure: observational status and proposed theoretical models.

Some nuclear physics......

- Cross section measurements at the Gamow peak and related difficulties;
- The Trojan Horse Method as a tool for nuclear astrophysics;
- The $^{11}\text{B}(p,\alpha)^8\text{Be}$ reaction via the THM: a step-by-step analysis;
- The $^7\text{Li}(p,\alpha)^4\text{He}$ reaction via the THM: recent results and applications to RGB;
- The $^6\text{Li}(p,\alpha)^3\text{He}$ reaction via the THM: recent results and applications to PMS.
Why studying Lithium, Beryllium and Boron (LiBeB)?

- First, their relative abundance are very low if compared to their neighbors of the periodic table (H, He, C etc.) and a specific process for their production is needed;
- second, it’s important to study their role in the framework of primordial nucleosynthesis;
- third, by studying the simultaneous abundances of lithium, beryllium and boron, it’s possible to determine details for a deeper understanding of the internal stellar structure and evolution.
Lithium, Beryllium and Boron (LiBeB) in astrophysics: introduction (I)

- Galactic cosmic rays (GRR) and solar system (SS) show very low relative abundances of Li, Be and B with respect the other elements (H, He, C, N, ...);

- **Main Production Sites**: Spallation processes on ISM; BBN (mainly for lithium and “probably” beryllium); further scenarios (induced neutrino nucleosynthesis, nova outburst......)

- **Main Destruction Sites**: Stellar interior in the temperature range of 2<T(MK)<5

- LiBeB can be used to better understand primordial nucleosynthesis (lithium) and mixing mechanisms acting in stellar interior.
Lithium, Beryllium and Boron (LiBeB): abundances vs. metallicity

Stellar abundances determination can be performed by means of the spectral analysis of stellar atmosphere, by studying characteristic absorption lines. For LiBeB we have to study the lines:

<table>
<thead>
<tr>
<th>element</th>
<th>λ observation (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium</td>
<td>6707.76;6707.91 (V)</td>
</tr>
<tr>
<td>Beryllium</td>
<td>3130.41;3131.06 (NUV)</td>
</tr>
<tr>
<td>Boron</td>
<td>2496.77;2497.72 (UV)</td>
</tr>
</tbody>
</table>

The depth of the absorption line gives information about the number of atoms of a given element in that atmosphere, even if its determination is not straightforward at all. For a given element X, its abundance can be expressed as:

\[ A(X) = 12 + \log \left( \frac{N_X}{N_H} \right) \]

where \( N_X \) is the number of atoms per cm\(^3\) and \( N_H \) the number of hydrogen atoms per cm\(^3\). For a given stellar atmosphere, the metallicity represents the amount of elements heavier than helium and it can be defined as:

\[ [\text{Fe/H}] = \log \left( \frac{\text{Fe}}{\text{H}} \right) - \log \left( \frac{\text{Fe}_\odot}{\text{H}_\odot} \right) \]

(see for example Gray: “The Observation and Analysis of Stellar Photospheres” (1992))
**LiBeB: A(X).vs.[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

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:
“*The Light elements lithium, beryllium and boron*”, A.M. Boesgaard, 2004;
“*Beryllium and boron in metal-poor stars*”
F. Primas, 2009
Lithium and primordial nucleosynthesis (BBN)

- **Li-problem**: Low-metallicity Pop.II stars reveal the presence of the so-called “Li-plateau” (Spite & Spite, A&A 1982), widely assumed as the primordial one. However, the lithium abundances deduced from WMAP are in disagreement with respect the stellar ones.

- **SBBN**: description of primordial abundances as a function of the only free parameter $\eta = n_B/n_\gamma$ (see e.g. Coc et al., ApJ, 2012).

- Primordial Lithium (Li/H)$^{\text{Stellar}} \sim 1-2 \times 10^{-10}$ (Fields et al., ApJ, 2005 and ref.)
- Primordial Lithium (Li/H)$^{\text{WMAP}} \sim 4 \times 10^{-10}$ (Cyburt et al., PLB, 2005 and ref.)

**Stellar Depletion??????**
Beryllium and Boron nucleosynthesis....

- GCR-Nucleosynthesis: Be and B can be produced via spallation processes (>100 MeV) from energetic protons and alpha-particles in Galactic cosmic rays (GCRs) colliding with CNO in ISM (Fields, ApJ, 2005). Effects of SN explosion have been also investigated (Kajino’s talk and Suzuki et al., ApJ, 1999).

- 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 \(^7\)Li and \(^{11}\)B (Kajino’s talk and Mathews & Kajino, Phys.Rev. D 2012).
The Lithium-Beryllium dip as signature of mixing phenomena

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, King et al. 2000, Pinsonneault 1997).

- **Observational status:** Depletion in Open Clusters for stars with 6400<Teff(K)<6800.
- **Dip di Li & Be:** 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).

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**Hyades (~600 Myr)**

**Praesepe (~600 Myr)**

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Boesgaard et al., APJ, 605, 864, (2004)

F-G stars: a very simple scheme

Beryllium Nuclear Destruction Zone \((T_\phi \geq 4)\)

Lithium Nuclear Destruction Zone \((T_\phi \geq 2.5)\)

Boron Nuclear Destruction Zone \((T_\phi \geq 5)\)

Observer to Spectral Analysis

- Lithium
- Beryllium
- Boron
Lithium, Beryllium & Boron: the Li-Be correlation

Figure 1.12: The Li-Be correlation as reported in [Boesgaard et al. (2004b)] and [Boesgaard et al. (2004c)]. Two groups are reported in this figure, corresponding to two different ranges of effective temperatures of the observed stars.

✓ Li-Be & Be-B correlation as signature of “rotation-induced” slow-mixing processes.
Observations vs. models: mixing induced by stellar rotation

The lithium and beryllium deficiency and the boron observational trend are in agreement with "non-standard mixing process (slow-mixing process)" in stellar interior mainly triggered by rotation:

Light elements Li, Be and B abundances are shown as the Be-deficiency varies for low-metallicity young star $(-0.5<\text{[Fe/H]}<0.1, 5800<T_{\text{eff}}\text{ (K)}<6500, M\sim1M_\odot$). The variation of their abundances, with respect the meteoritic ones, has been indicated as possible “probe” for stellar structure understanding.
An extremely primitive star in the Galactic halo

The most straightforward interpretation of the Spite plateau is that the Li observed in the plateau stars is the Li produced in the theoretical primordial Li abundance is a factor of 2–3 higher than the value observed on the Spite plateau. A number of explanations of this discrepancy have been proposed, which range from stellar phenomena, such as atomic diffusion, to new physics leading to a different Big Bang nucleosynthesis. Our upper limit implies that the Li abundance of SDSS J102915 +172927 is far below the value of the Spite plateau. At extremely low metallicities, the Spite plateau displays a

Still unsolved!!!!!
Input parameters for stellar codes

- 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);
- Uncertainties on the nuclear cross section for the burning $(p,\alpha)$ reactions responsible for lithium, beryllium and boron destruction inside stars.

Reaction rate determination

- $^7\text{Li}(p,\alpha)^4\text{He}$ & $^6\text{Li}(p,\alpha)^3\text{He}$
- $^9\text{Be}(p,\alpha)^6\text{Li}$
- $^{11}\text{B}(p,\alpha)^8\text{Be}$ & $^{10}\text{B}(p,\alpha)^7\text{Be}$
From Stars to the laboratory: direct measurements of charged-particle induced reactions

By considering the typical temperatures of some $10^6$ K at which burning $(p, \alpha)$ reactions typically occur in stellar environments, the Gamow peak is at about (for boron case)

$$E_0 = 1.22(Z_x^2 Z_y^2 \mu T_6)^{1/3} \text{keV} \approx 10 \text{keV}$$

Only extrapolations are possible on low-energies direct data because of the electron screening and Coulomb penetrability effects !!!!!!!
The indirect study of the $^{11}\text{B}(p,\alpha_0)^8\text{Be}$ via the THM applied to the $^2\text{H}(^{11}\text{B},\alpha_0^8\text{Be})\text{n}$ reaction

- Basic concepts of the method and overview already given in the previous talk of Cherubini and Pizzone;

The Experiment at LNS

- Study of the $^{11}\text{B}(p,\alpha)^8\text{Be}$ reaction ($Q=8.59$ MeV) through the QF $^2\text{H}(^{11}\text{B},\alpha^8\text{Be})\text{n}$ reaction ($Q=6.36$ MeV);
- $E_{\text{beam}}(^{11}\text{B})=27$ MeV & $I_{\text{beam}}(^{11}\text{B})=2-5$ nA;
- Target thickness $CD_2 \sim 190 \mu g/cm^2$;
- Displacement of the detectors around the QF-angular range.
Selection of the 2→3 $^2\text{H}(^{11}\text{B}, \alpha_0^{8}\text{Be})\text{n}$ channel: $^8\text{Be}$ determination and experimental Q-value

Alpha-decay of $^8\text{Be}(\text{g.s.})$ in 2 alphas ($Q_{\text{th dec}}^{\alpha} = 92$ keV) detected in coincidence on a Dual Position Sensitive Detector, DPSD.

**Experimental spectrum** centered at 92 keV.

**2→3 reaction** ($Q_{\text{th}} = 6.36$ MeV) detected in coincidence on a Dual Position Sensitive Detector, DPSD.

*Off-line reconstruction of the relative energy between the detected $\alpha$-particles*

**Q-value peak**

2→3 reaction ($Q_{\text{th}} = 6.36$ MeV)

**Experimental spectrum** centered at 6.35 MeV.

$^2\text{H}(^{11}\text{B}, \alpha_0^{8}\text{Be})\text{n}$

$E_{11\beta} = 27$ MeV

$E_{\alpha-\alpha} = 16^\circ \pm 1^\circ$

10th Russbach School on Nuclear Astrophysics
10-16 March 2013 Russbach (Austria)
The $^2\text{H}(^{11}\text{B, }\alpha^{^8}\text{Be})n$ reaction channel: are the data contaminated by Sequential Mechanism (SM)?

The same particles $\alpha$, $^8\text{Be}$ and neutron can be produced via the decays of intermediate nuclei. Study of the relative energies is then needed.
The $^2\text{H}(^{11}\text{B}, \alpha_0^{8}\text{Be})\text{n}$ reaction: QF selection via Momentum Distribution investigation

✓ The PWIA approach allows one to extract the experimental momentum distribution via the relation:

\[ |\Phi(p_n)|^2 \propto \frac{d^3\sigma}{d\Omega_\alpha d\Omega_{^{8}\text{Be}} dE_{\text{cm}}} \]

Exp. Fit $\rightarrow$ FWHM = 65$\pm$10 MeV/c

Hulthén $\rightarrow$ FWHM = 58 MeV/c

9th Russbach Symposium Nuclear Astrophysics
10-16 March 2013 Russbach (Austria)
Data selection: from the $^2\text{H}(^{11}\text{B}, \alpha_0^{8}\text{Be})\text{n}$ to the $^{11}\text{B}(p, \alpha_0)^8\text{Be}$ reaction

✓ Only the events belonging to the condition $|p_n| < 80$ MeV/c (quasi-free selection) will be taken into account;

✓ By using the simple PWIA formulation, the HOES cross section can be obtained via the factorization:

$$\frac{d\sigma}{d\Omega} \propto \frac{d^3\sigma}{d\Omega_p d\Omega_{8\text{Be}} dE_{cm}} = KF \cdot |\Phi(p_n)|^2$$

✓ The energy in the center-of-mass $^{11}\text{B}-p$ is determined by the relation:

$$E_{CM} = E_{^{12}\text{C}^*} - Q_2 = E_{^{12}\text{C}^*} - 8.59 \text{ MeV}$$

✓ No penetrability or electron screening effects influence the TH “bare-nucleus” cross section.
$^{11}$B$(p, \alpha_0)^8$Be: TH S(E)-factor determination

- Extraction of the bare-nucleus S(E)-factor:
  \[ S(E) = E^2\sigma_1^{\alpha_0}(E) \exp(2\pi\eta) \]

- $^9$Be & $^5$He (SM) evaluation;
- Separation between resonant l=1 (16.106 MeV $^{12}$C) and no-resonant contribution;
- Integration via angular distributions;
- Smearing procedure for the direct data (40 keV energy resolution);
- Normalization between 400-600 keV's;

The bare-nucleus S(E)-factor has been described as:

\[ S(E)_b = 2.04 - 1.37E + 0.12E^2 + 7.28 \times \exp[-0.5((E-0.148)/0.044)^2] \]

\[ S(0) = 2.07 \pm 0.41 \text{ (MeV b)} \]
\( {}^{11}\text{B}(\text{p},\alpha_0){}^{8}\text{Be} \): electron screening potential \( U_e \) determination via the TH

- The TH \( S(E) \)-factor (non-resonant) can be used for evaluating the electron screening potential;
- The shielded direct data can be fitted via the relation:

\[
S(E)_{sh} = S(E)_b \times \exp(\pi \eta U_e / E)
\]

leaving \( U_e \) as the only free parameter.

**RESULTS**

<table>
<thead>
<tr>
<th>( {}^{11}\text{B}(\text{p},\alpha_0){}^{8}\text{Be} )</th>
<th>( S(0) )</th>
<th>( U_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>THM</td>
<td>2.07\pm0.41 (MeV b)</td>
<td>472\pm160 eV</td>
</tr>
<tr>
<td>Becker et al., 1987</td>
<td>2.10\pm0.13 (MeV b)</td>
<td>(-)</td>
</tr>
<tr>
<td>Angulo et al., 1993</td>
<td>(-)</td>
<td>430\pm80 eV</td>
</tr>
</tbody>
</table>

\( U_e^{THM} = 472\pm160 \) eV

*Lamia L. et al, JpG, 2012*
The direct measurements at low-energies have been performed and discussed by Engstler et al., Z.Phys., 1992;

Only extrapolations have been performed in correspondence of the energy window relevant for astrophysics;

These measurements allowed to shed light on the electron-screening phenomena (Rolf’s group);

Thus, the first THM approach has been performed in order to measure the bare-nucleus $S(E)$-factor at astrophysical energies.......

$S(0) = 59 \pm 23 \text{ (keV b)}$

$U_e = 330 \pm 160 \text{ eV}$

$S(0) = 3.00 \pm 1.23 \text{ (MeV b)}$

$U_e = 470 \pm 150 \text{ eV}$
The $^7\text{Li}(p, \alpha)^4\text{He}$ reaction via the $^2\text{H}(^7\text{Li}, \alpha^4\text{He})n$ QF-reaction

- Study of the $^7\text{Li}(p,\alpha)^4\text{He}$ reaction ($Q=17.35$ MeV) through the QF $^2\text{H}(^7\text{Li},\alpha^4\text{He})n$ reaction ($Q=15.12$ MeV);
- $E_{\text{beam}}(^7\text{Li})=19, 19.5$ and $20$ MeV;
- $S(0)=55\pm3$ (keV b) and $U_e=330\pm40$ eV;

The updated $^7\text{Li}(p, \alpha)^4\text{He}$ TH reaction rate

Recent direct measurements by Cruz et al. (2005, 2008) allowed for a new normalization;

- Fit of the TH data $\Rightarrow$
  
  $S_b(E) = 53 + 213 \cdot E - 336 \cdot E^2$

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

The updated $^7\text{Li}(p, \alpha)^4\text{He}$ TH reaction rate

Reaction rate determination by means of the formula (Rolfs & Rodney, 1988)

$$N_A <\sigma v> = \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty S_b(E)e^{-\frac{2\pi E}{kT}} dE \quad (cm^3 mol^{-1} s^{-1})$$

- The $S_b(E)$ used has been measured, overcoming the extrapolation procedures;
- A simply correction factor has been derived, $f_{\text{corr}}(T_9)$
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 $1.5 M_\odot$ 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.
The $^6\text{Li}(p, \alpha)^3\text{He}$ reaction via the $^2\text{H}(^6\text{Li}, \alpha^3\text{He})n$ QF-reaction

- Study of the $^6\text{Li}(p, \alpha)^3\text{He}$ reaction ($Q=17.35$ MeV) through the QF $^2\text{H}(^6\text{Li}, \alpha^3\text{He})n$ reaction ($Q=15.12$ MeV);
- $E_{\text{beam}}(^6\text{Li}) \ @ \text{LNS} = 25$ MeV;
The updated $^6\text{Li}(p, \alpha)^3\text{He}$ TH reaction rate

- Recent direct measurements by Cruz et al. (2005, 2008) allowed for a new normalization.
- Fit of the TH data in (MeV b) →
  $$S_b(E) = 3.44 - 3.50E + 1.74E^2 + 0.23E^3$$
- $S(0) = 3.44 \pm 0.35$ (MeV b) and $U_e = 355 \pm 100$ eV;


$$S_b(E) = \exp(\pi \eta U_e/E)$$
The updated $^{6}\text{Li}(p, \alpha)^{3}\text{He}$ TH reaction rate

Reaction rate determination by means of the formula (Rolfs & Rodney, 1988)

$$N_{A} < \sigma v > = \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{N_{A}}{(kT)^{3/2}} \int_{0}^{\infty} S_{b}(E) e^{-\frac{2\pi \eta - E}{kT}} dE \quad (cm^{3}mol^{-1}s^{-1})$$

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!!!
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 $^6$Li in PMS as an open problem.
CONCLUSIONS
The THM (see Spitaleri et al. At.Phy.Nucl. 2011, PRC 2004) provides a valid alternative to the direct measurements for the evaluation of the low-energy region of astrophysically relevant reactions.

- It allowed us to measure the $^{11}\text{B}(p,\alpha)^8\text{Be}$ $S(0)=2.07\pm0.41$ (MeV b) and $U_e=472\pm160$ eV, without any extrapolation (see Lamia, Spitaleri et al. JpG, 2012);

- Thanks to the most recent direct measurements, an updated $^7\text{Li}(p,\alpha)^4\text{He}$ TH reaction rate has been deduced, with variation of about 10% in correspondence of the astrophysical temperatures. Evaluation on RGB nucleosynthesis;

- The direct measurements of Cruz et al. 2005-2008 allowed us to update the $^6\text{Li}(p,\alpha)^3\text{He}$ TH reaction. Astrophysical application on PMS star nucleosynthesis via the recent FRANEC code version (even if no observational data have been used for comparison);

PERSPECTIVES

- Application of the updated THM reaction rate to different astrophysical context;

- Extraction of the $^{10}\text{B}(p,\alpha)^7\text{Be}$ $S(E)$-factor and its measurement in correspondence of the 10 keV resonance (data analysis in progress);

- Extraction of the $U_e$ from the TH $^{10}\text{B}(p,\alpha)^7\text{Be}$ measurement and direct data to test the so-called “isotopic-independence”, i.e. the $U_e$ does not depend from the charge $Z$ of the isotopes $^{10}\text{B}$ or $^{11}\text{B}$ (Assembaum et al., 1987 or Engstler 1992).