# Convective proton and $^3$He ingestion into helium burning: Nucleosynthesis during a post-AGB thermal pulse

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A thermal pulse during the post-AGB phase of stellar evolution may lead to a unique mode of light element nucleosynthesis. The stage is set by the ingestion of the unprocessed envelope material into the hot He-flash convection zone below. If the temperature is sufficiently large and the $^{12}$C abundance high enough (e.g. $T_8 > 0.8$, X($^{12}$C) $\simeq 0.4$ and X(H) $\simeq 1 \cdot 10^{-3}$) protons react faster with $^{12}$C and form $^{13}$C than destroying $^7$Be. The latter forms by $\alpha$-capture of $^3$He after an initial reduction of the $^3$He abundance to about $3 \cdot 10^{-5}$X($^4$He) by the ppI reaction $^3\mathrm{He}(^3\mathrm{He},2\mathrm{p})^4\mathrm{He}$ (for $T_8 \simeq 1$). All $^3$He is burned within minutes to weeks depending on the temperature. $^7$Be is now present at about the previously mentioned level of $^3$He. Its further fate is determined by the reactions $^7\mathrm{Be}(\mathrm{e}^-,\nu)^7\mathrm{Li}$ and the $\alpha$-capture reactions of $^7$Be and $^7$Li. These captures lead to the production of $^{11}$B which in turn is finally destroyed by $^{11}\mathrm{B}(\alpha,\mathrm{n})^{14}\mathrm{N}$. The details of this mechanism of light element production in real stars is expected to be fairly dependent on the description of mixing.

## 1. Introduction

About 20 % of all post-AGB stars are hydrogen-deficient. Among them are the Wolf-Rayet type central stars of planetary nebulae (PNe) and the PG1159 stars, with their characteristic helium, carbon and oxygen abundance patterns [1–3].

In order to understand the evolutionary origin and status of hydrogen-deficient objects new stellar evolution calculations have been recently presented by Herwig [4]. One channel of post-AGB evolution leading to a hydrogen-deficient surface involves a so-called very late thermal pulse (VLTP) as first proposed by Fujimoto [5]. During such an event the entire unprocessed envelope is mixed into the region of the ongoing He-flash on the convective time scale. Corresponding models by Herwig et al. [6] have been constructed using an advanced numerical algorithm for the treatment of convective nucleosynthesis. It ensures consistent abundance profiles and energy generation rates even when nuclear

*This work has been supported by the *Deutsche Forschungsgemeinschaft (DFG)* (grant La 587/16).

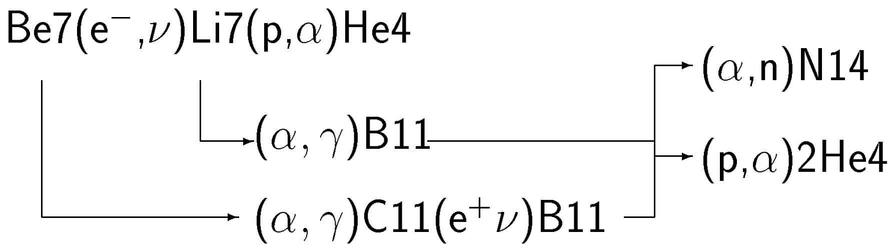


Figure 1. The ppII-chain and the additional reactions considered for ingestion of light elements into He-burning conditions. At relevant temperatures around $T_8 \sim 1.5$ the $\alpha$-capture on $^7$Li and $^{11}$B are four to five and three orders of magnitude larger than the $^{13}$C $+ \alpha$ reaction, respectively. $^7$Be is more similar to the carbon isotopes with its $\alpha$-capture being about tenfold that of $^{13}$C and the p-capture exceeding that of $^{12}$C by a factor of five. The e$^-$-capture of $^7$Be has a time scale of 0.1 yr.

and convective time scales are of the same order of magnitude. This is achieved by a simultaneous solution of the nuclear network equations and the equations of time-dependent convective mixing.

A group of stars which may be related to the hydrogen-deficient post-AGB stars are the R CrBr stars, of which some are not only hydrogen-free but at the same time lithium-rich [7]. The famous PN central star *Sakurai's object* (V4334 Sgr) resembles the R CrBr stars. However, it showed a rapid evolution of temperature, luminosity and surface abundances over the last decade [8,9]. Its evolution in the Hertzsprung-Russell diagram is similar to that of stellar models during a VLTP. Its lithium abundance exceeds the initial solar abundance by 0.5 to 1.0 dex. This large lithium abundance is surprising given the fragility of lithium ($T_{\rm min}(^7{\rm Li} + {\rm p}) \sim 2 \cdot 10^6\,{\rm K}$). We have thus investigated the fate of the light elements, in particular of $^3$He, which is present in the envelope at the time of ingestion into the convectively unstable intershell region of the ongoing He-flash beneath. Here, we present a new reaction channel which is to be considered as *hot H-deficient* $^3$He *burning.*

## 2. Nucleosynthesis of light elements during a VLTP

Any lithium production in a stellar environment is the result of the ppII reaction chain which is based on a readily available $^3$He reservoir. In the event of ingestion of unprocessed envelope material into the active and convectively unstable helium shell, protons are mainly captured by $^{12}$C and no production of $^3$He is possible. However, the $^3$He which is preserved in the envelope will be processed by the well known ppI-chain or by capturing an $\alpha$-particle. Any $^7$Be produced this way is obviously threatened by proton captures (ppIII-chain) as well as e$^-$-captures (ppII-chain). In addition, due to the high temperature in the helium shell ($T_8 \simeq 1 \ldots 1.5 ... 2.5$) $\alpha$-captures on any light isotopes had to be taken into account as well (Fig. 1). The reaction rates used in the present study have been taken from the `NACRE` compilation [10] except the $^{11}{\rm B}(\alpha, n)^{14}{\rm N}$ rate which was only available from Caughlan & Fowler [11].

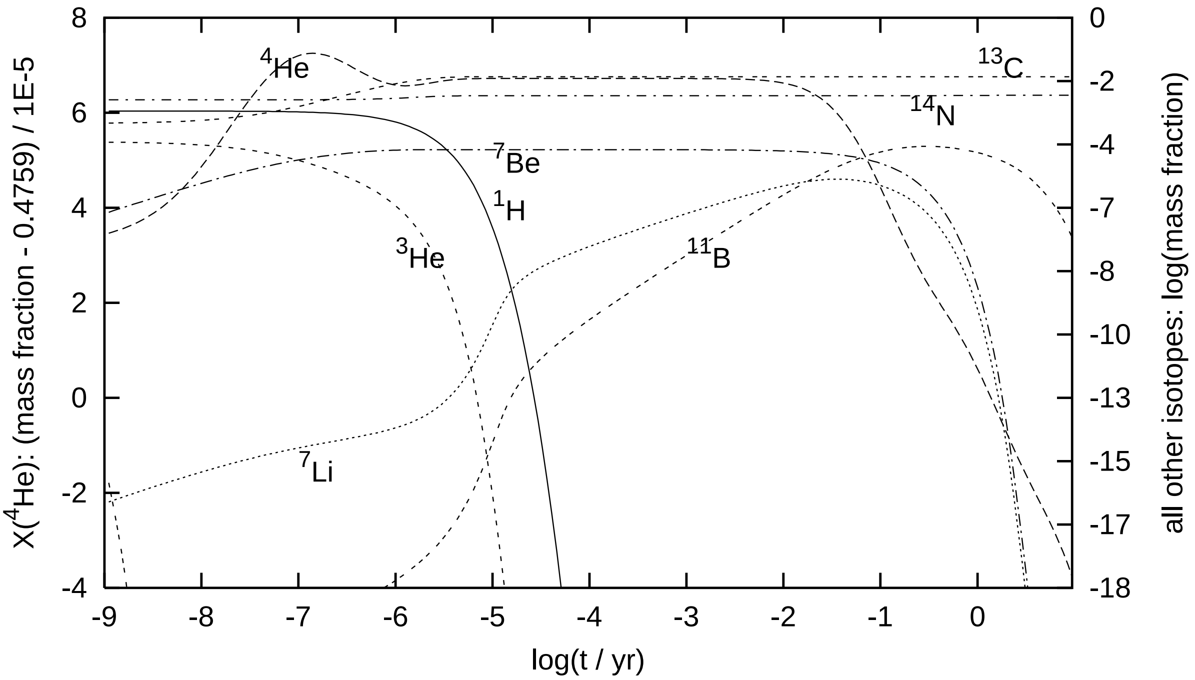


Figure 2. Time evolution of isotopic abundances for constant temperature $T_8 = 1.5$ and density $\rho = 1000\mathrm{g/cm}^3$. The initial abundances resemble the AGB envelope composition ($\log X(^3\mathrm{He}) = -3.9$) with modifications: $^4$He, $^{12}$C and $^{16}$O have the intershell abundance of AGB models with overshoot (0.47/0.40/0.11) and the initial hydrogen abundance has been chosen as $\log X(\mathrm{H}) = -3$ to account for the dilution effect of the mixing (all abundances are given as mass fractions).

In order to demonstrate the principal aspects of the hot H-deficient $^3$He burning we have constructed a series of one-zone nuclear network models which include the CNO isotopes, the pp-chains with the additions shown in Fig. 1 and helium burning, for typical initial conditions. A representative example is shown in Fig. 2.

During the first second of the evolution, the ppI reaction $^3\mathrm{He}(^3\mathrm{He}, 2\mathrm{p})^4\mathrm{He}$ prevails until $X_{^3\mathrm{He}} < \frac{3}{4}\frac{\sigma(^4\mathrm{He}+^3\mathrm{He})}{\sigma(^3\mathrm{He}+^3\mathrm{He})} X_{^4\mathrm{He}} \sim 1.2 \cdot 10^{-5}$. Then the ppII reaction $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ is dominating the nuclear burning of $^3$He. $^7$Be is built up to a mass fraction of $\sim 10^{-5}$ which corresponds to the $^3$He abundance at which the $^7$Be production takes over. The half-life of protons against destruction by capture of $^7$Be is 2.2d, much longer than the rapid capture of protons by the abundant $^{12}$C with a time scale of 35sec. Therefore $^7$Be produced under these conditions will not be destroyed by proton captures because the protons are quickly locked up in the $^{13}$C abundance. $^7$Be will be transformed into $^7$Li which peaks at $\log t/[yr] = -1$. Then, $\alpha$-captures are processing $^7$Li into $^{11}$B. If the temperature is significantly larger ($T_8 \gtrsim 2$) the time scale of $\alpha$-capture on $^7$Li is smaller than that of $\mathrm{e}^-$-capture by $^7$Be ($\tau_\alpha(^7\mathrm{Li}) < \tau_{e^-}(^7\mathrm{Be})$). In that case no significant $^7$Li abundance can build up because any $\mathrm{e}^-$-capture by $^7$Be is almost immediately followed by an $\alpha$-capture.

If, on the other hand, $T_8 \lesssim 0.8$ then $\tau_{^7\mathrm{Be}}(\mathrm{p}) < \tau_{^{12}\mathrm{C}}(\mathrm{p})$ and protons are not efficiently captured by $^{12}$C but instead destroy $^7$Be (the common ppIII-chain). Thus, the proposed mechanism of hot H-deficient $^3$He burning can only work in a temperature window from $T_8 = 0.8$ to $T_8 = 2$.

In a second step we have constructed models of coupled convective mixing and nuclear burning, using the same numerical method as described in Herwig [4]. Following a post-processing approach the chemical evolution has been simulated. The hydrostatic input data have been taken from the VLTP model sequence of Herwig et al. [6]. It turns out that $^7$Li is produced in the upper part of the He-flash convection zone, after the sudden energy release of hydrogen-burning leads to the well known split of this convective region. Without that short radiative separation of the flash convection zone the nuclear processes are dominated by the hottest temperatures in the convective zone ($T_8 = 2.5$) which exceed the limit at which lithium production is possible as described above. At the end of the post-processing simulation the lithium abundance in the region immediately below the surface exceeds a mass fraction of $10^{-8}$ which would be in accordance with the observed abundance of *Sakurai's* object.

## 3. Conclusions

We have presented a new mode of light element nucleosynthesis which likely occurs when unprocessed material is ingested into an active and convectively unstable helium-shell, e.g. during a very late post-AGB thermal pulse. We have, however, not yet modelled in detail the mixing processes which ultimately bring the lithium into the atmosphere. Given the fragile constitution of lithium, most other sources of lithium in stars like *Sakurai's* object can be ruled out. We thus conclude that the proposed mechanism might be responsible for some of the lithium abundance anomalies observed in stars.

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