The role of NCO reaction chain on the He ignition in degenerate stellar structures

L. Piersanti\textsuperscript{1,2}, S. Cassisi\textsuperscript{2} & A. Tornambè\textsuperscript{2,3}

\textsuperscript{1} Dipartimento di Fisica dell’Università degli Studi di Napoli “Federico II”, Mostra d’Oltremare, pad. 20, 80125, Napoli, Italy, luciano@astrte.te.astro.it
\textsuperscript{2} Osservatorio Astronomico di Collurania, Via M. Maggini, 64100, Teramo, Italy, cassisi@astrte.te.astro.it
\textsuperscript{3} Dipartimento di Fisica dell’Università degli Studi de L'Aquila, via Vetoio, 67100, L’Aquila, Italy, tornambe@astrte.te.astro.it

Some 25 years ago\textsuperscript{[5]} it has been suggested that the $^{14}N(e^{-},\gamma)^{14}C(\alpha,\gamma)^{18}O$ reaction (NCO reaction chain) plays a pivotal role in the onset of the Helium flash in the core of a low mass Red Giant Branch (RGB) star (see\textsuperscript{[3]} and\textsuperscript{[4]}). In fact in the He core the Fermi energy is large enough to approach the energy for the e-capture on $^{14}N$ well before the $3\alpha$ reactions produce energy at a significant level so that a not negligible amount of $^{14}C$ is produced in the most internal regions. In the physical conditions typical of a star approaching the tip of the RGB $\alpha$ captures on $^{14}C$ dominate over $3\alpha$ reactions. In 1980\textsuperscript{[6]} argued that the NCO reaction does not affect the He ignition in a star at the tip of RGB because the physical conditions in the inner region, particularly the density, do not allow the NCO reaction to be dominant over the $3\alpha$ reaction. Successively, in 1986, Hashimoto, Nomoto, Arai & Kaminisi\textsuperscript{[1]} recomputed the NCO cross sections and found that this reaction “... dominates over $3\alpha$ reaction to heat up the central region” of a low mass star approaching the tip of the RGB\textsuperscript{[2]}.

Woosley & Weaver\textsuperscript{[8]} accounted for this reactions chain to compute the pre-supernova models of cooled down CO WDs accreting He rich matter. They find that the inclusion of NCO reaction does not prevent the occurrence of an He detonation. Recently, Piersanti, Cassisi, Iben & Tornambè\textsuperscript{[7]} have included the NCO chain in the evolution of a low mass CO WD accreting H and He rich matter at a rate suitable to obtain an He detonation. Their investigation shows that the differences determined by the inclusion of the NCO chain are negligible, the final outcome remaining an explosion. They point out that their result is due to the fact that they use an evolutionary model, obtained by evolving an intermediate mass star with moderate mass loss from the Main Sequence phase till the cooling sequence. In such a model the $^{14}N$ abundance at the base of the He shell, where the He flash takes place, is zero.

In any case it is important to evaluate if the $^{14}N(e^{-},\gamma)^{14}C(\alpha,\gamma)^{18}O$ reaction plays some role in stellar evolution. In fact if this chain does trigger the onset of the central He flash in low mass star then it stops the growth in mass of the He core, modifying the luminosity level of the RGB tip and of the Horizontal Branch. In addition, if the NCO chain plays a role in heating up the He shell in low mass CO WDs accreting hydrogen or helium rich matter, then He burning could occur steadily allowing the CO core to grow in mass until the Chandrasekhar mass limit.

In order to better understand if this reaction has some role in the evolution of RG stars we have analyzed three sets of models at different metallicity (namely $Z=0.0001$, 0.001 and 0.02): for each sets we consider three different masses (namely $M=0.6$, 0.7 and 0.8 $M_{\odot}$). We
Table 1: The main characteristics of the models we have computed from the central He burning phase until the cooling sequence. Note that the last model refers to a pure He star.

| Z     | Y     | $M_{\text{tot}}$ ($M_\odot$) | $M_{\text{He-core}}$ ($M_\odot$) |
|-------|-------|------------------------------|----------------------------------|
| 0.0001| 0.244 | 0.520                        | 0.498                            |
| 0.001 | 0.238 | 0.515                        | 0.510                            |
| 0.02  | 0.980 | 0.800                        | -                                |

follow the evolution of these models from the Pre-Main Sequence phase until the onset of the He flash at the tip of the RGB. Being the e-capture strongly dependent on the density and being the maximum density located at the center, the physical conditions suitable for the NCO reaction are attained first at the center of the He core.

We find that for the higher metallicity cases (Z=0.02 and 0.001) the $3\alpha$ reaction occurs well before the central density exceeds the critical value at which the NCO reaction becomes active ($\rho = 10^6$ g cm$^{-3}$). Therefore in this case they do not play any role at all. For models with Z=0.0001 the central density becomes greater than $\rho$ before the $3\alpha$ ignites, therefore all the central $^{14}$N is converted into $^{14}$C and the $^{14}$C is converted into $^{18}$O, delivering a small amount of energy that heats up the center. Despite this, the successive evolution is similar to models which do not include the NCO reaction, in the sense that the $3\alpha$ reaction is ignited in the same physical conditions and the final He core mass is the same.

As a whole, we conclude that the NCO chain does not affect at all the evolution of a low mass star climbing the RGB. In fact for high metallicity the central density is too low to allow the onset of the electron capture on $^{14}$N; on the contrary, for lower metallicity, the central density exceeds the critical value for the onset of the NCO reaction but in this case the $^{14}$N abundance is very low and the produced energy can not heat up efficiently the structure.

Our result is in good agreement with [5] but it is quite different with respect to those obtained by [3]. This occurrence is due to the fact that Hashimoto and co-workers simulate the behavior of the He core of a low mass star accreting He rich matter on a cooled down He WD. In this way they ignore the presence of the overlying H-shell that keeps hot the He core. As a consequence, for a fixed metallicity, their models attain a too high central density with respect to realistic models.

For what concerns mass accreting CO WDs, it is interesting to note preliminary that an evolutionary model presents a CO core surrounded by a He shell and eventually by an H shell. We have computed three different models from the central He-burning phase until the cooling sequence, as indicated in Table 1. In the cooled models the $^{14}$N abundance at the physical base of the He shell overlying the CO core is very small ($<10^{-10}$ by mass). This is due to the fact that during the He-shell burning of $^{14}$N is converted into $^{18}$O via direct $\alpha$-capture (NO reaction).

The accretion of H or He rich matter causes the growth in mass of the He layer surrounding the CO core; the He-layers, accreted directly or by H-burning by-products, are rich of $^{14}$N so that one can expect that in this case the NCO reaction could play some role at the ignition of the He burning. To verify this scenario we focus the attention on the model of a low mass CO WD accreting He rich matter at a low rate, suitable for a violent dynamical He ignition (see [5]). As it can be seen in Figure 1 (panel a)) as soon as the physical conditions suitable
for NCO burning are attained, $^{14}$N is completely converted into $^{14}$C. The latter element undergoes $\alpha$-captures to produce $^{18}$O, heating up locally the structure (see panel b)). While the time elapses, the He layer continues to grow in mass and the $^{14}N(e^-,\gamma)^{14}C(\alpha,\gamma)^{18}O$ occur in more and more external zones. Therefore, it is possible to identify the existence of a $^{14}$C shell which moves outwards. This situation goes on until the $3\alpha$ reactions ignite in high degenerate physical condition causing the disruption of the accreting structure as Type Ia supernova. We stress once again that the final outcome remains an explosion triggered by $3\alpha$ reactions, the only difference with respect to the model without NCO chain being a very small reduction in mass of the He layers at the runaway.

We conclude that the $^{14}N(e^-,\gamma)^{14}C(\alpha,\gamma)^{18}O$ chain does not play any role at all in the ignition of the He flash in degenerate and semi-degenerate physical conditions due to the fact that the ignition density for the e-capture on $^{14}$N is very high. If the threshold density for the e-capture were lower than current value, then the NCO reaction would become of some importance. We believe that an up-date of the cross section for the e-capture on $^{14}$N is strongly required.

Figure 1: Selected evolutionary properties of a CO WD of 0.516 $M_\odot$ accreting He-rich matter at $\dot{M} = 10^{-8} M_\odot$ yr$^{-1}$ with and without NCO reactions. Panel a): the temporal evolution of the mass coordinate where the energy production via He-burning is a maximum. Panel b): the evolution in the $\rho - T$ plane of the base of the He-shell.

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