# NuGrid: s process in massive stars

R. Hirschi<sup>\*abc</sup>, U. Frischknecht<sup>d</sup>, M. Pignatari<sup>abe</sup>, F.-K. Thielemann<sup>d</sup>, M. E. Bennett<sup>ab</sup>, S. Diehl<sup>afg</sup>, C. L. Fryer<sup>af</sup>, F. Herwig<sup>abh</sup>, A. Hungerford<sup>ag</sup>, G. Magkotsios<sup>aei</sup>, G. Rockefeller<sup>ag</sup>, F. X. Timmes<sup>ai</sup>, and P. Young<sup>ai</sup>

<sup>a</sup>The NuGrid Collaboration

<sup>b</sup>Astrophysics Group, Keele University, ST5 5BG, UK

<sup>c</sup>IPMU, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

<sup>d</sup>Theoretical Astrophysics Group, University of Basel, Basel, 4056, Switzerland

<sup>e</sup>Joint Institute for Nuclear Astrophysics, University of Notre Dame, IN, 46556, USA

<sup>f</sup>Theoretical Astrophysics Group (T-6), Los Alamos National Laboratory, Los Alamos, NM,

87544, USA

<sup>8</sup>Computational Methods (CCS-2), Los Alamos National Laboratory, Los Alamos, NM, 87544, USA

<sup>h</sup>Dept. of Physics & Astronomy, Victoria, BC, V8W 3P6, Canada

<sup>1</sup>School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA

*E-mail*:r.hirschi@epsam.keele.ac.uk

The *s*-process production in massive stars at very low metallicities is expected to be negligible due to the low abundance of the neutron source <sup>22</sup>Ne, to primary neutron poisons and decreasing iron seed abundances. However, recent models of massive stars including the effects of rotation show that a strong production of <sup>22</sup>Ne is possible in the helium core, as a consequence of the primary nitrogen production (observed in halo metal poor stars). Using the PPN post-processing code, we studied the impact of this primary <sup>22</sup>Ne on the *s* process. We find a large production of *s* elements between strontium and barium, starting with the amount of primary <sup>22</sup>Ne predicted by stellar models. There are several key reaction rate uncertainties influencing the *s*-process efficiency. Among them, <sup>17</sup>O( $\alpha$ ,  $\gamma$ ) may play a crucial role strongly influencing the *s* process efficiency, or it may play a negligible role, according to the rate used in the calculations. We also report on the development of a new parallel (MPI) post-processing code (MPPNP) designed to follow the complete nucleosynthesis in stars on highly resolved grids. We present here the first post-processing run from the ZAMS up to the end of helium burning for a 15  $M_{\odot}$  model.

10th Symposium on Nuclei in the Cosmos July 27 - August 1 2008 Mackinac Island, Michigan, USA

<sup>\*</sup>Speaker.

## 1. Introduction

Massive stars are known to produce elements heavier than the iron group via rapid neutron captures during their explosion, r process (see for example the contribution by Qian and Kratz et al. 2007 [1]) and also via slow neutron captures (s process) during the pre-supernova evolution, forming the so-called weak s component. The weak s process in massive stars with initial solar like composition is well understood. <sup>22</sup>Ne is the main neutron source and it is produced starting from the initial CNO isotopes (The et al. 2000 and 2007 [2, 3], Raiteri et al. 1991 [4, 5], Pignatari et al. in prep.). The weak s process, producing mostly elements in the atomic mass range  $60 \le A \le 90$ , starts at the end of helium burning when the temperature is high enough to activate  $^{22}$ Ne( $\alpha$ , n) $^{25}$ Mg. More massive stars reach higher temperatures at the end of He-burning and therefore burn more <sup>22</sup>Ne. Consequently s-process production during central helium burning increases with increasing stellar mass. The <sup>22</sup>Ne left over from helium burning is the main neutron source during the subsequent carbon shell burning. The carbon shell s-process contribution depends on the history of convective zones after the He-core burning and on different nuclear uncertainties (e. g.  ${}^{12}C(\alpha, \gamma){}^{16}O$ ). The standard s-process production in massive stars depends on the initial metallicity. At low metallicity, the low iron seed abundance, the low <sup>22</sup>Ne content and the increasing strength of primary neutron poisons limits the s-process efficiency, permitting only negligible production of *s* elements (e. g. Raiteri et al. 1992 [6]).

## 2. Weak s process at low metallicity in rotating stars

At solar metallicity, the main effect of rotation on the *s*-process production is the enlargement of convective helium core due to additional mixing and therefore a behaviour like non-rotating more massive stars [7]. Thus a 25  $M_{\odot}$  star with rotation behaves like non-rotating stars with masses between 30 and 40  $M_{\odot}$ . Hence the *s*-process efficiency in He-core burning is enhanced in rotating stars (Frischknecht et al. in prep.).

At low metallicity, the impact of rotation is more important. Indeed, at the start of core Heburning, carbon and oxygen are mixed upward into hydrogen rich regions leading to a strong production of nitrogen (see Meynet et al. 2006 [8] and Hirschi 2007 [9]). Part of this primary nitrogen may enter the convective He core and be transformed into primary <sup>22</sup>Ne by  $\alpha$ -captures. As a consequence, with respect to the non-rotating models, the <sup>22</sup>Ne available in the He-core is strongly enhanced. According to Hirschi (2008 [10]), about 1% in mass of the helium core is composed of <sup>22</sup>Ne at the *s*-process activation.

We present in Fig. 1 one-zone post-processing runs up to the end of He-burning calculated with the PPN code (see next Sect.) with an initial metallicity of  $Z=10^{-6}$ . In order to reproduce the effect of rotational mixing on the helium burning core composition in the one-zone calculation, we replaced 1% in mass of <sup>4</sup>He by <sup>22</sup>Ne at the start of helium burning. The primary <sup>22</sup>Ne enhances the *s* process compared to the non-rotating case, where negligible amounts of *s* elements are produced. The highest nucleosynthesis efficiency is around Sr with overproduction factors ( $X_i/X_{ini}$ ) between thousand and ten thousand. As can be seen in Fig. 1, iron seeds and in general elements lighter than strontium feed the *s* nucleosynthesis in the mass region between strontium (Sr) and barium (Ba). Beyond Ba, the *s* efficiency rapidly falls, depending on the total neutron exposure. The major



**Figure 1:** The overproduction factors after He-burning in the one-zone post-processing calculations. Using a low  ${}^{17}O(\alpha, \gamma)$  rate (black crosses) leads to a strong increase of *s*-process overproduction between Sr and Ba. Isotopes with  $X_i/X_{ini}$  below the lower limit are not plotted.

neutron poisons are <sup>16</sup>O, <sup>25</sup>Mg and <sup>22</sup>Ne, where <sup>16</sup>O is the strongest neutron absorber. Whether or not <sup>16</sup>O is an efficient poison depends on the ratio of <sup>17</sup>O( $\alpha, \gamma$ ) to <sup>17</sup>O( $\alpha, n$ ). According to the study of Descouvement (1993 [11]), the  $(\alpha, \gamma)$  channel should be orders of magnitude weaker than the  $(\alpha, n)$  channel, in which case the neutrons captured by <sup>16</sup>O are recycled by <sup>17</sup>O $(\alpha, n)$ . On the other hand, using the rates of Caughlan and Fowler (1988 [12]),  ${}^{17}O(\alpha, \gamma)$  is about a factor ten slower than  ${}^{17}O(\alpha, n)$  and a significant fraction of neutrons captured by  ${}^{16}O$  are not re-emitted. In this case, <sup>16</sup>O is the strongest neutron poison. In Fig. 1, we show the importance of the <sup>17</sup>O( $\alpha, \gamma$ ) rate by comparing the isotopic distributions obtained using the rate of Caughlan and Fowler (1988 [12]) (red triangles) and using this same rate divided by a factor 1000 to reproduce the  $(\alpha, \gamma)/(\alpha, n)$ ratio suggested by Descouvemont (1993 [11]) (black crosses). The different s-process production between the two calculations demonstrates the importance of the  ${}^{17}O(\alpha, \gamma)$  to  ${}^{17}O(\alpha, n)$  ratio for the s process at low metallicity. This was also suggested by Rayet and Hashimoto (2000 [13]) in standard s-process calculations in massive stars at low metallicity. However, because of the large primary <sup>22</sup>Ne production in rotating stars, in the present calculations the impact of the <sup>17</sup>O( $\alpha, \gamma$ ) to  ${}^{17}O(\alpha, n)$  ratio on the s-process efficiency is much stronger than in Rayet and Hashimoto (2000) [13]). A better knowledge of these two rates at He-burning temperature is highly desirable in order to obtain more reliable s-process calculations at very low metallicity. The strong production of s elements between Sr and Ba is in agreement with Pignatari et al. (2008 [14]), where the  ${}^{17}O(\alpha, \gamma)$ rate of Descouvement 1993 [11] is used and where the amount of primary <sup>22</sup>Ne is in agreement with Hirschi 2008 [10]. The boosted s process due to primary  $^{14}$ N production may provide a new s-process component with important implications for nucleosynthesis at low metallicity. Massive rotating stars may therefore contribute considerable amounts of isotopic abundances between Sr and Ba to the Galactic chemical evolution at halo metallicities, which could provide a possibility to explain the high Sr enrichment and the high Sr/Ba ratio (see Pignatari et al. 2008 [14] for more details). In order to make a quantitative and more precise statement about the importance of this *s* process occurring in rotating low-metallicity stars, further investigations are needed.

#### 3. Multi-zone parallel (MPI) post-processing code, MPPNP

Although only a few isotopes are crucial for the energy generation in massive stars, many more are important for the nucleosynthesis, for example to determine how much s process is made in massive stars. Since it is not necessary to follow many of these species within a stellar evolution calculation, we developed a post-processing network, called PPN, that allows us to follow the complete nucleosynthesis taking place in massive stars. It also enables testing of the importance of various reaction rates and especially the use of the same set of nuclear reactions in different stellar environments. The MPPNP variant uses MPI and is therefore much faster than a serial code. Using MPPNP, we have post-processed a full stellar evolution model of 15  $M_{\odot}$  at Z=0.01 calculated with the Geneva code [15] from the ZAMS up to the end of helium burning with a 400-isotope network up to Ag. The overabundance pattern at the end of the core He-burning phase is shown in Fig. 2. As expected, the weak s-process production in a 15  $M_{\odot}$  star is modest, with overproduction factors up to 10 for s-only isotopes between iron and strontium. This is due to the low central temperature reached at the end of the core He-burning phase in a 15  $M_{\odot}$  star (compared to more massive stars) with a marginal activation of the  ${}^{22}Ne(\alpha,n){}^{25}Mg$  during He-burning. We are currently testing MPPNP in the advanced stages and we plan to calculate the full nucleosynthesis for a large range of masses and metallicities. The MPPNP code will also be able to post-process AGB models (see contribution by Pignatari) and another variant of PPN, called TPPNP will follow trajectories of multi-dimensional simulations of supernova explosion and convective-reactive events in stars (see contribution by Herwig).



**Figure 2:** Overproduction factors in the convective core at the end of He-burning. Isotopes with  $X_i/X_{ini}$  below the lower limit are not plotted.

#### References

- K.-L. Kratz, K. Farouqi, B. Pfeiffer, J. W. Truran, C. Sneden, and J. J. Cowan, *Explorations of the r-Processes: Comparisons between Calculations and Observations of Low-Metallicity Stars*, ApJ 662 (Jun., 2007) 39–52, [arXiv:astro-ph/0703091].
- [2] L.-S. The, M. F. El Eid, and B. S. Meyer, A New Study of s-Process Nucleosynthesis in Massive Stars, ApJ 533 (Apr., 2000) 998–1015.
- [3] L.-S. The, M. F. El Eid, and B. S. Meyer, s-Process Nucleosynthesis in Advanced Burning Phases of Massive Stars, ApJ 655 (Feb., 2007) 1058–1078, [arXiv:astro-ph/0609788].
- [4] C. M. Raiteri, M. Busso, G. Picchio, and R. Gallino, S-process nucleosynthesis in massive stars and the weak component. II - Carbon burning and galactic enrichment, ApJ 371 (Apr., 1991) 665–672.
- [5] C. M. Raiteri, M. Busso, G. Picchio, R. Gallino, and L. Pulone, S-process nucleosynthesis in massive stars and the weak component. I - Evolution and neutron captures in a 25 solar mass star, ApJ 367 (Jan., 1991) 228–238.
- [6] C. M. Raiteri, R. Gallino, and M. Busso, S-processing in massive stars as a function of metallicity and interpretation of observational trends, ApJ 387 (Mar., 1992) 263–275.
- [7] R. Hirschi, G. Meynet, and A. Maeder, *Yields of rotating stars at solar metallicity*, A&A 433 (Apr., 2005) 1013–1022, [arXiv:astro-ph/0412454].
- [8] G. Meynet, S. Ekström, and A. Maeder, *The early star generations: the dominant effect of rotation on the CNO yields*, A&A 447 (Feb., 2006) 623–639.
- [9] R. Hirschi, Very low-metallicity massive stars:. Pre-SN evolution models and primary nitrogen production, A&A 461 (Jan., 2007) 571–583, [arXiv:astro-ph/0608170].
- [10] R. Hirschi, C. Chiappini, G. Meynet, A. Maeder, and S. Ekström, Stellar Evolution at Low Metallicity, in IAU Symposium, vol. 250 of IAU Symposium, pp. 217–230, 2008.
- [11] P. Descouvemont, Microscopic three-cluster study of 21-nucleon systems, Phys. Rev. C 48 (Dec., 1993) 2746–2752.
- [12] G. R. Caughlan and W. A. Fowler, *Thermonuclear Reaction Rates V, Atomic Data and Nuclear Data Tables* 40 (1988) 283.
- [13] M. Rayet and M.-a. Hashimoto, *The s-process efficiency in massive stars*, A&A **354** (Feb., 2000) 740–748.
- [14] M. Pignatari, R. Gallino, G. Meynet, R. Hirschi, F. Herwig, and M. Wiescher, *The s process in massive stars at low metallicity. effect of primary* <sup>14</sup>N from fast rotating stars., ApJ L (2008) accepted, arXiv0810.0182.
- [15] P. Eggenberger, G. Meynet, A. Maeder, R. Hirschi, C. Charbonnel, S. Talon, and S. Ekström, *The Geneva stellar evolution code*, Ap&SS (Jun., 2007) 263.