

The γ -process nucleosynthesis in core-collapse supernovae

Lorenzo Roberti^{1,2,3,*}, Marco Pignatari^{1,3,4}, Maria Lugaro^{1,5,6}, Zsolt Fülöp⁷, and Gyorgy Gyurky⁷

¹Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Eötvös Loránd Research Network (ELKH), Konkoly Thege Miklós út 15-17, H-1121 Budapest, Hungary; MTA Centre of Excellence

²INAF – Osservatorio Astronomico di Roma Via Frascati 33, I-00040, Monteporzio Catone, Italy

³NuGrid Collaboration, <http://nugridstars.org>

⁴E. A. Milne Centre for Astrophysics, University of Hull, Hull HU6 7RX, UK

⁵School of Physics and Astronomy, Monash University, VIC 3800, Australia

⁶Eötvös Loránd University, Institute of Physics, Budapest 1117, Pázmány Péter sétány 1/A, Hungary

⁷Institute for Nuclear Research (ATOMKI), H-4001 Debrecen, Hungary

Abstract. Neutron-capture processes made most of the abundances of heavy elements in the Solar System, however they cannot produce a number of rare proton-rich stable isotopes (p -nuclei) lying on the left side of the valley of stability. The γ -process, i.e., a chain of photodisintegrations starting on heavy nuclei, is recognized and generally accepted as a feasible process for the synthesis of p -nuclei in core collapse supernovae (CCSNe). However this scenario still leaves some puzzling discrepancies between theory and observations. We aim to explore in more detail the γ -process production from massive stars, using different sets of CCSNe models and the latest nuclear reaction rates. Here we show our preliminary analysis, by identifying the γ -process sites and focusing on progenitors of CCSNe that experience a C–O shell merger just before the collapse of the Fe core.

1 Introduction

The existence of 35 stable p -rich isotopes of elements above Fe¹ shows that not all the heavy nuclides are made by the slow [1] and rapid [2] neutron capture processes, and alternative processes must exist. These neutron-deficient nuclei have been thought to be produced through a chain of photodisintegrations on heavy **isotopes**, historically known as p - or γ -process [3–6]. This process is still widely accepted today as a main candidate for the origin of most of the p -rich heavy isotopes. It is activated in O/Ne rich layers of massive stars during core collapse supernova (CCSN) explosions on pre-existing local and heavier nuclides.

Although the γ -process nucleosynthesis in CCSNe has been explored for many decades, there are still some fundamental problems with it. The main two historical limitations of

*e-mail: lorenzo.roberti@csfk.org

¹namely: ⁷⁴Se, ⁷⁸Kr, ⁸⁴Sr, ^{92,94}Mo, ^{96,98}Ru, ¹⁰²Pd, ^{106,108}Cd, ^{112,114,115}Sn, ¹¹³In, ¹²⁰Te, ^{124,126}Xe, ^{130,132}Ba, ^{136,138}Ce, ¹³⁸La, ¹⁴⁴Sm, ¹⁵²Gd, ^{156,158}Dy, ^{162,164}Er, ¹⁶⁸Yb, ¹⁷⁴Hf, ¹⁸⁰Ta, ¹⁸⁰W, ¹⁸⁴Os, ¹⁹⁰Pt, and ¹⁹⁶Hg.

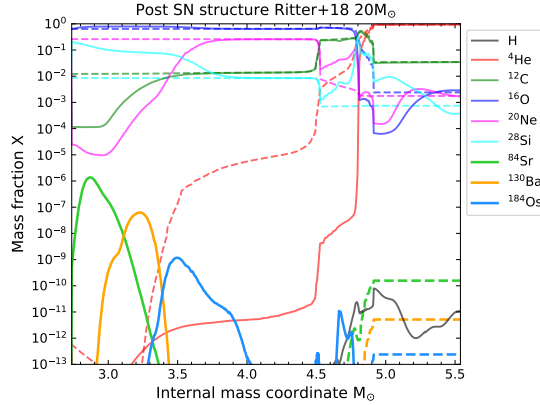


Figure 1. Abundance distribution before (dashed) and after (solid) the CCSN explosion in a 20 $M_{\odot}$ at $Z=0.02$ [14]. The p -nuclei ^{84}Sr , ^{130}Ba and ^{184}Os are taken as representative for the γ -process nucleosynthesis.

the γ -process in massive stars are that (1) the average p -process yields result in an under-production by about a factor of three relative to the amount required to explain the Solar System distribution [7, 8]; and (2) $^{92,94}\text{Mo}$ and $^{96,98}\text{Ru}$ are systematically under-produced by more than an order of magnitude compared to the other p -process species [9]. To overcome these problems, the γ -process from thermonuclear supernovae (SNIa), from the explosion of white dwarfs [10], has been proposed as an additional astrophysical source [8]. However, large uncertainties are affecting also this alternative γ -process astrophysical source, for example how many SNIa are generated from the Chandrasekhar mass progenitors (see discussion in [11]). Recently, [12] suggested that the efficiency of the γ -process could be enhanced in fast rotating massive stars at sub-solar metallicity, due to an increased production of s -process seeds. However, the frequency of such spinstars in the latest stellar generations is still unclear. Therefore, **it becomes of paramount importance** to explore in more detail possible solutions that could solve the problems of the γ -process production from massive stars, in particular for Mo-Ru region.

Our new project is a collaboration with scientists at the Institute for nuclear research (ATOMKI) in Debrecen and with an international research team of nuclear astrophysics experts, with the aim of studying in detail the γ -process nucleosynthesis in CCSNe. The main goals of this project are the analysis of γ -process yields in existing sets of CCSN models, the update of the nuclear reaction rates for the γ -process nucleosynthesis, and finally the production of γ -process stellar yields in new sets of CCSNe, using the NuGrid nucleosynthesis codes [13].

2 The γ -process nucleosynthesis in our CCSN models

In the preliminary analysis presented here we consider massive star explosions for progenitor with an initial mass of 15, 20, and 25 $M_{\odot}$ [14–17]. The typical production site for the γ -process nucleosynthesis shown in Figure 1 corresponds to the O/Ne-rich layers that the shock wave crosses after the CCSN explosion. This region of the star reaches a peak temperature between 2.5 and 3.3×10^9 K, which is the characteristic value at which photodisintegrations can efficiently convert the heavy material into neutron deficient nuclides. A useful

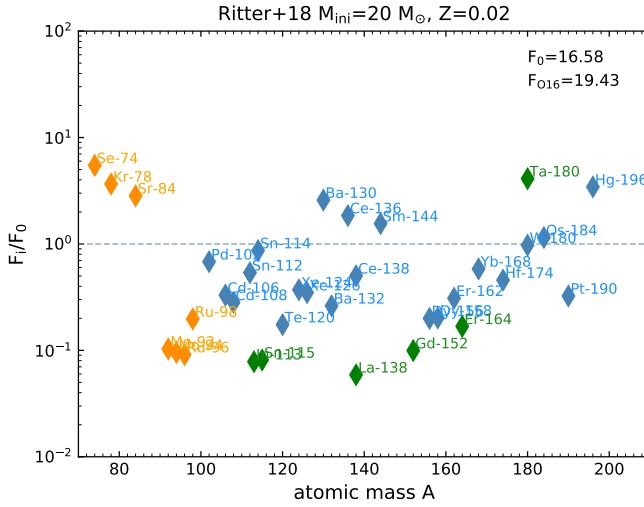


Figure 2. Normalized p -nuclide overproduction factors of the total ejected yields for the model showed in Figure 1. The orange symbols represent the p -nuclei that may have an additional explosive contribution, while the green symbols represent the p -nuclei that have also s -, r -process or neutrino-capture contributions.

parameter to evaluate the efficiency of the γ -process nucleosynthesis is the normalized p -nuclide overproduction factor F_i/F_0 (Figure 2), where the overproduction factor F_i represents the production of the i_{th} p -nuclide with respect to solar, while F_0 is the average overproduction factor for all the γ -process isotopes. The average overproduction factor F_0 is often compared to the overproduction factor of ^{16}O , one of the main products of CCSNe. It should be noted that not all the p -nuclei have a γ -process only origin. In fact, the lighter nuclei may have an additional contribution from other explosive nucleosynthetic components, e.g., α -process [18] or neutrino winds [19]. Some other p -nuclei may also have a s -, r -process and neutrino-capture contribution [9, 20]. Therefore, F_0 **must be considered** carefully: it could be enhanced by an isotope having also an additional component, or it could be reduced if some nucleosynthesis components are missing.

On top of the γ -process in the O/Ne-rich layers, massive stars may experience the ingestion of some C in the O convective shell in the latest stages of their evolution [14, 15, 21, 22]. This leads to the formation of an extended mixed convective zone in which the C shell material is brought to O burning temperature triggering an efficient γ -process nucleosynthesis (Figure 3). In this case, a large fraction of the CCSN yields of γ -process isotopes is dominated by the production in this convective C-O shell before the explosion, and their abundance might increase by orders of magnitude as compared to standard massive star models. Therefore, the C-O shell mergers may provide an additional production site for the γ -process nucleosynthesis in massive stars, leaving different fingerprints on the overproduction factors that will need to be studied in detail (Figure 4).

3 Conclusions and outlook

Although much progress has been made in the framework of the computation of stellar models and nucleosynthesis, the interpretation of the p -nuclei abundance pattern in the Solar

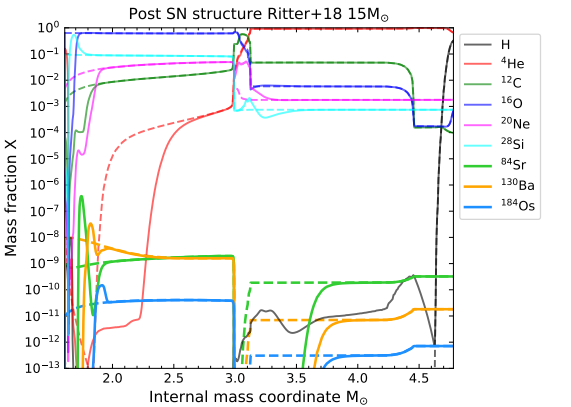


Figure 3. Abundance distribution before (dashed) and after (solid) the CCSN explosion in a 15 $M_{\odot}$ at $Z=0.02$ [14]. In this particular case, the star experiences a C–O shell merger just before the explosion and the γ –process nuclei abundances are dominated by the pre-supernova production during the merger.

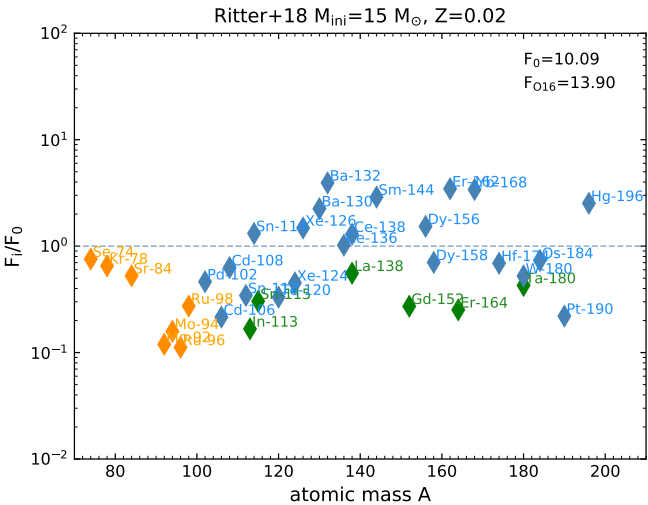


Figure 4. Same as Figure 2 but in the case of the star showed in Figure 3. In this case, there is a larger relative production of the isotopes that have an only γ –process contribution.

System is unclear and severe discrepancies still exist. Our upcoming more detailed study of the γ –process nucleosynthesis in massive stars is required to shed light on their production and to explore alternative scenarios. For example, the C–O shell merger in the latest stage of the evolution of massive stars needs to be analyzed. In this case, the production of γ –process isotopes is significantly increased before the explosion. Our goal in the next future is to compute a new set of CCSN models, taking into account models with C–O shell mergers and with an updated γ –process nuclear network.

Acknowledgements

We thank the support from the OTKA grant 138031 and the ERC Consolidator Grant (Hungary) programme (RADIOSTAR, G.A. n. 724560). LR and MP acknowledge the support to NuGrid from JINA-CEE (NSF Grant PHY-1430152) and STFC (through the University of Hull's Consolidated Grant ST/R000840/1), and ongoing access to *viper*, the University of Hull High Performance Computing Facility. MP and ML acknowledges the support from the "Lendület-2014" Programme of the Hungarian Academy of Sciences (Hungary). We thank the ChETEC COST Action (CA16117), supported by the European Cooperation in Science and Technology. This work was supported by the European Union's Horizon 2020 research and innovation programme (ChETEC-INFRA – Project no. 101008324), and the IReNA network supported by US NSF AccelNet (Grant No. OISE-1927130).

References

- [1] F. K  ppeler, R. Gallino, S. Bisterzo, W. Aoki, *Reviews of Modern Physics* **83**, 157 (2011), 1012.5218
- [2] J.J. Cowan, C. Sneden, J.E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke, G. Mart  nez-Pinedo, F.K. Thielemann, *arXiv e-prints arXiv:1901.01410* (2019), 1901.01410
- [3] A.G.W. Cameron, *AJ***62**, 9 (1957)
- [4] E.M. Burbidge, G.R. Burbidge, W.A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957)
- [5] M. Arnould, *A&A***46**, 117 (1976)
- [6] S.E. Woosley, W.M. Howard, *ApJS***36**, 285 (1978)
- [7] M. Rayet, M. Arnould, M. Hashimoto, N. Prantzos, K. Nomoto, *A&A***298**, 517 (1995)
- [8] C. Travaglio, T. Rauscher, A. Heger, M. Pignatari, C. West, *ApJ***854**, 18 (2018), 1801.01929
- [9] M. Arnould, S. Goriely, *Phys. Rep.***384**, 1 (2003)
- [10] W. Hillebrandt, M. Kromer, F.K. R  pke, A.J. Ruiter, *Frontiers of Physics* **8**, 116 (2013), 1302.6420
- [11] U. Battino, M. Pignatari, C. Travaglio, C. Lederer-Woods, P. Denissenkov, F. Herwig, F. Thielemann, T. Rauscher, *MNRAS***497**, 4981 (2020), 2007.13677
- [12] Choplin, A., Goriely, S., Hirschi, R., Tominaga, N., Meynet, G., *A&A* **661**, A86 (2022)
- [13] M. Pignatari, F. Herwig, R. Hirschi, M. Bennett, G. Rockefeller, C. Fryer, F.X. Timmes, C. Ritter, A. Heger, S. Jones et al., *ApJS***225**, 24 (2016), 1307.6961
- [14] C. Ritter, F. Herwig, S. Jones, M. Pignatari, C. Fryer, R. Hirschi, *MNRAS***480**, 538 (2018), 1709.08677
- [15] T. Rauscher, A. Heger, R.D. Hoffman, S.E. Woosley, *ApJ***576**, 323 (2002), *arXiv:astro-ph/0112478*
- [16] T.V. Lawson, M. Pignatari, R.J. Stancliffe, J. den Hartogh, S. Jones, C.L. Fryer, B.K. Gibson, M. Lugaro, *MNRAS*(2021)
- [17] A. Sieverding, G. Mart  nez-Pinedo, L. Huther, K. Langanke, A. Heger, *ApJ***865**, 143 (2018)
- [18] S.E. Woosley, R.D. Hoffman, *ApJ***395**, 202 (1992)
- [19] A. Arcones, F. Montes, *ApJ***731**, 5 (2011), 1007.1275
- [20] M. Pignatari, K. G  bel, R. Reifarth, C. Travaglio, *International Journal of Modern Physics E* **25**, 1630003-232 (2016), 1605.03690
- [21] C.A. Meakin, D. Arnett, *ApJ***637**, L53 (2006), *astro-ph/0601348*
- [22] R. Andra  ssy, F. Herwig, P. Woodward, C. Ritter, *MNRASp.* 2556 (2019), 1808.04014