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The p process in type II supernovae: current status

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Abstract. It is now considered plausible that the Ne-O layers of evolved massive stars ($M \geq 10 - 12$ $M_{\odot}$) could be the main site for the synthesis of the p nuclei. Nevertheless, there are problems connected with underproductions of p isotopes like ^{92,94}Mo and ^{96,98}Ru. These problems might be cured by a correction of some uncertain key reaction rates strictly connected with the production of neutrons, within their level of uncertainty (Costa et al. 2000). The impact of the uncertainty of the $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ on the 's seeds' production is discussed, together with the implications of a recent measurement of the main neutron producing reaction $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ (Jaeger et al. 2001), which seems to confirm the previous 'adopted' NACRE value (Angulo et al. 1999), with a reduction of the previous uncertainty of about two orders of magnitude in the 'upper' value.

Key words. nuclear rections – stars: supernovae: general

1. Introduction

The most successful models for the synthesis of p-nuclei indicates the O-Ne layers of type II supernovae as the best 'source'.

Calculations have been performed (Rayet et al. 1995) which suggest that the p nuclei are produced in the layers with peak temperatures in the $(1.8 - 3.3) \times 10^9$ K range, usually referred to as P-Process Layers (PPLs). Despite their success in re-producing a nearly (within a factor 3) solar-like distribution of the abundances of most of the p species, this model still suffer for some shortcomings, the most serious being concerned with an underproduction of ^{78}Kr, ^{84}Sr, ^{92,94}Mo and ^{96,98}Ru. Some of these shortcomings might be cured by properly taking into account the uncertainties present in the initial isotopic composition for the p process, as it comes out of the s process during core He-burning (Costa et al. 2000). Main sources of uncertainties are the rates of the two reactions $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ and $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ which respectively support and hinder the development of the s process in massive stars. An analysis of the impact of these uncertainties on the s process outcome ('seed' distribution for the p process) and partly on the p process has been done (Rayet et al. 2001) for the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$, while some new data concerning $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ are given here.

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2. $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})$ and $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)$ rates

At the typical temperatures of the s process in massive stars ($(2-3)\times10^8$ K) the ratio between the upper and adopted values of the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ rate ranges between 50 and 500, while for the $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ rate both the 'upper/adopted' and the 'adopted/lower' values are of the order of 10 (NACRE). Four values for the $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ rate (S_1-S_4) are defined as follows: S_1 is the lower value, S_4 is the upper value and S_3 is the geometrical average between S_2 and S_4, similarly to the R_1-R_5 values of the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ reaction rate defined by Costa et al. (2000), who performed s process calculations within a model of a 25 $M_\odot$ star with $Z=Z_\odot$ with the rates R_1-R_5 and the standard S_2 rate (s process model by Rayet & Hashimoto 2000).

New calculations obtained with a combination of the various R_i rates with the S_i rates for the $(\alpha\,,\gamma)$ have been performed with the same model and some results are summarised in Table 1 through the values of some 'indicators' of the s process efficiency (Prantzos et al. 1987): (1) The number of neutrons captures per ^{56}Fe nucleus; (2) the average overproduction factor F_0 for the 6 pure s species within the mass range $70 \leq A \leq 90$; (3) A_{max}, which is the maximum mass number for which the species in the $60 \leq A \leq A_{max}$ mass range are overproduced by at least a factor of about 10.

When R_1 is adopted, a lowering of the $(\alpha\,,\gamma)$ rate (S_1) has no important effects on the s process, while an enhancement can be disastrous, due to the stronger hindering of the neutron production. For higher (α,n) rates (R_{3-4}), the results are less influenced by the $(\alpha\,,\gamma)$ rate. This effect is linked with the enhancement of the (α,n)/(α,γ) rate ratio with higher (α,n) rates. The impact of the R_i rates on the p process outcome has been discussed by Costa et al. (2000) and calculations with values of the $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ different than the adopted S_2 NACRE value have not been performed yet, but the obtained s distributions suggest that higher S_i values together with R_1 could be disastrous for the p process model within SN II explosions, while with R_3 and R_4 the results should not crucially depend on the S_i rate. Both the S_i and R_i rates depend, on the still uncertain existence of a resonance at 635 keV in the structure of ^{26}Mg. The upper limit of the 635 keV resonance seems to have been greatly reduced recently (Jaeger et al. 2001). Around 2×10^8 K, the temperature at which the uncertainty is maximum, the upper value is reduced by nearly two orders of magnitude. If this result will be confirmed by other experiments, then the suggestion of a higher rate as a solution for the Mo-Ru puzzle would be weakened. Anyway, the possible synthesis of p-nuclei by type II supernovae is not ruled out yet, as there are still many sources of uncertainties concerned with the still poor modelling of unstable and explosive phases of stellar evolution.

	n_{cap}	F_0	A_{max}	
S_1	4.38	120	90	R_1
S_2	3.63	66.6	90	
S_3	2.24	18.3	90	
S_4	0.788	6.75	-	
S_1	16.5	4810	> 130	R_3
S_2	15.2	4170	> 130	
S_3	12.0	2580	125	
S_4	6.91	697	95	

Table 1. Typical 'indicators' of the s process efficiency.

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