s-process nucleosynthesis of $^{142}$Nd: crisis of the classical model

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Abstract. The recently improved information on the stellar neutron capture cross sections of neutron magic nuclei at $N = 82$, and in particular for $^{142}$Nd, turned out to represent a sensitive test for models of s-process nucleosynthesis. While these data were found to be incompatible with the classical approach, they provide significantly better agreement between the observed abundance distribution and the predictions of models for low mass AGB stars.

1 Introduction

In the last thirty years, s-process studies have been mainly pursued either by nucleosynthesis computations in stellar models for the Thermally Pulsing Asymptotic Giant Branch (TP-AGB) phases of low and intermediate mass stars [13, 4] or by a phenomenological model, the so-called classical approach, developed with the intention to provide a possibility for a "model-free" description (see e.g. Ref.[7]).

Until recently, the two descriptions remained compatible within their respective uncertainties, while the $^{13}$C($\alpha$,n)$^{16}$O neutron source was recognized to play a major role on the AGB, and was assumed to occur in convective thermal pulses [11, 10, 8]. Under such conditions, the classical analysis was considered suitable to extract "effective" conditions characterizing the stellar scenarios.

This situation changed drastically, when it was realized that $^{13}$C burns radiatively in the time interval between two successive He-shell instabilities [13]. The interplay of the different thermal conditions for the $^{13}$C and $^{22}$Ne neutron sources became so complex as to be hardly represented by a single set of effective parameters, as commonly used by the classical approach (essentially neutron density $n_n$, temperature $T$, mean neutron exposure $\tau_0$). This is particularly true for the mathematical treatment of the neutron irradiation, usually simplified through an exponential distribution of exposures in phenomenological studies, $\rho(\tau) \sim \exp(-\tau/\tau_0)$. Stellar models now show that this distribution is definitely non-exponential. Any attempt to maintain the classical picture would require a larger number of free parameters, in contradiction with the basic reason for this approach as a model-independent guideline for stellar calculations. In view of these conceptual differences, it is not surprising that the results of the classical analysis and of AGB models exhibit significant discrepancies. A region of the s-process path where this is particularly evident, involves the neutron-magic nuclei at $N = 82$, including the s-only isotope $^{142}$Nd. The small cross sections of these nuclei act as bottlenecks for the reaction flow and are, therefore, sensitive to the characteristics of the neutron exposure.
2 The new $^{142}$Nd cross section and its implications for s-process nucleosynthesis

The s-process abundance of $^{142}$Nd is influenced by small branchings in the neutron capture path at $^{141}$Ce and $^{142}$Pr (Fig. 1). The expected branching factor for bypassing $^{142}$Nd is about 5%. While a meaningful analysis was long hampered by the uncertainties in the nuclear physics data, especially for $^{142}$Nd, accurate measurements of the stellar (n,$\gamma$) cross sections of $^{140,142}$Ce, $^{141}$Pr, and of all stable Nd isotopes have been reported recently, along with new calculations of the cross sections of the unstable branch point nuclei $^{141}$Ce and $^{142}$Pr. Significant discrepancies were found with the previously adopted cross sections, thus requiring an updated analysis.

$^{142}$Nd is located immediately at the pronounced precipice of the $\langle \sigma \rangle N_z$ curve, which is caused by the small (n,$\gamma$) cross sections at $N = 82$. Hence, its cross section determines not only the branching analysis, but also the general shape of the s-process distribution. Since the $\beta$-decay rates of $^{141}$Ce and $^{142}$Pr are almost independent of the stellar temperature $T$, the branchings are completely defined, according to the classical model, by the effective s-process neutron density, $n_n$, which is best obtained from the neighboring branchings bypassing $^{148}$Sm: $n_n = (4.1 \pm 0.6) \times 10^8$ cm$^{-3}$. This value together with a thermal energy of $kT = 30$ keV and an electron density of $n_e = 5.4 \times 10^{26}$ cm$^{-3}$ has been used for an s-process analysis with an updated reaction network.

The best fit to the solar system distribution for the s-nuclei belonging to the main component is obtained for a mean neutron exposure $\tau_0 = (0.296 \pm 0.003) [kT/30]^{1/2}$ mbarn$^{-1}$. The left panel of Fig. 2 provides evidence for a significant overproduction of $^{142}$Nd with respect to the reference isotope $^{150}$Sm, despite part of the reaction flow bypasses this isotope. The overproduction exceeds by far the uncertainties of the cross section (2% at 30 keV) and of the solar abundance, the abundance ratio between the chemically related rare earth elements Nd and Sm being known to 1.8% [1]. Furthermore, the overproduction may be even larger in case of a non-negligible p-process contribution. Therefore, $^{142}$Nd provides the first significant hint that the simple assumptions of the classical approach are not adequate to describe the s-
process near magic neutron numbers. Failures of the classical model have been found previously for the s-only nuclei $^{116}$Sn and $^{134,136}$Ba [17, 18], but these discrepancies were masked by the large uncertainties of the solar Sn and Ba abundances.

A description of the stellar model and the adopted reaction network can be found in Ref.[4]. Updated s-process calculations have been made using stellar evolutionary computations with the FRANEC code [2] for low mass stars, from the main sequence up to end of the AGB phase. A relatively large range of masses ($1.5 \leq M/M_\odot \leq 3$) and metallicities ($-0.4 \leq [\text{Fe/H}] \leq 0$) have been examined as well as the influence of various mass-loss rates.

The best reproduction of the solar distribution of the main s-component was obtained for a $2 M_\odot$ star with $Z = 1/2 Z_\odot$, and a mass loss rate according to Reimers with $\eta = 0.75$.

The general improvement with respect to the classical solution (Fig. 2), is striking, especially since no fitting procedure was applied. $^{134,136}$Ba are now overproduced by only 5%, a value compatible with the uncertainties of the neutron capture cross sections and solar abundances, thus avoiding the 20% correction of the solar barium abundance suggested by the classical analysis [17]. Similarly, also $^{116}$Sn, that had required a 15% correction of the solar tin abundance [18], is now reproduced within uncertainties. As for $^{142}$Nd, the new cross section improves the situation drastically, resulting in very good agreement with the solar abundance. The previously overestimated $^{142}$Nd cross section had always led to a persisting 30% deficiency of the $^{142}$Nd abundance, incompatible with the expected p-process contribution of only a few percent [12].

Actually, to reproduce the s-isotopes in the solar system requires a more complex analysis including the chemical evolution of the Galaxy. Also in this context, the updated (n,\gamma) cross sections yield a satisfactory description of the solar $^{142}$Nd abundance [10, 12].
3 $r$-process residuals

The $r$-process residuals $N_r = N_\odot - N_s$ in Fig. 3 were calculated with the $s$-abundance average from the models for 1.5 and 3 $M_\odot$ stars, which represents a good approximation of the distribution obtained with a chemical evolution study. Compared to the $r$ residuals derived from the classical $s$ abundances the plot of Fig. 3 shows only minor differences. However, it should be noted that the stellar models yield a 20% $r$-process component of the solar barium abundance, in excellent agreement with recent observations in low metallicity stars [3].

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Figure 3: The $r$-process residuals $N_r = N_\odot - N_s$ obtained with the $s$ abundances from the stellar model (see text).