Presolar grain isotopic ratios as constraints to nuclear physics inputs for s-process calculations

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Abstract. The isotopic abundances in presolar SiC grains of AGB origin provide important and precise constraints to those star nucleosynthesis models. By comparing the values of the s-element abundances resulting from calculations with the ones measured in these dust grains, it turns out that new measurements of weak-interaction rates in ionized plasmas, as well as of neutron-capture cross sections, are needed, especially in the region near the neutron magic numbers 50 and 82.

1 Introduction

The Asymptotic Giant Branch (AGB) phase is a late stages of stellar evolution undergone by low- (≤ 3 M$_\odot$) and intermediate (≤ 7 M$_\odot$) mass stars. AGB stars have being studied for decades not because of their large number, nor because they are quite simple objects, but because they are site of the so called $s-process$, the slow neutron capture nucleosynthesis mechanism responsible for the production of about half part of the nuclei heavier than Fe in the Galaxy. In particular, stars with mass ≤ 3 M$_\odot$ are responsible for the synthesis of the main component of the s-process, namely of the elements from Sr to Pd. The flux of neutrons available for the captures crucially affects the effectiveness of the s-process nucleosynthesis. In low mass AGBs, neutrons are mainly delivered by the ^{13}C(α,n)^{16}O reaction, which is burnt in the ^{13}C reservoirs called *pocket* in the He-rich layers just below the H-burning shell (for more details about AGB stellar structure see e.g. [1, 2] or [3]).

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The formation mechanism of the ^{13}C-pocket determines its chemical composition, its extension (in mass and depth) and then it is the main source of uncertainties in modeling AGB star nucleosynthesis, more that the precision by which the $^{13}C(\alpha,n)^{16}O$ is know at astrophysical energies [4].

In addition to stellar physics, nuclear physics is also source of uncertainties in s-process studies. Indeed the nuclear inputs used for our calculations do not always have the needed precision. By its nature the s process runs along the $\beta-$stability valley, synthesizing increasingly heavier isotopes of an element through (n,γ) processes, when an unstable nucleus is produced it decays and the neutron capture chain continues along the stable isotopes of the element of the daughter nucleus. By definition the s-process is slow, i.e. the neutron capture rates are on average lower than the decay ones of the unstable nuclei produced. However, there are cases in which the rates of the two reactions are comparable and the processes compete, forming a branching of the nucleosynthesis path. The branching points of the s-process are key points and the distribution of the neutron flux between the 2 channels affects the abundance distribution of the synthesized isotopes. From the observed abundances it is then possible to obtain information about the neutron density and the physical conditions of the nucleosynthesis environment. However, it must be taken into account that given a branching point/nucleus a more intense neutron flux, a larger neutron capture cross section or a slower decay rate can produce the same effect on the nucleosynthesis yields. This is the reason why knowing with high precision the nuclear inputs is essential to account for the observations and to decide what are the most reliables ones among the several hypothesis and free parameters introduced by the stellar physics. In this note we want to analyzed relevant issues concerning the nuclear input parameters (cross sections and weak-interaction rates), using as a test-bench for nucleosynthesis calculations the isotopic ratios of heavy elements measured in presolar SiC. In doing that we adopt the MHD-based mixing scheme for the ^{13}C pocket formation presented by [7] (and references therein), which was shown to shape a pocket suitable to reproduce isotopic ratios of heavy elements measured in presolar SiC grains[1] by [5, 6].

2 MACS and $\beta-$ decay rates

The Maxwellian average cross sections (MACS) of (n, γ) reactions, employed in nucleosynthesis calculations, are usually known with sufficient precision for stable nuclei, for which they are relatively easy to be measured. Technical limits make instead difficult, or impossible, to measure neutron capture cross sections and decay rates of unstable nuclei in stellar conditions. For this reason the nuclear physics input uncertainties are concentrated in the proximity of the s-process branching points, which occur close to the magic neutron numbers where unstable nuclei and isomeric states concentrate too.

Nuclear physics input for astrophysical calculations are usual provided by databases, MACS for our AGB models are taken from the KADONIS on-line repository, in its version 1.0 [10], which collects the status of the art of experimental results and whose data are in general agreement with those reported by the National Nuclear Data Center of the Brookhaven National Laboratory [11]. The advent of radioactive ion beam facilities and the use of indirect measurement techniques (see e.g. [13] and references therein) are allowing new experiment to remedy the lack of data on neutron capture reactions of unstable nuclei,

[1]Presolar SiC grains are dusts that condense in the atmospheres of various stars including AGBs. Among these those belonging to the MainStream (MS) group are believed to have AGB origins due to their high content of s elements. The grains have come down to us included in primordial meteorites and by analyzing them it is possible to obtain their isotopic composition and the one of the envelope of the stars where they formed. Such analysis provide relevant constraints on the s-process nucleosynthesis [8, 9].

but data are still missing in several cases, therefore, when experimental data are not available, we used theoretical Hauser-Feshbach computations from the TALYS2008 [14].

A pivotal information for s-process calculations are the rates for weak interactions as a function of temperature and density. Half-lives of many nuclei are essentially unchanged for varying temperatures, but in some case the physical conditions (i.e. plasma temperature and degree of ionization) can modify $\beta-$decay (or electron capture) rates of order of magnitude. Nowadays, measurements of decay rates in plasmas under conditions of pressure, temperature, and degree of ionization typical of the stellar interior are either missing or very rare. New precious data could be provided in the near future by the PADORA plasma trap, which is currently under commissioning at INFN LNS [16]. Up to now the most extended and complete compilation of weak interaction rates, as a function of temperature, is the one by Takashi and Yokoi 1987 [17]. In this paper, we refer as standard (ST) case to the nucleosynthesis calculations we run employing the ensemble of the nuclear physics input from [10, 14] and [17].

To identify crucial points in the s-process pathway for which input data changes might be important, Palmerini et al. 2021 [23] considered a long series of possible local changes of the nuclear data affected by considerable uncertainties. The results of nucleosynthesis calculations performed using ad hoc modified parameter sets are referred to as version 2 (V2) models. The authors performed an extensive analysis including the branchings of the s-process that affect the nucleosynthesis of Kr, Sr, Zr, Nb, Mo, Cs and Ba. For sake of brevity, we deal here only about the analysis carried out for the elements belonging to the light-s (Kr and Sr) and heavy-s (Cs and Ba) peaks.

3 Light$-s$ vs heavy$-s$

The ^{85}Kr branching point is perhaps the most famous one among the branchings of the s-process. Here the neutron capture on ^{84}Kr (whose recommended cross section at 30 keV is 33.1 mb [10]) populates both the ground and the isomeric state of ^{85}Kr, according with the more recent data collected in our ST case the branching ratio turns out to be of about 60% in favor of the isomer (which has $t_{1/2} = 4.5h$), while the estimate results to be just the 40% repeating the calculations using the ^{84}Kr MACS from the previous release of Kadonis, the 0.3 [18].

The nucleosynthesis flow through the ^{85}Kr isomeric state feeds the production of $^{86-87}$Sr passing through $^{85-86}$Rb, only ^{88}Sr is instead produced if neutron captures on ^{85}Kr ground state populate ^{86}Kr and ^{87} Rb. Therefore, Sr isotopic ratios shown by presolar grains depend on cross sections of Sr as well as those of $^{84-85}$Kr and on the decay rates of ^{85}Kr^{m} and ^{86}Rb.

For sakes of comparison we adopt the ^{84}Kr(n,γ)^{85}Kr cross section reported in [18] in our set V2 of nuclear physics input. However, smaller values of the ^{88}Sr/^{86}Sr isotopic ratio could be obtained also considering MACS from K1, but assuming different values of the ^{85}Kr half-life in stellar conditions (about 10.5 yr) or of its cross section, which has only theoretical estimate with uncertainty of the order of 50% (73 ± 34 mb [10]).

Available data for neutron capture cross sections of Ba isotopes are generally affected by rather small uncertainties, but the s-process path that leads to the Ba synthesis passes through a long series of branching points. Indeed, around N = 82, the four Cs isotopes with mass from 134 to 137 form four branching points along the nucleosynthesis path. After ^{133}Cs, the flux proceeds through ^{134}Cs, where n-captures compete with $\beta-$decay (laboratory half-life of 2 yr), to excited states of ^{134}Ba and, in a smaller part to via electron captures to ^{134}Xe (half life of 6.8·10^5 yr). From ^{134}Cs, neutron captures feed the longer-lived ^{135}Cs and then ^{136}Cs (half-life of 13.16 d) and ^{137}Cs (half-life of 30.07 yr), whose decay rates remain essentially unchanged for varying temperatures. This is not so for ^{134}Cs and ^{135}Cs. According to [17] the

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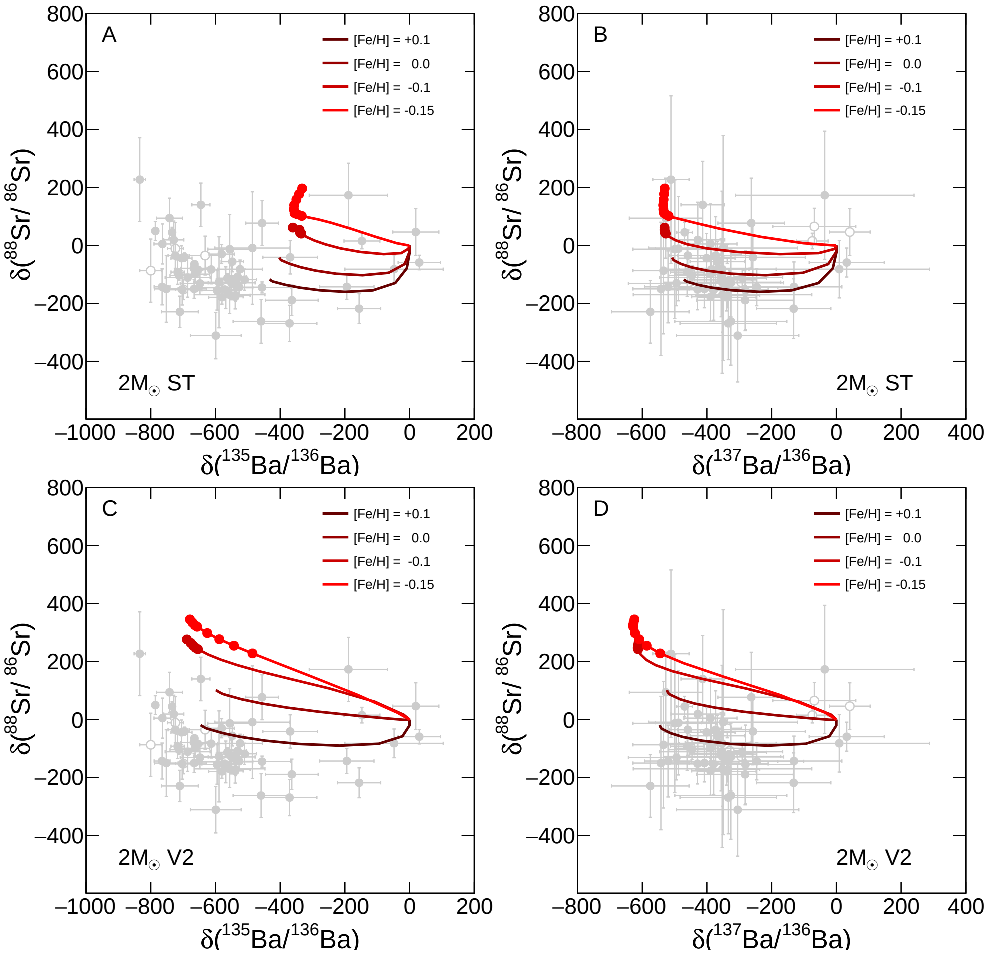

Figure 1. Predictions from $2M_{\odot}$ AGB models of different metallicities (red curves) with SiC grains data (from [19], gray dots with error bars). The case of the isotopic ratios ^{88}Sr/^{86}Sr versus ^{135}Ba/^{136}Ba (panels A and C) and ^{137}Ba/^{136}Ba (panels B and D) are shown. Panels A and B show the envelope composition resulting form calculations run by employing nuclear physics input from set ST, while panels C and D show the output of the same models run with input from set V2 (see the text for details). The full red dots represent model abundance ratios after third dredge-up episodes once the envelope has reached a carbon rich composition [see 7].

half-life of ^{134}Cs is reduced with respect to the laboratory by a factor of about 200. However to reproduce the galactic abundances of the 2 s-only nucleus ^{135}Ba and ^{136}Ba the temperature dependence of the decay rate for ^{134}Cs has to be assumed about 8 times less steep than suggested by [17] or by changing upward the cross section of ^{134}Cs by more than a factor of two [7] . Recently, thanks to an approach based on the solution of the Dirac-Hartree Fock equations, Taioli et al. (2022) [20] found the temperature dependence of the ^{134}Cs and the ^{135}Cs β−decay rates to smaller than so far assumed. In particular, the half-lives of ^{134}Cs estimated by the authors is longer than the one by [17] by a factor ranging from 2.5 (near 8-10 keV) to more than 30 (at 30 keV). Similar effects were found also for ^{135}Cs, whose branching importance is increased by the reduction of the efficiency of the ^{134}Cs decay. Such results confirm the findings of Li et al. (2021) [21], which also obtained an improved fit to Ba isotopic abundances in SiC grains thanks to a new and independent estimate of ^{134}Cs half-life. In our computations, we consider the reduced rates of both ^{134}Cs ^{135}Cs decays in our V2 cases.

4 Conclusion

In Figure 1 s-process predictions of AGB models with $2M_\odot$ are compared with measurements in presolar SiC grains by considering the relative behavior of the isotopes of Sr and Ba. Those are elements belonging to the light-s and the heavy-s peak, respectively, and their isotopic abundances are defined by the neutron flow in the region with $N = 50$ and $N = 82$. In particular, the case of the isotopic ratios ^{88}Sr/^{86}Sr as a function of ^{135}Ba/^{136}Ba and of ^{137}Ba/^{136}Ba are illustrated. The area covered by the grain data and the one covered by the models generally overlap, but in panel A.

The fit to the grains improves by changing the nuclear physics input from panel A to panel C, this is so thanks to the longer half-lives of ^{134}Cs and ^{135}Cs, which allow the models to cover a wider range of values of the ^{135}Ba/^{136}Ba ratios. Moreover, the distributions of the predictions for the ^{137}Ba/^{136}Ba and the ^{88}Sr/^{86}Sr isotopic ratios are larger when computed by adopting nuclear input from set V2 instead of those from ST.

In any case more improvements are possible and needed, because models in the C-rich phases (namely when C/O ratio in the stellar envelope is equal or larger than 1) reproduce the abundances of just a small portion of the grain sample. This is shown by the red full dots in Figure 1, which deal with the stellar abundances, after each thermal pulse, once the envelopes have became carbon rich. The fit do not improve significantly even considering $3M_\odot$ stars. Such a problem is pretty common in the classical approaches to account for s-isotope distribution of SiC grains in the literature [see e.g. 22]. A possible solution has been presented by [23] that suggested the magnetic winds responsible for the formation of the ^{13}C pocket to generate also a further enrichment in s elements of the stellar envelope. In this scenario, SiC grains can start forming in domains (spots) rich in C and s elements when the stellar envelopes are still O-rich.

We can conclude that very precise esperimetal data about unstable nuclei are mandatory to validate the extra-mixing scenario suggested by [23] to account for SiC grain formation and composition as well as all the other hypothesis that have been already formulated, or will be formulated, on this subject.

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