The impact of n_TOF data on s-process modelling

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Abstract. We show examples of the impact of the Maxwellian averaged capture cross sections determined at n_TOF over the past 20 years on AGB stellar nucleosynthesis models. In particular, we developed an automated procedure to derive MACSs from evaluated data libraries, which are subsequently used as input to stellar models computed by means of the FuNS code. In this contribution, we present a number of s-process abundances obtained using different data libraries as input to stellar models, with a focus on the role of n_TOF data.

1 Introduction

The slow neutron capture process (the *s* process [1, 2]) accounts for the formation of approximately half of elements heavier than iron. It is the result of a sequence of neutron radiative captures and β-decays. More in detail, starting from iron seeds, the *s* process produces heavy elements up to bismuth. Contrary to the rapid process (*r* process), β-decay rates are faster than neutron capture rates, and therefore the reaction flow proceeds along the β stability valley of nuclei. The *s* process can take place in two different scenarios: during He-shell flashes in the asymptotic giant branch (AGB) phase [3–6] of low- and intermediate-mass stars (also referred to as the main component, and responsible for the formation of isotopes with A>90) and in core-He burning and shell-C burning of massive stars [7] (also referred to as the weak component, and responsible for the formation of isotopes with 60<A<90).

Together with β-decay rates, neutron capture cross sections are the basic nuclear physics input to the slow neutron capture process. Since 2001, the neutron time-of-flight facility n_TOF at CERN has provided accurate cross section data for the *s* process. More in detail, (n,γ) cross sections were measured as a function of energy, using the time-of-flight method. Moreover, improved detection systems, innovative ideas, and collaborations with other neutron facilities have led to a considerable contribution of the n_TOF collaboration to *s* process studies. Results have been reported for stable and radioactive samples, i.e., ^{24,25,26}Mg, ^{54,57}Fe, ^{58,59,62,63}Ni, ^{70,72,73}Ge, ^{90,91,92,93,94,96}Zr, ^{139}La, ^{140}Ce, ^{147}Pm, ^{151}Sm, ^{154,155,157}Gd, ^{171}Tm, ^{186,187,188}Os, ^{197}Au, ^{203,204}Tl, ^{204,206,207}Pb and ^{209}Bi isotopes (see [8] for

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more details), and others are being studied or planned to be studied in the near future. In some cases, these results were then used to improve Evaluated Nuclear Data File such as ENDF/B-VIII.0 [9], JENDL-5.0 [10] and JEFF-3.3 [11] or TENDL-2021 [12] and other international projects. The same data were used to derive the neutron-induced cross section averaged over the stellar neutron-energy distribution, typically referred to as Maxwellian averaged cross section (MACS) - more details in Sec. 2. This quantity represents the key nuclear physics input to stellar models for the study of nucleosynthesis in Red Giants stars.

We have developed an automated procedure to derive pointwise MACS for temperatures between 10 and 1000 MK, using the data from evaluated nuclear data files (in ENDF format), in the format required by FuNS [13]. This system allowed us to study the impact of n_TOF data on AGB nucleosynthesis models, as well as to compare nuclear data in international libraries.

2 From the ENDF format to stellar reaction rates

The astrophysical reaction rate is a function of the number density of interacting particles times the reaction rate per particle pair $\langle\sigma v\rangle$. This latter term describes the probability of nuclear reactions between two particles, moving at relative velocity v. In a stellar plasma, the interacting particles are in thermodynamic equilibrium, and consequently, their kinetic energy is linked to their thermal motion (i.e. the relative velocity can be described by a Maxwell-Boltzmann distribution). More in detail, its maximum occurs at the velocity $v_T = \sqrt{\frac{2kT}{\mu}}$, μ being the reduced mass of the system formed by the interacting particles. By expressing the velocity distribution as energy distribution:

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E) e^{-\frac{E}{kT}dE}, \tag{1}$$

the reaction rate can be expressed in terms of the MACS:

$$\text{MACS} = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2} \int_0^\infty E\sigma(E) e^{-\frac{E}{kT}dE}. \tag{2}$$

Stellar models, as for example FuNS [13], require as input the reaction rate evaluated at temperatures between 10^7 K and 10^{10} K in intervals of $10^{0.1}$ Kelvin. With the aim of producing these input files, we have developed an automatic procedure running over all the isotopes contained in a library, consisting of these 4 steps:

1. download of the preferred evaluation from the IAEA webpage, each evaluation containing about 1000-3000 isotopes;
2. interpretation of the ENDF file, from which the pointwise (n,γ) cross section $\sigma(E)$ is reconstructed in the laboratory system;
3. numerical integration to obtain the MACS from Eq. 2, after transformation to the center of mass system;
4. calculation of the astrophysical reaction rate using as MACS times v_T times the number density of particles.

In the same procedure, we have also included the option to multiply the reaction rate for the stellar enhancement factor from the Karlsruhe Astrophysical Database of Nucleosynthesis in Stars (KADoNiS) [14].

3 Results

The procedure described above has allowed us to perform systematic studies of the impact of different databases on the *s* process nucleosynthesis calculations.

Firstly, we have compared the MACS at $kT = 8$ keV obtained from the latest versions of the major libraries, namely ENDF/B-VIII.0, JEFF-3.3, JENDL-5 and TENDL-2021. Their ratios are shown in Fig. 1 for isotopes heavier than iron (A>60). This study includes metastable states as well as short-lived radioisotopes and therefore it should not surprise if the ratios span over 4 orders of magnitudes. Excluding these latter cases, large deviations between libraries are still present. For instance deviations of 20% for ^{63}Cu and ^{77}Se, and of 50% for ^{82}Se or ^{122}Sn are observed, to mention a few.

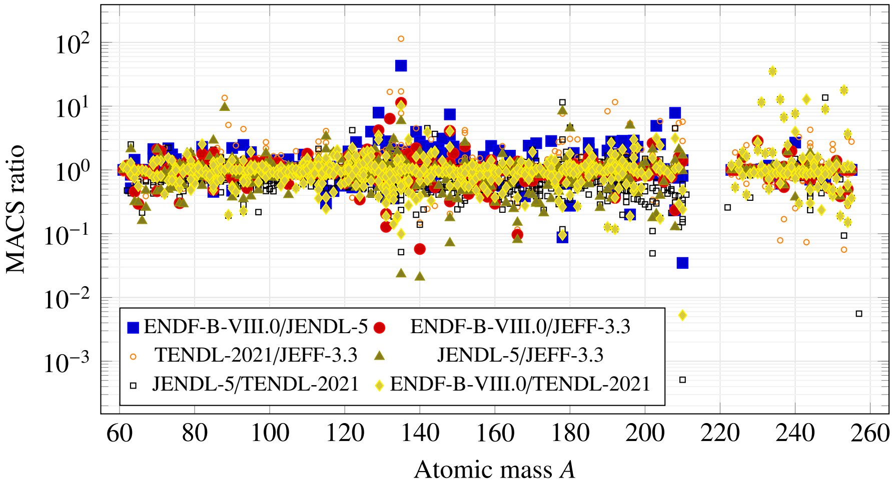

Figure 1. Ratio of MACS at $kT = 8$ keV obtained from major nuclear data libraries. Large deviations are observed for metastable states and short-lived radioisotopes.

Another interesting study is related to s-only isotopes, whose production is entirely ascribed to the *s* process due to the presence of stable isobars. For those nuclei, a semi-empirical approach to the *s* process results in the so-called "local-equilibrium approximation". More in detail, for nuclei far from closed shell configuration, the abundance builds up until the destruction rate approaches the production rate. Consequently, a steady flow is reached along the *s*-process path, and therefore the product of the abundance times the MACS is approximately constant [1]. To date at n_TOF, 4 of the 33 *s*-only isotopes were studied: ^{58}Ni [16], ^{70}Ge [17], ^{154}Gd [18] and ^{186}Os [19, 20]. The MACS obtained experimentally at n_TOF, and reported in Fig. 2 are in very good agreement.

As a last example of the application of the described procedure, Fig. 3 shows the results of a refined stellar model for a 2 $M_\odot$ asymptotic giant branch star with metallicity Z = 0.01 to derive *s*-process abundances. (n,γ) cross sections from ENDF/B-VIII.0, JEFF-3.3, JENDL-5, and TENDL-2021 evaluations were given as input to the stellar model, and the obtained information was then used to interpret presolar grain isotopic abundances of barium, strontium, nickel, molybdenum, and zirconium isotopes (see, e.g., [21, 22]). In Fig. 3 the results obtained with data from KADoNiS 0.3 & n_TOF data, considered as a reference (REF), are also reported. It looks evident how much strontium, barium, and zirconium isotopic ratios are sensitive to the adopted library.

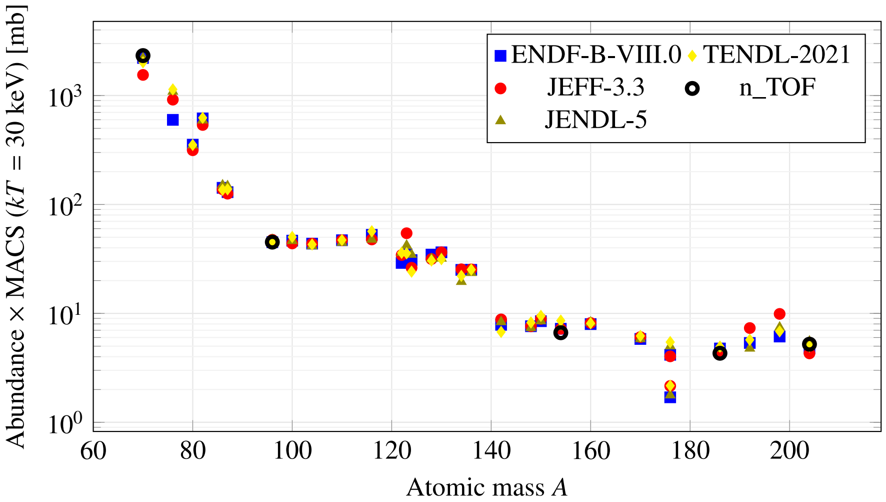

Figure 2. The product of the cross section (derived from nuclear data libraries) times the solar s-process abundances for s-only isotopes [15]. In the region between magic neutron numbers, the local equilibrium approximation is clearly visible. The four cases studied at n_TOF are also reported for comparison.

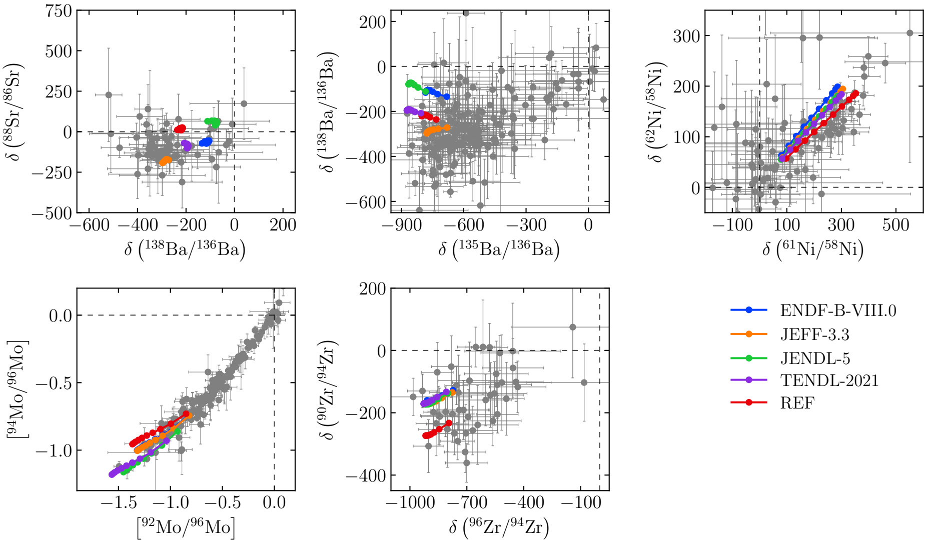

Figure 3. Comparison between AGB model calculations [23, 24] using different nuclear data input and isotopic abundances in presolar grains. The results obtained with data from KADoNiS 0.3, taken as a reference (REF), are shown in red. Grain data are from the PGD database [25].

4 Conclusions

The automated procedure described in this contribution seems to be a useful tool for systematic studies of the impact of cross section data on stellar models. In addition, it can be used to assess the impact of n_TOF cross section data on *s*-process nucleosynthesis calculations.

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