Chapter 11
Data for the s Process from n_TOF

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Abstract A considerable amount of (n,γ) reactions has been studied, so far, at the neutron time-of-flight facility n_TOF at CERN. The experimental program aims at determining and improving cross sections for a number of isotopes relevant to s-process nucleosynthesis. A brief summary of some physical cases related to the s-process nucleosyntheis is presented in this work together with ongoing experiments and challenging future programs.

11.1 Introduction

The origin of heavy elements ($A > 56$) is thought to be caused by successive neutron capture reactions and β decays. This s-process nucleosynthesis path extends up to lead and bismuth [1, 2]. The observed abundances are a mixture of abundance contributions from the s and r process with small contaminations from the p process [3, 4]. After the pioneering survey by Burbidge and collaborators [5], 6 decades of experiments and progress in stellar models have brought the s-process nucleosynthesis to a considerably refined level. For instance, it is now understood that the s process takes place in the He-burning layers of low-mass asymptotic giant branch (AGB) stars and during the He- and C-burning phases of massive stars. The nucleosynthesis of nuclides in the $A \approx$ 60–90 mass region (the so-called weak component) is driven by the ^{22}Ne(α,n)^{25}Mg reaction in massive stars, which provides the required neutron intensities at temperature higher than about 3–400 million Kelvin. On the contrary, at lower temperatures typical of AGB stars, the ^{13}C(α,n)^{16}O acts as primary neutron source and drives the synthesis of nuclides in the $A \approx$ 90–209 mass region (the so-called main component). In this framework, the comparison of the stellar abundance patterns with s-process calculations yields important constraints on stellar evolution modelling, provided that nuclear physics inputs are accurately known. Among all the various experimental quantities responsible for the good quality of stellar models, β-decay half-lives, capture cross sections of isotopes in the β-stability valley and reaction rates of the neutron reaction sources are the most relevant physics data.

11.2 Experimental Determination of Stellar Cross Section

The key nuclear physics quantity for s-process modelling are the Maxwellian-averaged capture cross sections (MACS), defined as:

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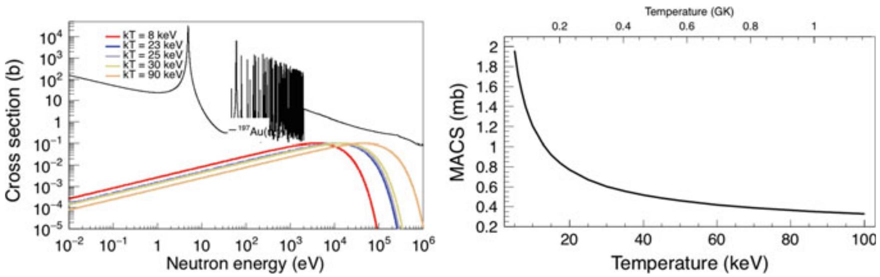

Fig. 11.1 Left panel: ^{197}Au(n,γ) cross section in the region of interest to the *s* process, the bottom curves represent the Maxwellian neutron energy distribution for different stellar burning stages. Right panel: Au MACS at stellar temperatures between 0.1 and 1 GK

$$< \sigma >= \frac{2}{\sqrt{\pi}(k_B T)^2} \int_0^\infty \sigma_\gamma(E) E e^{-\frac{E}{k_B T}} dE, \tag{11.1}$$

where T is the stellar temperature, and $\sigma_\gamma(E)$ the energy dependent capture cross section. The MACS takes into account the effect of the stellar temperature (between 0.1 and 1 GK) where the *s* process takes place. Two methods are currently adopted for the experimental determination of the MACS: activation and Time-of-flight technique. The first method is an energy-integrated measurement, where the neutron spectrum corresponds to a stellar spectrum. This method has extensively been used for measurements of MACS at $k_B T$ = 25 keV, relatively to the one of ^{197}Au, which is considered as a reference. With the second technique, adopted at n_TOF, $\sigma_\gamma(E)$ is measured and the MACS is obtained by folding with the neutron energy distribution, thus enabling the determination of the MACS as a function of the temperature. It is worth recalling the n_TOF research activities [6, 7] related to the international cooperative effort [8] to improve the ^{197}Au cross section standard, which is of primary importance for activation measurements. Figure 11.1 shows the $\sigma_\gamma(E)$ of ^{197}Au(n,γ), together with its MACS for different temperatures.

11.3 n_TOF Experimental Program

Some of the studies carried out at n_TOF (a non-exhaustive list of examples), about the role of branch-point isotopes, s-only isotopes, bottle necks in the *s* process path and neutron source reactions are hereafter briefly summarised.

11.3.1 Branch-Point Isotopes

The reaction flow path of the s process proceeds along the β-stability valley. When a long-lived isotope is encountered, depending on the stellar conditions, the competition between neutron capture and β decay can take place. Because of this competition, the reaction path divides into different branches and the resulting isotopic pattern can reveal the physical conditions: neutron density, temperature and pressure, of the stellar environment where the s process is taking place.

Despite their importance, some few measurements of (n,γ) cross sections on unstable isotopes are present in literature in the energy region of interest. For instance, among the 21 relevant cases [3] only 8 isotopes have been studied so far. And among them, the cross section of 5 isotopes has been measured as a function of neutron energy via time-of-flight at n_TOF. The results of ^{151}Sm(n,γ) and ^{63}Ni(n,γ) provided new information for the characterisation of the pulsed s-process nucleosynthesis in AGB stars and for the production of ^{63}Cu, ^{64}Ni, and ^{65}Zn in massive stars, respectively [9–11]. The preliminary results of the isotopes with half-lives of a few years, i.e. ^{147}Pm, ^{171}Tm and ^{204}Tl, indicate that their capture cross sections are smaller than theoretical predictions and therefore important consequences are expected. For the future, the n_TOF Collaboration is preparing the detector setup for the measurement campaign on the branching at ^{79}Se, which can constrain the temperature of the s-process nucleosynthesis in massive stars.

11.3.2 s-Only Isotopes: The Case of ^{154}Gd

The s process is known to be responsible for the production of about one half of the elemental abundances between iron and bismuth. Moreover about 40 isotopes can be produced only via the s process because they are shielded against the β-decay chains from the r-process region by stable isobars. Therefore their pure s-process origin allows one to check the robustness of stellar models in galactic chemical evolution models (GCE). In addition, they can be used to constrain the so-called ^{13}C pocket (i.e. the shape and the extension of the neutron source).

The n_TOF Collaboration has recently measured the ^{154}Gd(n,γ) cross section, because of a large disagreement between GCE models for this isotope. In Fig. 11.2 some examples of the capture yield determined at n_TOF are compared with the data in literature.

The preliminary new data could rule out one of the possible causes of the inconsistency, as the cross section seems sizeably lower than reported in literature (i.e. the MACS at $k_B T = 8$ keV is about 10% lower than previously thought).

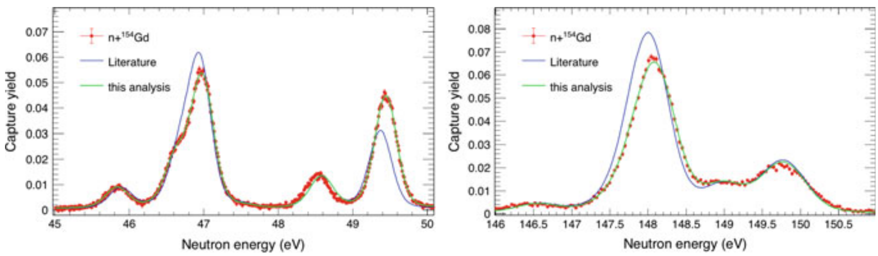

Fig. 11.2 ^{154}Gd(n,γ) capture yield measured at n_TOF compared to its evaluated cross section in nuclear data libraries

11.3.3 ^{140}Ce as Bottle Neck of s-Process Flow at N = 82

Isotopes with very small cross sections act as bottle necks in the neutron capture chain and build up large abundances. This nuclear feature can explain 3 sharp structures in the isotopic solar abundance distribution (see for instance the inset of Fig. 11.2 in [3]) related to the s-process. These 3 maxima correspond to nuclei with a magic number of neutrons (N = 50, 82 and 126), whose nuclear configuration makes them particularly stable. A precise and accurate knowledge of the neutron capture cross section is sometimes challenging, as the experimental signature is dominated by the background. However their MACS largely affect the efficiency for the production of heavier elements. The region at N = 82 has partially been investigated at n_TOF in the past, when the production of ^{140}Ce was studied [12], we are now measuring the ^{140}Ce(n,γ) cross section, in order to accurately model the synthesis of heavier elements and reproduce the observed abundances.

11.3.4 Constraining the ^{22}Ne(α,n) Reaction

The reaction rate of ^{22}Ne(α,n)^{25}Mg has an obvious fundamental role in the weak component. In addition, it determines the final abundance pattern of the main component, although it contributes only about 5% to the total neutron budget of AGB stars. The small size of the cross section in the energy range relevant to s process makes the direct measurement exceedingly difficult, and no conclusive results have been reported so far below $E_\alpha \approx 830$ keV. As a consequence, the uncertainty in the reaction rate is dominated by the poorly known properties of states in ^{26}Mg between the resonance at $E_\alpha \approx 830$ keV and the threshold. To characterise these levels, we have studied the n+^{25}Mg system and provided valuable pieces of information [13, 14] which are now being adopted in some international cooperative effort for the determination of the ^{22}Ne(α,n) reaction rate together with the one of the competing ^{22}Ne(α,γ) reaction.

11.4 Summary

In the last 2 decades, the nuclear data activity of the n_TOF Collaboration has provided relevant information for the characterisation of several aspects of the s-process nucleosynthesis. After two years of technical stop, foreseen in 2019–2021, the n_TOF facility will restart its operation and new data are expected from challenging experiments.

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