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Nuclear astrophysics at the n_TOF facility: Some key cases in low mass star evolution and Neutron Star Mergers

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Summary. — Nuclear astrophysics is an interdisciplinary field at the crossing of various branches, from experimental and theoretical studies of nuclear cross sections to stellar evolutionary models of high complexity. The physics of stellar interiors can be constrained only if the adopted inputs in stellar modelling are known with high accuracy. For the nucleosynthesis of heavy elements, neutron capture and neutron induced fission cross sections are among the major sources of uncertainty and, thus, any improvement in their estimates represents a progress toward a better comprehension of stellar processes. Here I will present an astrophysicist perspective on some measurements carried out at the n_TOF facility at CERN. I will discuss some cases related to the slow neutron capture process (the s-process) and to the rapid neutron capture process (the r-process).

1. – Introduction

Neutron capture and neutron-induced fission reactions play a key role in the nucleosynthesis of heavy elements. In particular, neutron capture cross sections on stable or long-lived radionuclides determine the slow neutron-capture process (s-process) path in low mass Asymptotic Giant Branch (AGB) stars and in massive stars [1-3]. It should be noted that about half of the elements heavier than iron are produced by this process. Fission, on the other hand, is important for the rapid neutron-capture process (r-process) nucleosynthesis, given that fission recycling determines the shape and position of the second and third r-process abundance peaks, at mass number A$\sim$130 and A$\sim$190 (see, e.g., [4]). In both cases, nuclear data are fundamental for a proper modelling of the nucleosynthesis, and to obtain information on the thermodynamic conditions in which neutron-capture processes take place. In case of a neutron star merger (NSM), they are essential to determine its light curve. The recent multi-messenger observations of the GW170817 event [5], in fact, have provided a fundamental insight into the r-process and are now calling for advances in the model description of r-process nucleosynthesis [6].

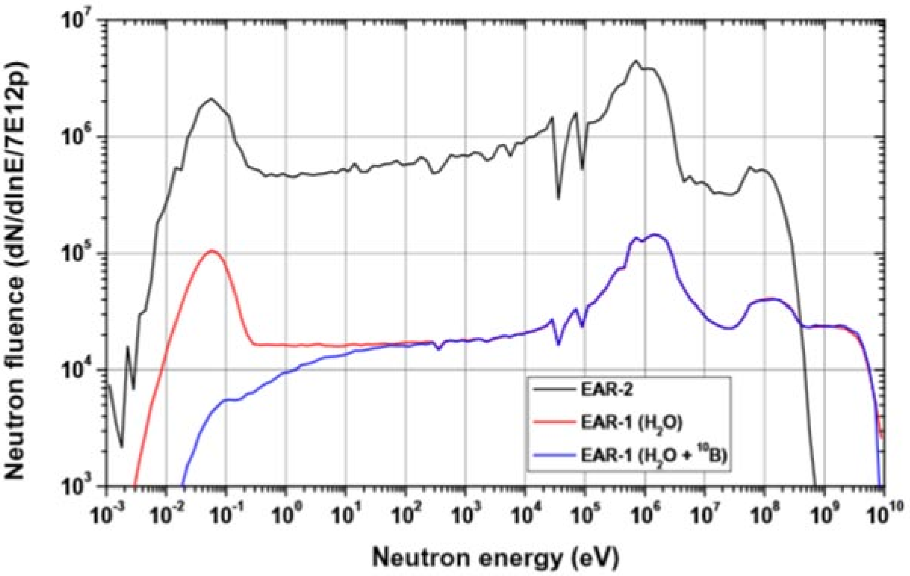

Fig. 1. – Neutron flux as a function of the neutron energy for the two n_TOF experimental areas. The EAR-2 neutron flux is on average 40 times higher than in EAR1. This, combined with the shorter time-of-flight at a given energy, leads to about two orders of magnitude higher signal-to-background ratio, when considering the background related to the natural radioactivity of unstable isotopes.

At the n_TOF facility at CERN, data on neutron-induced reactions for nuclear astrophysics are being collected since almost two decades. A wealth of important results has been obtained so far, both on capture and on fission reactions. This activity has recently received a boost with the construction of a second, high-luminosity beam line, where high accuracy measurements on short-lived isotopes (including actinides) have become finally possible. In summary, the n_TOF collaboration aims at measuring crucial isotopes of interest for s- and r-process nucleosynthesis, exploiting the unique features of the two neutron beams (one transported through the 185 m long horizontal flight path and the other through the 20 m short vertical flight path), i.e. the high instantaneous flux (see Fig. **1**), the high resolution and the wide neutron energy range (see, e.g. [7]).

2. – Capture measurements

The s-process consists of a series of neutron captures on stable (or long-living radioactive) isotopes and β-decays, followed by the decay of the freshly synthesized reaction products. Therefore, it develops along the β-stability valley. Among the roughly 500 neutron capture processes involved in the s-process, the most interesting ones are those corresponding to neutron magic nuclei, s-process branchings and s-only isotopes.

2˙1. *Magic nuclei.* – Nuclei with N=50, 82 and 126 belong to this category. Their particularly stable neutron configurations strongly reduce their neutron capture cross sections. As a consequence, the s-process distributions around those isotopes present peaks. The three peaks of the s-process are in correspondence of Sr-Y-Zr (N=50), Ba-La-Ce-Pr-Nd (N=82) and Pb (N=126). The neutron capture cross sections of these isotopes are the only ones able to shape the whole s-process distribution (between magic nuclei the so-called local approximation holds; see [8]). At the n_TOF facility, some of those isotopes have already been measured (^{90}Zr, [9]; ^{139}La, [10]) while others are currently under analysis (i.e. ^{88}Sr, ^{89}Y and ^{140}Ce). The latter, which has just been measured, is of particular interest to understand the origin of heavy elements in globular clusters belonging to our galaxy [11]. Note that a very high energy resolution, like that of the EAR1 area (ΔE/E$\sim 10^{-4}$), is needed to perform this type of measurements.

2˙2. *s-process branchings*. – Along the s-process path, there are unstable isotopes whose lifetime is comparable to the neutron capture timescale. In such a situation, the s-process bifurcates in two dinstinct branches. The study of those branchings allows theoreticians to derive hints about the physical properties locally characterizing the stellar environment (such as the temperature and the neutron density). At n_TOF, neutron capture on isotopes with half-lives of the order of tens on years have been already measured (see, e.g., the measurement of the neutron capture cross section of ^{151}Sm; [12]). In the last years, thanks to the larger flux achievable in the EAR2 experimental area, measurements on isotopes with even shorter lifetimes (of the order of some years) became feasible.

2˙3. *s-only isotopes*. – There is a class of isotopes which completely owe their production to the s-process, since they are shielded by their stable isobars from the r-process contribution. Those nuclei, named s-only, are extremely helpful to calibrate s-process nucleosynthesis theoretical models. In fact, the latter must fulfill the condition to obtain a flat distribution of s-only isotopes for the solar distribution (see, e.g., [13,14]). Among the isotopes with larger theoretical discrepancies, we list ^{134}Ba, ^{136}Ba, ^{152}Gd and ^{154}Gd. The latter has been recently measured at n_TOF, with new experimental values sensibly different from the literature [15].

3. – Fission measurements

The insensitivity of the r-process abundance pattern (for isotopes with A>120) to the parameters of the merging system is explained by an extremely neutron-rich environment, which guarantees the occurrence of several fission cycles before the r-process freezes out. In fact, the large neutron flux by-passes the closed shells at N=126 and N=152, synthesizing very neutron rich actinides (the most important having $92 \leq Z \leq 96$ and $180 \leq N \leq 186$). Those isotopes undergo fission: their fragments shape the r-process peak at A$\sim$130 and act as seeds for additional r-processing up to the A$\sim$250 fission region. The position of the third r-process peak at A$\sim$190 strongly depends on the adopted fission data [4]. Neutron-induced, beta-delayed and spontaneous fission reactions play important roles in the r-process nucleosynthesis. It is worth to notice that the description of fission recycling relies on model predictions of fission reactions. Current efforts aim at refining models so that they can provide a comprehensive and self-consistent description of the fission process, and can be used to predict the behavior of super-heavy actinides. To this end, research activity is concentrating on the optimization of various nuclear physics parameters (such as the fission barriers and nuclear level densities), at the basis of most fission models. In this respect, new fission data on a variety of actinides are needed, as the predictive power of current models can only by improved by comparison with a large set of experimental results. We stress here that models are also needed to predict the fission yields, i.e. the mass and charge distribution of fission fragments. New data on fission are therefore essential for optimizing these models and increase their predictive power. While beta-delayed and spontaneous fission are most probably the main reactions occurring in r-process nucleosynthesis following a NSM, they cannot be extensively studied in laboratories. On the contrary, neutron-induced fission reactions are experimentally accessible at neutron facilities around the world. Stronger constraints on fission models may come in particular from measurements of neutron-induced fission cross section and fission yields of an entire isotopic chain. In fact, a combination of data for various isotopes of the same element allows one to study simultaneously multiple-chance fission, thus better defining relevant model parameters.

At n_TOF, in the last years many neutron induced fission rates on actinides have been measured ([16], [17], [18], [19], just to mention the most recent ones). It should be noted that available data on those isotopes are scarce and affected by large uncertainties. At n_TOF, on the other hand, high accuracy can be reached thanks to the unique features of the neutron beam, in particular in EAR2, combined with state-of-the-art experimental setups. Above all, the availability of a sophisticated 2E-2v device (the STEFF detector; [20]) allows the measurement of fission yields with high resolution of the atomic mass and charge of the fission fragments, thus providing crucial data for model optimization.

4. – Conclusions

In the era of multi-messenger astronomy, a further effort is required to the experimental nuclear community in order to provide precise nuclear data to astrophysicists. In this framework, the n_TOF experiment represents one of the best facilities over the world, due to its high precision neutron capture and neutron induced fission measurements over a wide neutron energy range.

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