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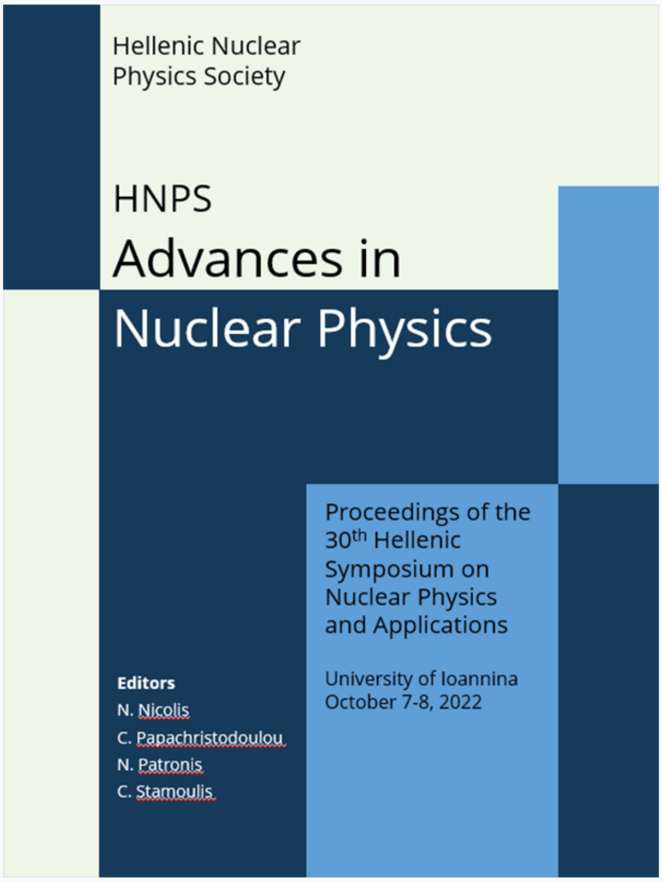

Nuclear astrophysics at n_TOF: focus on neutron sources in stars

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Nuclear astrophysics at n_TOF: focus on neutron sources in stars

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Abstract Since 2001, the neutron time-of-flight facility n_TOF at CERN has carried out a large number of cross section measurements of interest for several research fields, including Nuclear Astrophysics. The results of these measurements have improved our knowledge on the nucleosynthesis of chemical elements. Particularly relevant for the *s*-process, reported cross sections were used to constrain the Big Bang nucleosynthesis, to benchmark stellar models against nucleosynthesis in quiet and explosive scenarios, to interpret meteoritic abundances, as well as to study the neutron source reactions in Red Giant stars. After a brief description of the n_TOF facility and the related astrophysical program, the research activities about the $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ neutron source reactions are discussed.

Keywords s-process, n_TOF, cross section

INTRODUCTION

Neutron-induced reactions play a relevant role in understanding Big Bang and stellar nucleosynthesis. While BBN accounts for the formation of light elements up to ^{7}Li, stellar nucleosynthesis is responsible for the formation of heavier elements. It is well-established [1, 2] that the production of elements heavier than iron (A>60) is based on (n,γ) reactions, and subsequent β decays. Approximately half of the elemental abundances beyond iron are produced by the *s-process* during quiet burning phases in Red Giants stars, the rest being produced by the *r-process* in stellar explosion events.

The *s*-process reaction flow proceeds via a sequence of radiative neutron captures and β-decays from a distribution of seed nuclei around iron, thus building up elements from Fe to Bi. In particular, in the *s*-process nucleosynthesis (characterized by a low neutron density) β-decay rates are faster than radiative neutron capture rates, and therefore the *s*-process path follows the valley of β stability on the chart of nuclei.

In some cases, (n,p) and (n,α) reactions are also important. In fact, these reactions on a few light elements (for instance, ^{14}N, ^{25}Mg, ^{26}Al) can sizably modify the neutron distribution in the stellar interiors, thus affecting the efficiency of the *s-process* in synthesizing heavy elements. On the other hand, (n,p) and (n,α) reactions are of some relevance in the modelling of Big Bang nucleosynthesis or for the study of particular topics, as in the case of the stellar production of the ^{26}Al gamma ray emitter observed in our galaxy.

The experimental observable of interest to Big Bang and stellar nucleosynthesis is the neutron-induced cross section averaged over the stellar neutron-energy distribution, typically referred to as Maxwellian averaged cross section (MACS). So far at n_TOF, MACS were determined via time-of-flight (TOF). This technique is based on the measurement of energy-dependent cross sections over a wide energy region, and subsequent calculation of the MCAS at different temperatures, namely between kT=5 and 100 keV. In the last 20 years, the n_TOF collaboration has provided accurate nuclear data on a large number of intriguing physics cases (see for instance ref. [3] and references therein). In the near future, the effort will be on activation measurements as well.

THE N_TOF FACILITY AT CERN

The neutron time-of-flight facility n_TOF at CERN features two beam lines and corresponding experimental areas and an irradiation station, named EAR1, EAR2 and NEAR, respectively. EAR1 and EAR2 are located at 185 m and 19 m from the neutron-producing target, respectively, and are equipped with detection systems for TOF measurements. The NEAR station, conceived for activation measurements, has been recently constructed in the proximity of the neutron-producing target. The n_TOF facility is a white spallation source driven by the CERN proton synchrotron (PS). More in particular, 20 GeV/c protons from the PS impinge onto a massive 80×80×60 cm^3 Pb block [4], producing neutrons by spallation. Fast neutrons originating from the interaction of the proton beam with the lead target are then moderated by a water layer 5 cm thick, thus resulting in a wide neutron energy spectrum. As a result, neutron energies span over 11 energy orders of magnitude, from meV to GeV. The so-called instantaneous neutron flux, i.e. the number of neutrons per bunch, reaching EAR1 and EAR2 is quite high, as the result of the combination of the PS features and the ones of the neutron-producing target.

THE NUCLEAR ASTROPHYSICAL PROGRAM AT N_TOF

Since 2001, n_TOF has produced cross section data of interest for the s-process, as well as data for BBN and other astrophysical studies. More in detail, (n,γ) cross sections were deduced as a function of energy, using the time-of-flight method at EAR1 and EAR2. Moreover, improved detection systems, innovative ideas and collaborations with other neutron facilities have led to a sizable contribution of the n_TOF collaboration to the research field. Particularly important was the close collaboration with GELINA [5] at the European Commission Joint Research Center in Belgium, SARAF [6] in Israel, ISOLDE at CERN and the Paul Sherrer Institute (PSI) in Switzerland. Several cooperative projects were carried out in order to improve the quality of the cross-section data (see for example, the case of ^{197}Au [7–10], ^{171}Tm [11] or ^{7}Be [12,13]).

In summary, results of (n,γ) measurements have been reported for stable and radioactive samples of interest to the *s-process*: ^{24,25,26}Mg [14,15], ^{54,57}Fe [16], ^{58,59,62,63}Ni [17-20], ^{70,72,73}Ge [21-23], ^{90,91,92,93,94,96}Zr [24,25], ^{139}La [26], ^{140}Ce [27], ^{147}Pm, ^{151}Sm [28], ^{154,155,157}Gd [29,30], ^{171}Tm [31], ^{186,187,188}Os [32,33], ^{197}Au [7-10], ^{203,204}Tl [34], ^{204,206,207}Pb [35-37] and ^{209}Bi [38] isotopes. In addition, results on ^{7}Be(n,α) and ^{7}Be(n,p) for the cosmological lithium problem related to BBN, as well as ^{26}Al(n,α) and ^{26}Al(n,p) [39,40] relevant for the puzzle of the ^{26}Al γ-ray emitter in the Milky way, were reported.

NEUTRON SOURCE REACTIONS IN RED GIANT STARS

The main neutron source in low-mass asymptotic giant branch stars is the $^{13}C(\alpha,n)^{16}O$ reaction [41], which produces neutrons in radiative conditions (see, e.g., [42]). The formation of the so-called ^{13}C-pocket, which is needed to reproduce spectroscopic observations and pre-solar grain measurements, is highly debated. Consequently, the uncertainty of the reaction rate of $^{13}C(\alpha,n)^{16}O$ is surely one source of uncertainty in the modelling of the evolution of AGB stars that must be reduced. On the other hand, another relevant reaction for the production of neutrons – especially in massive stars – is the $^{22}Ne(\alpha,n)^{25}Mg$ reaction [43]. For both reactions, the uncertainty on the reaction rate at stellar temperature does not allow stellar models to be constrained conclusively. Direct measurements of the $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ cross sections in the energy region of interest to the *s-process* are difficult. In fact, the extremely small experimental count rate makes the experimental signature largely dominated by background events induced by cosmic rays. To tackle this situation, one could exploit the principle of time-reversal invariance applied to strong interaction, thus determining the cross section of the (α,n) reactions by measuring the (n,α) reaction cross sections. Unfortunately, these experiments are also challenging, and so far only feasibility studies have been conducted at n_TOF.

On the other hand, $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ cross sections feature structures and resonances, which are linked to the excited levels of the compound system (namely ^{17}O and ^{26}Mg, respectively) formed in the nuclear reactions. The energy and spin/parity of these states can be determined from neutron-spectroscopy. For instance, excited levels of ^{26}Mg above the α-threshold, were deduced in a joint measurement campaign between n_TOF and GELINA [19,20]. This study represented an important step forward in the knowledge of low-energy resonances in the $^{22}Ne(\alpha,n)^{25}Mg$ reaction cross section. In fact, five resonances were firmly identified below the lowest directly observed resonance in the $^{22}Ne(\alpha,n)^{25}Mg$ cross section.

CONCLUSIONS

The quest for accurate and new nuclear data on stable and radioactive isotopes for Nuclear Astrophysics has been partially addressed by the n_TOF initiatives carried in the past 20 years. Current research activities will bring to publications related to several neutron-induced reactions studies. The corresponding experimental data will be deposited in the publicly available experimental nuclear reaction database EXFOR, as happened in the past. In the next future, the n_TOF collaboration aims at performing challenging measurements exploiting the improved characteristics of the renovated experimental areas EAR1 and EAR2, and the new irradiation station NEAR.

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