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# Nuclear astrophysics measurements with ELISSA at ELI-NP

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**Summary.** — ELISSA is a new silicon-strip detector array under development at the Extreme Light Infrastructure - Nuclear Physics facility in collaboration with INFN-LNS, Catania. ELI-NP will provide very intense, brilliant gamma beams, tunable from 200 keV to 19.5 MeV. Several reactions important for the astrophysical p-process, Big Bang Nucleosynthesis and supernova explosion have been selected for the first measurement campaigns starting in 2019.

## 1. – Introduction

The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility, under construction in Bucharest-Magurele, Romania, consists of two major components: the High Power Laser System and the Gamma Beam System (GBS) [1]. ELI-NP will allow either combined or stand-alone experiments using the high-power laser and the gamma beam.

The GBS is an advanced source of gamma-ray photons able to produce beams of monochromatic and high spectral density gamma-ray photons. The gamma-ray beam is produced through Compton backscattering of laser light off an accelerated electron beam. The GBS will consist of two stages: a low-energy stage in which gamma rays are produced with energies up to 3.5 MeV and a high-energy stage in which gamma rays are produced with energies up to 19.5 MeV. The main specifications of the system are: photon energy continuously tunable in the range 0.2–19.5 MeV, high degree of linear polarization, better than 0.5% bandwidth, larger than $10^4$ photons/s/eV spectral density, and source spot sizes of about 10–30 microns.

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Dedicated diagnostics systems for tuning and beam optimization are developed after each interaction point. Additional monitoring instruments will be associated with the experimental stations for measuring the energy, intensity, and polarization of the gamma beam.

## 2. – ELISSA development

Resistive-strip silicon detectors represent a good solution for detecting charged particles as they provide good position resolution over a large solid angle with a relatively limited channel count. A silicon array would make it possible to measure reactions on solid targets and all the reactions on heavy nuclei intervening in the p-process. Resistive-strip silicon detector arrays have been successfully designed and commissioned for studies of nuclear astrophysics reactions (*e.g.* ORRUBA [2]).

The ELISSA array consists of X3 silicon-strip detectors (manufactured by Micron Semiconductor Ltd.) arranged into a barrel configuration [3]. The X3 is a 4-strip detector, 4 cm wide, position sensitive along the longitudinal axis (7.5 cm long), leading to a position resolution better than 1 mm around 10 MeV. The barrel could be made up of 3 rings of 12 position sensitive detectors, for a total angular coverage of 100° in the laboratory system. This setup results in a very compact design with a good angular resolution. Since position is determined by charge partition, the number of electronic channels is strongly reduced, as about 300 channels would be necessary for the whole barrel. The angular coverage is extended by using end cap detectors such as the assembly of four QQQ3 segmented detectors by Micron Semiconductor.

## 3. – Experimental program

Several reactions, including the $^{24}\mathrm{Mg}(\gamma,\alpha)^{20}\mathrm{Ne}$ reaction, and their measurement with ELISSA have been described in details in a published ELI-NP Technical Design Report [3]. Additional reactions are introduced in this section.

**3**·1. *The* $^{7}Li(\gamma,t)^{4}He$ *reaction.* – One of the unresolved problems in nuclear astrophysics is the so-called "cosmological Li problem". Big-Bang Nucleosynthesis (BBN) predicts the abundances of light elements $^{4}$He, D, $^{3}$He and $^{7}$Li that are produced shortly after the Big Bang. There is good agreement between calculated and observed abundances for all these light nuclei except for $^{7}$Li [4]. The calculated primordial abundance of $^{7}$Li at WMAP baryonic density by Coc *et al.* [5] is between 4.56 and $5.34 \times 10^{-10}$ depending on the reaction network, while Cyburt *et al.* [6] has calculated a value of $(5.24 \pm 0.71) \times 10^{-10}$. There is a factor of 3–4 discrepancy between the calculated primordial abundance at WMAP baryonic density and the observed abundance of $^{7}$Li.

The most recent experimental measurements on $^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}$ are more than 30 years old. A recent compilation of the world data by Descouvemont *et al.* [7] points out conflicting results below 1 MeV and the lack of data above 1.2 MeV. The most recent and complete experimental data on the $^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}$ cross section at lower energies, $E_{cm} \leq 1.2\,\mathrm{MeV}$, have been measured at Caltech in 1992–1994 by Brune *et al.* [8]. The overall systematic error in the measurement was estimated to be 6%.

The mirror alpha capture reactions $^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}$ and $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ are receiving a lot of theoretical attention recently [9] as theoretical models could provide the capture cross section at solar energies where experimental measurements are not possible. Neff [9] has

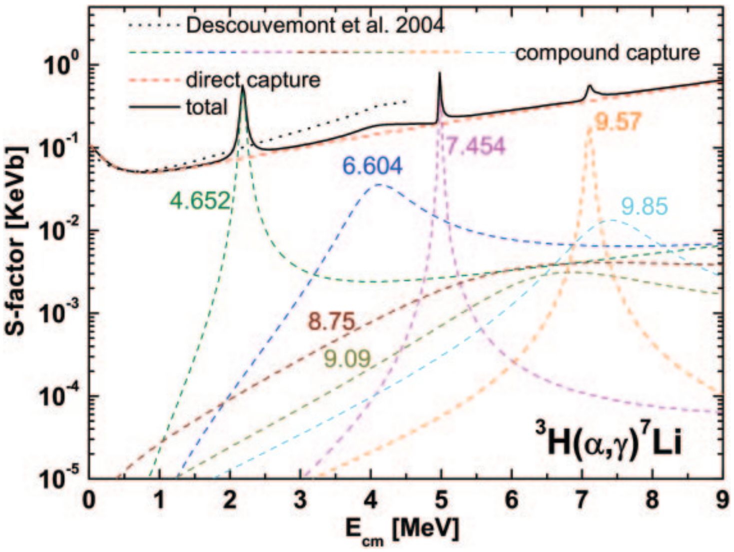

Fig. 1. – Calculated $^3$H$(\alpha,\gamma)^7$Li S-factor. Various radiative capture contributions are shown together with direct capture.

calculated the radiative capture cross sections for the $^3$He$(\alpha,\gamma)^7$Be and $^3$H$(\alpha,\gamma)^7$Li reactions in the fully microscopic fermionic molecular dynamics approach using a realistic effective interaction. The calculations are in good agreement with recent measurements of $^3$He$(\alpha,\gamma)^7$Be below 3 MeV center-of-mass energy, describing well the energy dependance and the absolute normalization of the capture cross section. The author points out that a model which successfully describes $^3$He$(\alpha,\gamma)^7$Be should also perform well for the $^3$H$(\alpha,\gamma)^7$Li cross section. A comparison with the experimental data of Brune *et al.* [8] reveals a good agreement on the energy dependence but the absolute normalization is about 15% larger, much more than the experimental uncertainties. With the extensive measurements of the $^3$He$(\alpha,\gamma)^7$Be reaction, the best contender for an experimental discrepancy is the $^3$H$(\alpha,\gamma)^7$Li reaction.

The total cross section for $^3$H$(\alpha,\gamma)^7$Li in the energy range of $4\,\text{MeV} \leq E_\gamma \leq 11\,\text{MeV}$ has been calculated by using the contributions from both direct capture and the compound capture of 7 resonant state. With the $R$-matrix code AZURE2 [10], the compound capture cross section from the 7 resonant states is calculated (fig. 1).

The primary goal of the measurement is to determine the cross sections and angular distributions for the $^7$Li$(\gamma,t)^4$He reaction at $\gamma$ energies between 4 and 11 MeV. A Monte Carlo simulation based on GEANT4 has been developed to study the influence of target thickness on the count rate and separation of the tritons and $\alpha$-particles. The results show that the optimal target thickness is $150\,\mu\text{g/cm}^2$ for $^7$Li and $400\,\mu\text{g/cm}^2$ for $^7$LiF. Additional simulations using the VIKAR code developed by Pain [11] show that target effects are important and separation of tritons and alpha particles is difficult below 4 MeV. A thinner target, $100\,\mu\text{g/cm}^2$ of $^7$Li, is more suitable at lower energies (fig. 2).

Assuming a maximum $\gamma$-beam flux of $10^9$ s$^{-1}$ at ELI-NP, we estimate to measure any off-resonance points in about 10 minutes with good statistical precision for both cross section and angular distribution measurements. Measurements above 7–8 MeV would be an ideal first day experiment with ELISSA at ELI-NP.

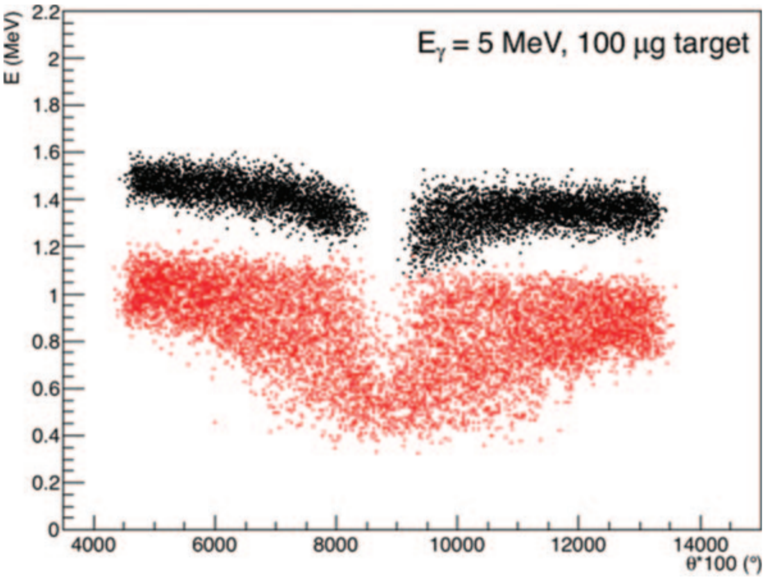

Fig. 2. – Simulated energy *vs.* angle spectrum for tritons and alpha particles for $E_\gamma = 5\,\text{MeV}$ and a target thicknesses of $100\,\mu\text{g/cm}^2$ using the VIKAR code. Tritons are shown in black, $\alpha$-particles in red.

**3**˙2. *P-process reactions.* – In stellar explosive sites like supernovae, the astrophysical p-process is an important way of nucleosynthesis to produce the proton-rich, stable nuclides beyond Fe which cannot be reached by the s- and r-processes [12]. It is thought that these nuclides are synthesized by photodisintegration of pre-existing s- and r-processes nuclei. The p-process contains capture and photodisintegration reactions for about 2000 proton-rich and stable nuclei beyond Fe. For most of them, experimental data are not available. There are 35 nuclides classified as the p-process nuclides ranging from $^{74}$Se to $^{196}$Hg that are produced by re-processing the pre-existing seed nuclei. P-nuclei of Mo and Ru are produced only by p-process in the scenario of supernova explosion. Astrophysical simulations show that the nucleosynthesis of $^{92,94}$Mo and $^{96,98}$Ru are systematically underproduced, by benchmarking the predicted abundances of these nuclei to their corresponding abundances observed in the Solar System composition. Therefore, it is expected that to experimentally determine the astrophysical reaction rates around Mo and Ru would remedy this unsolved problem of p-process nucleosynthesis [13]. The isotopes of Sm are also predicted to be produced by photodisintegration reactions within the p-process. It has been pointed out that the $^{146}$Sm would be a potential p-process chronometer, which could constrain the chemical evolution in the solar nebula and early planetary bodies. All these reactions proposed to be measured at ELI-NP have the potential to solve important astrophysical issues in the p-process.

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