# Nuclear Astrophysics at ELI-NP: the ELISSA prototype tested at Laboratori Nazionali del Sud

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**Abstract.** The Extreme Light Infrastructure-Nuclear Physics (ELI-NP) facility, under construction in Magurele near Bucharest in Romania, will provide high-intensity and high-resolution gamma ray beams that can be used to address hotly debated problems in nuclear astrophysics, such as the accurate measurements of the cross sections of the $^{24}$Mg($\gamma$,$\alpha$)$^{20}$Ne reaction, that is fundamental to determine the effective rate of $^{28}$Si destruction right before the core collapse and the subsequent supernova explosion.

For this purpose, a silicon strip detector array (named ELISSA, acronym for Extreme Light Infrastructure Silicon Strip Array) will be realized in a common effort by ELI-NP and Laboratori Nazionali del Sud (INFN-LNS), in order to measure excitation functions and angular distributions over a wide energy and angular range.

A prototype of ELISSA was built and tested at INFN-LNS in Catania (Italy) with the support of ELI-NP. In this occasion, we have carried out experiments with alpha sources and with a 11 MeV $^{7}$Li beam. Thanks to our approach, the first results of those tests show up a very good energy resolution (better than 1%) and very good position resolution, of the order of 1 mm. Moreover, a threshold of 150 keV can be easily achieved with no cooling.

## 1 Introduction

### 1.1 The ELI-NP facility

The ELI-NP project aims at establishing a European Research Infrastructure Centre for ultra-high intensity lasers, laser-matter interactions, nuclear and material science, using laser-driven radiation sources [1]. This multidisciplinary facility will provide new opportunities to study fundamental processes that occur in ultra-intense laser fields during laser-matter interactions.

ELI-NP will benefit also from a very bright gamma beam system (GBS). The system was conceived as a dedicated device based on the inverse Compton backscattering of high-intensity laser pulses off

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high brightness relativistic electron bunches and able to provide gamma beams with unprecedented features: continuous tuneable gamma-ray energy over a broad range (from 200 keV to 19.5MeV), high spectral density (about $10^4$ photons/s/eV), small relative energy bandwidth (lower than 0.5%), high degree of linear polarization (higher than 95%), and high peak brilliance [2].
Such a facility will open new experimental perspectives for studies in the field of photonuclear physics. Moreover, thanks to these excellent features, the ELI-NP facility will provides unique opportunities for nuclear astrophysics research.

### 1.2 Nuclear Astrophysics at ELI-NP

Using the gamma radiation beam with unique characteristics at ELI-NP, we will be able to respond to the need of Nuclear Astrophysics to perform accurate measurements of small cross sections (order of $\mu$b or even less) of nuclear reactions of the hydrogen and helium burning processes and hence of the astrophysical S-factor that are essential for stellar evolution modeling. Measuring capture reactions by means of the inverse photodisintegration reaction, besides being inherently low-background measurements, have the advantage of having a different systematic uncertainty than those of characteristic charged particle induced reactions measured at low energies of astrophysical interest. Such systematic issues, for example, involving the target and its deterioration, (effective) beam energy definition, etc., lead to different systematic errors and thus may allow us to resolve conflicting data.

### 1.3 A physical case: the $^{24}$Mg($\gamma$,$\alpha$)$^{20}$Ne reaction

Silicon burning sets the chemical composition of the star right before the core collapse and the subsequent supernova explosion, thus constituting a key process for the understanding of core-collapse supernovae [3]. When $^{16}$O is depleted at the conclusion of core oxygen burning, the most abundant nuclei are $^{28}$Si and $^{32}$S. The stellar core contracts and the temperature increases, reaching values as large as T= 2.8-4.1 GK, depending on the stellar mass. Fusion reactions such as $^{28}$Si+$^{28}$Si or $^{28}$Si+$^{32}$S are unlikely to occur owing to the Coulomb barrier between interacting nuclei, even at such high temperatures [4]. Instead, nucleosynthesis takes place through photodisintegration of less bound nuclei and radiative captures of the dissociated light particles (protons, neutrons, and $\alpha$-particles) to create gradually heavier and more tightly bound nuclei [5]. Therefore, many photodissociation cross sections have to be known with adequate accuracy to model silicon burning. However, sensitivity studies show that the $^{24}$Mg($\gamma$,$\alpha$)$^{20}$Ne reaction governs the downward flow from $^{24}$Mg to $^{4}$He, thus determining the effective rate of $^{28}$Si destruction, making its reaction rate critically important to stellar models [3].
At present, the $^{24}$Mg($\gamma$,$\alpha$)$^{20}$Ne reaction rate has been calculated from the $^{20}$Ne($\alpha$,$\gamma$)$^{24}$Mg rate. In the temperature range of interest, around $3.9\cdot10^9$ K, the $^{20}$Ne($\alpha$,$\gamma$)$^{24}$Mg reaction rate may be subject to systematic errors of the order of a factor of 2, as can be seen from the different results reported in [6]. A direct $^{24}$Mg photodissociation measurement using gamma beams of energies 10-12 MeV will allow us to determine a much more accurate cross section to be used in nuclear reaction network calculations to improve the knowledge of the pre-supernova chemical composition.

## 2 The ELISSA detector

Generally speaking, photodissociation reactions are not so hard to study as the phase space factor enhances the ($\gamma$,p) and ($\gamma$,$\alpha$) cross sections with respect to the inverse process, provided that a high quality gamma beam is available, such as the one delivered by the ELI-NP facility. In addiction, it is worth noting that the emitted fragments have low energies, ranging from few hundreds keV to few

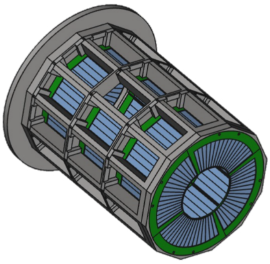

**Figure 1.** Final design of the ELISSA detector. It will be made of n. 3 rows of PSD detectors to form a barrel plus n. 8 end cap detectors to extend the angular coverage.

MeV, making it necessary to use a low-threshold detector. Moreover, excitation functions and angular distributions should be measured over a wide range allowing for a better understating of reaction mechanism. Indeed, taking into account the presence of beam induced background at forward angles, an angular coverage as large as possible should be covered in order to ensure a range large enough to perform an effective nuclear spectroscopy. Finally, silicon strip detectors would couple enhanced angular and energy resolution with high detection efficiency. High granularity is not a crucial aspect as a low counting rate is expected, making the probability of multiple hit very small. This type of array has already been successfully applied for nuclear astrophysics studies, e g. ORRUBA (Oak Ridge Rutgers University Barrel Array) or ANASEN (Array for Nuclear Astrophysics Studies with Exotic Nuclei) [7, 8].
Thus, the Extreme Light Infrastructure Silicon Strip Array (ELISSA) is under construction [9]. The performed Monte Carlo simulation using a code based on GEANT4 tracking libraries and the n-body event generator of ROOT, as described in [10], proved that the barrel configuration is particularly suited as it guarantees a very good resolution and granularity, ensuring also a compact detection system (useful as it would allow a simple integration with ancillary detectors, such as neutron arrays) and a limited number of electronics channel [11]. So that, the final design of ELISSA will consist of 3 rings of 12 X3 position-sensitive detectors produced by Micron Semiconductor Ltd. [12], in a barrel like configuration, ensuring a total angular coverage in the laboratory system of about 100. The angular coverage is extended down to about 20 (160 at backward angles) by using end cap detectors such as the assembly of four QQQ3 segmented detectors by Micron Semiconductor Ltd [12]. A sketch of the final expected setup is shown in fig. 1.

## 3 Tests on ELISSA prototype

To test the performance of the X3 detectors and make sure that their energy and angular resolutions are suitable for the realization of the ELISSA detector, we have carried out experiments with alpha sources and with a 11 MeV $^{7}$Li beam at the INFN-LNS tandem in Catania (Italy), in collaboration with ELI-NP (Romania). In this occasion, a prototype of the ELISSA detector realized at INFN-LNS was installed at the "Camera 2000" scattering chamber. The tests were performed on February 3-4, 2016. The prototype is made up of a single X3 detector and a single QQQ3 detector, so it replicates in a smaller scale the whole detector, and their readout is performed by means of standard analog electronics. While QQQ3 are DSSSD, so their position resolution is fixed by the strip size and energy resolution is constant to a good approximation, X3 detectors showed more peculiar features. So that,

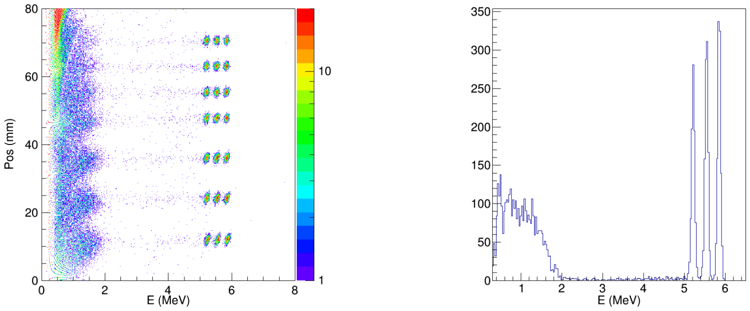

**Figure 2.** Left panel: Position vs. Energy plot of the X3 detector. See the text for details. Right panel: Energy spectrum for a fixed position.

in the following we focus on the X3 detector. To measure the detection threshold, we have performed a run using a standard 3-peak alpha source and a $^{241}$Am source shielded by a 17 $\mu$m thick Al foil. This degrader shifted the energy peak to 1 MeV and, due to energy straggling, the energy range reached energy as low as zero. The result of this run is reported in the left panel of fig. 2 showing the position Vs. energy plot obtained using a mask (asymmetric respect the center of the detector and with 1mm and equally spaced slits in each side) in front of the detector. In the right panel the energy spectrum is shown for a fixed angle, corresponding to the slit at about 57mm. From the plot it is clear that a threshold of 150 keV can be easily achieved with no special expedient.

Energy and position resolutions were measured detecting scattering and reactions induced by the $^{7}$Li beam on Au, C and $CD_2$ targets. In this way, we determined an energy resolution of $\leq$1% at high energy (scattering off gold) and $\leq$8% in the case of $^{7}$Li scattered off $^{12}$C (energy resolution measured at about 1 MeV), essentially due to straggling in the target and target inhomogeneity. At energies of about 11 MeV, the position resolution is better than 1 mm while at lower energies, below about 1 MeV, a position resolution of about 6 mm was found [9]. Notwithstanding such position resolution deterioration, the detector performances are still good enough for the measurement of angular distribution and the kinematical identification of the reactions induced on the target by gamma beams, since it corresponds to an angular resolution of about 1.5 degrees.

To sum up, these tests allows us to say that the X3 detectors, as well the standard QQQ3 detectors, are perfectly suited for nuclear astrophysics studies with ELISSA.

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