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# Astrophysics Studies at the Future ELI-NP European Research Center

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Extreme Light Infrastructure - Nuclear Physics (ELI-NP), the Romanian pillar of ELI, is under construction. The development of the high power laser system (HPLS, 2x10PW) and of the high intensity gamma beam system (GBS) have also started. The Technical Design Reports for the future experiments are in the elaboration process in the framework of large international collaborations. One of the major research areas where ELI-NP will provide a powerful tool for advancing science is nuclear astrophysics. Several experimental setups for gamma, neutron and charged particle detection will address experiments regarding the *s*-, *r*- and *p*-processes, stellar evolution and the CNO cycle. An overview of some of the proposed astrophysics studies at ELI-NP and the related setups will be given.

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## 1.Introduction

Extreme Light Infrastructure – Nuclear Physics (ELI-NP) [1,2] will combine in a unique infrastructure two types of extremely intense photon beams: at low energies, two laser arms of 10PW maximum power each; and at high energies, two beams in the gamma ray range, produced by Compton backscattering of laser beams off an accelerated electron beam.

Not only that both these types of photon beams will be available in the same infrastructure, but also the characteristics of each of these beams are unique and beyond state of the art worldwide at the moment of starting operations. Moreover, within the scientific scope of ELI-NP there is the coherent combination of the two high power laser beams, in order to open the possibilities of accessing the next power stage in laser-based infrastructures. Apart from the 10 PW beams, there will be intermediate power (but higher repetition rate) outputs from each of the two arm of the laser system, at 1 PW and 100 TW respectively. The laser and gamma radiation beams will be delivered to 8 experimental halls.

Part of ELI, the European distributed research infrastructure dedicated to the next generation high intensity photon sources, ELI-NP will be a user facility, any research team in the world being able to submit proposals and perform experiments here. An international scientific committee will evaluate the experiment proposals and select and prioritize the ones to be performed, while a European-level structure – probably ELI-ERIC (European Research Infrastructure Consortium) - shall ensure the complementarity of the scientific programs of the pillars of ELI.

During the construction and implementation phase of the project, a preparatory entity, ELI-DC (ELI – Delivery Consortium), is making the connection between the funding-wise independent implementations of the ELI centers in Romania, Hungary and the Czech Republic.

**Figure 1.** Main experimental building of ELI-NP.

## 2.Implementation Status of the ELI-NP Project

### 2.1 Buildings and Large Equipment

Construction of the ELI-NP buildings began in June 2013, following a public tender procedure valued over 60MEuros.

Buildings are scheduled to be completed in 2015, when the delivery and installation of the large equipment will begin.

On the difference to the other two ELI centers in Europe, ELI-NP will feature not only a high-power, ultra-short pulse laser system, but also a very high intensity gamma radiation beam. The 2-arms laser system (HPLS, 2x10PW) and the Gamma Beam System (GBS) are the two very large machines at ELI-NP and made the object of two public tender procedures. The development of both machines, which are beyond the present-day state of the art, has begun, and completion is expected in 2018.

The parameters of the 10PW laser beams that will be provided by the ELI-NP infrastructure are listed in Table 1.

| **Parameters** | **Estimated value** |
|---|---|
| Pulse Energy (IPE) [J] | 150 ≤ IPE ≤ 250 |
| Pulse Duration (IPD) [fs] | 15 ≤ IPD ≤ 25 |
| Central wavelength (CWL) [nm] | 810 ≤ CWL ≤ 820 |
| Spectral bandwidth (SB) [nm] | 50 ≤ SB ≤ 70 (FWHM)<br>[720; 890] (Hard-clip) |
| Beam height from the floor [mm] | $1500^{+10}$ |
| Strehl Ratio (ISR) | 0.8 ≤ ISR ≤ 0.9 |
| Input Beam Pointing (IBP) – rms [μrad] | 2 ≤ IBP ≤ 3 |
| Beam polarization state | Linearly polarized in the horizontal plane |
| Pulse repetition rate (PRR) | Maximum PRR = 1 pulse/min |

**Table 1.** Main parameters of the ELI-NP 10 PW laser beams to be delivered for experiments.

The GBS will provide two very high intensity gamma photon beams, one at intermediate energies up to 3.5MeV and one at energies up to 19.5MeV, produced by laser Compton backscattering. The linear electron accelerator part of the GBS will have two stages of acceleration (followed by the two laser-electron interaction point corresponding to the two energy ranges) with the maximum energy for the final stage of 720MeV. The main parameters of the GBS are listed in Table 2.

| **Parameter** | **Specification** |
|---|---|
| Minimum Photon Energy [MeV] | 0.2 |
| Maximum Photon Energy [MeV] | 19.5 |
| Tunability of the photon energy | Continuously variable |
| Linear polarization of the gamma ray beam [%] | ≥ 99 |
| Frequency of the γ-ray macropulses [Hz] | 100 |
| Number of γ-ray micropulses per macropulse | 32 |
| Micropulse–to–micropulse separation [ns] | 16 |

| | |
|---|---|
| Divergence [rad] | (0.25 – 2.0) x $10^{-4}$ |
| Average diametral FWHM of beam spot [m] | ≤ 1.0 x $10^{-3}$ |
| Average bandwidth of the gamma-ray beam | ≤ 5.0 x $10^{-3}$ |
| Time-average spectral density at the peak energy [1/(s eV)] | (0.8 – 4.0) x $10^{4}$ |

**Table 2.** Main parameters of the ELI-NP GBS beams to be delivered for experiments.

Regular meetings between the ELI-NP researchers and engineers and the providers of these machines ensure the development of the equipment according to specifications and needs of the users and also the optimization of the development of experimental setups by the ELI-NP research team.

### 2.2 Technical Design Reports (TDR) for the Experimental Areas

There are 8 experimental halls at ELI-NP, dedicated to laser (4 halls), gamma (2 halls, plus one for experiments with GBS-produced positrons) and combined laser and gamma beam experiments (one hall). The equipment to be placed within these areas must be decided following the development and review of a detailed TDR for each of them. Work is now in progress for drafting the TDR's.

After defining the main science scope of ELI-NP (at the beginning of operation) through a broad interaction with the scientific community [3], two years ago the process to pass from experiment ideas to experiment description and simulations has begun. International working groups were formed, led by prestigious scientists in the relevant fields, which are now defining the details of the experimental setups in the TDR's.

Supporting laboratories and workshops in the new infrastructure are also an area of very active developments in the present stage. They will be very important in both implementation and operation phases of ELI-NP, during the installing and commissioning of the equipment, constructing the experimental setup, maintenance and further developments/upgrades.

### 2.3 Socio-Economic Effects of ELI-NP

The socio-economic effects are among the top aims of the European funding, especially for the operational programme in which ELI-NP is funded. ELI-NP will have a major positive role, both locally and at a regional level, and both short-term and long-term effects in the society.

Since the very first phases of the project, it was obvious that due to its very ambitious aims, highly skilled human resources will be needed for the successful outcome of the implementation and starting operations. This is why a very competitive hiring process was planned and put in place, to attract the best competencies from around the world in the areas relevant for ELI-NP. More than 200 researchers, engineers and technicians will work at ELI-NP when starting operations, with a gradual, continuous increase to that number.

The Academic Forum of ELI-NP brings together the representatives of most of the prestigious Romanian Universities with scientific and technical majors. This Forum is the place where common initiatives of educational programmes and strategies are developed by the academic environment, together with the research institutes, with the aim of increasing the scientific awareness of the young generation, promoting the idea of a career in research for students, and assure a solid base of well-prepared workforce in the scientific and technical areas for the "knowledge society" of tomorrow.

The Industrial Forum of ELI-NP is an entity that recently got also its legal status, formed by representatives of the industry, interested in the many aspects of the project, from the development of equipment and delivery of materials for the implementation phase, to the performance of experiments at the new research infrastructure in the operational phase.

## 3. Astrophysics Experiments with the Gamma Beam System

The Gamma Beam System of ELI-NP will allow the performance of photonuclear reactions experiments, relevant for astrophysics in the study of direct reactions or in reverse kinematics. In this section, three examples of proposed experiments, using charged particle detectors, are presented.

### 3.1 The $^{16}O(\gamma,\alpha)^{12}C$ Reaction

The ratio of carbon-to-oxygen (C/O) at the end of helium burning is still an open question in modern nuclear astrophysics, after being considered as such decades ago [4]. To solve this problem one must determine the p-wave [$S_{E1}$(300)] and d-wave [$S_{E2}$(300)] cross section S-factors, defined in [4], of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at the Gamow peak (300 keV) with an accuracy of approximately 10% or better.

New measurements of the $^{12}C(\alpha,\gamma)^{16}O$ reaction were recently reported [5 and references herein] with energies in the center of mass around 1.0 MeV. But still, the accuracies in the calculation of the astrophysical S-factors are very low (±40-80%) and based on these, a very low value (~10 keVb) of the extrapolated E1 S-factor cannot be ruled out [6,7]. The new data also point out to a significant ambiguity in the value of the extrapolated E2 S-factor [8]. These new experiments used some of the highest intensity alpha-particle beams (100 - 500 μA) with impressive luminosities of $10^{33}$ $cm^{-2}s^{-1}$ and $10^{31}$ $cm^{-2}s^{-1}$, and 4π arrays of HPGe and $BaF_2$ detectors, that provided large counting statistics. Yet the accuracies of the measured S-factors were limited by the quality of the measured angular distributions needed to separate the E1 and E2 components.

The complete angular distributions measured with the eTPC (Electronic-readout Time Projection Chamber) gas detector proposed for ELI-NP will allow us to measure $S_{E1}$ and $S_{E2}$ separately and result an accurate form for extrapolating to stellar energies the measured E1 and E2 cross sections. For example a measurement of an angular distribution (2,000 counts) with the gas eTPC detector, at $E_\gamma$ = 8.26 MeV (Ec.m. = 1.1 MeV) with beam intensity of $10^9$ $s^{-1}$ (on target) will require 15 days of beam time.

### 3.2 The $^{24}Mg(\gamma,\alpha)^{20}Ne$ Reaction

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 too unlikely to occur owing to the Coulomb barrier between interacting nuclei, even at such high temperatures [9]. Instead, nucleosynthesis takes place through photodisintegration of less bound nuclei and radiative captures of the dissociated light particles (protons, neutrons, and α-particles) to create gradually heavier nuclei. In detail, since α-captures on $^{20}Ne$ are less likely to occur than the competing (γ,α) reactions, the $^{24}Mg(\gamma,\alpha)^{20}Ne$ reaction governs the downward flow from $^{24}Mg$ to $^{4}He$. It means that the effective rate of $^{28}Si$ destruction is established by the photodisintegration of $^{24}Mg$, making its reaction rate critically important to stellar models of silicon burning [10].

The $^{24}Mg(\gamma,\alpha)^{20}Ne$ reaction rate has been calculated from the $^{20}Ne(\alpha,\gamma)^{24}Mg$ rate, but this rate may be subject to systematic errors of the order of a factor of ≈ 2 at T ≈ 3.6 GK, due to the presence of a large number of resonances affecting the reaction cross section.

Using high quality gamma beams of energies 10 - 12 MeV produced at ELI-NP, a direct $^{24}Mg$ photodissociation measurement will allow to determine a much more accurate cross section, which used in nuclear reaction network calculations will lead to the improvement of the knowledge on the chemical composition in the pre-supernova stage.

### 3.3 The *p*-process

As a group, the p-nuclei (containing more protons relative to other stable isotopes of the same element, stable nuclides with mass numbers of A ≥ 74) are the rarest among the stable nuclides. Their abundances are typically a factor of ≈ 100 smaller compared to those of adjacent s- and r-nuclei. Their synthesis is still very uncertain, the required formation conditions being unlikely in any hydrogen-rich zone of common stars. One of the most likely scenarios is type II supernova, when the shock wave passes through the O–Ne-rich layer of a massive star the temperature, density and composition might be suited for the production of p-nuclei [10].

The *p*-process operates far from equilibrium so the entire network must be followed by explicit computation – the *p*-process is among the most complicated nucleosynthesis network as it involves thousands of nuclei, nuclear reactions and β-decays. Among the most important nuclear reactions are photodissociation processes, including (γ,n), (γ,p) and (γ,α) reactions.

A common feature of *p*-process calculation is the underproduction of species such as $^{92}Mo$, $^{94}Mo$, $^{113}In$ and $^{115}Sn$, pointing at an unsolved problem of current *p*-process computations [10]. Nuclei such as $^{74}Se$, $^{78}Kr$, $^{84}Sr$, $^{92}Mo$, and $^{96}Ru$ show a very strong dependence on the (γ,p) cross section, making it necessary a more thoroughly investigation of the corresponding photodissociation reactions [11].

The investigation of reactions such as $^{96}Ru(\gamma,\alpha)^{92}Mo$ or $^{74}Se(\gamma,p)^{73}As$ is proposed for ELI-NP using an array of silicon detectors, computations showing the possibility to obtain relevant results in relatively short exposure times, due to the intensity and quality of the gamma ray beam.

## 4. Astrophysics Experiments with the High Power Laser System

The unparalleled power and intensities reached by the two 10PW laser arms at ELI-NP will open new possibilities for experiments in astrophysics, by creating plasma conditions similar to the ones in astrophysical context, and by experiments relevant for nucleosynthesis with laser-accelerated particles.

### 4.1 Production of Extremely Neutron-Rich Isotopes

The formation of isotopes with very large number of neutrons is a highly interesting research area, and the extremely intense laser pulses available at ELI-NP will make possible a fission-fusion experiment for their production [3]. Specifically, the neutron-rich nuclei around the waiting point N=126 [12], belonging to the higher path of the astrophysical r-process are targeted.

The Radiation Pressure Acceleration (RPA) regime allows for very high density ion bunches to be created, and in the proposed experiment solid state density $^{232}$Th bunches are to be created with energies of 7 MeV/u [13], which then passing through a thin carbon layer disintegrate into light and heavy fission fragments. Also, accelerated light ions from the CH2 backing of the first ("production") Th target will be able to produce fission of $^{232}$Th in the second ("reaction") target. A schematic view of the experimental layout is shown in Fig. 2. The fluctuations in neutron number of both target and beam fragments may be exploited in this setup, to get to the area of more neutron-rich nuclei. Rate estimations were performed for various parameter sets, showing the feasibility of a carefully designed fission-fusion experimental setup at ELI-NP.

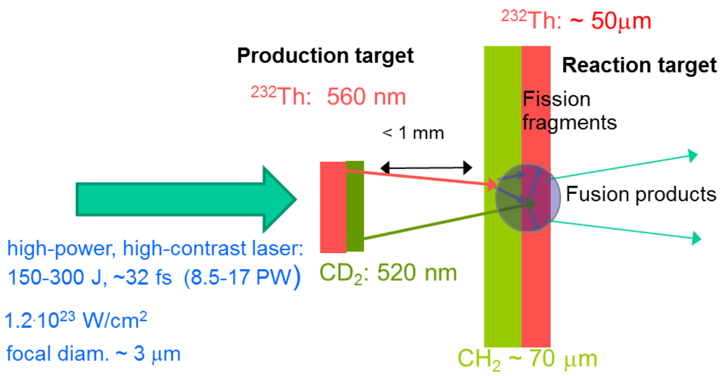


**Figure 2.** Setup of the fission-fusion experiment *(P. Thirolf, presentation at ELI-NP).*

### 4.2 Electron Screening in Astrophysical Plasmas

For the understanding of many astrophysical processes, such as stellar evolution and supernova explosions, the phenomenon of Electron Screening (ES) [14] plays an important role. The interacting nuclides are surrounded by electron clouds, which act as a screening potential and thus the projectile sees a reduced Coulomb barrier. This reduction in both height and extent of the barrier leads to higher interaction cross sections for the screened nuclei, $\sigma_s(E)$, compared to those of bare nuclei, $\sigma_b$ (E). An enhancement factor can then be defined by [15], larger than 1.

Although the total (screened) cross sections have been extracted by direct measurements of nuclear reactions induced by a beam of low-energy particles incident on solid or gaseous targets [16,17], the effect of ES in stars, because of the presence of plasma, can be very different from that one studied in laboratory with these methods.

The reproducing of astrophysical plasmas through the laser-matter interaction in laboratory is the first aim of this experiment proposal, followed by the study of the influence of ES on the thermonuclear reactions taking place. At laser intensities of more than $10^{22}$ W/cm$^2$ and in conditions attainable at ELI-NP, relevant experiments in this respect can be performed.

There are mainly three experimental approaches resulting from results previously published in literature:

- laser generated plasmas by employing solid micro/nano structured targets;
- the collision of two or more interacting plasmas generated by one or more laser beams;
- the irradiation of clusters in an ambient gas.

### 4.3 Enhanced decay of $^{26}$Al in hot plasma environments

The $^{26}$Al nucleus was the first radioisotope detected in the interstellar medium, by observing its characteristic 1809 keV emission line [18].

The half life of $^{26gs}$Al ($5^+$) state is $7.2\times10^5$ years, and thus the presence of this nucleus is an evidence of ongoing galactic nucleosynthesis. Possible sources of the origin of $^{26}$Al are proposed to be Wolf-Rayet stars and Asymptotic Giant Branch (AGB) stars and novae [19].

At hot stellar temperatures, the dominant contribution to the $^{26gs}$Al(p,$\gamma$)$^{27}$Si (main destruction mechanism for $^{26}$Al isotope) reaction rate is capture through low-lying resonances, for which the strengths have not been measured and an experimental benchmarking of theoretical studies remains elusive. Moreover, the disintegration process of $^{26}$Al is further complicated by the presence of a $0^+$ isomer at 228 keV above the ground state.

Theoretical work predicts the reduction of the effective lifetime of $^{26gs}$Al by a factor of $10^9$ within the temperature range from 150 to 400 MK due to a variety of physical processes influenced by hot plasma environments. The first stage for this experiment will be the exposure of a small $^{26}$Al target to an isochorically heated environment with the ELI-NP lasers. The proposal is described in section 5.2.8 of the ELI-NP Whitebook [3].

## 5. Conclusions

After gathering hundreds of top researchers worldwide for the development of its physics case, exposed in the White Book and approved by an international review panel, ELI-NP attracts more and more top researchers and engineers and is in the process of forming an international community of future users, who are working now for the detailed technical description of the proposed experiments.

Among the fields that are most likely to benefit from the new experimental capabilities of ELI-NP, there is the Astrophysics, a frontier research area that has already a well-established tradition in pushing further, with its requirements, the experimental facilities.

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