

PAPER • OPEN ACCESS

Photodisintegration reactions for nuclear astrophysics studies at ELI-NP

To cite this article: C Matei *et al* 2018 *J. Phys.: Conf. Ser.* **940** 012025

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the [collection](#) - download the first chapter of every title for free.

Photodisintegration reactions for nuclear astrophysics studies at ELI-NP

C Matei¹, D Balabanski¹, D M Filipescu¹ and O Tesileanu¹

¹ Extreme Light Infrastructure - Nuclear Physics / Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, Bucharest-Magurele, 077125, Romania

E-mail: catalin.matei@eli-np.ro

Abstract. Extreme Light Infrastructure - Nuclear Physics facility will come online in Bucharest-Magurele, Romania, in 2018 and will deliver high intensity laser and brilliant gamma beams. We present the physics cases and instruments proposed at ELI-NP to measure capture reactions by means of the inverse photodisintegration reaction. We propose to study the $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction using a Time Projection Chamber detector with electronic readout. Several other reactions, such as $^{24}\text{Mg}(\gamma, \alpha)^{20}\text{Ne}$ and reactions on heavy nuclei relevant in the p-process, are central to stellar evolution and will be investigated with a proposed Silicon Strip Detector array and a 4π neutron detector. The status of the experimental facilities and first-day experiments will be presented in detail.

1. The ELI-NP facility

The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) 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 main specifications of the system are: photon energy tunable in the range 0.2-19.5 MeV, high degree of linear polarization ($\geq 99\%$), small bandwidth ($\leq 0.5\%$), spectral density larger than 10^4 photons/s/eV, and source spot sizes of about 10-30 microns.

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. Each stage is equipped with a dedicated diagnostics system for tuning and beam optimization. Additional monitoring instruments will be associated with the experimental stations for measuring the intensity and energy of the gamma beam.

2. Proposed measurements

Many nuclear reactions relevant in stellar environments proceed through very small cross sections which are difficult to determine experimentally. Photodissociation reactions are in principle easier to study as the phase space factor enhances the cross section 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.



2.1. The $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction

The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction is one of the most important reactions in nuclear astrophysics as its reaction rate strongly influences the present C/O ratio in the Universe. The $^{12}\text{C}(\alpha, \gamma)$ cross section has been measured experimentally down to energies around 1 MeV but must be extrapolated to helium-burning energies around 300 keV. This extrapolation is difficult as the cross section is a mixture of ground state transitions and cascade transitions with a complicated energy dependence and interference pattern. The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section is composed of 3 major components: $E1$, $E2$ ground state transitions, and several weaker cascade transitions. Modeling the evolution and explosion of massive stars requires a 10% uncertainty [2] on the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction cross section but the present uncertainties are of the order of 30%.

The cross section at 300 keV can only be determined through a combination of experimental measurements and theoretical extrapolation. There are two energy ranges which are important for the study the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section: at energies below 1 MeV to approach the Gamow peak or at higher energies to constrain the R-matrix extrapolation.

Several measurements of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction using gamma-ray detectors have been carried out with center of mass energies in the vicinity of 1.0 MeV. However, the astrophysical S-factors were determined with very low accuracies and one cannot rule out a low value of the extrapolated $E1$ S-factor. The new data also point out to a significant ambiguity in the value of the extrapolated $E2$ S-factor [3]. The goal of the measurements at ELI-NP will be to measure detailed cross sections and angular distributions, thus obtaining accurate values of the $E2/E1$ ratio. One of the advantages of measuring the photodissociation of ^{16}O is a gain in cross section due to detailed balance. Such an experiment requires gamma-ray beams in the range between 8 and 10 MeV. For example, a measurement of an angular distribution (1500 counts) with the gas e-TPC detector described in Sec. 3.1, at $E_\gamma = 8.26$ MeV with beam intensity available at ELI-NP will require 21 days of beam time [5].

The majority of $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ experimental and theoretical work over the last 50 years have concentrated in the energy region below 10 MeV. Measuring at higher energies, all the way to 14 MeV, would allow to include more states in the R-matrix analysis and to reduce the uncertainty of the extrapolation [6]. The aim of such measurements at ELI-NP would be to determine angular distributions and cross sections between known resonances with statistical precision of 3% or better. For example, a measurement of the weakest cross section between the 2^+ states at 9.84 and 11.52 MeV will require 12 hours of beam time for each experimental point.

2.2. Other (γ, α) and (γ, p) reactions

The 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 [4]. A direct ^{24}Mg photodissociation measurement using gamma beams of energies between 10.4 and 12 MeV will allow us to determine a much more accurate cross section needed in pre-supernova nuclear reaction network calculations. We expect 0.5 events/s in this energy region using the SSD array (see Sec. 3.2) with a 100 μg ^{24}Mg target and a conservative beam intensity [5].

One of the neutron sources for s-process nucleosynthesis in massive stars is the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction. Although the study of low-lying resonances in ^{22}Ne have been investigated before, there is considerable uncertainty in their strength. For example, the 470 keV resonance, could yield up to 1 event/hour when measured with the e-TPC detector at ELI-NP [5].

The $^{18}\text{O}(p, \gamma)^{19}\text{F}$ reaction could be the origin of the loss of catalytic materials from the CNO cycle, providing at the same time a link to the NeNa cycle. Large uncertainties dominate the strength of some of the low-lying resonances with the resonance at 90 keV known only with an upper limit. We expect a count rate of 5 events per day with the e-TPC and the beam intensities available at ELI-NP [5].

2.3. *p*-process reactions

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 produced in the *s*- and *r*-processes, where photodisintegration plays a primary role [4]. In the *p*-process nucleosynthesis, we measure photodissociation processes, including (γ, n) , (γ, α) and (γ, p) reactions. 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. Another critical process is the $^{96}\text{Ru}(\gamma, \alpha)^{92}\text{Mo}$ reaction, whose cross section dramatically changes the final abundance of ^{96}Ru .

Measurements of (γ, n) cross sections for the *p*-process nuclei, known as the destruction cross section, have never been measured because of their low natural abundance. Among the *p*-process nuclei, two odd-odd nuclei ^{180}Ta and ^{138}La draw highest attention and will be measured with the highest priority [7].

3. Proposed instruments

We consider a large area Silicon Strip Detector (SSD) and a gas Time Projection Chamber (e-TPC) to address important (γ, α) and (γ, p) reactions in nuclear astrophysics [5]. A 4π neutron detector based on ^3He proportional counters is proposed for photoneutron cross section measurements relevant for the *p*-process [7].

3.1. Time Projection Chamber Detector

The detector which is most suitable to investigate the multi alpha-particle decay of light nuclei such as ^{12}C and ^{16}O and the cross section of astrophysically-relevant (γ, p) or (γ, α) reactions, is a gaseous detector in which the gas acts at the same time as target for the nuclear reaction and detection medium. For this purpose an active target TPC with electronic readout (e-TPC) is proposed [5].

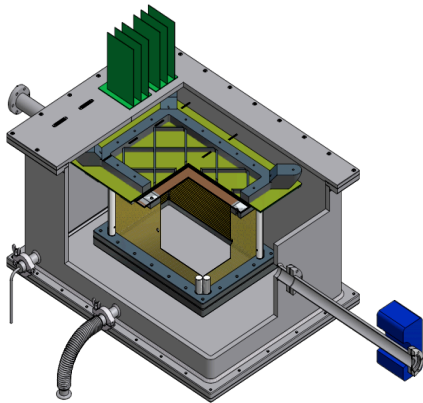


Figure 1. The internal structure of the e-TPC detector.

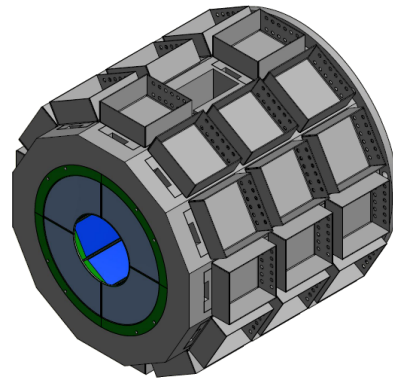


Figure 2. Drawing of the proposed silicon barrel detector array.

The active volume of the chamber, in which the reaction happens and the decay products are detected, will have a length of 35 cm and a square cross-section of 20 cm \times 20 cm, centered around the beam axis with a window for the gamma beam and another on the side for an alpha source. The schematic diagram of the e-TPC detector is shown in Fig. 1. The multiplication of the drifting electrons will be achieved by a sequence of 35 cm \times 20 cm Gas Electron Multiplier (GEM) foils fabricated at CERN. Combination of the 2D position in the collection plane with time information will allow the 3D reconstruction of the reaction products which is vital for

reactions in which more than two particles are involved or when more events happen within a short time-window of the information collection.

3.2. The Large Area Silicon Strip Detector

Silicon detectors represent an excellent solution for detecting charged particles: they guarantee exceptional energy resolution, with almost 100% efficiency, the thresholds can be set very low, they are very little sensitive to neutrons, gamma rays and electrons, which constitute the beam induced background. 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. In the past years, SSD arrays have been successfully designed for studies of nuclear astrophysics reactions (e.g. ORRUBA [8]).

The array shown in Fig 2 consists of X3 silicon-strip detectors manufactured by Micron Semiconductor arranged into a barrel configuration [5]. The X3 are 4-strip detectors 4 cm wide, position sensitive along the longitudinal axis (7.5 cm long), leading to a position resolution better than 1 mm. The barrel can 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 for reactions such as $^{24}\text{Mg}(\gamma, \alpha)^{20}\text{Ne}$. 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. If necessary, smaller angles can be covered by adding additional smaller rings at the two ends of the barrel.

3.3. High-efficiency 4π neutron detector

We propose to use a high-efficiency 4π triple-ring detector based on ^3He proportional counters for measuring (γ, n) reactions [7]. The active detection elements are 20 cylindrical counters (2.5 cm diameter and 49.5 cm length), each containing 12 bars of ^3He . The proportional counters are placed equally spaced in three concentric rings of 80, 140 and 200 mm diameter respectively. The first ring contains 4 detectors, while the other two contain 8 detectors each. The neutron moderator is a cube of $36 \times 36 \times 50 \text{ cm}^3$ made of polyethylene. The moderator is covered by additional 5-cm-thick polyethylene plates with 1-mm-thick cadmium metal for background neutron suppression. GEANT4 and MCNP simulations have been used to calculate an efficiency between 60 and 75 % for neutrons below 1 MeV.

4. Conclusions

The Gamma Beam System at ELI-NP will provide quasi-monochromatic, very intense gamma-ray beam with a high degree of polarizability starting in 2018. An ambitious experimental program to measure photodisintegration reactions relevant to nuclear astrophysics has been proposed. Several instruments are funded and in various stages of prototyping or execution: an active target TPC with electronic readout, a large area silicon detector array, and a 4π high-efficiency neutron detector.

References

- [1] EuroGammaS Association, Technical Design Report EuroGammaS proposal for the ELI-NP Gamma beam System *Preprint* arXiv:1407.3669 physics.acc-ph
- [2] W A Fowler 1984 *Rev. Mod. Phys.* **56** 149
- [3] M. Gai 2013 *Phys. Rev. C* **88** 062801(R)
- [4] C Iliadis 2007 *Nuclear Physics of Stars* (Weinheim: Wiley-VCH Verlag)
- [5] ELI-NP 2015 *GBS TDR4 - Charged Particle Detection at ELI-NP* to be published
- [6] D B Sayre 2012 *Phys. Rev. Lett.* **109** 142501
- [7] ELI-NP 2015 *GBS TDR2 - Gamma Above Neutron Threshold* to be published
- [8] S D Pain 2008 *AIP Conf. Proc.* **1090** 570