What do we expect to learn from γ-beam experiments related to nuclear astrophysics at ELI-NP?

The astroparticle physics and nuclear astrophysics research program at ELI-NP

Dimiter L. Balabanski[1,*]

[1]Extreme Light Infrastructure - Nuclear Physics (ELI-NP), Horia Hulubei National Institute for RD in Physics and Nuclear Engineering (IFIN-HH), 077125 Bucharest-Magurele, Romania

Abstract. This paper addresses some of the of open problems in photonuclear physics which await to be resolved using high-brilliance γ-ray beams, such as precise measurements of total or partial cross sections of photonuclear reactions related to astroparticle physics and nuclear astrophysics. The readiness for such measurements at ELI-NP, as well as the state-of-the-art instrumentation which is available are discussed. The possibility to utilize γ-beams with orbital angular momentum in photonuclear experiments is addressed, too.

1 Introduction

In recent reviews [1–4], the status and perspectives of photonuclear research were discussed, covering both, fundamental science and applications. The development of narrow-bandwidth γ beams with sufficient brilliance, based on the laser Compton backscattering (LCB) technique [5, 6], made possible detailed studies of lowest-lying excitation modes in atomic nuclei, i.e., $E1$, $M1$, and $E2$ excitations.

ELI-NP is a new user facility built in Romania as a part of the European large research infrastructure. There, the world's most powerful laser of 10 PW became operational in 2023 [7]. In addition, a γ-beam system, VEGA, is under construction. While waiting for the γ-ray beams, a versatile research program has been developed [8, 9] and the corresponding instruments for its realization were constructed and commissioned. Meanwhile, the research teams are involved in experiments in different laboratories, building expertise and producing results related to the future research program at the VEGA system of ELI-NP.

Nowadays nuclear astrophysics programs are a central topic for every nuclear physics laboratory round the globe. At ELI-NP, the nuclear astrophysics and astroparticle programs stay at the center of the research focus, too. This paper focuses on prospective studies related to nuclear astrophysics and astroparticle physics at ELI-NP. At the dawn of this century the National Research Council of the National Academies of Sciences, Engineering, and Medicine of USA published the report "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" [10] . Among them are:

> **How do cosmic accelerators work and what are they accelerating?**
> **How were the elements from iron to uranium made?**

---

[*] e-mail: dimiter.balabanski@eli-np.ro

2 Nuclear astrophysics studies at ELI-NP

Following the historical first detection of a binary neutron star merger by the LIGO-Virgo collaboration [11], the era of multi-messenger astronomy began, providing nuclear astrophysics with fundamental new insights into the astrophysical site for the *r*-process and on the nature of neutron-rich matter. Several research activities have been undertaken at ELI-NP related to nuclear astrophysics, *i.e.*, experimental activities in Romania and abroad, as well as theoretical studies in the field. These include:

- Experiments at the FEL HIγS facility of Duke University, NC, USA related to the Big Bang nucleosynthesis (BBN) photodisintegration reaction of ^{7}Li [12], the ^{16}O(γ,α)^{12}C reaction [13, 14], and (γ,p) and (γ,α) photo-nuclear reactions related to the *p*-process. The pilot experiment with detection of charged particles was carried out in 2019 [12] and the next measurements were done after the pandemia in 2022-2023. The measurement of the cross section of the ^{16}O(γ,α)^{12}C reaction [13, 14] was done with the Warsaw TPC [13–15];
- Experiments at the 3 MV Tandetron accelerator of IFIN-HH related to direct measurements of the ^{19}F(p,α)^{16}O reaction [16, 17];
- Experiments at the 9 MV Tandem accelerator of IFIN-HH related to measurements of nuclear level densities (NLD) and γ strength functions (γST) for nuclei of astrophysics interest [18, 19];
- Experiments at the 3 MV and 9 MV accelerators of IFIN-HH related to measurements of the cross sections (p,n) or (α,n) reactions [20];
- Calculations of the cross sections of photodisintegration and neutron-caption reactions, over the chart of nuclei [21, 22];
- Studies of the modification of nuclear astrophysics cross-sections in reactions with twisted photons [23, 24];
- Estimates of NLD for unstable nuclei of astrophysics interest.

Several state-of-the-art instruments have been constructed at ELI-NP for the realization of this program:

- The mini-TPC time-projection chamber with 256-channel electronic readout [15, 25]. The ELI-NP team is developing image-analysis algorithms for data sorting [25] which reduce considerably the data-processing time. In near future a time-projection chamber with a 1024-channel electronic readout, the ELITPC, will be available, too, within a joint project with the University of Warsaw. It is a replica of the Warsaw TPC [13–15];
- The 4π ELISSA spectrometer, which is designed as a barrel of three rings with lamp-shape end cups, consisting of Si DSSD detectors [26, 27];
- The ELIGANT-TN array, consisting of 28 ^{3}He proportional counters, for measurements of the cross sections of reactions with emission of neutrons [20, 29].

These instruments are used at experiments at the IFIN-HH accelerators, and will be available to users once the VEGA γ-ray facility becomes operational.

The mini-TPC is an active target detector which was specifically designed to operate with low gas pressures in the range from 100 mbar to 300 mbar and is optimised for studying reactions induced by narrow neutral beams, such as γ-rays or neutrons. The detector was built in collaboration with the University of Warsaw. The gas serves as both, target and detection medium. When a nuclear reaction occurs in the volume of the detector, the emitted charged particles trigger the ionization of the gas. The number of produced electrons correlates with the stopping power of the reaction products in the gas, *i.e.*, the kinetic energy of the reaction products. The secondary electrons emitted in the stopping of the reaction products are accelerated toward a collection pad by the applied constant electric field. To facilitate electron multiplication, a stack of gas electron multiplier (GEM) foils [28] is employed. They preserve the positional characteristics of electrons while undergoing amplification, ensuring accurate event reconstruction. An amplification of $\sim 10^6 - 10^8$ can be achieved using this method. After electron amplification, the charge is recorded by a *u-v-w* readout pad. This assembly, which is constructed with multi-layered PCB technology, consists of three layers of *u-v-w* grids arranged at 60° with respect to each other. This gives a total of $92\times92\times72$ channels for charge collection, which defines the spatial position resolution of the recorded events. The correlation between the spatial coordinates within the collection plane and the temporal data corresponding to the electron drift facilitates a three-dimensional reconstruction of particle trajectories.

3 Astroparticle physics studies at ELI-NP

The acceleration of cosmic rays in the range from 10^9 to 10^{16} eV is understood to be due to magnetic fields in space. However, the cosmic-ray spectrum reaches energies larger than 10^{20} eV. Nowadays the Pierre Auger Observatory [30] provides data about the highest-energy cosmic rays. The primary disintegration of the ultra-high energy cosmic rays (UHECR) in galactic or extra-galactic space is through the interaction of the particle species with the strongly Doppler-shifted cosmic microwave background leading to photonuclear reactions mainly in the GDR region. A reliable photo-nuclear cross-section inputs for a large set of $A \leq 56$ nuclei would significantly improve our understanding of the UHECR propagation and generation model [31, 32].

The objectives of the PANDORA project [33], which aims at UHECR interdisciplinary studies, are systematic measurements of the photonuclear response of nuclei with $A \leq 56$. On the nuclear physics side, there is a strong need for good quality photonuclear reaction data for most of the light nuclei of astrophysical interest below iron. The situation is further complicated by the non-availability of reliable theoretical models for required photo-nuclear cross sections since the prediction of mean-field theories and statistical models do not agree well with measured values in this region. These measurements would lead to new insights into the effect of clustering, shell structure, and *NN* correlations on the photonuclear response of these nuclei. The experiments will be carried out at the RCNP laboratory of Osaka University in Japan, and at iThemba Labs, Cape Town, South Africa, with virtual photons in (p,p′) reactions at zero degrees, and at ELI-NP with real photons. The PANDORA experimental program started at the RCNP laboratory in 2023. First experiments include a test measurement for ^{12}C [34], which demonstrates the correct handling of the experimental data, and a measurement for ^{10,11}B, ^{12,13}C, and ^{27}Al.

4 Selected results

Experimental studies related to reactions related to nuclear astrophysics or astroparticle physics require measurements of the emitted charged particles, protons or α particles. For this reason, the ELISSA spectrometer [26, 27] and the mini-TPC detector [15, 25] were constructed at ELI-NP. In a proof-of-principle experiment at HIγS, the BBN photodisintegration of ^{7}Li was studied [12]. Quasimonoenergetic photon beams in the energy range 4.4 – 10 MeV were impinging on a natural LiF target deposited on a 1.3 μm milor backing placed in the center of the detector array. The large-area annular silicon detector array (SIDAR) was used in the experiment in a lamp-shape configuration covering front and backward angles, and tritons and α particles were detected in coincidence by the segmented Si detectors. The deduced ^{7}Li(γ,t)^{4}He ground-state cross section, which is presented in Fig. 1 is in disagreement with previous data sets obtained using bremsstrahlung photons and electrodisintegration in the 6 to 10 MeV energy range which fail to observe the resonances in the cross section [36, 37].

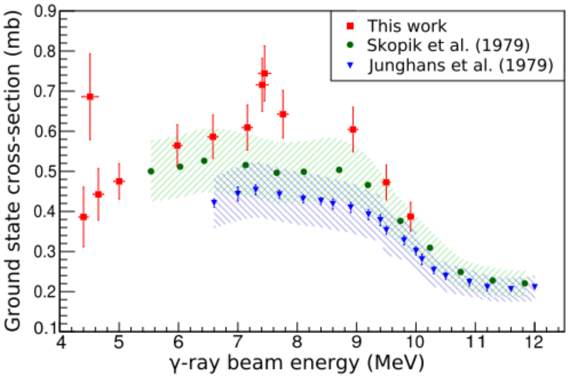

Figure 1. The ^{7}Li(γ,t)^{4}He ground-state cross section from the HIγS beam experiment is denoted as 'this work' [12]. The error bars represent both statistical and systematic uncertainties added in quadrature. Experimental results from Refs. [36, 37] are also shown including 15% systematic uncertainty band. Figure from Ref. [12]

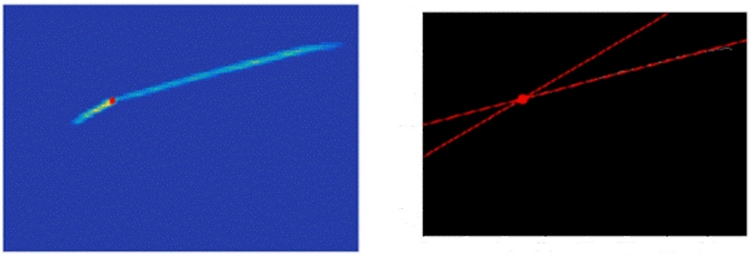

Figure 2. Image generated from the signals from one combination of *u*-*v*-*w* readout pads. Left: The original image with the reaction center detected; Right: Reaction vertex identification

In a TPC experiment, a large amount of data is recorded, typically several tens of TB. Most of the recorded data are background events. This asks for efficient algorithms for data sorting and data reduction. At ELI-NP, we have developed tools that use image processing algorithms to reconstruct the events in 3D [25]. The first step in this process is the creation of the images. Firstly, the background noise is removed from the 256 channels containing the signals from the three read-out planes. Secondly, a smoothing algorithm is applied on signals. Finally, a group of three image frames is constructed, using the data collected from the three pairs of read-out planes of the detector. One such image frame is presented in the left-hand side of Fig. 2. Then images are compressed and stored for further processing. The second step involves the detection of charged-particle tracks in each of the image frames. The abscissa for each image represents time and the ordinate corresponds to the channel number. The amplitude of the signal for each plane is represented by a color gradient. A line detection algorithm is used to find the tracks in each frame and define the origin of the reaction event. The line reconstruction is presented in the right-hand side of Fig. 2. The last step is to deduce the stopping power on the reaction residues from the reconstructed images. The image-analysis algorithms make it possible to reduce significantly the data-sorting time, as well as the volume to the processed data to typically below 10 TB.

Astrophysics models consider also the creation of orbital angular momentum (OAM) or twisted (vortex) photons in the Universe in the presence of strong magnetic fields [38–40]. This opens the need for revisiting a wide range of nuclear photonics problems, such as photodisintegration reactions. So far, in nuclear astrophysics studies photodisintegration reactions were considered to be induced by normal photons, having spin $1\hbar$. The modification of the photonuclear reaction cross sections in experiments with twisted photons, having OAM $\geq 2\hbar$, were evaluated [24] for about 140 nuclei of highest interest for nuclear astrophysics, and it has been demonstrated that the (γ,γ') and (γ,n) cross section are modified and for some nuclei, the relative contribution of GQR ($L = 2$) can be larger than 20%.

The laser-Compton backscattering between an electron beam and a vortex laser pulse was proposed to generate the twisted γ rays [41], and was considered to attain high photon energy while preserving the OAM of the incident laser photons [42–45]. So far, this process has not been demonstrated experimentally. The possibility of creating intense vortex γ-ray beams in laser-ion interactions was likewise discussed [46]. Generation of vortex photons was reported at high-power laser facilities, where electrons are accelerated in laser-matter interaction and high-energy photon bursts were produced via non-linear Compton scattering [47–51], however, the intrinsic OAM carried by these photons is not well understood yet. While an experiment with twisted photons for GQR studies at a γ-beam facility would be quite straightforward, it would be quite challenging to perform such studies with high-power lasers.

In conclusion, a versatile research program related to astrophysics and cosmic-ray physics is implemented at ELI-NP which started to deliver first results.

Acknowledgements: This work was supported by the Romanian Ministry of Research, Innovation and Digitalization under contracts PN 23 21 01 06 and PN-III-P4-PCE-2021-0595, within PNCDI III.

References

[1] A. Zilges, D.L. Balabanski, N. Pietralla, and J. Isaak, Prog. Part. Nucl. Phys. **122**, 103903 (2022)
[2] C. R. Brune, C. Matei, S. D. Pain and R. Smith, Eur. Phys. J. A **59**, 165 (2023)
[3] D.L. Balabanski, P. Constatnin, Eur. Phys. J. A **60**, 39 (2024)
[4] D.L. Balabanski, W. Luo, Eur. Phys. J. Spec. Top. (2024) printed online
[5] R.H. Milburn, Phys. Rev. Lett. **10**, 75 (1963)
[6] F.R. Arutyunian, V.A. Tumanian, Phys. Lett. **4**, 176 (1963)
[7] C. Radier, O. Chalus, M. Charbonneau, *et al.*, High Power Laser Sci. Eng. **10**, e21 (2022)
[8] S. Gales, K.A. Tanaka, D.L. Balabanski, *et al.*, Rep. Prog. Phys. **81**, 094301 (2018)
[9] K.A. Tanaka, *et al.*, Matter Radiat. Extremes **5**, 024402 (2020)
[10] National Research Council of the National Academies of Sciences, Engineering, and Medicine, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (The National Academies Press, Washington DC, 2003)
[11] B.P. Abbott *et al.* (LIGO and Virgo Collaborations), Phys. Rev. Lett. 119, 161101 (2017)
[12] M. Munch, C. Matei, S.D. Pain, *et al.*, Phys. Rev. C **101**, 055801 (2020)
[13] M. Cwiok, W. Dominik, A. Fijalkowska, *et al.*, EPS Web Conf. **279**, 04002 (2023)
[14] M. Cwiok, W. Dominik, A. Fijalkowska, *et al.*, EPS Web Conf. **290**, 01004 (2023)
[15] M.Gai, D.Schweitzer, S.R.Stern, *et al.*, Nucl. Instrum. Meth. Phys. Res. A **954**, 161779 (2020)

[16] G.L. Guardo, T. Petruse, D. Lattuada, *et al.*, Eur. Phys. J. A **59**, 65 (2023)
[17] T. Petruse, G.L. Guardo, D. Lattuada, *et al.*, Eur. Phys. J. A (2024) in preparation
[18] P.-A. Söderström, A. Kusoglu, D.L. Balabanski, *et al.*, Nuovo Cim. C **47**, 58 (2024)
[19] P.-A. Söderström, A. Kusoglu, D.L. Balabanski, *et al.*, Phys. Rev. C (2024) submitted
[20] Rajat Roy, D.A. Testov, D. Choudhury, *et al.*, (2024) these proceedings
[21] H. Y. Lan, Y. Xu, W. Luo, *et al.*, Phys. Rev. C **98**, 054601 (2018)
[22] H.Y. Lan, W. Luo, Y. Xu, *et al.*, Phys. Rev. C **105**, 044118 (2022)
[23] D.L. Balabanski, J. Phys. Conf. Series **2453**, 012030 (2023)
[24] Y. Xu, D.L. Balabanski, V. Baran, *et al.*, Phys. Lett. B (2024) submitted
[25] A.I. Rotaru, D.A. Testov, D.Kahl, *et al.*, *Fundamental and Applied Problems of Modern Physics, Sect. I Nuclear and Particle Physics* (Uzbekistan Academy of Sciences, Tashkent, 2023) pp. 38-42
[26] C. Matei, D.L. Balabanski, O. Tesileanu, *et al.*, Nuovo Cim. C **39**, 360 (2016)
[27] G.L. Guardo, D. Balabanski, S. Chesneyskaya, *et al.*, *Springer Proceedings in Physics, v. 219* (Springer, Cham, 2019) pp. 219-223
[28] F. Sauli, Nucl. Instrum. Methods. Phys. Res. A **368**, 531 (1997)
[29] P.-A. Söderström, *et al.*, Nucl. Instrum. Meth. Phys. Res. A (2024) in preparation
[30] The Pierre Auger Collaboration, Nucl. Instrum. Meth. Phys. Res. A **798**, 172 (2015)
[31] E. Khan, S. Goriely, D. Allard, *et al.*, Astropart. Phys. **23**, 191 (2005)
[32] R. Alves Batista, *et al.*, J. Cosmol. Astropart. Phys. **10**, 063 (2015)
[33] A. Tamii, L. Pellegri, P.-A. Söderström, *et al.*, Eur. Phys. J. A **59**, 208 (2023)
[34] A. Gavrilescu, P.-A. Söderström, *et al.*, UPB Sci. Bull. A (2024) in preparation
[35] D.W. Bardayan, *et al.*, Phys. Rev. C **63**, 065802 (2001)
[36] G. Junghans, K. Bangert, U. E. P. Berg, *et al.*, Z. Phys. A **291**, 353 (1979)
[37] D.M. Skopik, J. Asai, E.L. Tomusiak, and J.J. Murphy, Phys. Rev. C **20**, 2025 (1979)
[38] M. Harwit, Astrophys. J. **597**, 1266 (2003)
[39] F. Tamburini, B. Thide, G. Molina-Terriza, and G. Anzolin, Nature Phys. **7**, 195 (2011)
[40] T. Maruyama, T. Hayakawa, T. Kajino, and M.-K. Cheoun, Phys. Lett. B **826**, 136779 (2022)
[41] U. D. Jentschura and V. G. Serbo, Phys. Rev. Lett. 106, 013001 (2011)
[42] V. Petrillo, G. Dattoli, I. Drebot, and F. Nguyen, Phys. Rev. Lett. **117**, 123903 (2016)
[43] M. Katoh, M. Fujimoto, H. Kawaguchi, *et al.*, Phys. Rev. Lett. **118**, 094801 (2017)
[44] Y.-Y. Chen, K. Z. Hatsagortsyan, and C. H. Keitel, Matter Radiat. Extremes **4**, 024401 (2019)
[45] O. V. Bogdanov, P. Kazinski, and G. Y. Lazarenko, Phys. Rev. D **99**, 116016 (2019)
[46] V. G. Serbo, A. Surzhykov, and A. Volotka, Ann. Phys. (Berlin) **534**, 2100199 (2021)
[47] Z Gong, R.H. Hu, H.Y. Lu, *et al.*, Plasma Phys. Control. Fusion **60**, 044004 (2018)
[48] Y.Y. Liu, Y.I. Salamin, Z. Dou, *et al.*, Opt. Lett. **45**, 395 (2020)
[49] J. Wang, X.B. Li, L.F. Gan, *et al.*, Phys. Rev. Applied **14**, 014094 (2020)
[50] Y.T. Hu, J. Zhao, H. Zhang, *et al.*, Appl. Phys. Lett. **118**, 054101 (2021)
[51] M. A. Bake, T. Suo, and X. Baisong, Plasma Sci. and Technol. **24**, 095001 (2022)