Experiments with brilliant gamma beams at ELI-NP: A glimpse in the future

Dimiter L. Balabanski
Extreme Light Infrastructure – Nuclear Physics, Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, Reactorului Str. 30, 077125 Bucharest – Magurele, Romania
dimiter.balabanski@eli-np.ro

Abstract. The emerging experimental program with brilliant gamma beams at the Extreme Light Infrastructure – Nuclear Physics facility (ELI-NP), which is under construction in Magurele, Romania is presented with emphasis on the prepared day-one experiments. Experiments at ELI-NP will cover nuclear resonance fluorescence (NRF) measurements, studies of large-amplitude motions in nuclei, photofission and photonuclear reactions of astrophysics interest, and measurements of photonuclear reaction cross sections. The physics cases of the flagship experiments at ELI-NP are discussed, as well as the related instruments which are under construction for their realization.

1. Introduction

The Extreme Light Infrastructure (ELI) Pan-European facility initiative represents a major step forward in quest for extreme electromagnetic fields and related research. The Extreme Light Infrastructure – Nuclear Physics (ELI-NP), which is under construction in Magurele, Romania, is one of the three pillars of the ELI, and aims at utilization of extreme electromagnetic fields for nuclear physics and quantum electrodynamics research and applications. At ELI-NP, high-power laser pulses together with brilliant gamma beams are the main research tools. It is one of the three Pan-European nuclear physics laboratories, which are at present under construction in the EU as landmark facilities within the ESFRI scheme [1]. The ELI-NP facility will be commissioned in 2018 and will become operational as a user facility in 2019.

The ELI-NP gamma-beam system (GBS) [2] will be superior to the laboratories which are operational at present [3,4] in terms of beam intensity and bandwidth. It aims at providing almost fully polarized (> 95%), narrow bandwidth (≤ 0.5%) γ-ray beams in the energy range between 200 keV and 19.5 MeV with a spectral density of $10^4$ photons/(s·eV). The quasi-monochromatic γ beams will be produced via Compton backscattering of laser pulses off electron bunches accelerated to relativistic energies. The 100-Hz laser pulses will be delivered by a Yb:YAG laser. The electron bunches will be accelerated by a warm linac. The high-brilliance and narrow bandwidth of the gamma beam is due to the high spectral luminosity of the photon-electron collision, $L = 2.5 \cdot 10^{35}$ cm²·s⁻¹ [5], which is achieved by tight focusing of the electron beam at the interaction point, e.g., the focal spot sizes of the laser and electron beams are ≤ 30 μm. The electron beam emittance is of upmost importance for the production of a brilliant quasi-monochromatic gamma beam by the ELI-NP GBS.
The ELI-NP GBS research program, which is under discussion within the nuclear photonics community, covers nuclear resonance fluorescence (NRF) measurements, studies of large-amplitude motions in nuclei, photofission and photonuclear reactions of astrophysics interest, and measurements of photonuclear reaction cross sections. Recently, the ELI-NP GBS research program was published in a series of technical design reports (TDR) [6-9] and reviewed in a number of papers [10-12]. The targeted experiments, which take advantage of the expected parameters of the ELI-NP gamma beams, cannot be done at present elsewhere and focus at key topics of photonuclear research. Given the fact that the ELI-NP project is realized within the EU Structural Funds, it is of importance to demonstrate early results. Thus, the day-one experimental program at the ELI-NP GBS is designed following few basic principles, e.g., start experiment preparations early enough and pick up the lowest-hanging fruits first, prioritize and identify flagship topics that are most attractive, yet doable on the defined short time scale, which is needed for generating further energy in the project. Here, the current ideas for day-one experiments, related to NRF and gamma-ray experiments above the particle evaporation threshold (GANT), photonuclear reactions of astrophysics interest and photofission measurements, are discussed. The expected performance of the instruments for their realization is presented, too.

2. NRF experiments
The NRF technique is an outstanding tool for the investigation of low-lying dipole excitations in atomic nuclei. In the experiment photons are scattered off bound nuclear states. For a recent review see Ref. [13]. The high-brilliance, narrow-bandwidth, pencil-size, polarized ELI-NP beams will result in unique experiments addressing the availability, sensitivity and precision experimental frontiers of NRF measurements. There are experiments that can performed already in the commissioning phase of ELI-NP. A most appealing case, which can be done already at low energies, is a photo-activation measurement of $^{184}$Ta, i.e., a measurement of the subsequent $\gamma$ decay as a function of the gamma-beam energy. There are indications from a bremsstrahlung experiment about the doorway states, through which the 9$^+$_isomer is de-excited [14,15]. At ELI-NP this experiment can be done with the needed sensitivity and precision. Other ideas for day-one NRF experiments include studies of actinides that have 10,000-year lifetimes. NRF experiments at present-day facilities require large-mass targets, of the order of grams, while at ELI-MP milligram targets will be used. Thus, the availability frontier will be push further down at ELI-NP. On a longer term, parity-doublet studies [6,16] would be of a high impact, addressing both the sensitivity and precision frontiers.

For the realization of this experimental program, the ELIADE detector array [6] is constructed with highest priority. It consists of eight segmented HPGe Clover detectors with a digital readout. Both features are of importance for dealing with the time structure of the gamma beam, which has 10-Hz macropulses, each of them consisting of a train of 32 micropulses separated by 16 ns. The ELIADE array is designed in such a way that polarization and angular correlation measurements will be possible. The detector efficiency is about 6%, which will make possible $\gamma\gamma$ coincidence measurements. An artistic view of the ELIADE array is presented in Fig. 1, which reveals the positioning of the Clover detectors in two rings at $90^\circ$ and $135^\circ$ with respect to the gamma beam direction and in a horizontal and a vertical plane. Recently, in-beam tests of the detectors were done, using a triggerless data acquisition system (DAQ), and the expected performance has been achieved [17].

3. GANT experiments
Experiments above the neutron evaporation threshold include gamma-induced photodisintegration and studies of collective modes in nuclei, as described in the corresponding TDR [7]. The designed GANT research program is complimentary to what is possible to be done at other facilities round the world and aims at addressing hot problems in a number of research fields, such as photodisintegration cross sections for low-abundance nuclei relevant to the $p$-process nuclear synthesis, nuclear structure of GDR from the studies of the $\gamma$ and neutron decays, studies of neutron-capture reactions on $s$-process branching points, where $\gamma$-decay of longer lived isotopes competes with neutron capture, and measurements of the cross sections of photonuclear reactions. Some studies can be done already during the commissioning
of the GBS, e.g. \(^{9}\text{Be}(\gamma,n)\) reaction at \(\gamma\)-beam energies of 1.65 to 3.20 MeV. The cross section for this reaction has been measured several times. However, there is considerable discrepancy between the reported results [18,19]. An independent measurement could resolve this discrepancy in early ELI-NP operation.

The \(\gamma\) decay of GDR in \(^{208}\text{Pb}\) is a case for a day-one experiment because very detailed measurement on the absorption cross sections with fine structures is available for this case [20], while only few data with large uncertainties exist for the \(\gamma\)-decay branch [21]. On a longer term, detailed studies of E1 strength in atomic nuclei will be possible, which will provide reliable estimates of nuclear polarizability, an observable, which some theories relate to the symmetry term of the nuclear equation of state (EoS) [22-24]. In addition, detailed studies of the gamma-decay of the GDR both to the ground and excited states will be possible, which will set constraints on different theoretical models. It is worth noting that these experiments will have similar resolution to what is achieved with the Grand Raiden spectrometer at RCNP, Osaka in \((p,p')\) experiments [25]. Thus, the ELI-NP experimental program will provide high-resolution complimentary measurements of the distribution of the E1 and M1 strength in nuclei using a \(\gamma\) probe.

It has been demonstrated that the neutron-capture rates can be determined by inverse photodisintegration and photoexcitation studies [26,27]. Such measurements be pursued for many of the critical \(s\)-process branching point nuclei, which will help to determine the neutron flux and the temperature conditions at the \(s\)-process sites. An important aspect of this research program, is the resolution of large discrepancies of the partial \((\gamma,xn)\) cross sections, which are reported [28-30].

**Figure 1.** An artistic view of the ELIADE array, revealing the positioning of the HPGe Clover detectors with respect to the direction of the \(\gamma\) beam.

**Figure 2.** Schematic view of the placement of the ELIADE and ELIGANT-GN detector arrays in the E8 experimental hall of the ELI-NP laboratory complex. The \(\gamma\) beam is transported from right to left along the axis of the detector arrays.

Two main experimental instruments are been built to pursue the foreseen research program. The first one, named ELIGANT-TN, is based on \(^{3}\text{He}\) tubes embedded in polyethylene for measurements of thermal neutrons. The ELIGANT-TN array is designed to have flat efficiency of about 40% over a large range of energies of the incident neutrons [31]. The second instrument, named ELIGANT-GN, is a 4\pi array of scintillators for measurements of \(\gamma\) rays and fast neutrons in different energy ranges. It consists of 34 LaBr\(_3\):Ce and CeBr\(_3\) 3” x 3” scintillators of cylindrical shape, up to 60 BC501A liquid scintillators and up to 30 G820 \(^{6}\text{Li}\) glass scintillators [32]. The ELIGANT-GN array will allow simultaneous studies of the \((\gamma,\gamma')\) and \((\gamma,n)\) de-excitation of the GDR. The \(\gamma\)-ray efficiency will be sufficient for \(\gamma\gamma\) coincidence measurements, too. All detectors, which are needed for the construction of the arrays have been delivered and the tests demonstrated that the expected performance is achieved. At present the
implementation team works on the construction of the detector assembly. A schematic view of the placement of the ELIade and the ELIGANT-GN arrays in the E8 experimental hall of the ELI-NP laboratory building is shown in Fig. 2.

4. Charged particle detection experiments

Photonuclear reactions with detection of charged particles are another topic of interest within the ELI-NP research program. The physics cases under study are related to nuclear reactions of astrophysics relevance. Two instruments are under construction for these studies, a 4π silicon strip detector (SSD) array, named ELISSA, and a time-projection chamber with electronic readout, ELITPC, which are described in the corresponding TDR [9]. Two flagship experiments are considered, e.g. studies of the \(^{7}\text{Li}(\gamma,\alpha)^{4}\text{He}\) and the \(^{16}\text{O}(\gamma,\alpha)^{12}\text{C}\) reactions. The measurement of the \(^{7}\text{Li}\) photodisintegration is closely related to the understanding of the Big Bang nucleosynthesis (BBN), while the study of the \(^{16}\text{O}(\gamma,\alpha)^{12}\text{C}\) reaction cross section will look for an answer of the decades old problem of understanding of the \(^{4}\text{He}\) burning in massive stars. The first experiment will be carried out with the ELISSA detector array, where one can measure effectively \(t\) and \(\alpha\) particles, the products of the \(^{7}\text{Li}\) photodisintegration. A pilot measurement [33] was performed at the H\(_{\gamma}\)S facility with the ORRUBA array [34] from ORNL. This study will continue with better resolution and at lower \(\gamma\)-beam energies at ELI-NP. The ELISSA SSD detectors have undergone laboratory tests and the expected performance have been reached [35]. Since both, electromagnetic and nuclear interactions are time reversal, following the principle of detailed balance, the cross-section of an \((\alpha,\gamma)\) process can be determined from the measurement of the time inverse \((\gamma,\alpha)\) reaction. An advantage of measuring the photo-dissociation of \(^{16}\text{O}\) is a factor of 50–100 gain in cross-section. Such an experiment requires intense \(\gamma\)-ray beams of energies of 10 MeV and less. The proposed measurements of the \(^{16}\text{O}(\gamma,\alpha)\) photo-dissociation reaction with the gas-filled active target ELITPC detector, which is under construction at ELI-NP [9], are a continuation of the studies performed at the H\(_{\gamma}\)S facility [36]. A schematic drawing of the ELITPC detector is presented in Fig. 3. The figure reveals the electrode case structure and the positioning of the GEM detectors [37] and the segmented anode of the electronic readout. The ELITPC will use GET electronics [38] for data processing of the 1024-channel readout.

ELITPC experiments at the ELI-NP GBS will benefit from the \(\gamma\)-beam brilliance, the higher reaction rates which will be achieved due to the greater thickness of the extended gas target and, simultaneously, the low-energy charged particles produced can be detected with sufficient angular and energy resolution. In addition, more complex decay events can be reconstructed, and background events can be detected, and rejected from the analysis. Quick and easy changes of the gas target material will allow for studies with different chemical elements, \(i.e.\) studies of different reactions of interest. The experiment will profit from the usage of highly isotopically enriched gases. The design of the ELITPC is in an advanced stage. A prototype, called mini-TPC, which has a 256-channel readout, has been successfully tested in-beam, using an \(\alpha\) beam, and the track reconstruction of scattered \(\alpha\)-particles was demonstrated [39].
5. Photofission experiments
The goal of these studies is the exploration of the unique photofission reactions enabled by the GBS at ELI-NP, which are described in the corresponding TDR [8]. The flagship experiment is the investigation of fission transmission resonances in the second and third potential minima in the actinides, thus mapping the fission barriers as a function of the photon-beam energy in the range of about 5 to 7 MeV [40]. The experiments aim at the characterization of these transmission resonances through angular distributions, masses and charges of the fission fragments. A pilot experiment on $^{238}\text{U}$ has been carried out at the HILS facility [41], but the available beams there lack resolution to resolve the resonance states. The advantages of the photofission studies at ELI-NP are the high flux, $1.5 \cdot 10^8 \text{γ/s}$, and the small bandwidth $\Delta E/E = 0.3\%$, e.g. 15 keV at 5 MeV. This will allow resolving the fewer 1$^-$ and 2$^+$ transmission resonances in the second and third minimum that will be preferentially populated in photofission in contrast to the many more resonances that are populated with hadronic probes. This will lead to an accurate mapping of the potential energy surface (PES) of the actinide nuclei.

Related to GBS photofission studies, the research programme includes also measurement of kinetic energy, angular, mass and charge distribution of fission fragments, measurements of absolute photofission cross-sections, studies of rare photofission events, such as triple fission, highly asymmetric fission, clusterization phenomena, the predicted cold valleys of fission potential, etc [8].

Two instruments are being developed for photofission studies at the ELI-NP GBS, the ELI-BIC and ELITHGEM detector arrays [8]. Their design is in an advanced phase. The ELI-BIC array consists of four double-sided Frisch-grid Bragg ionization chambers (DSBIC). Each ionization chamber in the ELI-BIC array will be coupled to eight $\Delta E$-E detectors covering a solid angle of $\pi$, for the study of light charge particles, mostly long range $\alpha$-particles from ternary fission events. A $\Delta E$-E detector consists of a gas detector coupled with a double sided Si strip detector. The ELITHGEM array consists of thick gas electron multipliers (THGEM), which allows measurement of angular distributions of fission fragments. The ELI-BIC and ELITHGEM detectors have undergone different tests and it has been demonstrated that the expected performance has been reached [42,43].

6. Summary
The progress of the preparation of the day-one research program at the ELI-NP GBS has been reported. All instruments, which are required to take data at the start of the facility, are in advanced stage of construction and will be commissioned during the commissioning phase of the GBS. The detectors and the electronics, which are needed for construction of the arrays, have been delivered and the tests demonstrate that the expected performance have been achieved. Cases of flagship experiments were defined, and certain low-hanging fruits which should be measured first at the start of the facility have been identified.

In short, the ELI-NP physics team will be ready in time with all the instrumentation needed for taking data at the ELI-NP GBS, and will be prepared to provide services to the international nuclear physics community when ELI-NP becomes operational as an open access facility in 2019.

Acknowledgments
Work supported by the Extreme Light Infrastructure Nuclear Physics (ELI-NP) Phase II, a project co-financed by the Romanian Government and the European Union through the European Regional Development Fund – the Competitiveness Operational Programme (1/07.07.2016, COP, ID 1334).

References
[1] ESFRI Strategy Report on Research Infrastructures: Roadmap 2016, ISBN: 978-0-9574402-4-1, www.esfri.eu/roadmap-2016
[2] Adriani O et al. 2014 arXiv:1407.3669 [physics.acc-ph]
[3] NewSUBARU synchrotron radiation facility, University of Hyogo, http://www.lasti.u-hyogo.ac.jp/NS-en/
[4] High Intensity Gamma-Ray Source (HIGS), Triangle Universities Nuclear Laboratory,
http://www.tunl.duke.edu/facilities/

[5] Bacci A et al. 2013 J. Appl. Phys. 113 194508
[6] Ur C A et al. 2016 Rom. Rep. Phys. 68 S483
[7] Camera F et al. 2016 Rom. Rep. Phys. 68 S539
[8] Balabanski D L et al. 2016 Rom. Rep. Phys. 68 S621
[9] Tesileanu O et al. 2016 Rom. Rep. Phys. 68 S699
[10] Filipescu D et al. 2015 Eur. Phys. J. A 51 185
[11] Gales S et al. 2016 Phys. Scr. 91 093004
[12] Balabanski D L et al. 2017 Europhys. Lett. 117 28001
[13] Kneissl U, Pietralla N, Zilges A, 2006 J. Phys. G 32 R217
[14] Belic D et al. 2002 Phys. Rev. C 65 035801
[15] Belic D et al. 1999 Phys. Rev. Lett. 83 5242
[16] Beene J et al. 2015 Phys. Lett. B 741 128
[17] Capponi L et al. 2017 Nucl. Instr. Meth. Phys. Res. A (in preparation)
[18] Unsunomiya H et al. 2015 Phys. Rev. C 92 064323
[19] Arnold C W et al. 2012 Phys. Rev. C 85 044605
[20] Tamii A et al. 2011 Phys. Rev. Lett. 107 062502
[21] Beene J R et al. 1990 Phys. Rev. C 41 920
[22] Reinhardt P-G, Nazarewicz W 2010 Phys. Rev. C 81 051303
[23] Pickarewicz J 2011 Phys. Rev. C 83 034319
[24] Roca-Maza X et al. 2011 Phys. Rev. Lett. 106 252501
[25] Tamii A 2009 Nucl. Instr. Meth. Phys. Res. A 605 326
[26] Raut R et al. 2013 Phys. Rev. Lett. 111 112501
[27] Sauerwein A et al., 2014 Phys. Rev. C 89 035803
[28] Varlamov A V et al. 1999 Atlas of Giant Dipole Resonances, Preprint INDC (NDS) 394
[29] Berman B, Fultz S 1975 Rev. Mod. Phys. 47 713
[30] Dietrich S, Berman B 1988 At. Data Nucl. Data Tables 38 199
[31] Unsunomiya H et al. 2017 Nucl. Instr. Meth. Phys. Res. A 871 135
[32] Krzysiek M et al. 2017 Nucl. Instr. Meth. Phys. Res. A (in preparation)
[33] Matei C et al. 2017 Phys. Rev. C (in preparation)
[34] Pain S D et al. 2007 Nucl. Instr. and Meth. in Phys. Res. B 261 1122
[35] Chesnevskaya S et al. 2017 JINST (in preparation)
[36] Zimmerman W R et al. 2012 Phys. Rev. Lett. 110 152502
[37] Shalem S K et al. 2006 Nucl. Instr. Meth. Phys. Res. A 558 468
[38] Pollacco E et al. 2012 Phys. Procedia 37 1799
[39] Bihałowicz J S 2015 AIP Conf. Proc. 1645 301
[40] Krasznahorkay A 2011 Handbook of Nuclear Chemistry vol 1, ed A Vertes et al. (Dordrecht: Springer) p 281
[41] Csige L et al. 2013 Phys. Rev. C 87 044321
[42] Choudhury D et al. 2017 Acta Phys. Pol. B 48 559
[43] Balabanski D L et al. 2017 EPJ Web Conf. (in print)