Experimental programme with high-brilliance gamma beams at ELI-NP

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

1. Introduction
The Extreme Light Infrastructure Nuclear Physics (ELI-NP) [1] is in its final phase of implementation. The high-power laser system (HPLS) and the laser-beam transport system (LBTS) are undergoing commissioning. The gamma-beam system (GBS), after certain delay, is on the route of implementation. Parallel to the construction of the basic experimental systems, the HPLS, LBTS and GBS, the ELI-NP team is finalizing the work on the construction of the major experimental stations and is working on the preparation of the commissioning and day-one experiments. The ideas for first experiments, as well as the design of the experimental set-ups, were recently reviewed [2–4]. The emerging day-one experimental programme with brilliant gamma beams covers nuclear resonance fluorescence (NRF) measurements, experiments at gamma-beam energies above the neutron evaporation threshold, such as measurements of photonuclear reaction cross-sections and studies of large-amplitude motions in nuclei, photo-fission experiments and studies of photonuclear reactions of astrophysics interest, e.g. reactions with emission of charged particles. The status and the performance of the instruments, which are under construction for the realization of this experimental programme, are presented.

2. Day-one experiments with gamma-beams at ELI-NP
Photonuclear physics is a field, which dates back to the pioneering experiments in nuclear physics in the 1930s of the last century. It is related to the discovery of the giant dipole resonance (GDR) [5] and since then is an outstanding tool for studies of different nuclear excitations, photonuclear reactions and photo-fission. The availability of narrow bandwidth beams and the spin selectivity of the photon scattering enables detailed studies of the fragmentation of the strength of collective excitation modes, such as E1, M1 and E2, even at excitation energies where the density of levels is high.

The ELI-NP GBS is expected to provide high-brilliance, narrow bandwidth, polarized gamma-beams with parameters superior to parameters of the beams which are available so far worldwide. This will result in experiments with higher sensitivity and improved accuracy.
2.1. Nuclear Resonance Fluorescence

Nuclear Resonance Fluorescence is a process of absorption of a photon, which excites a nuclear level, and the subsequent $\gamma$ decay by emission of a photon. NRF experiments form the core of the ELI-NP GBS research program. For their realization, a gamma-ray spectrometer, called ELIADE [6], is designed and is under construction. It consists of eight highly-segmented, large-volume HPGe Clover detectors, positioned in two rings, at 90° and 135° with respect to the gamma beam and in the horizontal and vertical planes, which allows measurements of gamma-ray multipolarities and angular correlations. At present, the assembling of the spectrometer is ongoing. A photograph of the ELIADE frame with a reaction chamber, which is used for alignment, as mounted in the ELI-NP experimental hall, is shown in the left-hand-side of Figure 1. The source commissioning of the array will be finalized in 2019.

![Figure 1: The ELIADE (left) and the ELIGANT-GN (right) support frames mounted in the ELI-NP experimental halls.](image)

NRF studies will be carried out with the start of the facility during the commissioning and day-one phase. The pencil-size gamma beams at ELI-NP will provide access to targets that are available in small quantities and will open the actinide region for studies of low-lying E1 and M1 excitations. Detailed high-resolution studies of the dipole strength distribution in the region of the pygmy dipole resonance (PDR) will be done. An experiment, which can be done already in the commissioning phase, is a photo-activation measurement of $^{180}$Ta, i.e. a measurement of the subsequent $\gamma$ decay as a function of the $\gamma$-beam energy. The detailed knowledge of the doorway states and the flux which passes through them, provides a sensitive thermometer for studying the star conditions during the nucleosynthesis. Indications from a bremsstrahlung experiment about the doorway states, through which the $F = 9$, $T_{1/2} > 1.2 \cdot 10^{15}$ year isomer is de-excited, have been reported [7,8]. At ELI-NP, due to the availability of high-brilliance beams with narrow bandwidth, this measurement can be done with the needed sensitivity and precision.

2.2. Gamma-beam experiments above the neutron evaporation threshold (GANT experiments)

GANT experiments are a specific niche for the ELI-NP GBS experimental program. Two research fields will be explored within this programme, measurements of photo-neutron reaction cross-sections and studies of large-amplitude motions in nuclei.

The data base of photo-neutron reaction cross sections suffers from inconsistencies. Measurements of the same reaction, which were done at different laboratories, disagree with each other. This asks for
new precise measurements, which can be done with high-resolution gamma beams. Recently, an effort has been undertaken to resolve this problem by measuring key photo-neutron reaction cross sections at laser Compton backscattering (LCS) facilities [9]. However, present-day LCS laboratories provide beams with bandwidths of few percent, which asks for energy unfolding of the measured cross sections, a procedure which relies on the precise determination of the incident LCS γ-ray beam energy spectra. Experiments at ELI-NP will be done with gamma beams with a bandwidth which is an order of magnitude better, thus yielding more reliable results. An example for the existing discrepancies is the photodisintegration cross section in 7Be, which has been measured in several experiments. The last three measurements were performed at LCS facilities and provide discrepant results within the energy ranges where the cross section varies significantly within the energy spread of the incident γ-ray beam, while for the slow energy variation regions all three data sets are in relatively good agreement [10-12]. Photo-neutron (γ,n) cross sections will be measured at ELI-NP using an in-beam neutron multiplicity technique utilizing the high-and-flat efficiency neutron detector ELIGANT-TN [13].

Simultaneous γ-ray and neutron spectroscopy GANT experiments will be done with the ELIGANT-GN 4π spectrometer which consists of 30 LaBr3:Ce and CeBr3 large volume 3” x 3” scintillation detectors and of up to 60 BC501A liquid and GS20 3″ Li glass scintillators for detection of neutrons [13,14]. A photograph of the support frames of ELIGANT-GN is displayed in the right-hand-side of Figure 1. In front is the support frame for the γ-ray scintillators, which will be mounted at backward angles, and at the back is the frame for the neutron detectors, which will cover the upper hemisphere. The source commissioning of the array will be finalized in 2019. First experiments with the ELIGANT-GN array, which will enable coincidence γ-ray measurements, will address detailed studies of the fragmentation of the E1, E2 and M1 strength of collective nuclear excitations.

2.3. Gamma-beam experiments with detection of charged particles
Charged-particle experiments will focus studies of photonuclear reactions related to nuclear astrophysics research. Day-one experiments, which are considered at ELI-NP, are the photodisintegration of 7Li and the 16O(γ,α)12C reaction at energies close to the Gamow window. The mirror α-capture reactions 3H(α,γ)7Li and 3He(α,γ)7Be have been at odds in the last five years as the different theoretical models agree well with the 3He(α,γ)7Be experimental cross section but could not reproduce the 3H(α,γ)7Li experimental results. Our approach is to study the time-reversal 7Li(γ,α)3He reaction, research which already started at the HlYS γ-beam facility, Duke University [15] and will be continued at ELI-NP with improved energy resolution. A study of the 12C(α,γ)16O reaction will help the understanding of He burning in massive stars. The cross section of this reaction has been measured down to energies around 1 MeV but must be extrapolated to helium-burning energies down to 300 keV. There are two energy ranges, which are important for the study of the 12C(α,γ)16O reaction cross section, at energies below 1 MeV to approach the Gamow peak and at higher energies to constrain the R-matrix extrapolation. The approach for such studies at ELI-NP is the measurement of the time-reversal 16O(γ,α)12C reaction.

Two instruments will be used for the realization of these experiments, a 4π array of Si strip detectors, called ELISSA [16,17] and a time-projection chamber (ELITPC) with an 1024-channel electronic read-out [16]. The ELISSA detectors were tested with sources and in-beam and the expected performance was demonstrated [18]. A mini-TPC detector with 256-channel read-out was constructed and the needed performance for such experiments was demonstrated [19,20].

2.4. Photo-fission experiments
Photo-fission experiments at ELI-NP address a versatile programme for detailed studies of photo-fission phenomena, such as measurement of kinetic energy, angular, mass and charge distribution of fission fragments, measurements of absolute photo-fission cross-sections, studies of rare photo-fission modes, such as triple fission, highly asymmetric fission, clustering phenomena, mapping of the fission barriers, e.g. the predicted cold valleys of fission potential, etc. [21].

The flagship experiment within this research programme is the investigation of fission transmission resonances in the second and third potential minima in the actinides. Studies of the photo-fission cross-
section and fragment identification, will result in mapping the fission barrier landscape as a function of the photon-beam energy in the range from 4 MeV to 8 MeV [22]. First measurements will be done on $^{238}$U. It was recently measured at the HiYS facility in Duke University and the results indicate the existence of a third minimum of the fission barrier [23]. The measurements at ELI-NP will benefit from the improved resolution and the much higher gamma-beam intensity.

Two instruments are designed and are under construction for these studies, a 4π detector consisting of twelve thick GEM detector units, called ELITHGEM, and an array of four double-sided Fritsch-gridded Bragg ionization chambers (BIC), called ELI-BIC. Each thick GEM detector unit consists of a THGEM board, coupled with a transmission mesh and a segmented delay-line read-out electrode providing a true pixelated radiation localization. Each BIC is coupled to eight $4\pi$ telescopes which consists of ionization chambers as $4\pi$ detectors and DSSD Si detectors serving as $E$ detectors. The performance of the detectors has been tested and it was proved that they are sensitive and effective in their performance and meet the demands for high resolution photo-fission experiments [24].

3. Conclusion

A diverse research program is been prepared at ELI-NP, which covers all possible directions of photonuclear studies. State-of-the-art instrumentation is constructed for the realization of these experiments. All detector arrays will be ready in time to take first available beams and perform the defined commissioning and day-one experiments.

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