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Gamma-beam photofission experiments at ELI-NP: The future is emerging

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Abstract. At the Extreme Light Infrastructure – Nuclear Physics facility (ELI-NP), high-power laser systems together with high-brilliance gamma beams are the main research tools. The status of the construction of the facility is reported. The emerging photofission experimental program with brilliant gamma beams at ELI-NP is presented with emphasis on the prepared day-one experiments. 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 aims at research using extreme electromagnetic fields. The Extreme Light Infrastructure – Nuclear Physics (ELI-NP), which is under construction in Magurele, Romania, is one of the three laboratories of ELI, and is focused at the utilization of extreme electromagnetic fields for nuclear physics and quantum electrodynamics research and applications. It is one of the three new Pan-European nuclear physics laboratories, which are recognized as landmark facilities under the ESFRI scheme [1].

The main research tools at ELI-NP are a two-arm high-power laser system (HPLS) and a high-brilliance gamma-beam system (GBS) [2,3]. Each of the HPLS Ti:Sapphire lasers, which operate with a common front end, will deliver pulses of duration below 22 fs, which will reach peak power of 10 PW with a contrast of 10^{13}:1 at 100 ps ahead of the pulse peak. Each arm has three outputs, *e.g.* 10 PW operating at 1/60 Hz, 1 PW at 1 Hz, and 100 TW at 10 Hz. Each output is equipped with its own amplifier. The equipment is placed in the ELI-NP laboratory complex, in a clean room built on an anti-vibration slab which is specified of having a power spectral density of the vibrations at the level of 10^{-10} g^2/Hz in the frequency range from 1 Hz to 200 Hz [3]. Thus, the needed pointing stability of the HPLS will be achieved. The long-term drift of the pointing will be avoided by providing constant temperature in the laboratory building of 22 ºC, which is stabilized to ±0.5 ºC by a 5 MW geothermal cooling/heating system.

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The GBS, which is being mounted on the same anti-vibration platform, is based on the inverse Compton backscattering of laser pulses off relativistic electron bunches, which results in pulsed gamma beams with continuous tuneable gamma-ray energy over a broad range (from 200 keV to 19.5 MeV), high spectral density (about 10^4 photons/s/eV), narrow relative bandwidth (≤ 0.5%), high degree of linear polarization (≥ 95%), and high peak brilliance. The high-brightness electron beam is provided by a compact linear RF electron accelerator composed of an S-band photo-injector and damped C-band accelerating structures. Electrons are delivered as trains of 32 micropulses of 250 pC each, separated at 16 ns from each other, repeating every 10 ms. The electron beam is characterized by small emittance of 0.2–0.6 mm·mrad and energy spread below 0.1% [4,5]. The electron accelerator will to be operated in two stages, the first one providing electrons with energies up to 300 MeV and the second one where electrons are further accelerated up to more than 720 MeV. Green-light, J-class, cryo-cooled, Yb:YAG lasers will provide pulses at the wavelength of 515 nm at 100 Hz repetition rate, which will interact with the electron bunches. There are two interaction points, one for each stage of the electron accelerator, providing gamma beams with energies up to 3.5 MeV and up to 19.5 MeV, respectively. Laser-pulse recirculators, placed in optical cavities, ensure the interaction of the laser pulses generated at 100 Hz with the 3.2 kHz electron microbunches at each interaction point. Each laser pulse will be re-circulated between two parabolic mirrors for 32 times without significant degradation of the quality of the pulses [6]. The whole system is time synchronized to an accuracy better than 0.5 ps. The small energy bandwidth of the gamma beam is obtained by using custom-developed collimation systems with continuously adjustable aperture [7].

A diverse research program in the field of nuclear photonics is under development at ELI-NP. Related to the GBS photofission studies, the program includes high-resolution photofission experiments in the actinide nuclei, investigation of the second and third potential minima of the multiple-humped fission barrier by transmission resonance spectroscopy, measurement of kinetic energy, mass, atomic number and angular 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]. It is worth noting that these studies will be complimented by research within the HPLS experimental program which includes investigation of the fission-fusion reaction mechanism [9]. This will be achieved by reactions of laser-driven actinide beams on deuterium targets [10].

2 Photofission studies

The high-energy part of the photonuclear cross-section curve for the actinide nuclei has drawn the attention of nuclear physicists for exploring nuclear giant dipole resonances and the associated photofission processes. The low-energy tail of the photonuclear cross-section is gaining more interest nowadays because of the pygmy resonances found at these energies. In the low-energy part of the fission cross section curve, also the occurrence of nuclear transmission resonances is expected. These resonances are interesting because it turns out that structural effects influence large amplitude motions, such as fission. They are understood as due to the coupling of states in the different minima in the multiple-humped potential energy surface of the fission barrier.

The high spectral density, high-resolution, narrow band-width, and high polarization of the tuneable ELI–NP gamma-beam system will provide an opportunity to move a step ahead in the ongoing investigations to explore nuclear structure effects in the low-energy tail of the fission cross section in actinide nuclei, by studying transmission resonances in the low cross-section sub-barrier region. First measurements will be done on ^{238}U, which was recently measured at the HIγS facility in Duke University [11]. The measurements at ELI-NP will benefit from the improved resolution and much higher intensity.

Further, the experiments at ELI-NP GBS aim at measuring the absolute cross section, mass, atomic number, angular and kinetic energy distributions of fission fragments following the decay of the states in the different minima of the multiple-humped fission barrier in the region of the light actinides and studies of ternary fission. For the realization of these studies, state-of-the-art instrumentation, which is described in the following section, is being designed and constructed.

3 Instrumentation for ELI-NP

Two instruments are being developed for photofission studies at ELI-NP, the ELI-BIC and ELITHGEM detector arrays.

3.1 ELI-BIC

The first set-up, called ELI-BIC, includes an array of four double-sided Frisch-grid Bragg ionization chambers (DSBIC) for detailed studies of transmission resonances as well as of kinetic energy, mass, atomic number and angular distributions of the fission fragments.

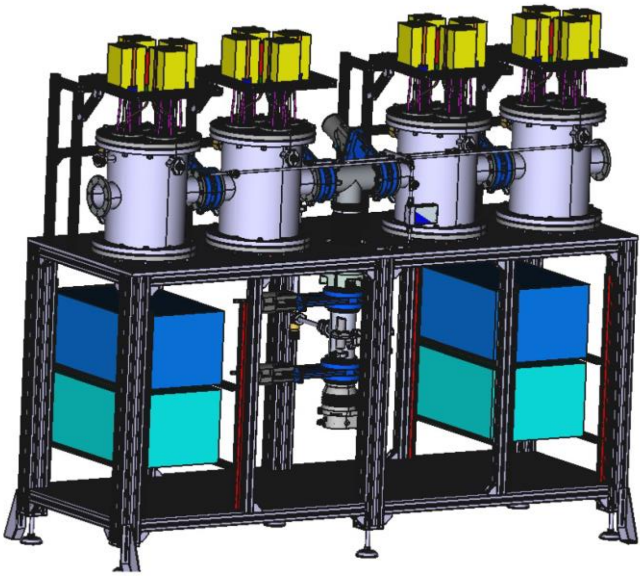

Fig. 1. CAD design of the ELI-BIC array. The instrument is mounted on a support platform together with the front-end electronics and the gas handling and vacuum systems.

A 100−200 μg/cm^2 thin target tilted at a 10° angle with respect to the γ-beam and having dimensions 0.5×3 cm^2 will be mounted in each of the chambers. For getting full beam coverage on the targets, the set-up will be positioned at 18 m from the γ-beam production point. The targets will be placed in the centre of the cathode of each ionization chamber. Such a multi-target set-up results in an increase of the effective target thickness, and thus the fission yield of the (γ,f) reaction, especially at deep sub-barrier energies. Each ionization chamber in the ELI-BIC array will be coupled to eight ΔE-E detectors covering a solid angle of π, for the study of light charged particles, mostly long range α-particles from ternary fission events. Each ΔE-E detector consists of a gas detector coupled with a Si double sided strip detector (Si DSSD). The design of the ELI-BIC detector assembly is shown in Fig. 1.

3.1.1 Performance test of one DSBIC detector

A novel-design DSBIC detector was constructed for integration in the ELI-BIC array [12]. The performance of one newly constructed DSBIC was tested in-beam with cold/thermal neuron beam at KFKI, Budapest, using the ^{237}Np(n_{th},f) reaction. The waveforms from the two anodes and grids, after pre-amplification, were digitized using a 14-bit 500 MS/s waveform digitizer with an external trigger, *i.e.* signals were recorded only when both grids were fired. The data was recorded for two days, using an on-line acquisition software developed at MTA Atomki, Hungary. Off-line analysis of the data was carried out using a ROOT-based [13] analysis program to determine the various properties: mass, kinetic energy and angular distribution of the fission fragments. Fig. 2 shows a pre-neutron mass distribution with grid inefficiency correction, without correcting for the pulse height defect (PHD). To check the energy resolution of the DSBIC, ΔE/E, a test experiment was performed using a triple alpha source (^{239}Pu+^{241}Am+^{244}Cm), from which a ΔE/E = 1% was obtained.

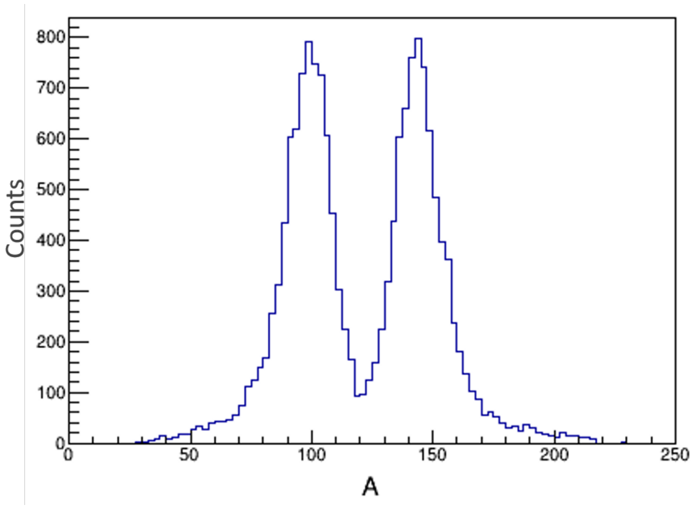

Fig.2. Pre-neutron mass distribution of fission fragments from the ^{237}Np(n_{th},f) reaction, measured with a DSBIC detector which will be used in the ELI-BIC array. The spectrum is without a PHD correction**.**

3.1.2 Performance test of one ΔE-E detector

A performance test was carried out for one ΔE-E detector using a triple alpha source (^{239}Pu+^{241}Am+^{244}Cm), at MTA Atomki, Hungary. The distance between the detector and the source was kept as 2 cm. The data was acquired using an analogue readout with MUX interface and was recorded using an in-house acquisition software. Off-line analysis was carried out using a ROOT-based analysis program [13]. An energy resolution of ~40 keV at 5~6 MeV α-energy was obtained for the ΔE-E detector, as shown in Fig. 3.

3.2 ELITHGEM

ELITHGEM is a multi-target detector array consisting of position sensitive gas detector modules based on the state-of-the-art thick gas electron multiplier (THGEM) technology [14]. The array is dedicated for the measurements of fission cross sections and angular distribution of the fission fragments as a function of incident photon energy. These measurements enable mapping of the potential energy surface (PES) of the actinides by which the harmonicity of the potential barrier can be examined and the parameters of the fission barrier can be extracted. The designed array (ELITHEM) is a 4π spectrometer consisting of 12 THGEM detector units, each unit consisting of a THGEM board manufactured at CERN, coupled with a transmission mesh and a segmented delay-line read-out electrode providing a true pixelated radiation localization. At the low-pressure operation mode, the signals are very fast, *e.g.* rise time of 3–4 ns.

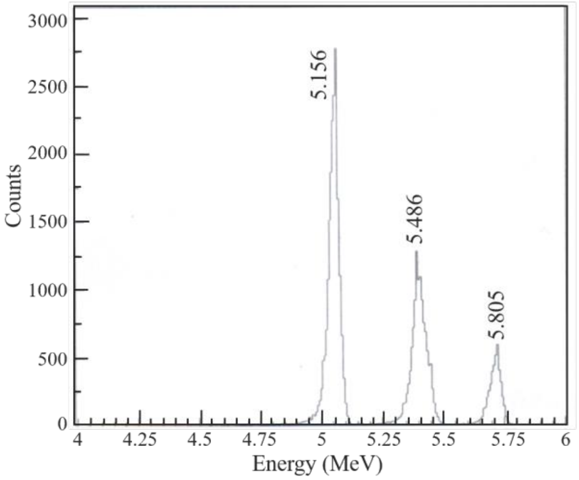

Fig. 3. Energy spectrum of a triple alpha source (^{239}Pu+^{241}Am+^{244}Cm) obtained using the newly designed ΔE-E detector which will be used in the ELI-BIC array.

3.2.1 Performance test of one THGEM detector unit

The performance of one THGEM detector unit was tested using spontaneous fission of ^{252}Cf, at MTA Atomki, Hungary. A two-dimensional position spectrum is shown in Fig. 4. The plot demonstrates the uniform distribution of the fission fragments. The signals were collected using fast preamplifiers, CFD and TDC. The data was recorded on-line using an in-house acquisition software. Off-line analysis was carried out using a ROOT-based [13] analysis program.

In short, the detectors, which were designed and developed for the photofission program at ELI-NP, are sensitive and effective in their performance and meet the demands for high resolution photofission experiments. The designed DSBIC has an energy resolution of 1%. The ΔE-E detector, consisting of an ionization chamber and a Si DSSD detector, which is coupled to the DSBIC, also demonstrates good energy resolution and is effective in detecting the α-particles. The THGEM detector unit has good position sensitivity and is stable with time. More performance experiments have been planned to be carried out with these detectors.

4 Possible future experimental set ups.

Our distant vision for photofission experiments at ELI-NP includes the combination of the above mentioned fission detectors with arrays of gamma and neutron detectors, enabling high-precision measurements of photon-induced prompt-fission gamma-ray spectra (PFGS) and of neutron spectra, as well as gamma decay spectroscopy of excited fission fragments. A dedicated array, consisting of 30 scintillator detectors (3″ × 3″ $LaBr_3$:Ce and $CeBr_3$ crystals), 20 ^{6}Li glass detectors and up to 60 BC501A liquid scintillators, called ELIGANT-GN, is being developed at ELI-NP for experiments involving excitations above the particle emission threshold. The BC501 liquid scintillator detectors are sensitive to neutrons with energies above 1 MeV and the ^{6}Li glass detectors for neutrons below 1 MeV. Thus, the combination of the two provides opportunity for a sensitive study of neutrons within a wide range of energy [15]. Another γ-ray spectrometer, the ELI-NP array of Ge detectors (ELIADE), is also being developed for nuclear resonance fluorescence experiments [16]. In experiments beyond day-one, the photofission detectors will be combined with these instruments for carrying out more fission studies.

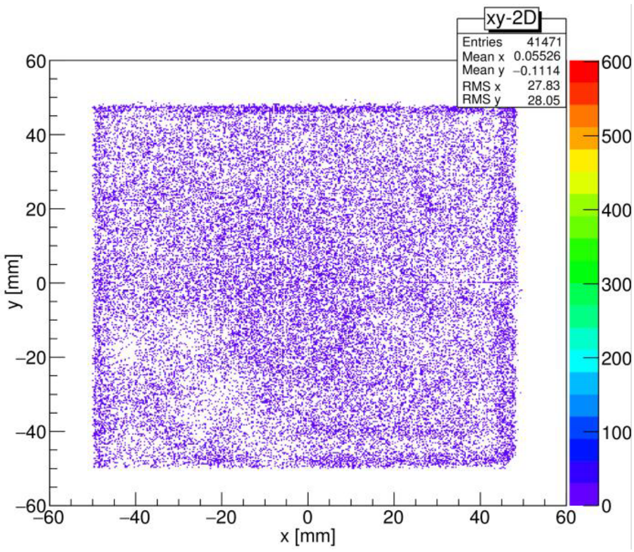

Fig. 4. Two-dimensional position spectrum from spontaneous fission of ^{252}Cf obtained using one THGEM detector unit.

The high beam flux of the quasi-monoenergetic γ-beam at ELI-NP and the multi-target fission detector array coupled with the neutron and gamma detector array, enable more precise measurements of PFGS, fission mass distribution and the correlation between the two. Taking advantage of the tuneability of the high resolution photon beam, one can investigate the energy dependence of various properties of the fission fragments, γ- and neutron emission. The γ-ray and neutron detectors coupled with the fission detector array will enable the study of γ-fission, γ-neutron and neutron-fission correlations using the TOF technique.

At ELI-NP, the possibility of development of an ion guide isotope-separation on-line (IGISOL) facility for the studies of neutron-rich nuclei, lying away from the valley of β stability, is also foreseen [8, 17, 18].

5 Summary

At ELI-NP diverse photofission research program is under development, which includes detailed studies of photofission phenomena with high-brilliance gamma beams. The program will be complemented by studies of the fission-fusion reactions at the ELI-NP HPLS. Photofission will be used also as a tool for production of exotic nuclei. The needed instrumentation for all these studies is under development. The detectors, which will be used for day-one experiments at ELI-NP are designed, and the produced prototypes demonstrate that the expected performance has been achieved.

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