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Photofission experiments at the ELI-NP facility

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Abstract. At ELI-NP, high-power lasers together with a very brilliant γ beam are the main research tools. The high-power laser system (HPLS) and the γ beam system (GBS) of ELI-NP are presented. The expected performance of the electron accelerator and production lasers of the GBS, and the targeted operational parameters of the γ beam are described. Possible laser-induced fission and γ beam photofission experiments which are under preparation at ELI-NP, and the different set-ups and instrumentation, are designed for these experiments, are presented.

Keywords. High-power lasers; brilliant narrow-width γ beam; laser-induced fission; photofission.

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1. Introduction

The mission of the ELI-NP research infrastructure is to promote nuclear physics research with laser-driven electron, proton or heavy-ion beams and brilliant γ beams. The ELI-NP research complex will host two ultrahigh-power 10 PW lasers and a γ beam system (GBS), which will deliver laser and γ-ray beams with parameters beyond those available at the present state-of-the-art machines. The construction of the building complex started in May 2013 and will be completed in the spring of 2015. The main laboratory building covers an area of more than 12000 m^2. Its lay-out is displayed in figure 1. The building complex, which covers about 33000 m^2 includes an office building, a guest house with 60 rooms and a canteen. ELI-NP will operate as an open-access facility. The high-power laser system (HPLS) and the GBS are placed in the laboratory building, adjacent to the corresponding experimental areas, as shown in figure 1. They will be mounted on an antivibration slab, damping vibrations to frequencies $\leq$10 Hz with amplitudes down to $\pm$1 μm, thus acting like a large optical table.

The HPLS, which is under construction, will have six output lines – two at 10 PW with a frequency of $\geq$1/60 Hz, two at 1 PW with a frequency of $\geq$1 Hz and two at 100 TW with a frequency of $\geq$10 Hz. Each output will have its optical pulse compressor. The duration of the pulses from each of the six outputs of the HPLS shall be tunable from the best compression level to at least 5 ps pulse duration, with both positive and negative

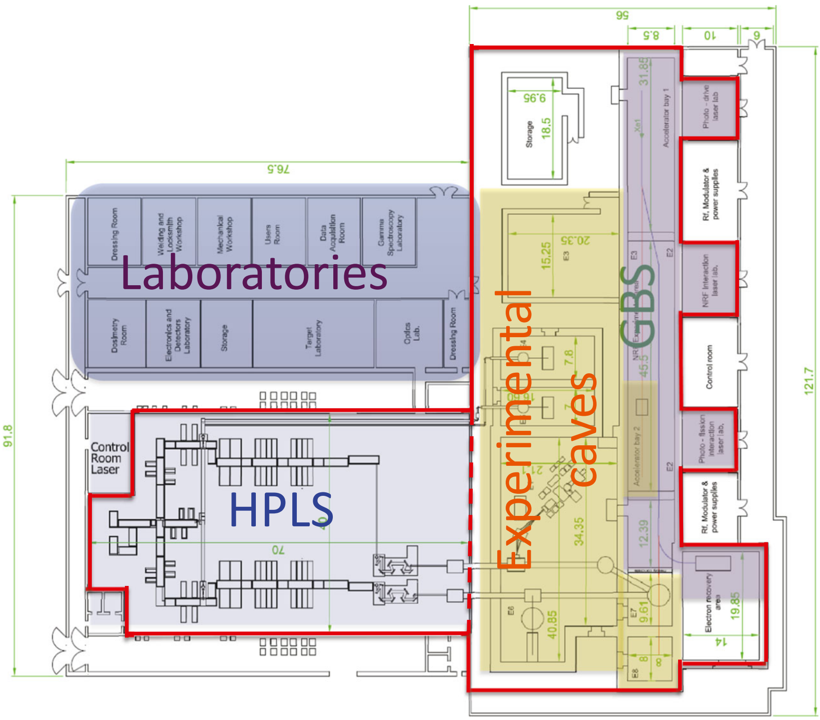

Figure 1. Lay-out of the ELI-NP laboratory building. The dimensions are in metres. The bold contour indicates the borders of the antivibration slab.

chirps. The HPLS outputs will be synchronized with an accuracy below 200 fs [1]. The laser system will deliver pulses synchronously with the GBS electron and γ bunches.

The GBS is designed and is been constructed by the European consortium EuroGammaS, led by the Italian INFN LNF, which includes research and industrial partners from eight European countries. It will produce highly polarized (>95%) tunable γ beams of 10^4 photons/s/eV spectral density in the range of 200 keV to 19.5 MeV with a bandwidth of >0.3% [2,3]. The γ beams will be produced through laser Compton backscattering (LCB) off an accelerated electron beam delivered by a linear accelerator. The LBC process can be looked upon as the most efficient frequency amplifier. Maximum up-shift is achieved in head-on collisions, producing γ-rays with energies $E_\gamma \sim 4\gamma_e^2 \cdot E_L$, where γ_e is the Lorentz factor of the accelerated electron, $\gamma_e = (1-\beta^2)^{-1/2}$, $\beta = v_e/c$, v_e the electron velocity, c is the speed of light and E_L is the energy of the laser photons. In reality, the production laser shoots at a small angle with respect to the axis of the e^- beam. For a green-light laser, $E_L = 2.4$ eV, LCB off 300 MeV electrons results in a γ beam of $E_\gamma \leq$ 3 MeV, while LCB off 720 MeV electrons yields γ-rays with $E_\gamma \leq 19.5$ MeV. However, the process has a relatively low cross-section ($\sigma_{\rm CBS} \approx 10^{-25}$ cm^2), which needs to be compensated by high photon and electron densities at the interaction point.

Studies of fission phenomena and related research are some of the issues which are the focus of the emerging ELI-NP research programme. These include studies of the properties of fission barrier and rare fission events, energy, mass, charge and angular distributions of fission fragments, as well as nuclear structure studies of exotic nuclei produced in laser-driven fission or photofission.

This paper addresses the problems in the field of fission research which were identified at the ELI-NP facility. For the realization of the ELI-NP fission research programme, a number of state-of-the-art instruments are foreseen, whose parameters are described in the following sections.

2. The nuclear physics research programme at ELI-NP

2.1 *Experiments at the HPLS*

The invention of chirped pulse amplification (CPA) [4] and optical parametric CPA [5] led to a dramatic increase of laser power and catalyzed a new field of research, the high-intensity laser interaction with matter. Experiments with 100 TW lasers demonstrated that it is possible to produce accelerated beams of electrons, protons or heavy ions through laser–matter interactions.

In a pioneering work, Tajima and Dawson [6] proposed to accelerate the electrons with an intense laser pulse. As a result of the laser–matter interaction, a wake of plasma oscillations is produced due to localized volumes of low and high densities of electrons. The wakefield, generated by an intense laser pulse propagating in an underdense plasma, exerts a ponderomotive force on electrons in the longitudinal direction. Exploiting the laser wakefield acceleration mechanism acting on gas jet targets, electron beams up to GeV energies have been realized with typically pC charges/laser pulse, an energy spread of 1–2% and an emittance of 10^5 mm·mrad.

Subsequent steps in the field of laser-driven beam acceleration are the production of proton and heavy-ion beams and experiments with them. In these studies, solid density targets are used. Two major acceleration mechanisms have been identified in this density regime: target normal sheath acceleration (TNSA) [7] and radiation pressure acceleration (RPA) [8]. In TNSA the acceleration of the ions is due to the strong fields set up by a sheath of laser-accelerated relativistic electrons. The electrons are generated by the laser at the front surface and transported to the rear side of the target, establishing, by charge separation, a sheath electrostatic field there. The electric fields then drag the ions through the target. Proton beams with $\sim$60 MeV energy have been produced within TNSA regime, yet with large energy spreads. In the TNSA mechanism, the proton energy E_{p} scales with the laser intensity I, as $E_{\mathrm{p}} \sim \sqrt{I}$. The need to reach both, higher energies, >100 MeV, and narrow-width beam quality, required by most applications, has further stimulated the search for alternative schemes of ion acceleration beyond the TNSA mechanism.

The RPA mechanism is driven directly by the radiation pressure exerted by super-intense laser pulses on overdense plasmas. The maximum energy and the number of ions generated by the interaction of a high-intensity laser pulses with solid targets are improved significantly if the targets are of thickness below the collisionless skin depth of the laser, i.e., partly transparent targets are employed. In RPA the electrons are driven out of the foil via light pressure, dragging the ions behind, in the resulting dipolar field. The momentum of the laser is imparted directly to the object to be accelerated. Experiments indicate that the final energy simply scales as $E_{\mathrm{p}} \sim I$, where I is the laser intensity.

At ELI-NP, laser-driven ion beam acceleration will be studied at laser intensities of the order 10^{23} W/cm^2, i.e., these are intensities, existing within the Sun. The experiments will aim at the production of heavy-ion beams, including actinide beams. The ultimate goal of this programme is to explore the suggested fission–fusion mechanism [9]. In this reaction, laser-accelerated actinide ions, e.g., ^{232}Th, impinge on a ^{232}Th target, where the target- and the beam-like Th ions will fission. Due to the very high beam intensity, exceeding the existing classical ion beams by many (up to 15) orders of magnitude, high-temperature high-ion density will be created. As a result, subsequent fusion of neutron-rich fragments will occur, resulting in a highly neutron-rich fusion products. The most important scientific objective in this case is the study of neutron-rich nuclei in the region of r-process waiting point $N = 126$, which can be achieved by the fusion of two light neutron-rich fragments. At the waiting point for a given charge number Z, neutron capture becomes balanced by (γ, n) photodisintegration. Such experiments require huge experimental development in the field of laser-driven ion acceleration. Experiments, aiming at the acceleration of heavy-ions are in their infancy and, therefore, this experimental programme will be implemented in steps, beginning with studies aiming at mastering the process of ion-beam acceleration. As a next step, fission of accelerated actinide beams will be realized, and finally, the fission–fusion mechanism will be explored.

For the implementation of this experimental programme, the construction of a large-acceptance (gas-filled) separator is suggested. It will allow both the analysis of the produced heavy-ion beams, and the separation of isotopes of interest, which will be produced in fission–fusion experiments. Behind the separator several measurement stations are considered, such as a β-decay tape station, combined with a γ-ray spectrometer and neutron detectors. The development of instrumentation will follow the stages of the experimental programme, beginning with beam analysis, characterization of fission products, e.g., in a gas catcher combined to a multireflection trap, etc.

2.2 *Experiments at the GBS*

The availability of a brilliant narrow-width γ-ray beam opens an avenue for photofission research, as it makes high-resolution studies possible in γ-ray-induced reactions. This programme will address high-resolution photofission experiments in the actinides, investigation of the second and third potential minima through studies of transmission resonances [10–12], angular and mass distribution measurements of fission fragments, measurements of absolute photofission cross-sections, studies of rare photofission events such as ternary fission [13], highly asymmetric fission, etc.

In addition, the possibility to produce exotic neutron-rich nuclei in photofission and to study their structure and decays is investigated. The IGISOL technique [14] will be used for the extraction and selection of isotopes of interest. The nuclei of interest will be slowed down and neutralized in the gas of an ion guide and will be separated by combining a laser-ion source and a mass separator. A clear advantage of an ELI-NP IGISOL facility is the possibility to produce beams of isotopes of refractory elements. In this case, the fissile targets will be irradiated directly by the γ-beam.

2.2.1 *Studies of photofission phenomena.* Photofission measurements enable selective investigation of extremely deformed nuclear states in light actinides and can be utilized to better understand the landscape of multiple-humped potential energy surface (PES) in these nuclei. The selectivity of these measurements originates from the low and reasonably well-defined amount of angular momentum transferred during the photoabsorption process. High-resolution studies can be performed on the mass, atomic number and kinetic energy distributions of the fission fragments following the decay of well-defined initial states in the first, second and third minima of the PES in the region of light actinides.

The selectivity of photofission measurements allows high-resolution investigation of fission resonances in photofission in the second and third minima of the fission barrier of light actinides. Detailed study of superdeformed (SD) and hyperdeformed (HD) states using transmission resonance spectroscopy will be possible with the ELI-NP brilliant, narrow-width γ beams.

Our experimental approach to investigate extremely deformed collective and single-particle nuclear states of light actinides is based on the observation of transmission resonances in the prompt fission cross-section [10,11]. Observing transmission resonances as a function of excitation energy caused by resonant tunnelling through excited states in the third minimum of the potential barrier, allows us to identify the excitation energies of the HD states. Moreover, the observed states can be ordered into rotational bands, with moments of inertia, proving that the underlying nuclear shape of these states is indeed of HD configuration. For the identification of rotational bands, the information on spin can be obtained by measuring the angular distribution of the fission fragments. Furthermore, the PES of the actinides can be parametrized very precisely by analysing the overall structure of the fission cross-section and by fitting it with the nuclear reaction code (EMPIRE 3.1 and TALYS 1.2) calculations.

So far, sub-barrier photofission experiments were performed only with bremsstrahlung photons and integrated fission yields have been determined. In these experiments, the fission cross-section was convolved with the spectral intensity of the photon beam, resulting in a typical effective γ-ray bandwidth of only $\Delta E/E \approx 6 \cdot 10^{-2}$. However, a plateau was observed in the fission cross-section, referred to as the ‘isomeric shelf’, presumably as a result of the competition between prompt and delayed photofission [15,16]. Due to the lack of high-resolution photofission studies in the corresponding energy region ($E \approx$ 4–5 MeV), no experimental information exists to confirm this concept. ELI-NP offers an opportunity to overcome previous limitations. The capabilities of this next-generation γ source allows one to aim at identifying the sub-barrier transmission resonances in the fission decay channel with integrated cross-sections down to $\Gamma\sigma \sim 0.1$ eVb. The narrow-energy bandwidth will also allow for a significant reduction of the presently dominant background from non-resonant processes. Thus, ELI-NP is expected to allow preferential population and identification of vibrational resonances in photofission cross-section and ultimately to enable observation of the fine structure of the isomeric shelf.

These studies call for developments of state-of-the-art fission detectors to exploit the unprecedented properties of the high-flux, Compton-backscattered γ beams having a very small, submillimetre beam spot size. A multitarget detector array is under development at MTA Atomki, consisting of position-sensitive gas detector modules based on the state-of-the-art THGEM technology [17]. The foreseen unprecedented submillimetre γ beam-spot size allows to develop considerably more compact photofission detectors than the earlier ones. Besides, the well-focussed γ beam also defines a distinct fission position. So a remarkably improved angular resolution can be achieved. For measuring the mass and

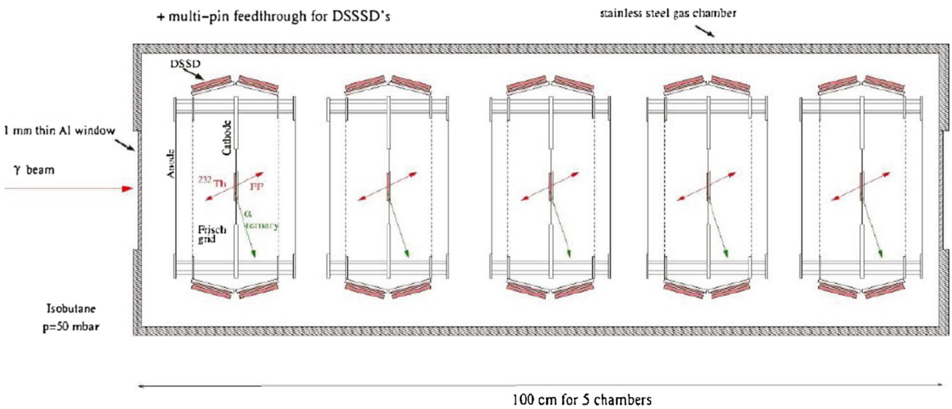

Figure 2. Schematic representation of a five-fold Frisch-gridded twin ionization chamber.

atomic number distribution of the fission fragments, a highly efficient, five-folded, Frisch-gridded twin ionization chamber [18], which will be used as Bragg ionization chamber (BIC) [19], is under development at MTA Atomki. This experimental set-up is shown in figure 2. The twin ionization chamber will be equipped with double-sided Si strip detectors to measure light particle (α) emission probability from the highly-deformed compound state and to detect any ternary particles from fission. An increased α decay probability would also be a conclusive evidence for the HD structure of the fissioning system. Atomic numbers will be extracted by tracking the Bragg curve of the ions using a desktop digitizer and advanced digital signal processing (DSP) techniques.

Another topic which will be addressed at ELI-NP is the search for exotic fission modes like true ternary fission, collinear cluster tripartition (CCT) and lead radioactivity. It will be very interesting to study nuclear fission accompanied by light charge particle emission, to measure the light particle decay of excited states and to search for the predicted enhanced α decay of HD states of the light actinides.

Information about ternary fission from neutron-induced and spontaneous fission is obtained from experiments. As ternary particles are released close to the scission point, they provide valuable information about the scission point and also fission dynamics. Ternary photofission has never been studied. Compared to neutron-induced or spontaneous fission experiments, the use of polarized beam fixes the geometry of the process, which is advantageous for detailed studies. Among the open problems related to the process are the mechanism of emission of ternary particles and the role of deformation energy, role of the spectroscopic factor, formation of heavier clusters, to list a few.

2.2.2 *Structure of exotic nuclei.* The GBS γ-ray beam will selectively cover energy regions of the giant dipole resonance (GDR) of the fissile target, which makes it an ideal tool to induce photofission of the target nuclei. The construction of an IGISOL beam line at ELI-NP is under consideration. The IGISOL technique [14] allows the extraction of the isotopes of refractory elements, which do not exit from standard ISOL targets. So far, photofission has been explored as a mechanism for the production of neutron-rich nuclei at bremsstrahlung facilities, such as ALTO [20] and ARIEL [21]. In such facilities mA electron beams of energies $\geq$50 MeV are sent on a converter, producing bremsstrahlung photons, which cover the energy range of the GDR of the fissile target. The bremsstrahlung hits the target, which is located in a gas cell. The ions, produced in fission, leave the target. They are slowed down in the gas and the isotopes of interest are selected through a combination of a laser-ion source and mass separator. A major bottleneck of this technique is the formation of space charge in the gas cell. Its major source are low-energy γ-rays, which interact with the gas in the cell. These γ-rays form the dominant part of the bremsstrahlung spectra, and thus set a natural limitation of the application of the technique.

At ELI-NP a γ beam, covering the energy range of the GDR is produced through LCB. The low-energy part of the spectrum can be cut through collimation, due to the space distribution of the LCB γ-rays.

Yield calculations were performed in GEANT4. For this purpose, several classes were implemented, inheriting the basic classes of GEANT4, i.e., the primary γ beam was defined as G4GeneralParticleSource class, and the photofission process, which is not available in GEANT4, was implemented as a G4PhotoFission class [22]. The code was validated to calculate the photofission yield in the case of the proposed ALTO gas cell [22]. In this case, the photofission of four ^{238}U thin targets, placed in a gas cell, was considered. Fission was induced by bremsstrahlung that was produced by the interaction between the 50 MeV electron beam and a W converter, placed 5 mm away in front of a gas cell.

Several benchmark target geometries were considered for ELI-NP. In one of the cases, a stack of 200 thin ^{238}U foils, with a total mass of 800 mg was considered. The foils were tilted with respect to the beam, such that the ions, produced in photofission, can stay in the gas, not reaching the next foil. The interaction of the beam with the targets is shown in figure 3. About $6 \cdot 10^2$ fission/s per 10^6 γ-rays were obtained with this target geometry. It should be noted that about 30% of the γ beam photons interact with the target, the gas-cell window and the gas. Thus, 10^8 fissions/s can be expected at ELI-NP, considering a γ beam of $5 \cdot 10^{10}$ photons/s.

The isotope yield distribution was estimated, based on the measured fission yields, in low-energy projectile fission of ^{238}U on ^{208}Pb [23], a process which takes place via the exchange of a virtual photon ($E^* < 25$ MeV).

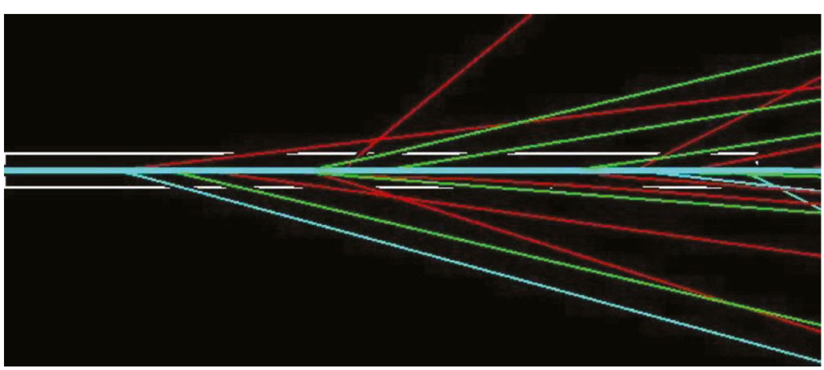

Figure 3. Interaction of the γ beam with a stack of thin ^{238}U targets, placed in a gas cell. Scattered γ-rays are also indicated in the figure.

In-beam studies of the excited states of the exotic nuclei will be possible at ELI-NP, too. For these studies, the ELIADE detector array will be used. It consists of eight segmented clover detectors with anti-Compton shields and several large-volume $LaBr_3$(Ce) scintillators. In-beam γ-ray spectroscopy of fission fragments will be done with this experimental set-up. In addition, the ELIADE array will be coupled to different ancillary detectors, which will provide the opportunity to measure lifetimes or g factors of the excited states. The latter option opens a niche for such studies, because g-factor measurements of isomers in neutron-induced fission are extremely difficult, due to the large (n, γ) of the possible implantation targets, Fe or Gd. Such a problem does not exist in photofission experiments.

3. Conclusions

The ELI-NP research centre will host a HPLS and a GBS with parameters beyond those of the nowadays state-of-the-art facilities. The power of the HPLS lasers exceeds the existing lasers by an order of magnitude and every minute will deliver, on the target, intensities in the range of 10^{23} $\mathrm{W/cm^2}$. This makes it possible to design and perform new classes of nuclear physics experiments, which is not possible elsewhere.

The spectral density, brilliance and bandwidth of the γ-ray beams, which will be delivered by the GBS, are orders of magnitude better compared to the existing facilities. The outstanding performance of γ beams, combined with its high polarization, creates opportunities to carry out a versatile research programme in nuclear physics and tackle key problems in photofission research. The possibility of setting up a photofission IGISOL facility has been investigated. The estimated isotope yields in many cases are compatible to the yields from other laboratories. A clear advantage of the ELI-NP IGISOL beam line is the possibility to deliver isotopes of refractory elements.

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