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Future Experiments with Intense Laser Beams and Brilliant Gamma Beams at the ELI-NP Facility

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Abstract. The Extreme Light Infrastructure (ELI) Pan-European facility initiative represents a major step forward in quest for extreme electromagnetic fields. Extreme Light Infrastructure Nuclear Physics (ELI-NP) is one of the three pillars of the ELI facility, that aims to use extreme electromagnetic fields for nuclear physics and quantum electrodynamics research. At ELI-NP, high-power lasers together with a very brilliant gamma beam are the main research tools. Their targeted operational parameters are described. The emerging experimental program in the field of nuclear physics of the facility is reported. The different instruments which are considered to operate in the ELI-NP experimental halls are discussed, with an emphasis on the instrumentation which is designed for nuclear structure, reactions and astrophysics research.

1. The ELI-NP Research Facility
ELI-NP [1] is one of the three laboratories of the European Extreme Light Infrastructure, the other two being laser-driven secondary beams in Prague, the Czech Republic [2] and the attosecond pulsed lasers in Szeged, Hungary [3]. The mission of the ELI-NP research facility is to promote nuclear physics studies with laser-driven electron, proton or heavy-ion beams and brilliant \( \gamma \) beams. The laboratory complex at ELI-NP will host a high-power laser system (HPLS), which will consist of two ultra high-power lasers and a very brilliant gamma-beam system (GBS), which will deliver narrow-bandwidth \( \gamma \) beams with parameters beyond the present state-of-the-art. They will be mounted on an anti-vibration slab, damping vibrations to frequencies \( \leq 10 \text{Hz} \) with amplitudes down to \( \pm 1 \mu \text{m} \), thus acting like a large optical table. The HPLS and the GBS will be commissioned in 2017-2018 and the laboratory will be available for experiments as an open-access facility in 2018.

The HPLS will have six output lines – two at 10 PW with a frequency of \( \leq 1/60 \text{ Hz} \), two at 1 PW with a frequency of \( \leq 1 \text{ Hz} \) and two at 100 TW with a frequency of \( \leq 10 \text{ Hz} \). 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 chirp. The HPLS outputs will be synchronized with accuracy below 200 fs [4]. The laser system will deliver pulses synchronously with the GBS electron and \( \gamma \) bunches.

The GBS will produce highly polarized \(( > 95\% \) tunable \( \gamma \) beams of a high spectral density of \( 10^4 \) photons/s/eV in the range from 200 keV to 19.5 MeV with a bandwidth of \( > 0.3\% \) [5, 6]. The \( \gamma \) 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 or as a "photon accelerator". Maximum up-shift is achieved in head-on collisions, producing \( \gamma \) rays with energies \( E_\gamma \sim 4\gamma_e^2 \cdot E_L \), where \( \gamma_e \) is the Lorentz factor of the accelerated electron, \( \gamma_e = (1 - \beta^2)^{-1/2} \), \( \beta = v_e/c \), \( v_e \) is the electron velocity, \( c \) is the speed of light and \( E_L \) is the energy of the laser photons. For a green-light laser, \( E_L = 2.4 \text{ eV} \), LCB off 300-MeV electrons results in a \( \gamma \) beam of \( E_\gamma \leq 3 \text{ MeV} \), while LCB off 720-MeV electrons yields \( \gamma \) rays with \( E_\gamma \leq 19.5 \text{ MeV} \). The relatively low cross section of the process, \( \sigma_{CBS} \approx 10^{-25} \text{ cm}^2 \), will be compensated by high photon and electron densities at the interaction point.

In reality, the production laser shoots at a small angle \( \phi \) with respect to the axis of the \( e^- \) beam, as presented in Fig. 1. In this case the energy of the \( \gamma \) rays is:

\[
E_\gamma = \frac{4\gamma^2 E_L}{1 + \gamma^2 \theta^2 + a_0^2/2} (1 - \Delta),
\]

where \( \theta \) is the observation angle for the \( \gamma \) beam, \( a_0 \) is a laser parameter, \( a_0 = \frac{4.3 \lambda_L}{w_0} \sqrt{\frac{U_L}{\Delta \sigma_{tL}}} \), which takes into account the laser pulse energy \( U_L \), wavelength \( \lambda_L \), beam-spot size \( w_0 \) and FWHM pulse length \( \sigma_{tL} \), and the dimensionless parameter \( \Delta \), \( \Delta \approx \frac{4\gamma^2}{m_e c^2} \hbar \nu_L \), which takes into account the red shift due to the electron recoil, \( \hbar \nu_L \) is the laser photon energy.

**Figure 1.** Compton backscattering between an electron bunch moving with a relativistic speed and a laser pulse. In the case of a multibunch structure is delivered by the electron accelerator within a macropulse, as in the case of ELI-NP, a laser recirculation system needs to be implemented.

2. **Nuclear Science at ELI-NP**

The nuclear physics research program at ELI-NP will be carried out with both, the ultra high-power lasers of the HPLS and the brilliant \( \gamma \) beams of the GBS. A lay-out of the laboratory building is presented in Fig. 2. It covers an area of about 12000 m\(^2\) and will host the HPLS, the GBS, experimental areas, support laboratories and workshops.
Figure 2. Lay-out of the ELI-NP building. The dimensions are in meters.

2.1. HPLS Nuclear Physics Experiments

The road towards high-power lasers began with the invention of Chirped Pulse Amplification (CPA) [7], resulted in a dramatic increase of the laser power and catalysed a new field of research, the high-intensity laser interaction with matter. Tajima and Dawson [8] proposed to accelerate 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 on electrons a ponderomotive force in the longitudinal direction. Experiments with hundred-terawatt lasers demonstrated that it is possible to produce accelerated beams of electrons, protons or heavy ions through such laser-matter interactions. For a recent review see Ref. [9].

At ELI-NP laser-driven ion-beam acceleration will be studied at laser intensities at the order $10^{23}$ W/cm$^2$. The experiments will aim at the production of heavy-ion beams, including actinide beams. The ultimate goal of this program is to explore the suggested fission-fusion mechanism [10]. In this reaction, laser-accelerated actinide ions, e.g. $^{232}$Th, impinge on a
$^{232}$Th target, where the target-like and the beam-like Th ions will fission. Due to the very high beam intensity, exceeding 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 very neutron-rich fusion product. The most important scientific objective in this case is the study of neutron-rich nuclei in the region of the r-process waiting point $N = 126$, which can be achieved through fusion of two light neutron-rich fragments. Such experiments require huge experimental development in the field of laser-driven ion acceleration. Experiments, aiming the acceleration of heavy ions are in their infancy and, therefore, this experimental program will be implemented in steps, starting 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 program the construction of a a large-acceptance (gas-filled) separator is suggested. It will allow both, the analysis of the produced heavy-ion beams, as well as the separation of the isotopes of interest, which will be produced in fission-fusion experiments. Behind the separator several measurement stations are considered, such as a $\beta$-decay tape station, combined with a $\gamma$-ray spectrometer and neutron detectors. The development of the instrumentation will follow the stages of the experimental program, starting with beam analysis, characterization of fission products, e.g. in a gas catcher combined to a multi-reflection time-of-flight (MRTToF) beam-purification trap, etc.

2.2. The GBS Experimental Program

The availability of brilliant narrow-width $\gamma$-ray beams in a large energy range opens an avenue for high-resolution $\gamma$-ray induced studies. As a result, an experimental program, covering different aspects of nuclear structure, reactions and astrophysics research, has been defined.

2.2.1. Nuclear Resonance Fluorescence Experiments. The $\gamma$-ray beam brilliance and bandwidth at ELI-NP will increase the sensitivity of nuclear resonance fluorescence (NRF) experiments, compared to the existing present-day facilities. ELI-NP offers the opportunity to perform NRF studies on small target samples. This opens up an entire new area of applicability of the NRF method to materials that may be available only in quantities of a few milligrams. For example, studies the low-energy dipole response in the actinide region will be possible. The low-lying dipole strength, such as the scissors mode, and of the fragmentation of the strength of soft modes, such as the Pigmy Dipole Resonance (PDR), will be studied, too. The brilliance of the $\gamma$-ray beam will enable $\gamma\gamma$ coincidence experiments, which provides an opportunity for detailed investigation of the decay of photo-excited states. Studies of the ground-state transition width $\Gamma_0$ with the self-absorption method [11] will benefit from the narrow bandwidth of the $\gamma$ beam. This will allow measurements of nuclear lifetimes in a model independent way with a very high precision. All these studies will benefit from the high polarization of the $\gamma$-ray beam.

The ELLI-NP Array of DEtectors (ELIADE) will be used in these experiments. The ELIADE spectrometer will consist of eight segmented Clover detectors with anti-Compton shields, which will be combined with four 3” x 3” LaBr$_3$ detectors. The Clover detectors will be positioned at the vertical and horizontal positions of 90° and 135° rings. The LaBr$_3$ detectors will be positioned at 90°. The top-performance photopeak efficiency of the array will be $\approx 10\%$.

In addition, different applications of narrow-width $\gamma$ beams will be developed, such as characterization of materials and studies of trace materials. Other area of applications is 3D $\gamma$-ray imaging of bulk samples. These studies are related to non-proliferation of nuclear materials and nuclear-waste management.

2.2.2. Photofission experiments. The availability of a brilliant narrow-width $\gamma$-ray beam opens an avenue for photo-fission research, since it makes possible high-resolution studies in $\gamma$-ray
induced reactions. This program will address high-resolution photo-fission experiments in the actinides, investigation of the second and third potential minima through studies of transmission resonances [12, 13, 14], angular and mass distribution measurements of fission fragments, measurements of absolute photo-fission cross-sections, studies of rare photo-fission events, such as ternary fission [15], highly asymmetric fission, etc.

These studies call for developments of state-of-the-art fission detectors to exploit the unprecedented properties of the high-flux, LCB $\gamma$ beams having a very small, sub-millimeter beam spot size. A multi-target detector array is under development at MTA Atomki, Debrecen, Hungary, consisting of position sensitive gas detector modules based on the state-of-the-art THGEM technology [16]. The foreseen unprecedented sub-millimeter $\gamma$ beam-spot size allows to develop considerably more compact photofission detectors than those of before. Besides, the well-focused $\gamma$ beam also defines a distinct fission position, such that a remarkably improved angular resolution can be achieved. For the measurement of the mass and atomic number distribution of the fission fragments a highly-efficient, five-folded, Frisch-gridded twin ionization chamber [17], which will be used as Bragg ionization chamber (BIC) [18], is under development at MTA Atomki. The twin ionization chamber will be equipped with double-sided Si strip detectors in order to measure light-particle ($\alpha$) emission probability from the highly-deformed compound state and to detect any ternary particles from fission. An increased $\alpha$ decay probability would also be a conclusive evidence for the HD structure of the fissioning system. Atomic numbers of the fission fragments will be extracted by tracking the Bragg curve of the ions using a desktop digitizer and advanced digital signal processing (DSP) techniques.

In addition, the possibility to produce exotic neutron-rich nuclei in photo-fission and study their structure and decays is investigated. The GBS $\gamma$-ray beam will cover selectively energy region of the giant dipole resonance (GDR) of the fissile target, which makes it an ideal tool to induce photo-fission of the target nuclei. The construction of an IGISOL beam line at ELI-NP is under consideration. The IGISOL technique [19] allows the extraction of the isotopes of refractory elements, which do not come out 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]. There 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 a mass separator. A major bottleneck of this technique is the creation of space charge in the gas cell. Its major source are low-energy $\gamma$ rays, which interact with the gas of the cell. These $\gamma$ rays form the dominant part of the of the bremsstrahlung spectra, and thus set a natural limitation of the application of the technique.

At ELI-NP a $\gamma$ beam, which covers 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 $\gamma$ rays.

Yield calculations have been performed in GEANT4. For this purpose, several classes were implemented, inheriting the basic classes of GEANT4, i.e. the primary $\gamma$ beam was defined as G4GeneralParticleSource class, and the photofission process, which is not available in GEANT4, has been implemented as a G4PhotoFission class [22].

Benchmark calculations, considering a target which is a stack of thin $^{238}$U foils, with a total mass of 800 mg, were performed. The foils were tilted with respect to the beam, such that the ions, produced in photofission, can be stopped in the gas, not reaching the next foil. About $6 \cdot 10^2$ fission/s per $10^6$ $\gamma$ rays were obtained with this target geometry. It should be noted that less than 30% of the $\gamma$-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 $\gamma$ beam of $5 \cdot 10^{10}$ photons/s.
2.2.3. **Experiments above the Neutron Separation Threshold.** The brilliant, narrow-width, highly-polarized \( \gamma \)-ray beam which will be delivered by the ELI-NP GBS will open up new horizons for the investigation of the nuclear photo-response at and above the particle separation threshold. An example for such studies is the detailed investigation of different soft modes, such as e.g. the pygmy dipole resonance (PDR) at and above the particle threshold, which is essential for nucleosynthesis in astrophysics. PDRs are placed much lower in energy than giant dipole resonances (GDR) and they represent only a small fraction of the total E1 strength (few percent), while GDRs exhaust almost fully the E1 strength. Both, the GDR and the PDR can be covered within the energy range of the ELI-NP beams. The PDR occurs close to the neutron emission threshold and its decay is governed by the coupling to the large number of states around the threshold. These experiments will be complimentary to the PDR NRF studies. At present, high-resolution studies of PDR strength can be done with proton probes at Osaka, at the RCNP high-resolution spectrograph Grand Raiden [23, 24]. Similar or better resolution will be achieved with \( \gamma \) probes at ELI-NP.

This experimental program will include also studies of \((\gamma,n)\) cross section, e.g. p-process related measurements, such as the \(^{138}\text{La}(\gamma,n)^{137}\text{La}\) and the \(^{180m}\text{Ta}(\gamma,n)^{179}\text{Ta}\) reactions, which are of key importance for the understanding of the process and provide constraints on the explosive dynamics of massive stars.

Two major instruments are under consideration for the realization of this experimental program, a 4\(\pi\) neutron spectrometer of \(^3\text{He}\) counters and an array of large-volume \(\text{LaBr}_3\) and liquid scintillator detectors for neutron time-of-flight and \(\gamma\)-ray correlated measurements.

2.2.4. **Nuclear Astrophysics Studies.** The ELI-NP facility provides unique opportunities for nuclear astrophysics research. For example, the \(\gamma\)-induced nuclear reactions of astrophysical interest were extensively studied during the years, but still represent a challenge for the experimental and theoretical work. The difficulty arises from the very small cross sections due to the fact that the reactions occur deep below the Coulomb barrier especially for the case of \((\gamma,\alpha)\) reactions. Therefore a very intense \(\gamma\) beam would be of interest for such investigations. All p-nuclei can be synthesized from the destruction of pre-existing nuclei of the s- and r-type by a combination of \((p,\gamma)\) captures and \((\gamma,n), (\gamma,p)\) or \((\gamma,\alpha)\) photo-reactions. Other studies are related to specific key reactions of astrophysics interest, such as the \(^{16}\text{O}(\gamma,\alpha)^{12}\text{C}\) reaction. After hydrogen is exhausted in the stellar core, stars leave the main sequence and undergo subsequent nuclear core burning stages involving heavier nuclear species, namely, helium, carbon, neon, oxygen and silicon burning provided that stellar masses are large enough. The outcome of helium burning is the formation of the two elements: carbon and oxygen [25]. The ratio of carbon-to-oxygen (C/O) at the end of helium burning has been identified three decades ago as one of the key open questions in Nuclear Astrophysics [25] and it remains so today. The importance of the C/O ratio for the evolution of heavy stars that evolve to core collapse (type II) supernova has been discussed extensively [26] but more recently it was shown that the C/O ratio is also important for understanding the \(^{56}\text{Ni}\) mass fraction produced by lower mass stars that evolve into Type Ia supernova (SNeIa) [27]. Thus the C/O ratio is also important for understanding the light curve of SNeIa. The principle of detailed balance allows the determination of the cross section of an \((\alpha,\gamma)\) process from the measurement of the time inverse \((\gamma,\alpha)\) reaction with \(\gamma\)-ray beams. Since both the electromagnetic and nuclear interactions are time reversal symmetric the cross sections are related to each other in terms of the spin factors and De Broglie wavelengths by:

\[
\omega_A \frac{\sigma_A(\alpha,\gamma)}{\lambda_A} = \omega_B \frac{\sigma_B(\gamma,\alpha)}{\lambda_B}. \tag{2}
\]

One of the advantages of measuring the photo-dissociation of \(^{16}\text{O}\) is a gain due to detailed
balance. Such an experiment requires a $\gamma$-ray beam of energies 10 MeV and less (approaching 8 MeV) since the Q value of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction is 7.162 MeV.

A number of scientific instruments are under discussion to be used in these experiments. These include a time-projection chamber (TPC) with a GEM read-out, which is currently being developed at the University of Warsaw, Poland, a $4\pi$ Si DSSD array, which is being designed by the INFN LNS Catania, Italy, and a bubble chamber. All of these will allow to achieve the needed sensitivity and approach the above defined problems.

3. Summary

The ELI-NP research center will host a HPLS and a GBS with parameters beyond the state-of-the-art. The power of the HPLS lasers exceeds existing lasers by an order of magnitude and will deliver every minute on the target intensities in the range of $10^{23}$ W/cm$^2$. The spectral density of $10^4$ photons/s/eV will provide brilliance and narrow bandwidth of the $\gamma$ beams, which will be delivered by the ELI-NP GBS, that are much beyond the parameters of the beams which are delivered at the existing facilities. This makes it possible to design and perform new classes of nuclear physics experiments, which cannot be done elsewhere.

In short, the outstanding performance of the high-power lasers and the $\gamma$ beam opens the possibility to carry out a versatile research program in nuclear physics and tackle key problems in nuclear structure, astrophysics and reactions.

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