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THE EXTREME LIGHT INFRASTRUCTURE NUCLEAR PHYSICS FACILITY: TOWARDS EXPERIMENTS WITH BRILLIANT γ-RAY BEAMS*

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The Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility which is being built at Bucharest–Magurele aims at utilizing extreme electromagnetic fields for nuclear physics and quantum electrodynamics studies. Two ten pentawatt high-power laser systems and a brilliant γ beam are the main research tools of the facility. Here, we present the current status and the perspectives for experiments with intense γ rays at ELI-NP.

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1. Introduction

The Extreme Light Infrastructure (ELI) project was initiated in 2005 aiming at the production and studies of ultra-high laser fields [1]. Within its preparatory phase, the sites and the scientific directions of the project were defined. Nowadays ELI is built as a distributed facility with three research pillars: *(i)* laser-driven secondary radiation sources in the Czech Republic, *(ii)* attosecond pulses in Hungary, and *(iii)* nuclear science in Romania.

The ELI-NP project aims at establishing an European Research Infrastructure Center for ultra-high intensity lasers, laser-matter interactions, nuclear and material science, using laser-driven radiation sources [2]. This multidisciplinary facility will provide new opportunities to study fundamental processes that occur in ultra-intense laser fields during laser–matter interactions. It will also open new dimensions in nuclear research with intense γ beams, produced in Compton back-scattering, and in material research with intense positron beams. The facility, worth 295 million euro and funded

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by the European structural funds, will be developed in two phases and will be available for users in 2017. Here, we present the parameters of the planned γ-beam system (GBS) and provide a glimpse in the scientific program associated with it. We also discuss the scientific instrumentation which is considered for the realization of this program.

2. Physics with intense quasi-monochromatic γ rays

2.1. The ELI-NP γ-beam system

One of the main research tools at the ELI-NP laboratory is the brilliant γ-ray beam. The γ beam is produced through Compton back-scattering of laser light off an accelerated electron beam. Laser photons with energy E_0 are exploited to generate photon beams with high energies E_γ via Compton back-scattering at a small angle θ from a counter-propagating fast electron beam, characterized by its relativistic factor γ according to

$$E_\gamma = 4\gamma^2 \frac{1}{1 + (\theta\gamma)^2 + \frac{4\gamma E_0}{mc^2}} E_0 \approx 4\gamma^2 E_0 \,. \tag{1}$$

The ELI-NP γ-beam system will enable the production of a brilliant, highly collimated beam of γ rays with a narrow bandwidth. Such a facility will open new experimental perspectives for studies in the field of photonuclear physics. Compared to the existing γ-beam facilities, ELI-NP will provide beams which are about two orders of magnitude more intense with an order of magnitude narrower bandwidth and a smaller beam spot. The expected parameters of the ELI-NP GBS are presented in Table 1 [3].

Advanced γ-ray beams, based on Compton back-scattering between electron bunches and counter-propagating laser pulses, are considered to be the new roadmap to open the field of nuclear photonics. Such Thomson–Compton colliders aim at producing extreme γ-ray beams for nuclear physics and nuclear photonics experiments. The required output specifications for the ELI-NP GBS, which are listed in Table I, are based on the needs of the interested scientific community and the realistic expectancies that are technically feasible within the time frame of the project implementation [3]. The electrons will be accelerated by a two-stage electron Linac up to energies of $E_e = 300$ MeV in the first stage and $E_e = 700$ MeV in the second stage. Thus, two γ beams will be available — a low-energy beam, in the range from 200 keV to 3.5 MeV, and a high-energy beam up to 19.5 MeV. By varying the energy of the accelerated electrons, the energy of the γ beam will be tuned with a very high precision. A possible solution for the electron accelerator is a normal-conducting electron Linac to produce high peak brightness in the single bunch as well as a multi-bunch beam with effective high repetition rate to increase the average current.

TABLE I

Parameters of the ELI-NP γ-beam system.

Parameter	Range
γ-ray energy [MeV]	0.2–19.5
γ-beam divergence [rad]	$\leq 2 \times 10^{-4}$
Average relative bandwidth of the γ-ray beam	$\leq 5 \times 10^{-3}$
Average spectral density at peak energy [$\mathrm{s}^{-1}\mathrm{eV}^{-1}$]	$\geq 5 \times 10^{3}$
Average brilliance at peak energy [$\mathrm{s}^{-1}\mathrm{mm}^{-2}\mathrm{mrad}^{-2}/0.1\%$]	$\geq 1 \times 10^{11}$
Minimum frequency of γ-ray macropulses [Hz]	≥ 100

The electron beam characteristics are fundamental for these kind of sources. Normalized r.m.s. emittances in both planes below 0.5 mm$\times$mrad are needed as well as an energy spread below 0.1%. For the γ-beam production, a high power laser, *e.g.* a Yb:YAG laser, collides with the electron beam, for a possible solution see *e.g.* Ref. [4]. The total number of laser scattered photons is given by $N_\gamma = L \times \sigma_{\mathrm{th}}$, where the Thomson cross section is $\sigma_{\mathrm{th}} = 0.67 \times 10^{-28}$ m^2 (0.67 barn) and L is the luminosity parameter. In the case of colliders, the luminosity parameter is defined as

$$L = \frac{N_{\mathrm{L}} N_e}{2\pi \left(\sigma_x^2 + w_0^2\right)} f \,, \qquad (2)$$

where N_{L} is the optical photons number of the laser pulse, N_e is the electrons number per bunch, σ_x is the r.m.s. electron bunch spot size (considering a round beam), w_0 is the laser focal spot size, and f is the collision repetition rate, obtained multiplying the RF repetition rate for the number of electron bunches into a RF pulse. The luminosity of the suggested ELI-NP γ beam facility is $L \approx 10^{35}$ s^{-1}cm^{-2} [4].

One of the most stringent parameters of such a γ beam, determining its high quality, is a very narrow bandwidth, which combined with its high-brilliance, results in a high spectral density of $\geq 10^4$ photons/s/eV, about two orders of magnitude higher as compared to existing γ beams.

2.2. The ELI-NP γ-beam experimental program

The ELI-NP γ-beam experimental program considers studies related to nuclear resonance fluorescence (NRF) and experiments above the particle separation threshold, such as studies of giant resonances, nuclear astrophysics reactions, and photo-fission experiments [3]. A schematic lay-out of such experiments is displayed in Fig. 1. The incoming narrow bandwidth

γ beam excites a single excited state, whose decay is studied in the experiment. The excited state can be below or above the particle separation energy, which lies at about 8 MeV. Below the particle threshold, the NRF method is applied and above it γ-induced reactions, such as (γ,n), (γ,p), (γ,α), (γ,f), *etc.*, as well as giant resonances can be studied. The physics program will benefit from the challenging parameters of the γ beam: tunable energy (0.2–20 MeV), very narrow bandwidth (0.3%), high spectral density (10^4 photons/s/eV), and high (more than 95%) linear or circular polarization of the γ beam.

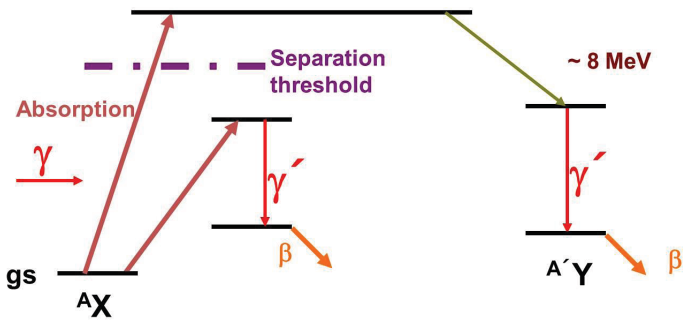

Fig. 1. Principle of γ-beam experiments.

The photo-response below the particle separation energy is currently investigated in NRF experiments [5] at existing γ-beam facilities, such as the bremsstrahlung facilities at the S-DALINAC electron accelerator in Darmstadt (see *e.g.* Ref. [6]) or at the High Intensity γ-ray Source (HIγS) at Duke University (see *e.g.* Ref. [7]). NRF experiments have been possible at existing facilities only if sufficient amounts of (preferably isotopically enriched) target material of the order of about 1 g has been available. The production of such an amount of target material is not always possible at a reasonable cost. The advances in γ-ray beam brilliance at ELI will increase the sensitivity of NRF experiments and thus it 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 mg. For example, the dipole response of the long-lived radioactive isotope ^{14}C, the basis of radio-carbon dating method, will be accessible. These experiments will shed light on the neutron-spectroscopic factors for the p- and sd-shell orbitals in that mass region that nowadays is accessible to *ab initio* no-core shell models calculations [3]. There are many strategic studies and applications related to national security and nuclear waste treatment which are also possible with the NRF method.

The ELI-NP γ beam will have unique properties in world-wide comparison and opens new possibilities for high resolution spectroscopy at higher nuclear excitation energies above the particle separation threshold. Such studies will lead to a better understanding of nuclear structure at higher excitation energies with many doorway states, their damping widths, and chaotic behaviour, but also new fluctuating properties in the time and energy domain. The excitation energy region around the particle separation threshold is of particular importance for nuclear physics. On the one hand, this energy region is of interest for theoretical reasons because the coupling of bound quantum states to the continuum of unbound states requires an extended formalism, the mastering of which becomes extremely important for exotic nuclei near the drip-lines where all structures are weakly bound [8]. On the other hand, this energy region covers the Gamow-window of thermally driven reactions of nucleons with heavy nuclei. Its understanding is a prerequisite for the modelling of nuclear reaction cascades in hot cosmic objects and thus for nucleosynthesis.

Above the threshold, the particle-decay channel opens up. In nowadays state-of-the-art experiments either no γ rays can be observed at all or their intensity cannot be used as a measure for the total electromagnetic excitation strength to the resonance due to the unknown particle-decay branching ratio. Neutrons cannot be measured with a competitive energy resolution at acceptable solid-angle coverage. An intense and high-energy resolving γ-ray beam from ELI-NP will open up new horizons for the investigation of the nuclear photo-response at and above the separation threshold. An example for such studies is the detailed investigation of the pygmy dipole resonance (PDR) above and below 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. 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. Most frequently microscopic models (RPA, RRPA, QPM, TDHF theory) are invoked to interpret and understand the experimental results [3]. The use of ELI-NP γ beam provides substantial advantages for these studies, such as the narrow width in energy, the easy energy variation and the fact that γ rays are polarized. Both, the GDR and the PDR can be covered within the energy range of the ELI-NP beams. In the experiments will be measured the excitation functions for elastic and inelastic γ scattering, revealing possible fine structures/splitting of PDR and GDR, the excitation function with high resolution for (γ,n) and (γ, charged particle) channels, allowing to determine the branching ratios for various decay channels. The polarized beam will also allow determining the E1 or M1 type of excitation for the observed structures [3].

The ELI-NP facility provides unique opportunities for nuclear astrophysics research. For example, the γ-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 (γ,α) reactions. Therefore, a very intense γ 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,γ) captures and (γ,n), (γ,p) or (γ,α) photo-reactions. One question raised by the p-process studies is to know to what extend the calculated p-nuclei abundances do reproduce the Solar system ones. A variety of explosive stellar sites, in which matter is heated to temperatures in the range $T_9 = 1.5$–3.5 ($T = 2$–3×10^9 K), success in synthesizing p-nuclides with relative abundances in rough agreement with the Solar system isotopic content. However, a serious discrepancy concerns the large isotopic ratios of the Mo and Ru p-nuclei in the Solar System (of the order of 10% of the corresponding elemental abundances), for which no satisfactory explanation has been found so far. Solution of such problems looked for by utilizing quasi-monochromatic γ beams, as recently demonstrated at HIγS [9].

Other studies are related to specific key reactions of astrophysics interest, such as the $^{16}O(\gamma,\alpha)^{12}C$ 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 [10]. 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 [10] 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 [11] but more recently it was shown that the C/O ratio is also important for understanding the ^{56}Ni mass fraction produced by lower mass stars that evolve into Type Ia supernova (SNeIa) [12]. 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 (α,γ) process from the measurement of the time inverse (γ,α) reaction with γ-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

$$\omega_A \frac{\sigma_A(\alpha,\gamma)}{\lambda_A} = \omega_B \frac{\sigma_B(\gamma,\alpha)}{\lambda_B} \,. \quad (3)$$

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

Last, not least, the brilliant γ beams of ELI-NP open an avenue for photo-fission studies. So far, bremsstrahlung was used to induce fission of actinide nuclei [13]. Three classes of experiments have been identified:

— High-resolution photo-fission studies in the actinides, investigation of the second and third potential minima, angular and mass distribution measurements of fission fragments, measurements of absolute photo-fission cross sections, studies of rare photo-fission events, such as triple fission, highly asymmetric fission, *etc.*

— Separation and manipulation of rare isotopes, produced in photo-fission, with an emphasis on the isotopes of refractory elements, which can be separated with the IGISOL technique [14]. After their separation, the nuclei of interest will be transported to different measurement stations.

— In-beam γ-ray spectroscopy of fission fragments.

3. Instrumentation for the ELI-NP γ-beam experiments

In order to carry out the scientific program of ELI-NP, different state-of-the-art instruments are considered to be built. These include:

— A high-resolution spectrometer of large HPGe (Clover) detectors, combined with good timing *e.g.* $LaBr_3$ detectors;

— A spectrometer with medium resolution of large $LaBr_3$ detectors;

— A tape station and a close-geometry spectrometer for high-resolution β-decay studies;

— A 4π neutron detector array;

— A 4π charged particle array of segmented DSSSD detectors;

— A double-arm position-sensitive ionization Bragg chamber;

— A high-pressure bubble chamber;

— An (optical) time-projection chamber; and

— A large-acceptance ion guide, coupled to a mass-spectrometer and a laser ion source.

4. Conclusions

The ELI-NP facility mixes two research cultures, the physics of intense laser fields with the nuclear structure and astrophysics community. As a result of this cross-fertilization, two research facilities with parameters beyond the state-of-the-art emerge, namely a high-power laser system with two amplification arms to deliver every minute 10 PW and intensities on the target in the range of 10^{23} W/cm^2, and a brilliant γ beam system to deliver 10^{13} photon/s with energies up to 19.5 MeV. Their outstanding performances will allow to address a virgin scientific field, at the frontiers of high-field QED and photo-nuclear physics.

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