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Future Prospects of Nuclear Reactions Induced by Gamma-Ray Beams at ELI-NP[1, 2]

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Abstract—The future prospects of photonuclear reactions studies at the new Extreme Light Infrastructure—Nuclear Physics (ELI-NP) facility are discussed in view of the pursuit of investigating the electromagnetic response of nuclei using γ-ray beams of unprecedented energy resolution and intensity characteristics. We present here the features of the γ-ray beam source, the emerging ELI-NP experimental program involving photonuclear reactions cross section measurements and spectroscopy and angular measurements of γ-rays and neutrons along with the detection arrays currently under implementation.

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1. INTRODUCTION

The Extreme Light Infrastructure—Nuclear Physics (ELI–NP) [1] is one of the three pillars of the Extreme Light Infrastructure Pan-European initiative listed on the ESFRI (European Strategic Forum for Research Infrastructures) 2006 road-map, a project distributed among three European countries (the Czech Republic, Hungary and Romania) and funded by the European Commission through Structural Funds. Currently under construction in Magurele, Romania, ELI–NP is expected to be the most advanced research infrastructure in the world focused on photonuclear physics studies and applications at the time when it will become operational, in 2018. It will hosttwo 10 PW lasers and a very brilliant, state-of-the-art gamma beam system (GBS) and it will cover frontier fundamental physics, new nuclear physics and astrophysics as well as applications in nuclear materials and radioactive waste management, materials science and life sciences [2–4].

We present here the physics program proposed for the GBS at ELI-NP and also we have given details on the experimental setups which are currently under implementation. Precise data on photonuclear reactions and nuclear structure will be produced at the ELI-NP facility using the small diameter, high flux, narrow bandwidth and nearly 100% linearly polarized γ-ray beams provided by the GBS. Based on the detection instrumentation, γ-ray beam experiments at ELI-NP are grouped into the following classes: nuclear resonance fluorescence (NRF) experiments which make use of high energy resolution high purity Germanium detectors (HPGe), gammaabove neutron emission threshold experiments which employ neutron detectors and fast response γ-rays detectors, charged particle experiments using silicon detectors and time projection chambers and photofission experiments. We present here the NRFand gamma above neutron threshold experiments.

2. GAMMA BEAM SYSTEM

Experiments which employ real photon beams are among the first techniques used to investigate nuclear systems and can provide information on both the excitation and decay modes of atomic nuclei excited states. This type of experiment consists in irradiating nuclei with quasi-monochromatic or continuous γ-ray beams. Bremmstrahlung γ-ray beams are produced by intense electron beams stopped in radiator targets,

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[2] The article is published in the original.

while quasi-monochromatic γ-ray beams have been generated until recently using fast positron in flight annihilation, tagged bremmstrahlung and radioisotopes produced by neutron or proton capture reactions.

The gamma beam system at ELI-NP will be based on the inverse scattering of laser photons on relativistic electrons, a technique which provides quasi-monochromatic, pencil-like and highly polarized γ-ray beams. There are currently several facilities which make use of this technique, such as the High Intensity Gamma-Ray Source (HIγS) facility at Duke University [5] and the NewSUBARU synchrotron radiation facility [6].

In collision with relativistic electrons, laser photons are scattered into a very narrow cone oriented on the direction of the incident electron beam. Equation 1 gives the energy of the scattered photon E_γ as a function of the energy of the incident laser photon E_p, the incident angle of the laser photon θ_p, the Lorentz factor γ for the relativistic electron incident along the z axis and the scattering angle θ_γ:

$$E_\gamma = \frac{(1+\beta\cos\theta_p)E_p}{1-\beta\cos\theta_\gamma + (1-\cos\Delta\theta)E_p/(\gamma\cdot m_0c^2)} \quad (1)$$

where $\beta = v/c$ is the speed of the incident electron relative to the speed of light and $\Delta\theta$ is the angle between the momenta of the incident and scattered photons. Following this relation, we obtain energy amplification factors of 10^6–10^7, from eV laser photons to MeV γ-rays. The scattering diagram is represented in Fig. 1.

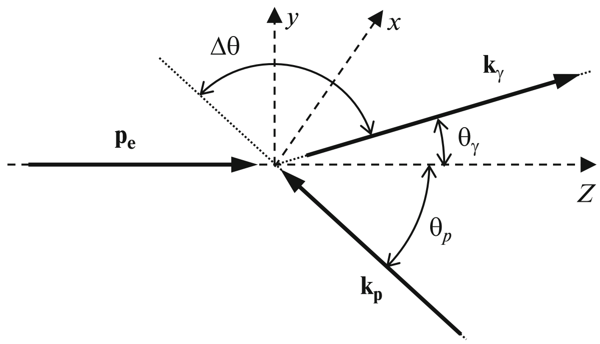

Fig. 1. Geometry of an in plane inverse Compton scattering of a laser photon against a relativistic electron, where the electron of $\mathbf{p_e}$ momentum is incident along the z axis and the laser photon is incident at a polar angle θ_p with $\mathbf{k_p}$ momentum and scattered at a polar angle θ_γ with $\mathbf{k}_\gamma$ momentum.

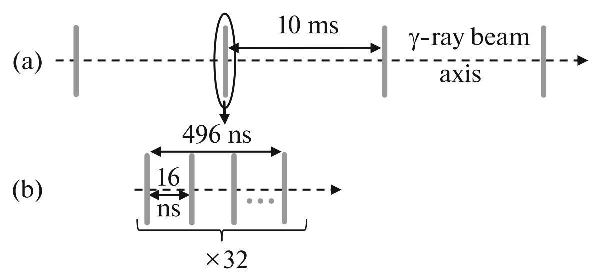

Fig. 2. Diagram of ELI-NP γ-ray beam time structure (a) the 100 Hz macro-structure and (b) the micro-structure. See text for details.

At HIγS, γ-ray beams up to 100 MeV are produced by the Compton backscattering of a Free Electron Laser beam against several hundred MeV electrons. At NewSUBARU, γ-ray beams with energies up to 76 MeV are produced in the collision of laser photons produced by a CO_2 (λ = 10.59 μm) or a Nd:YVO_4 laser (λ = 1.064 μm, 532 μm in the first and second harmonic, respectively) with 0.5–1.5 GeV electrons.

At ELI-NP, γ-ray beams will be produced using a Yb:YAG laser (λ = 515 nm in the second harmonic) in collision with a high brightness electron beam provided by a warm radiofrequency (RF) linac. High intensity and low-emittance electron beams will be provided by the linac in two acceleration stages: a first stage will accelerate electrons up to 0.3 GeV and a second stage will continue the acceleration process up to ⩾0.7 GeV. An RF photoinjector based on a multibunch RF photo-gun and S-band acceleration structures [7] will deliver the electron beam with a macrotime structure of 100 Hz. One macro-bunch will be composed of 32 electron micro-bunches of 250 pC charge with a repetition interval of 16 ns. The laser will produce 100 Hz frequency light pulses which will be synchronized with the electron bunches using a multipass recirculating system with a fixed focus point and constant crossing angle θ_p of 7.5° and shot to shot separation of 16 ns. The time structure of the ELI-NP γ-ray beam is represented in Figure 2.

Up to 2.6 × 10^5 photons in full width at half maximum bandwidth per one laser shot—electron beam interaction are expected to be provided by the GBS. The energy of the γ-ray beam will be continuously tunable between 0.2 and 19.5 MeV, with a relative energy resolution better than 0.5%. The γ-ray beam is expected to have a linear polarization degree higher than 99%. A comparison between the γ-ray beam energy range, energy resolution and intensity within bandwidth of NewSUBARU, HIγS and the ones expected at ELI-NP, as well as simulation results on the energy spectrum and polarization parameters for the ELI-NP γ-ray beam can be found in [8].

3. EXPERIMENTS WITH γ-RAY BEAMS

The experimental program proposed for the ELI-NP γ-ray beam facility comes as an answer to the scientific comunity's need for reliable and precise nuclear data on photon induced reactions and it is conceived as to take advantage of the unique intensity, spectral density and polarization parameters of the GBS. In the proposed experiments, nuclei are to be irradiated by the intense ELI-NP γ-ray beams with energies up to 19.5 MeV, inducing mostly electromagnetic dipole (E1 and M1) and quadrupole (E2) transitions to bound states excited from the ground state.

Nuclear structure studies on the electromagnetic responses of atomic nuclei will be performed using the highly monochromatic γ-ray beams in combination with adequate photon and particle detectors. Mainly low-spin collective states such as theGiant Dipole Resonance (GDR), Pygmy Dipole Resonance (PDR) and M1 spin flip resonance are excited in photonuclear reactions. The energy and angular distribution of radiation emitted in the subsequent decays of excited states will be recorded with complex detection arrays suitable for nuclear resonance fluorescence experiments (see Section 3.1), for detection of high energy γ-rays and neutrons using the time of flight technique (see Section 3.2). This type of experiments provides the energy, spin and parity of the nuclear excited states, the branching ratios between various decay modes, the excitation cross section, the multipolarity of the ejectile particle and multipole mixing ratios of γ-ray transitions.

The ELI-NP photon flux is anticipated to be higher than the ones available at the HIγS and NewSUBARU facilities by a factors of 10 and 10^3 respectively. Also, the γ-ray beam will be highly concentrated in space with a transverse beam cross section of a few tens of μm, depending on the opening of the collimator. This will allow the enrichment of present GDR, PDR and M1 spin flip resonance systematics for isotopes available only in minute quantities of a few milligrams, such as radioactive targets or low-abundance nuclei produced in the astrophysical p-process. The NRF experiments will focus mainly on the investigation of PDR and spin-flip M1 resonance below S_n in 0^+ ground state nuclei, using the ~100% linearly polarized γ-ray beams to separate E1 and M1 resonances. Experiments above the neutron separation threshold will investigate PDR and spin-flip M1 resonance with emphasis on odd-N nuclei with S_n as low as 6 MeV. The energy range of the ELI-NP γ-ray beam is expected to cover nearly the full strength of PDR and spin-flip M1 for odd-N nuclei. The enhanced photon flux and brilliance characteristic to the ELI-NP γ-ray beams will allow for the first time to observe the photon decay of excited GDR collective states above the neutron threshold back the to ground state or to lower excited states in (γ,γ') reactions. The branching ratio between the γ and neutron decays of GDR excited states is a key ingredient in the the search for experimental evidence of scales associated with the coupling between collective states and internal and external degrees of freedom.

Photonuclear reactions cross sections were systematically investigated using positron annihilation photon beams at the Lawrence Livermore National Laboratory (USA) and France Centre d'Etudes Nucleaires de Saclay. There are large discrepancies between the partial photoneutron reaction cross sections measured at the two facilities that can not be resolved in a systematic manner [9]. Having the benefit of energy tunable, intense beams of monoenergetic photons, we propose to investigate the electromagnetic excitation of atomic nuclei by measuring total and partial photoneutron reaction cross sections in order to resolve these discrepancies.

Photonuclear reactions studies in the vicinity of the particle emission threshold, the energy region of interest for astrophysics [10], are limited by the energy resolution and the intensity of the incident γ-ray beams. Due to the high energy resolution of GBS, photon induced reactions will be investigated at energies much closer to the emission threshold compared to the previous experiments, as existing quasi-monochromatic γ-ray beams have typical energy resolutions of 2–5%. Thehigh photon flux of the GBS allows for the first time to measure (γ, *n*) reaction cross sections on scarce *p*-nuclei for which only ~1 mg samples are available. The photoneutron reaction cross sections on the very low abundance ^{180}Ta and ^{138}La, highly demanded for nuclear astrophysics p-process calculations, will be measured for the first time at ELI-NP.

3.1. Nuclear Resonance Fluorescence Experiments

Nuclear resonance fluorescence experiments consist in the photo-excitation of nuclei to bound states below the neutron and proton separation energies and the observation of the subsequent γ decays of the populated levels using photon detection systems. We plan to use high purity Germanium semiconductor detectors for their excellent energy resolution in the range of a few keV allowing a detailed analysis of γ-ray transitions and scintillation detectors like $LaBr_3$ or $CeBr_3$ which havean inferior energy resolution to HPGe detectors, but higher detection efficiency and faster signals.

The time structure of the ELI-NP γ-ray beam had to be taken into consideration while designing the detection system. The slow time response of the HPGe detectors does not allow to discriminate transitions induced by different micro-bunches in one macro-bunch. Thus, pile-up signals can be induced in the detectors as a result of the ~10^6 photons delivered by one macro-bunch of 100 Hz frequency. To overcome this challenge, an array of eight HPGe detectors of the segmented Clover type called ELIADE (ELI-NP Array of DEtectors) is proposed to be used at ELI-NP. Every Clover crystal will have eight segments resulting from a four-fold longitudinal segmentation and one transversal segmentation. Four Clover detectors will be placed on a ring with an angular position which can be varied between 90 and 98 degrees and four detectors will be placed on a fixed ring at 135 degrees, as shown in Fig. 2. The 90 degrees ring can host up to 8 detectors, where in the additional positions can be placed either another 4 HPGe Clover detectors or 4 large volume 3" × 3" $LaBr_3$ detectors. The distance between the detector and the target is variable in the range from 15 to 25 cm. The chosen geometry enables the placement of detectors in paralel and perpendicular planes relative to the linear polarization plane of the γ-ray beam, which is the optimum orientation for polarization sensitive experiments [11].

3.2. Gamma Above Neutron Threshold Experiments

Energy and angular differential photoneutron reactions and elastic and inelastic (γ, γ') scatterings will be studied at ELI-NP by irradiating nuclei of interest with γ-ray beams with energies above the neutron separation threshold. The ELI-NP GBS is expected to provide monochromatic γ-ray beams with energies up to 19.5 MeV, which is below the three neutron emission threshold for most nuclei. Excited states above the S_n in a target nucleus ^{A}X undergo either neutron decays to the ground state and excited states in the residual nucleus ^{A-1}X or, with much lower probability, γ transitions to the ground state or to excited states in ^{A}X. Excited states above the S_{2n} in ^{A}X can decay by neutron emission to excited states above the S_n in the the residual nucleus ^{A-1}X, which in turn decay by neutron emission to excited states or to the ground state of the residual nucleus ^{A-2}X. The neutron decays to excited states below the neutron emission threhsold in $^{A-1, A-2}X$ nuclei are followed by γ cascades towards the ground state.

We propose to record the energy and angular distribution of neutrons and γ-rays emitted in (γ, *n*), (γ, 2*n*), (γ, γ) and (γ, γ') reactions using a mixed 2π detection system. An array of 34 $LaBr_3$ and $CeBr_3$ γ-ray scintillation detectors and 62 BC501 liquid scintillator and ^{6}Li glass neutron detectors is currently under implementation. Large volume 3" × 3" $LaBr_3$ and $CeBr_3$ detectors provide high detection effficiency, high energy resolution (3.5% and 4.0%, respectively, at 662 keV) and fast responses. Fast response detectors are required to discriminate signals that correspond to radiation emitted in photonuclear reactions induced by photons from different micro-bunches with a repetition rate of only 16 ns.

The time of flight technique will be employed for recording the energy of reaction neutrons. We use two types of neutron detectors: BC501 liquid scintillator detectors sensitive to neutrons with energies above 1 MeV and ^{6}Li glass detectors for energiesbelow 1 MeV. The liquid scintillation detectors provide a light output proportional to the kinetic energy of recoil protons from the *n* + *p* scattering, therefore they are suitable for detection of high energy neutrons. ^{6}Li glass detectors provide signals based on the $^{6}Li(n, \alpha)^{3}H$ conversion reaction. The large reaction Q-value (4.78 MeV) allows the detection of neutrons with energies as low as 50 keV.

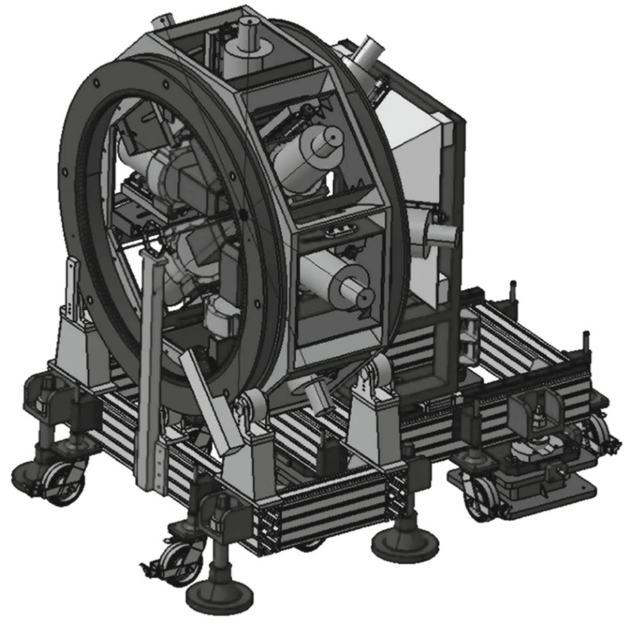

Fig. 3. A view of the CAD design of the ELIADE array.

Both the neutron and the gamma-ray detectors will be placed on rings symmetric to the north-south axis, which ensures a wide range of angular positions relative to the beam axis. The bromide detectors will be placed in the lower backward hemisphere withrespect to the γ-ray beam direction at a variable distance between 20 to 30 cm away from the target. One detector will be placed at the south pole and at least one detector in the equatorial plane, for polarization sensitive experiments.

The neutron detectors are to be placed in the upper backward hemisphere with one detector placed at the north pole and one in the equatorial plane. The distance between the target and the detectors will be between 1 to 1.5 meters for the BC501 detectors and between 0.4 to 1 meter for the ^{6}Li glass ones.

Photoneutron cross section measurements will be performed at ELI-NP using a 4π flat efficiency neutron detection system. The reaction neutrons will be moderated inside a 46 × 46 × 50 cm^3 polyethylene block. The "slowed down" neutrons will be recorded by 31 ^{3}He counters placed in 3 concentric rings. The target will be centered inside the detection system. A similar detection system is already in test at the NewSUBARU facility. The flat efficiency has been obtained using MCNP simulations and experimental calibration using a ^{252}Cf source. The flat efficiency technique is essential for neutron multiplicity sorting experiments to be performed at ELI-NP.

4. CONCLUSIONS

The Extreme Light Infrastructure —Nuclear Physics is a new large scale facility currently under construction in Magurele, Romania, which will host two 10 PW lasers and a very brilliant, state-of-the-art gamma beam system. We presented here the characteristics of the GBS and the physics program related to nuclear structure and reactions studies using the γ-ray beam source. For studies of electromagnetic responses of atomic nuclei, the energy and angular distribution of radiation emitted in the subsequent decays of photon induced excitations are to be observed with detection arrays suitable for NRF experiments and for detection of neutrons and high energy γ-rays emitted in photonuclear reactions above the neutron separation threshold. Precise photo-neutron reactions cross sections will be measured using a 4π flat and high efficiency neutron detection system. Thus, ELI-NP will become an important source of new nuclear data.

5. ACKNOWLEDGMENTS

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