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Physics studies with brilliant narrow-width γ-beams at the new ELI-NP Facility

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Abstract. The Extreme Light Infrastructure Nuclear Physics (ELI-NP) Facility in Magurele is a European research centre for ultrahigh intensity lasers, laser–matter interaction, nuclear science and material science using laser-driven radiation beams. It is the first project within the European Strategic Forum for Research Infrastructure (ESFRI) agenda financed by the European Regional Development Fund. The nuclear physics research programme of the facility is focussed on studies with brilliant narrow-width γ-beams and experiments in extreme laser fields.

Keywords. Brilliant narrow-width γ-beam; γ-ray-induced nuclear reactions; photofission; nuclear resonance fluorescence.

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1. Introduction

The Extreme Light Infrastructure Nuclear Physics (ELI-NP) Facility aims to use extreme electromagnetic fields for nuclear physics research. It is one of the three pillars of the ELI project [1], the other two being laser-driven secondary beams in Prague, the Czech Republic [2] and attosecond pulsed lasers in Szeged, Hungary [3].

New opportunities will be opened in the fields of nuclear physics, strong-field quantum electrodynamics and material science because of the availability of two major instruments with the state-of-the-art parameters, namely a high-power laser system (HPLS) with two amplification arms of 10 PW each and a brilliant narrow-width γ-beam system (GBS) [4]. The HPLS will deliver minute by minute intensities on target in the range of 10^{23} W/cm^2 and the GBS will deliver 10^{13} photons/s with energies up to 19.5 MeV, which are produced by Compton backscattering of a laser beam off a beam of accelerated electrons produced by a linear accelerator. Both systems are hosted by a building complex shown in figure 1. The facility will be available for use in 2017. Here, the scientific programme related to nuclear physics studies is discussed and the related instrumentation which are considered for its realization is presented.

(a)


(b)


Figure 1. (**a**) Architect's vision of the main building complex at ELI-NP which hosts the HPLS, GBS and the experiment vaults; (**b**) status of the construction of the main building complex as on March 2014.

2. Nuclear physics studies with brilliant γ-beams at ELI-NP

The nuclear physics research programme at ELI-NP considers both, experiments at the HPLS and experiments with brilliant γ-beams. Here, the emerging experimental programme at the ELI-NP GBS is discussed. Compared to the existing facilities, the GBS of ELI-NP will provide beams which are about two orders of magnitude more intense with bandwidth an order of magnitude narrower and much smaller beam spot. The ELI-NP GBS will be delivered by the European consortium EuroGammaS led by the Italian INFN LNF. For the parameters of the GBS see, e.g., [4,5]. A solution for the realization of the GBS is described in [6]. One of the most stringent parameters of such a γ-beam, which gives 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 the existing γ beams.

The ELI-NP γ-beam experimental programme considers studies related to nuclear resonance fluorescence (NRF) and experiments above the particle separation threshold, such as the studies of giant resonances, nuclear astrophysics reactions and photofission experiments [7]. A schematic lay-out of such experiments is displayed in figure 2. The incoming narrow-bandwidth γ-beam excites a single excited state, the decay of which 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 programme 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.

The technical design reports (TDR) associated to each type of experiment are now in preparation. A set of TDRs, which are focussed on using the GBS, will combine two main objectives:

(1) Basic science in the fields of high-resolution nuclear spectroscopy and astrophysics of the r-, s- and p-processes in nucleosynthesis. Main achievements with the γ-beam facility are likely to occur, as a result of high resolution at higher nuclear excitation energies in studies related to collective modes in nuclei. For example, major advancements are expected in the fields of photonuclear reactions related to nuclear astrophysics, as well as to photofission studies. A detailed investigation of the pygmy dipole resonance above and below the particle threshold is essential for studying nucleosynthesis in astrophysics.

(2) Applications of nuclear techniques, such as developing NRF for nuclear materials and radioactive waste management, brilliant γ, X-ray, positron and electron microbeams in material and life sciences. The project aims to develop techniques for remote characterization of nuclear materials or radioactive waste via NRF and this will be of great importance to the society. New production schemes of medical isotopes via the (γ, n) reactions might also be of socioeconomical relevance.

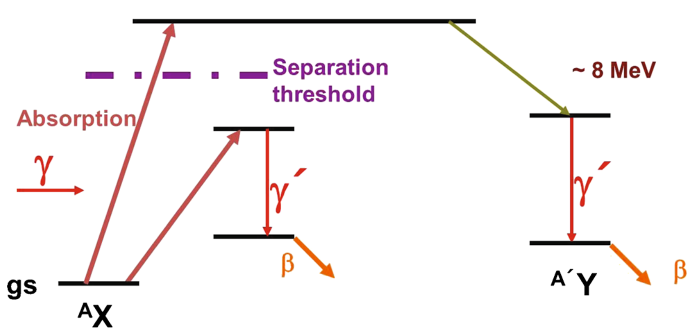

Figure 2. Principle of γ-beam experiments.

2.1 *Nuclear resonance fluorescence*

The progress in γ-ray beam brilliance at ELI will increase the sensitivity of NRF experiments and thus will offer opportunity to perform NRF studies on small target samples. This opens up an entire new area, i.e., the NRF method can be used for materials that may be available only in quantities of a few milligrams. E.g., the dipole response of the long-lived radioactive isotope ^{14}C, the basis of radiocarbon dating method, will be possible to be studied. 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 [7]. The ELI-NP Array of DEtectors (ELIADE) will be used in these experiments. The ELIADE spectrometer consists of eight Clover detectors of EXOGAM type with anti-Compton shields, which will be combined with four $3'' \times 3''$ $LaBr_3$ 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 ≈10%.

2.2 *Nuclear astrophysics studies*

The ELI-NP Facility provides unique opportunities for nuclear astrophysics research. For example, the γ-induced nuclear reactions of astrophysical interest were extensively studied in the past, but still they are a challenge for the experimental and theoretical physicists. The difficulty arises due to the very small cross-sections because the reactions, especially the (γ, α) reactions, occur deep below the Coulomb barrier. Therefore, only a very intense γ-beam can be used for such investigations. All p-nuclei can be synthesized from the destruction of pre-existing nuclei of the s- and r-types by a combination of (p, γ) captures and (γ, n), (γ, p) or (γ, α) photoreactions. Other studies are related to the specific key reactions of astrophysics, 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 the stellar masses are large enough. The outcome of helium burning is the formation of the two elements: carbon and oxygen [8]. The ratio of carbon-to-oxygen (C/O) at the end of helium burning was identified three decades ago as one of the key open questions in nuclear astrophysics [8] and it remains so even 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 [9], but more recently, it was shown that the C/O ratio is also important for understanding the ^{56}Ni mass fraction produced by the lower mass stars that evolve into type Ia supernova (SNeIa) [10]. 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. As both the electromagnetic and nuclear interactions are time-reversal symmetric, the cross-sections, σ_i, $i = A, B$, are related to each other in terms of the spin factors, ω_i, and the De Broglie wavelengths, λ_i, by:

$$\omega_A \frac{\sigma_A(\alpha, \gamma)}{\lambda_A} = \omega_B \frac{\sigma_B(\gamma, \alpha)}{\lambda_B}. \quad (1)$$

One of the advantages of measuring the photodissociation 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) because the Q value of the ^{12}C(α, γ)^{16}O reaction is 7.162 MeV.

Discussions are underway about the scientific instruments to be used in these experiments. These include a time-projection chamber (TPC) with a GEM read-out, a bubble chamber and a 4π DSSSD array, which can achieve the needed sensitivity and can approach the above-defined problems.

2.3 *Studies of large-amplitude collective motion in nuclei*

The particle-decay channel opens up above the threshold (see figure 2). In the current state-of-the-art experiments either no γ-rays can be observed at all or their intensity cannot be used as a measure of the total electromagnetic strength of 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 investigating nuclear photoresponse at and above the separation threshold. An example for such studies is the detailed investigation of different soft modes, such as e.g., the pygmy dipole resonance (PDR) above and below the particle threshold, which is essential for nucleosynthesis in astrophysics. PDRs are much lower in energy than giant dipole resonances (GDR) and represent only a small fraction of the total $E1$ strength (few percent), while GDRs exhaust the $E1$ strength almost fully. 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. The ELI-NP γ-beam provides substantial advantages for the 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, the excitation functions for elastic and inelastic γ scattering will be measured, revealing possible fine structures/splitting of PDR and GDR, the excitation function with high resolution for (γ, n) and (γ, charged particle) channels, allowing the measurement of the branching ratios for various decay channels. The polarized beam will also allow the measurement of $E1$ or $M1$ type of excitation for the observed structures [7].

Two major instruments are under consideration for realizing this experimental programme: a 4π neutron spectrometer and an array of large-volume $LaBr_3$ detectors.

2.4 *Photofission studies*

The availability of a brilliant narrow-width γ-beam opens up an avenue for photofission research, because narrow-width γ-beam can be used in high-resolution studies in γ-induced reactions. This programme will address high-resolution photofission experiments in the actinides, investigation of the second and third potential minima, measurement of angular and mass distribution of fission fragments, measurements of absolute photofission cross-sections, studies of rare photofission events, such as triple fission, highly asymmetric fission, etc. For its realization two experimental set-ups are considered, a set of Bragg spectrometers for studying transmission resonances and an array of THGEM, MWPC and DSSSD detectors for studying rare photofission events. The energy and mass resolution of the Bragg spectrometers will be reaching or going beyond the state-of-the-art. The Frisch grid of the spectrometer will also provide some fragment angular distribution information. The set-up for rare fission events is optimized for measuring angular distribution, for identification and for energy measurements of light ternary particles.

In addition, an ISOL Facility is being designed for the separation and manipulation of rare isotopes, produced in photofission, with an emphasis on the isotopes of refractory elements. The IGISOL technique [11] will be utilized. A large acceptance ion guide which will host a stack of fissile targets is under study. It will be placed in-beam after the high-energy γ-beam interaction point of the GBS. The spectrum of the γ-beam will cover the GDR of the fissile isotopes, e.g., ^{238}U or ^{232}Th. The fission fragments will be slowed down and neutralized in the gas of the ion guide. Ions of the elements of interest will be ionized with a laser ion source (LIS) and the isotopes of interest will be selected with a mass separator. After their separation, the nuclei of interest will be transported to different measurement stations.

In-beam γ-ray spectroscopy of fission fragments is also contemplated. The ELIADE array will be used in these experiments. Triple and higher-fold γ-coincidence events will be recorded. The ELIADE array might be coupled to a Bragg spectrometer for identifying one of the fragments. Fast-timing, g-factor and fission plunger experiments are considered for different assemblies of the set-up.

3. Conclusions

The ELI-NP research centre will host a GBS with parameters beyond the state-of-the-art. Its spectral density, brilliance and bandwidth are orders of magnitude better than those of the existing facilities. The outstanding performance of the γ-beam, which will be available at ELI-NP, opens up the possibility of carrying out a versatile research programme in nuclear physics and tackle key problems in nuclear structure, astrophysics and reactions.

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