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NUCLEAR PHOTONICS AT ELI-NP

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Abstract. The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) centre that began implementation in Romania, part of the European distributed research facility ELI, will feature an ultra-intense gamma-ray beam, with unique characteristics that will allow for new types of experiments in nuclear physics and related areas. In the present work, two experimental topics where ELI-NP will bring significant progress are discussed: Nuclear Resonance Fluorescence, and Photofission.

Key words: nuclear photonics, photoreactions, electron accelerators, Compton gamma sources, Nuclear Resonance Fluorescence.

1. INTRODUCTION

With the advent of new, laser-based gamma ray sources, featuring extremely high intensities at very narrow bandwidths, it becomes possible nowadays to access and manipulate the atomic nucleus with photons (nuclear photonics). New experiments with applications in a wide range of fields, spanning from industry to medicine, start a new age in nuclear physics.

The Compton backscattering of intense light from short-pulse lasers on accelerated electrons produce highly mono-energetic gamma rays, in narrow beams and with tunable energies via the kinetic energy of the electrons. The already narrow relative bandwidth of the gamma radiation produced with this technique (10^{-3}) can be further improved by orders of magnitude with the help of crystal monochromators and gamma optics, as recently demonstrated experimentally [1]. This selectivity of the energy makes it possible to access individual excitation levels in nuclei and thus to boost the study of complex nuclear structure and to envisage a plethora of new applications.

Due to the Compton backscattering effect, incoming photons from the laser beam interact with the relativistic electrons traveling in the opposite direction and a photon emission up-shifted in energy up to the range of gamma-rays occurs within a narrow cone along the direction of propagation of the electrons [2]:

$$\epsilon_\gamma = \frac{4h\nu_{laser}\gamma^2}{1 + 4h\nu_{laser}\gamma^2/E_{rel} + (\gamma\theta)^2}\ , \tag{1}$$

where ν_{laser} is the frequency of the photons in the laser beam, θ the scattering angle of the gamma-ray photon, γ is the Lorentz factor of the accelerated electrons and E_{rel} their energy. For electron energies above a few hundred MeV, as the ones that will be encountered at ELI-NP, the up-shifting factor in energy is approximately $4\gamma^2$.

Demonstration machines for the production of gamma ray beams through back-scattering of laser light were designed decades ago, the first of its king being LADON, at the ADONE facility in Frascati, Italy [3]. Consequently, other facilities were built, the ones in operation at the present time being HIGS (High Intensity γ-ray Source) on Duke University campus in the United States, based on a Free Electron Laser (FEL) design [4], and LEPS (Laser Electron Photon Experiment) at the SPring-8 facility in Japan [5].

Recent increases in laser power and advances in accelerator technologies enable the construction of more intense, collimated and narrow bandwidth gamma beams. These will not only make a quantitative jump with respect to existing facilities, permitting much more efficient operation, but will also make the qualitative step from ”impossible” to ”feasible” for many experiments.

In the following sections, we will make a short overview on the sources of γ radiation at the Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility, and on two classes of experiments among the ones proposed by the scientific community, where ELI-NP will allow for relevant advances.

2. γ PHOTON BEAMS AT ELI-NP

A major distributed research facility, the Extreme Light Infrastructure (ELI), listed among the top priority research projects in the European Union, shall become the European flagship in high power laser science. One of the research centres that are part of ELI, namely ELI-NP, began implementation in Romania, on the Măgurele physics campus close to Bucharest [6], and is dedicated to nuclear science with the aid of ultra-intense photon beams.

ELI-NP will be based on two major machines: the Multi-Petawatt Laser System (MPLS) and the Gamma Beam System (GBS). This latter equipment will produce a high quality γ-ray beam by the Compton backscattering of light photons off accelerated electrons.

2.1. THE GAMMA BEAM SYSTEM

The ELI-NP Gamma Beam System will consist of a warm electron linac, an interaction laser, control and security equipment, and auxiliary equipment. The electron linear accelerator shall be built in two acceleration stages, each with its own laser-electrons interaction points able to produce γ photons with intermediate energies (up to about 4.5 MeV) and in the full energy range (0.2 to 19.5MeV) respectively.

The beam will feature a small divergence (0.1 mrad), allowing extremely high gamma fluxes at the target position. Several experimental rooms will have access to the beam, for experiments involving the lower part and the whole range of γ energies respectively, and combined experiments with the gamma and laser beams.

2.2. γ RADIATION INDUCED IN 10PW LASER EXPERIMENTS

During the experiments with the ultra-short pulse (20-30fs), high power laser system, the interaction of the photon pulse with matter will be the source for secondary particles and radiation. The ultra-intense laser pulses will produce extreme electric fields of $\sim 10^{15}\mathrm{V\,m^{-1}}$, that will accelerate charged particles at high energies within very short distances [6].

Radiation, including in the γ rays domain, may be produced through bremsstrahlung as well as in the nuclear reactions occurring between the accelerated particles and targets. Measuring the prompt gamma rays that hold information on nuclear processes, is a difficult experimental task beyond present-day capabilities, but among the goals of ELI-NP.

The ultra-short duration of the excitation photon pulses may lead to novel methods for the investigation of nuclear parameters.

3. NUCLEAR RESONANCE FLUORESCENCE

Nuclear Resonance Fluorescence (NRF) is a process in which a nucleus radiates photons with high energies (seldom in the MeV range) within a narrow bandwidth, after it has been excited by gamma rays. The process can be elastic (if after the excitation the nucleus decays back to the ground state) or inelastic (when the decay proceeds to another level with lower energy). The main advantage of the NRF method is that the excitation and deexcitation processes take place via the electromagnetic interaction, which is the best understood interaction in physics.

The NRF technique allows the recovery of several nuclear quantities in a model-independent way: such as, for example, the excitation energies, level widths Γ, γ decay branching ratios, or spin quantum numbers and parities of the excited states (for even-even nuclei) [7].

For a bremsstrahlung continuous excitation spectrum, or for quasi-monochromatic sources where the energy bandwidth is large compared to the level width, as it is still the case with the best present $\Delta E_\gamma/E_\gamma = 10^{-2}$ and future $\Delta E_\gamma/E_\gamma = 10^{-3}$ sources (this latter value being the starting value for the ELI-NP gamma beam), the energy integrated differential cross-section can be determined [8]:

$$I_s = \frac{2J+1}{2J_0+1} \cdot \left(\pi \frac{\hbar c}{E_\gamma}\right)^2 \cdot \frac{\Gamma_0 \Gamma_f}{\Gamma} \cdot \frac{W(\Theta)}{4\pi}\,, \tag{2}$$

where J and J_0 are the spins of the excited and ground state, W the angular distribution, and Γ_0, Γ_f and Γ are the decay widths to the ground state, to the final level and the total decay width, respectively. Γ is connected to the lifetime τ of the excited level:

$$\Gamma = \frac{\hbar}{\tau}. \tag{3}$$

Defining the statistical factor $g = (2J+1)/(2J_0+1)$, the product $g \cdot \Gamma_0$ is proportional to the reduced dipole excitation probabilities from the ground state, which are, in numerical form [7]:

$$B(E1)\uparrow = 0.955 \frac{g\Gamma_0}{E_\gamma^3} \left[10^{-3} e^2 fm^2\right]\,, \tag{4}$$

$$B(M1)\uparrow = 0.0864 \frac{g\Gamma_0}{E_\gamma^3} \left[\mu_N^2\right]\,, \tag{5}$$

where the energies are E_γ are taken in MeV and the transition widths Γ_0 in meV.

Branching ratios may be directly measured, providing then the $g\Gamma_0$, and, consequently, the dipole transition strengths.

By measuring the angle distribution of the scattered photons, multipolarities of the γ transitions and spins can be determined in NRF experiments [7, 8].

Decades after the golden era of NRF using bremsstrahlung sources, due to the recent advances in diagnostics and with the newly available photon beams that feature high fluxes and good energy resolution, NRF returns as a powerful investigation tool for nuclear scientists. The energy of emitted photons depends on the nuclear structure and NRF consequently found applications in areas where isotope-specific identification is required: homeland security, non-invasive assay in industry, management of nuclear materials, to name just a few. To this end has contributed also the high penetration power of the gamma photons.

4. INVESTIGATION OF SUB-BARRIER FISSION RESONANCES USING GAMMA BEAMS

Next-generation γ-beam facility from ELI-Nuclear Physics will open up new perspectives for photofission studies of the multiple-humped fission barrier landscape in particular.

At the international level one of the primary fields is that of designing and building the new generation of advanced nuclear reactors that will use another fuel cycle than the existing reactors. The only fertile nuclei present in nature are ^{238}U and ^{232}Th, generating two different fuel cycles, with ^{232}Th in almost inexhaustible quantities. Until now, all existing nuclear reactors were based on U-Pu fuel cycle. The Thorium fuel cycle, which is very promising, is based on a ^{233}U and ^{232}Th mixture.

Nowadays research is headed towards building of a hybrid system (*Accelerator Driven System* – ADS) [9] which consists in steering of a thorium-based reactor with a high intensity and highly energetic proton accelerator.

One particular difficulty raised by such sub-critical reactor should be stressed. It has been estimated that the spectrum of the emitted neutrons by the spallation source will extend up to energies ranging between 150 - 200 MeV, while the nuclear data bases ENDF were limited up to a standard neutron incident energy value of 20 MeV. The first step needed to continue the way towards Th-based nuclear reactors is to determine the nuclear data for all the actinides involved for the entire range of neutron energies. Evaluations done at such high neutron energies are difficult due to the fact that the fission probability grows dramatically not just for the nuclei from the main reaction chain (n,xn), but to secondary chains too (for example (n, pxn), (n,αxn), (n,dxn), with x > 10), and parameters of each individual fission channel should be available. One would prefer to determine these parameters in experiments where the first compound nucleus formed is exactly the one for which we want to fit the parameters of the fission barriers.

As it was shown in the model developed by Strutinsky, when shell model corrections are applied to the single humped fission barrier from the liquid drop model, this becomes double- or triple-humped. This barrier can be represented by a set of normal or inverted parabolas that are continuously interconnected [10].

Neutron induced fission experimental data at neutron energies less than several hundreds of keV, reveals a resonant structure in the excitation functions, especially for fertile nuclei, structure that is directly related with the fission probability. These resonances occur at energies that correspond to the positions of the vibrational states in the second or third well.

The experimental investigation of the resonances has a crucial importance not only for applications but also for fundamental studies of the nuclear structure of nuclei at super- and hyper-deformations. As it was already mentioned, the usual way to perform these types of experimental investigations is with high resolution neutron beams. A complimentary experimental technique emerged in which direct nuclear reactions on the same actinide targets are involved in order to populate different compound nuclei (or the same in (d,p) reactions) [11].

Several inconveniences of these methods may be overcome when using high resolution photon beams. In photo-reactions a considerably larger number of targets can be used and after photo-absorption the nuclei can be populated in extended excitation energy range, the lower boundary being imposed by the detection limit. This method is a very powerful tool to get information about the barriers associated to the discrete part of the transition states independent of the continuum part described by the level densities at saddles which become important at overbarrier excitation energies. The recent developments and advances of gamma ray sources make this approach possible, while the future sources now in the implementation process will make this method a very powerful tool for subbarrier fission resonance investigation [12].

This will be particularly interesting also from the point of view of population probabilities of compound nucleus states in gamma induced reactions, because presently gamma ray strength functions used in reaction computer codes need to be further improved.

We also hope that due to the excellent parameters that we expect for ELI-NP gamma beam ($\Delta E/E = 10^{-3}$ and 10^6 photons/sec/eV), we will be able to analyze the fine structure of fission sub-barrier resonances at very low excitation energies close to the bottom of the isomeric well.

5. CONCLUSIONS AND PERSPECTIVES

Many new NRF experiments, aiming for a better description of nuclear properties for a wide range of nuclides, will be possible at ELI-NP due to the unique characteristics of the new photon sources available.

As presented in the previous section, the general aim of photofission experiments that will be performed at ELI-NP is the extension of fission experimental data libraries, that will also lead to a better understanding of the fission process and consequently of the properties of super- or hyper-deformed nuclei.

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