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Photoneutron cross section measurements on Sm isotopes

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Abstract.
The Extreme Light Infrastructure - Nuclear Physics, one of the three pillars of the Extreme Light Infrastructure Pan-European initiative, is a new large scale facility dedicated to nuclear physics with extreme electromagnetic fields. ELI-NP will host two 10 PW lasers and a very brilliant Gamma beam system with unprecedented intensity and energy resolution parameters. We propose to perform photon induced nuclear reactions using the very brilliant γ-ray beams provided by the Gamma beam system to examine in detail the photon absorption process and its decay modes. Here the experimental program related to nuclear research on reactions above the neutron separation threshold, which is under preparation at ELI-NP, is presented.

1 Introduction

Currently the Extreme Light Infrastructure - Nuclear Physics (ELI-NP) laboratory [1], a new large scale European project, is under development. A high power laser system and a very brilliant gamma beam are the two main research equipment at the core of ELI-NP. The gamma beam system (GBS) will produce highly polarized (> 99%) tunable γ-ray beams of spectral density of 10^4 photons/s/eV in the range from 200 keV to 19.5 MeV with a bandwidth better than 0.3% [2, 3]. The γ-ray beams will be produced through laser Compton scattering (LCS) of an accelerated electron beam delivered by a linear accelerator.

The unique parameters of the GBS will allow a thorough investigation of the excitation and particle and gamma decay of Giant Resonances (GR), which are collective vibrations of the nucleus made up with coherent contributions of many particle-hole excitations and can be classified depending on their multipolarity and their isovector/isoscalar nature.

The nuclear collective mode naturally excited with 10 - 20 MeV γ-ray beams is the Giant Dipole Resonance (GDR), where nuclei undergo an out-of-phase dipole oscillation between protons and neutrons. Recent interest focuses on evidence for the pygmy dipole resonance (PDR), a new, soft vibration mode below the GDR which several theoretical analysis describe as a resonant oscillation of a weakly bound neutron skin against an isospin saturated proton-neutron core. Another GR which emerges near the neutron emission threshold and has not been clearly separated experimentally from the PDR is the spin-flip M1 resonance.

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2 GBS experiments above neutron emission threshold

Using the brilliant GBS at ELI-NP, we propose to study the GDR excitation and the competition of its various decay channels as well as that of direct and statistical decay processes to improve our understanding of the GDR structure. We will attempt to clearly separate the pygmy and M1 resonances by investigating their neutron and gamma decays. We present here the physics programme at ELI-NP related to these subjects and the current status with the development of experimental techniques.

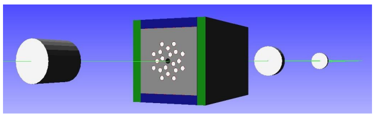

Figure 1. Photoneutron measurement setup - schematic view. From right to left: collimator C1 (6 mm aperture) and C2 (2 mm aperture), neutron detector and beam flux monitor.

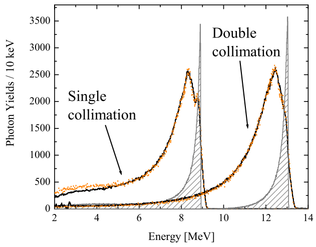

Figure 2. Experimental γ-ray beam spectra (solid line), Geant4 simulations (dotted line) and the incident γ-ray beam (grey line) with single (10 cm thick collimator 2 mm aperture) and double (additional 10 cm thick collimator 6 mm aperture) collimation.

2.1 Preparatory experiment

The research team involved in conceiving the ELI-NP Technical Design Reports (TDR) has initiated an experimental campaign at some of the most important existing gamma beam facilities in order to develop new experimental and data analysis techniques and adapt the existing ones for the operational parameters of the ELI-NP GBS. The photoneutron measurements performed on seven Sm isotopes [5] using quasimonochromatic γ-rays at the beam line GACKO of the synchrotron radiation facility NewSUBARU [6, 7] is part of that experimental campaign.

LCS γ-ray beams up to 13 MeV maximum energy were produced by Compton scattering of Nd:YVO_4 laser photons on electrons with energies between 573 and 850 MeV. NewSUBARU provides a $\sim 10^5$ photons per second in 3 – 5% bandwidth γ-ray beam. The γ-ray beam flux was monitored with a 6"×5" NaI(Tl) detector and the number of incident γ photons was obtained using the "pile-up method" described in [8]. The samarium samples were mounted at the center of a 4π neutron detector comprised of 20 ^{3}He proportional counters placed in three concentric rings embedded in a polyethylene moderator. The reaction neutrons average energy was obtained using the "ring ratio technique" [9]. The schematics of the experimental setup is displayed in Figure 1.

The γ-ray energy profile was measured with a large volume Lanthanum Bromide ($LaBr_3$:Ce) detector with the laser operated at a reduced power to avoid pile-up effects. Using Geant4 [10, 11], we simulated the interaction between the laser photons and the relativistic electrons by considering the laser and electron beam phasespaces. This simulation code which has direct application at the ELI-NP facility was tested against experimental $LaBr_3$:Ce LCS spectra recorded at the NewSUBARU facility and the analysis along with a complete description of the code will be given in a separate paper [12]. A typical result of the simulation code is displayed in Figure 2.

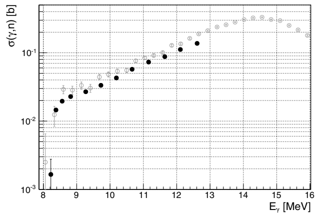

Figure 3. Photoneutron reaction cross section on ^{148}Sm: full circles - Filipescu, NewSUBARU, 2013; gray circles - Carlos, Saclay, 1974.

A thorough investigation of the (γ,n) reaction cross section in the vicinity of the S_n was possible because of the good energy resolution of the LCS γ-ray beam provided at NewSUBARU. Results for ^{148}Sm are displayed in Figure 3 along with existing measurements from Saclay which overestimate our data by approximately 20%, as is the case for all our Sm data. This systematic discrepancy was observed also by [13–15].

2.2 Photoneutron reaction cross section measurements

The systematics of the GDR were established using quasi-monoenergetic annihilation photon beams at the National Lawrence Livermore Laboratory (USA) and France Centre d'Etudes Nucleaires de Saclay [16, 17]. Systematic discrepancies between partial photoneutron reaction cross sections from the two laboratories are well–known [18]. For many nuclei the (γ,1n) reaction cross sections are noticeably larger at Saclay, but the (γ,2n) cross sections are larger at Livermore. Using the future GBS at ELI-NP, we propose to investigate the GDR excitation process by measuring total and partial photoneutron reaction cross sections in order to resolve these discrepancies.

Photodisintegration reaction cross section are key ingredients for p-process nucleosynthesis calculations, as the p-nuclides are transformed from pre-existing stable nuclei by series of (γ,n), (γ,p) and (γ,α) reactions and β^- decays [4]. Small abundance p- nuclides will be explored for the first time at ELI-NP, as (γ,n) studies for such nuclides require γ-ray beams with significantly higher intensity than that available at existing facilities. Such is the case of the ^{180}Ta(γ,n)^{179}Ta and ^{138}La(γ,n)^{137}La reactions of high interest for p-process astrophysics calculations [4]. We are currently developing a fast neutron detector similar to the one described in the previous section containing BF_3 neutron counters instead of ^{3}He ones. Geant4 Monte Carlos simulations on neutron counters geometry configurations are performed to obtain maximum detection efficiency with low energy dependence.

2.3 Investigation of GR decay

Pygmy dipole and spin-flip M1 resonance are investigated below S_n in 0^+ ground state nuclei by nuclear resonance

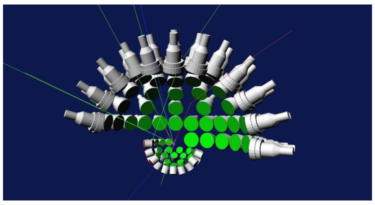

Figure 4. Geometric configuration of multi purpose neutron and γ-ray detection array.

fluorescence (NRF) experiments [19] where ~100 % linearly polarized γ-ray beams are used to separate E1 and M1 resonances. Complementary to NRF investigations, we propose to investigate PDR and spin-flip M1 resonance by detecting the multipolarity of neutrons emitted in (γ,n) reactions with a liquid scintillation detector array with emphasis on odd-N nuclei with S_n as low as 6 MeV. Nearly full strengths of PDR and spin-flip M1 resonance are expected to emerge in the large dynamic energy range for odd-N nuclei. GDR neutron decay in terms of neutron multiplicity and decay branches will be investigated to address the systematic discrepancy in (γ,1n) and (γ,2n) cross sections between the Livermore and Saclay data [18]. Neutron multiplicities and energies will be obtained using time of flight measurements and 512 ns time range multi-stop TDC recording with the liquid scintillation detector array.

The high intensity of the ELI-NP GBS will provide for the first time an opportunity to study the gamma decay from the GDR, as the dominant GDR decay mode is usually particle emission with photon decay having a small ($\leq 10^{-3}$) probability. Ground-state photon decay, dominated by E1 transitions, can yield data on the electromagnetic strength of resonances and can provide simple, well-defined conditions under which the multistep theory of nuclear reactions can be investigated. Decays to excited states can provide important information about the coupling of the GDR to low-frequency collective modes. For such experiments are mandatory: i) a well defined monochromatic, intense and polarized beam of high energy γ-ray beam ii) highly efficient γ rays detectors with excellent time and good energy resolutions placed in horizontal and vertical planes to measure the electric and magnetic character of the decay radiation.

We plan to develop a multi purpose neutron and gamma radiation detection setup consisting in a flexible array up to 40 large volume scintillator detectors and liquid scintillation neutron detectors each. A great challenges is the time structure of the γ-ray beam which will be delivered in 100 Hz macropulses each containing 32 micropulses of 1 – 2 ps width and 16 ns period. For a 10 MeV gamma beam of 0.3 % bandwidth and $10^4\ {}^{photons}/_{s \cdot ev}$ spectral density, we expect to have $\sim 1.5 \cdot 10^{5}\,{}^{photons}/_{microbunch}$. Special care must be taken to prevent pile-up efects given by such a high number of γ photons delivered simultaneously. We are currently performing Geant4 simulations to find an optimal experimental geometry which ensures a reasonable detection efficiency and low cross talk and pile-up effects in both the γ and neutron detectors.

3 Conclusions

A very brilliant and intense γ beam system soon to be commissioned at the ELI-NP facility will allow new experimental investigations of the Giant Resonances excitations and decays. The physics programme for GBS experiments above neutron emission threshold has been presented, along with a preparatory experiment performed at GACKO, NewSUBARU.

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