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Abstract. The Extreme Light Infrastructure – Nuclear Physics (ELI-NP) is a facility dedicated to nuclear physics research with extreme electromagnetic fields. The expected gamma-ray beams with energies up to 20 MeV, 0.5% relative energy resolution and ~10^8 photons per second intensity will allow precise photonuclear measurements. Nuclear structure experiments will involve photo-excitations of mainly low-spin collective states and the observation of the radiation emitted in the subsequent decays. Photoneutron reactions and elastic and inelastic photon scattering are proposed to be recorded using a mixed gamma-neutron detection system using $LaBr_3$:Ce, $CeBr_3$, BC501A and GS20 detectors. Photoneutron (γ,xn) with x=1,2 reactions cross sections measurements will be performed with a 4π flat efficiency neutron detection system dedicated for neutron multiplicity sorting experiments. The detection system is comprised of ^{3}He counters embedded in a moderator block. The paper will introduce the experimental setups dedicated to studies of the nuclear Giant Dipole Resonance excitation mode using the high energy resolution and high intensity ELI-NP gamma-ray beams. The feasibility studies performed using extensive Geant4 simulations, results of detector tests will be presented.

INTRODUCTION

The Extreme Light Infrastructure – Nuclear Physics (ELI-NP) is a facility dedicated to nuclear physics research with very brilliant gamma-beam system (GBS). Quasi-monochromatic, pencil-like and highly polarized γ beam will be produced using the inverse scattering of laser photons on relativistic electrons (LCS). Beams with energies between 0.2 to 19.5MeV will be produced using a Yb:YAG laser (λ = 515 nm in the second harmonic) in collision with a high brightness electron beam (E_e up to 720 MeV) provided by a linac. There has been defined an extensive scientific program e.g study of electromagnetic responses of atomic nuclei, photo-neutron reaction cross-section measurements, charged particle emission in photoreactions or photo-fission studies. A review on ELI-NP and on the GBS system can be found in Refs [1-3].

For the design of an experimental systems at ELI-NP, it is important to consider specific time structure of expected gamma beams. Every 16 ns there will be a "micro-bunch" composed of ~10^4 gamma rays. 32 "micro-bunches" will constitute a "macro-bunch" with a time interval of 10 ms between each [2]. This implies, that detection system should be able to separate events arriving in time distance of 16 ns. As it is possible to detect one event at a time, a detector

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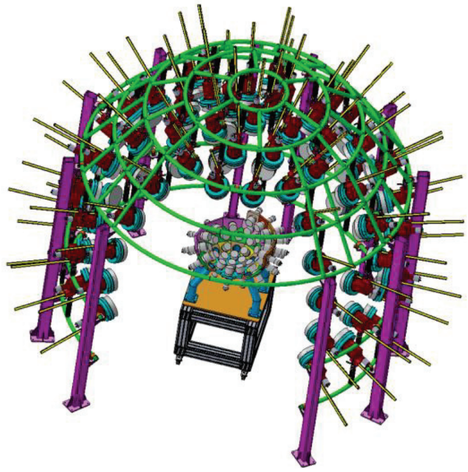
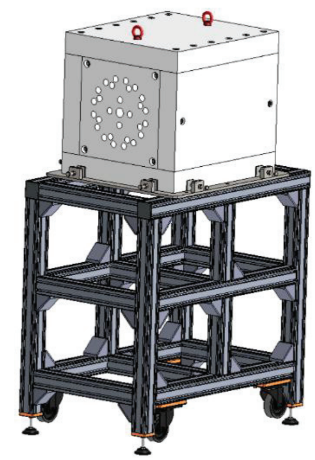
could reach a maximum count rate value of 3200 Hz. In some cases, when it is not possible to disentangle events separated by 16 ns, it could be possible to select only one “micro-bunch” from each “macro-bunch”. In such scenario, the maximum event count rate will be 100 Hz.

In this work, we will consider gamma beam energies (E_{beam}) higher than the neutron binding energy (S_n). For such condition, one can expect to measure mainly neutrons and γ rays. Above S_n, nuclear excited states which will be mainly populated are the Pygmy Dipole Resonance (PDR) or the Isovector Giant Dipole Resonance (IVGDR). The IVGDR and PDR states have an intrinsic width of the order of the MeV. Therefore, the beam energy bandwidth will characterize the detector response. In other words, the GBS bandwidth (FWHM) is of the order of 1% of E_{beam}, therefore it is not necessary to use detectors with an energy resolution smaller than ~ 1% (FWHM) of the E_{beam}. Two dedicated detection systems (see Fig. 1) were designed to measure gamma rays and neutrons emitted in de-excitation process. Both systems will be described in this paper.



(a)



(b)

FIGURE 1. Design drawing of ELIGANT-GN (a) and ELIGANT-TN array (b).

PHYSICS CASES

Recent overview of the physics cases for ELI-NP has been given in Ref [3]. This paper will focus on the physics cases related to the “Gamma Above Neutron Threshold” (ELIGANT) working group.

The IVGDR is the nuclear collective mode that can be excited with polarized monochromatic γ-ray beams. In general, Giant Resonances (GR) [4,5] are collective vibrations of the nucleus that result from the coherent contribution of many particle-hole (p-h) excitations and exhaust a large fraction of the corresponding sum rules. They are usually classified according to their multipolarity and isovector or isoscalar nature. In a macroscopic model the IVGDR is a collective vibration of almost all neutrons against the protons and it substantially exhausts the nuclear photo-absorption cross section. The importance of studying the IVGDR comes from the fact, that it brings information about the proton-neutron effective interaction and the asymmetry part of the nuclear equation of state. The data concerning the gamma and neutron decays, which are very important properties, are rather limited. The gamma decay measurements are extremely difficult as the nucleus has an excitation energy higher than the particle binding energy. Therefore, high beam intensities and efficient detector systems are required. The measurement of the neutron decay requires both an estimation of the neutron kinetic energy and precise knowledge of the excitation energy of the nucleus, which will be provided by ELI-NP GBS.

In addition, the decay measurements are probably a unique way to understand the nature of the PDR, namely the oscillation of the neutrons against a N=Z core. At present, several experiments show the existence of such extra strength below the GDR region [6-9] but they are not capable to pin down its microscopic structure. Theoretically, while some models predict only single-particle (that is, non-collective) excitations in that region, other models show the emergence of collective states that have, however, rather complex structure [10]. The PDR plays a role for the r-process nucleosynthesis (see for example Ref. [11,12]). Without some robust understanding it is hard to assess the reliability of theories that are employed to make simulations of the r-process.

The ELI-NP facility will allow the unique opportunity to have a gamma beam which can accurately scan in energy the IVGDR and the PDR collective states. This will provide the energy dependence of observables like the branching ratio and the decay mechanism over the whole range of stable nuclei and in a large excitation energy window. For the majority of the GDR decay measurements the most important aspect is the bandwidth of the GBS beam. In fact, the smaller is the bandwidth the more accurate will be the energy scan discussed previously. The GBS intensity is not an extremely important parameter in fact, as the gamma beam does not degrade on targets, one could use very thick (cm long) targets to compensate for the low intensity. The intensity can be very useful only in the case of very rare isotopes/samples (as for example ^{138}La).

An atlas of the IVGDR properties can be found in Refs [13-15] and a discussion on the GDR decay can be found in Refs [4,5]. The measurement of the GDR excitation cross section was recently performed at RCNP using polarized protons [16,17], while the gamma decay directly to specific states was measured in the past [18] and, below nuclear binding energies, recently using inelastic scattering of ^{17}O [19-21].

Another important interest of ELIGANT group is related to total and partial photonuclear cross sections measurements. Most of the available cross-sections were obtained using bremsstrahlung (BR) [15] and quasi-monoenergetic annihilation (QMA) photons [22,23] produced by positron annihilation in flight. There are noticeable and complex disagreements between photonuclear reaction data obtained in different experiments. The main reason of the disagreements is the absence of intense beams of monoenergetic photons.

ELIGANT-GN ARRAY

Gamma rays and neutrons emitted during de-excitation of PDR/GDR states are proposed to be recorded using ELIGANT-GN detection system. The array is designed to consist of two hemispheres (see panel "a" of Fig. 1):

- *"small"*: placed at 30 cm from target, for gamma detection, including: 17 $CeBr_3$ and 17 $LaBr_3$:Ce scintillators,
- *"large"*: placed at 1.5 m from target, for fast neutron detection using time-of-flight (TOF) technique, consisting of: 33 BC501A liquid scintillators and 29 GS20 (^{6}Li glass) detectors.

As discussed in the Technical Design Report [24], because of the ELI-NP beam time structure, the γ-ray detectors must be fast, and large enough to fully stop the shower produced by high-energy γ rays. Scintillators like $LaBr_3$:Ce [25] or $CeBr_3$ [26] are well suited for the ELIGANT-GN array because of their excellent time properties, high density, they can be grown in large sizes and they have an easy maintenance. Moreover, a signal produced with scintillator detectors has the same shape, independently on its amplitude or γ-ray interaction position.

The neutron kinetic energy is usually measured using the Time of Flight (TOF) technique. For that purpose, the classic liquid scintillator BC501A [27] has been widely used, and was considered as well suited for the array. As the neutron identification efficiency [28,29] of BC501A strongly decreases for low energy neutrons (E_n < 1 MeV), in ELIGANT-GN it is planned to use also ^{6}Li glass detectors (GS20) [30]. Detection principle of GS20 detector is based on the ^{6}Li(n,α)^{3}H reaction, which has a high cross section for low-energy neutrons.

In order to predict the performance of the array, the dedicated GEANT4 simulation code was developed. Time and energy responses of the array, detection efficiencies, background estimation, with a focus on proposed Day1 experiment, concerning gamma and neutron decay of GDR in ^{208}Pb were studied [31].

Detectors were tested using standard low-energy gamma sources but also under different in-beam conditions. 24 BC501A detectors arranged in two walls (see Fig. 2), were coupled to ROPSHERE array at IFIN-HH experiment (N. Mărginean/M. Bentley/D. Filipescu *et al.*) using ^{6}Li beam at 22 MeV on ^{58}Ni target. Calculations predicted around 14% of all produced particles to be neutrons in wide energy range (up to around 8 MeV). Preliminary results of emitted neutrons energy spectrum based on TOF have shown good agreement with theoretical predictions.

Finally, the attempt to calibrate the efficiency of BC501A scintillator was taken in two separate measurements at IFIN-HH (C. Matei *et al.* ; M. Krzysiek/D. Filipescu *et al.*) using well-known ^{7}Li(p,n) reaction which allows to produce quasi-monochromatic neutrons in wide energy range.

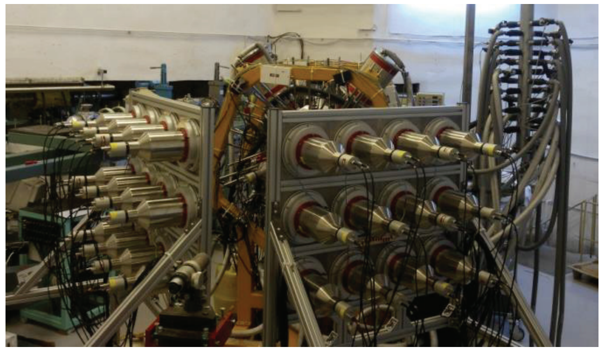


FIGURE 2. 24 BC501A detectors configured in two wall coupled with ROSPHERE at IFIN-HH.

ELIGANT-TN ARRAY

Photoneutron (γ,xn) with x=1,2 reactions cross sections measurements will be performed with ELIGANT-TN system. The array consists of 28 ^{3}He neutron counters embed in polyethylene moderator (see panel "b" of Fig. 1 and Fig 3). The detection method is based on ^{3}He(n,p)^{3}H reaction, which cross section is very high for thermal neutrons. Counters are arranged in 3 rings:

- *inner:* 4 counters, 5.9 cm radius;
- *middle:* 8 counters, 13 cm radius;
- *outer:* 16 counters, 15.5 cm.

Such configuration allows to apply so-called neutron multiplicity sorting [32]. The essential part of the method, is to achieve flat detection efficiency in wide range of neutron energies. Method allows to distinguish (γ,xn) reactions. The expected performance of the array was studied with dedicated GEANT4 simulation code and the efficiency was estimated at level of ~35-37 % up to 5-MeV neutrons [33].

At the preparatory phase, ELI-NP team was strongly involved in measurements at NewSUBARU facility under the PHOENIX collaboration that was established to perform experimental part of Coordinated Research Project on Photonuclear Data and Photon Strength Functions launched by IAEA. Total and partial cross section of (γ,xn) with x=1,...,4 for ^{209}Bi, ^{9}Be, ^{197}Au, ^{169}Tm, ^{89}Y, ^{181}Ta, ^{165}Ho, ^{59}Co, ^{159}Tb, ^{139}La, ^{103}Rh were measured. First case for ^{209}Bi nucleus was already published [34].

FIGURE 3. ELIGANT-TN array mounted at IFIN-HH for commissioning experiment.

Finally, commissioning experiment of ELIGANT-TN array was performed at IFIN-HH using (p,n) monitoring reaction at ^{nat}Cu and ^{nat}Al (T. Ronsetrom *et al.*). The experimental setup with the array is shown in Fig. 3. Preliminary results have shown very good agreement of obtained cross sections with existing data.

SUMMARY

The ELI-NP facility aims to provide a strong input to the data related to nuclear structure. The planned experiments will profit from unique properties of gamma beams, especially their small diameter, high-flux, narrow bandwidth and nearly 100% polarization. An experimental program dedicated to studies above the neutron binding energy has been defined, and two dedicated detection systems were designed to study gamma and neutron decays of high-lying low-spin states, namely PDR and IVGDR to give a new insight into the nature of these excitation modes. Moreover, the parameters of very brilliant, intense, monoenergetic γ-beam of ELI-NP project will give opportunity to re-measure total and partial photonuclear cross sections in order to solve the discrepancies in existing data.

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REFERENCES

1. ELI-NP White Book, available at http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf
2. O. Adriani, S. Albergo, D. Alesini, et al., *ELI-NP-GBS Technical Design Report*, arXiv:1407.3669 [physics.acc-ph] (2014).
3. D. M. Filipescu, A. Anzalone, D. L. Balabanski, *et al.*, Eur. Phys. J. A **51,** 185 (2015).
4. P. F. Bortignon, A. Bracco, R. A. Broglia, *Giant Resonances: Nuclear Structure at Finite Temperature* (Harwood Academic, Amsterdam, 1998).
5. M. N. Harakeh and A. van der Woude, *Giant Resonances: Fundamental High-Frequency Modes of Nuclear Excitation* (Oxford University, Oxford, 2001).
6. P. Adrich, A. Klimkiewicz, M. Fallot, *et al.*, Phys. Rev. Lett. **95**, 132501 (2005).
7. O. Wieland, A. Bracco, F. Camera, *et al.*, Phys. Rev. Lett., **102**, 092502 (2009).
8. A. Bracco, F.C.L. Crespi and E.G. Lanza, Eur. Phys. J. A **51** 99 (2015).
9. D. Savran, M. Babilon, A. M. van den Berg, et al., Phys. Rev. Lett. **97**, 172502 (2006).
10. N. Paar, D. Vretenar, E. Khan, and G. Colò, Rep. Prog. Phys. **70**, 691 (2007).
11. S. Goriely, Phys. Lett. B **436**, 10 (1998).
12. S. Goriely, E. Khan, M. Samyn, Nuclear Phys. A **739**, 331 (2004).
13. B. Berman, S. Fultz, Rev. Mod. Phys. **47**, 713 (1975).
14. A. Shiller, M. Thoennessen, At. Data Nucl. Data Tables **93**, 549 (2007).
15. A.V. Varlamov, V.V. Varlamov, D.S. Rudenko, Atlas of Giant Dipole Resonances, INDC(NDS) **394** (1999)
16. A. Tamii, P. von Neumann-Cosel, I. Poltoratska, *et al.*, Eur. Phys. J. A **50**, 28 (2014).
17. C. Iwamoto, H. Utsunomiya, A. Tamii, et al., Phys. Rev. Lett. **108**, 262501 (2012).
18. J. R. Beene, F. E. Bertrand, M. L. Halbert, *et al.*, Phys. Rev C **39**, 4, 1307 (1989).
19. F. C. L. Crespi, A. Bracco, R. Nicolini, *et al.*, Phys. Rev. Lett. **113**, 012501 (2014).
20. L. Pellegri, A. Bracco, F.C.L. Crespi, *et al.*, Phys. Lett. B **738**, 519 (2014).
21. M. Krzysiek, M. Kmiecik, A. Maj, *et al.*, Phys. Rev. C **93**, 044330 (2016).
22. B. Berman, S. Fultz, Rev. Mod. Phys. **47**, 713 (1975).
23. S. Dietrich, B. Berman, At. Data Nucl. Data Tables **38**, 199 (1988).
24. F. Camera, H. Utsunomiya, V. Varlamov, *et al.*, Romanian Reports in Physics, 68, ELI-NP Technical Design Reports Supplement S539 – S619, (2016).

25. “LaBr3:Ce Data Sheet”, Saint-Gobain Ceramics & Plastics, Inc , https://www.crystals.saintgobain.com/sites/imdf.crystals.com/files/documents/brillance380-material-data-sheet_69765.pdf
26. “High resolution low background CeBr3 scintillators” Application Note, Scionix Holland B.V., http://scionix.nl/wp-content/uploads/2017/07/CeBr3-scintillation-detectors.pdf
27. “Neutron/gamma PSD liquid scintillator EJ-301, EJ-309”, http://eljentechnology.com/images/products/data_sheets/EJ-301_EJ-309.pdf
28. H. Laurent, H. Lefort, D. Beaumel, *et al.*, Nucl. Instrum. Meth. A **326**, 517 (1993).
29. M.Cavallaro, S.Tropea, C.Agodi, *et al.*, Nucl. Inst. Meth. A **700**, 65 (2013).
30. “Lithium Glass Scintillators”, https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/glass-scintillator-material-data-sheet_69772.pdf
31. M. Krzysiek *et al.*, “Simulation of the ELIGANT-GN array performances at ELI-NP for gamma beam energies larger than neutron threshold”, Nucl. Inst. Meth. A (submitted)
32. H. Utsunomiya *et al.*, Nucl. Inst. Meth. A **871**, 135-141 (2017) .
33. I. Gheorghe (private communication, 2017)
34. I. Gheorghe *et al.*, Phys. Rev. C **96**, 044604 (2017) .