NEUTRON AND GAMMA-RAY MEASUREMENTS AROUND THE PARTICLE SEPARATION THRESHOLD AT THE EXTREME LIGHT INFRASTRUCTURE-NUCLEAR PHYSICS*

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The ELIGANT instrumentation at ELI-NP is one of the main sets of instruments designed and constructed over the last decade for photonuclear physics around and above the neutron separation threshold developed for the γ-ray beams. The main goals of these setups include photo-neutron cross-sections and evaluation of γ-ray strength in the giant dipole resonance and pygmy dipole resonance regions. In this contribution, we will give an overview of the current status of ELI-NP, the Gamma Above Neutron Threshold programme in general, the scientific goals of giant dipole resonances, and γ-ray strength functions both at ELI-NP and within the role of complementary measurements.

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1. Introduction

The Extreme Light Infrastructure–Nuclear Physics (ELI-NP) facility [1–4] is a major European nuclear physics infrastructure aiming at providing users with high-intensity laser beamlines delivering 100 TW, 1 PW, and 10 PW of laser power on target from the high-power laser system (HPLS), as well as high-brilliance γ-ray beams with energy up to 20 MeV and a very narrow bandwidth from the Variable Energy Gamma-ray (VEGA) system [5]. The HPLS is operational, providing beam time for internal and external users, while the VEGA system is still under implementation. The scientific focus of the VEGA system will cover a broad range of topics from nuclear

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astrophysics to applications to basic science [1, 6]. One of the exciting directions of the latter are the studies of the nuclear properties in the continuum and quasi-continuum that manifest as large amplitude resonances such as the giant dipole-resonance (GDR) and the pygmy dipole resonance (PDR). For studies of the states in these regions, the ELI Gamma Above Neutron Threshold (ELIGANT) instrumentation [7–13] has been developed for high-efficiency detection of high-energy γ rays as well as neutron detection with good efficiencies covering the entire energy range from thermal up to tens of MeV. The ELIGANT instrumentation is a very good tool for the study of collective nuclear dipole excitations, including the γ-ray and neutron decay branchings from the GDR, the properties of the PDR around the neutron separation energy, and the γ-ray strength functions (γSFs), its functional form and universality, across the nuclear chart.

The high-brilliance, low bandwidth γ-ray beams at ELI-NP are projected to be produced by the laser Compton backscattering (LCS) technique using the interaction of laser photons scattering off an electron beam in a system called VEGA [5]. In its complete form, this system will consist of an electron storage ring coupled to a resonant optical cavity. The energy range of the electrons is intended to be a step-less variable with a range of 234–742 MeV, and photons from two different laser wavelengths at 1 μm and 0.5 μm, respectively, will cover γ-ray energies in the range of 1–19.5 MeV. The beam is expected to be almost completely polarised with $\xi \geq 95\%$, and the bandwidth of the beam is predicted to be BW $\leq 0.5\%$. The primary parameters of the VEGA system are listed in Table 1, and a comparison with other γ-ray beam facilities in the same energy range is shown in Table 2.

Table 1. Design specifications of the VEGA system. Adapted from Ref. [5].

Name	Symbol	Specification
Maximum energy	$E_\gamma^{\max}$	≤ 20 MeV
Bandwidth	BW	$\leq 0.5\%$
Polarization	ξ	$\geq 95\%$
Divergence	D_θ	≤ 0.15 mrad
Beam spot	D_x	≤ 1.5 mm
Peak spectral density	SD	$\geq 5 \times 10^3$ γ/s/eV
Off-peak spectral density	OSD	$\leq 10^{-2}$ γ/s/eV

Table 2. Comparison between the parameters of VEGA and other LCB facilities in the same energy range. Adapted from Ref. [5].

Facility	Location	E [MeV]	BW [%]	SD [γ/s/eV]	Ref.
VEGA	ELI-NP, Romania	0.2–20	0.5	5×10^3	[5]
HIγS	Duke, USA	1–158	0.8–10	10^2	[14]
SLEGS	Shanghai, China	0.4–22	1–4	10^2	[15]
NewSUBARU	RCNP, Japan	0.5–76	1–2	10^2	[16]
CLS	Saskatoon, Canada	≤ 15	0.1	10^3	[17]

2. Gamma above neutron threshold

The ELIGANT family of instruments consists of two main detector arrays, the ELIGANT Gamma Neutron (ELIGANT-GN) array [7, 9, 11] for simultaneous spectroscopy of high-energy γ rays and neutrons, and the ELIGANT Thermal Neutron (ELIGANT-TN) array [7, 8, 10, 12, 18] for photoneutron cross-section measurements. These two instruments are intended to work complementary where the ELIGANT-TN array can measure total neutron emission cross section and γSFs. In contrast, the ELIGANT-GN array will be used to investigate in-depth the nuclear structure properties of the resonant states. These two different setups are shown in Fig. 1.

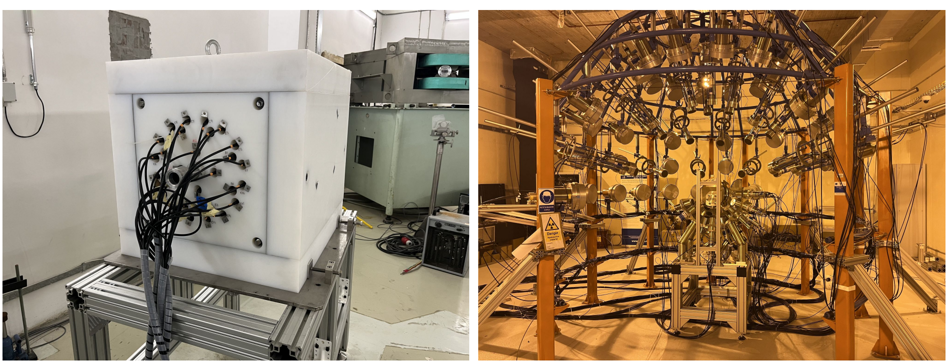

Fig. 1. (Left) Photograph of the ELIGANT-TN neutron counter set up for a preparatory experiment with charged particle beams [19]. (Right) Photograph of the ELIGANT-GN array set up in its γ-ray beam experimental area.

The flat efficiency neutron detector ELIGANT-TN was designed in 2015 within the ELI-NP project, together with a twin detector at NewSUBARU [8, 20, 21]. It is a neutron counter consisting of a large high-density polyethylene (HDPE) moderator with 28 ^{3}He gas detectors. The main body of the moderator volume is made out of HDPE blocks with an area of $46 \times 46\,\mathrm{cm}^2$ and a total length of the moderator body of 64 cm. In this body, 28 holes in a pattern of three rings containing 4, 8, and 16 holes are filled with ^{3}He gas counters with a pressure of 12 bar. In the centre, the VEGA or New-SUBARU beam passes through and interacts with the target in a 4.4 cm hole.

The ELIGANT-GN array has been designed using a $2 \times 2\pi$ approach: an upper hemisphere for neutron detectors and a lower hemisphere for γ-ray detectors. The two detector types partially overlap in the array's central area. The γ-ray detection setup in the ELIGANT-GN array comprises 15 large-volume $LaBr_3$:Ce detectors and 19 large-volume $CeBr_3$ detectors of cylindrical shape, with a diameter of 76 mm and a height of 76 mm. These detectors are energy-calibrated with dedicated, high-energy γ-ray sources [22, 23]. The neutron detector setup comprises 36 EJ-301 liquid scintillator detectors and 25 GS-20 ^{6}Li glass detectors for fast and slow neutrons. The total size of the neutron detector structure is 3.2 m in diameter and can provide time-of-flight (TOF) measurements with a distance of up to 1.5 m for the liquid scintillator detectors and up to 1 m for the lithium glass detectors. The liquid scintillators were first used in-beam in an experiment at the 9 MV Tandem facilities at the Horia Hulubei Institute for Physics and Nuclear Engineering (IFIN-HH) in 2017 [24]. The γ-ray detectors were tested both with sources [25] and in-beam [26], as well as used for the first physics experiments on $\gamma\gamma/\gamma$ decay [27] prior to 2022 where a large set of campaigns were launched, to be discussed in more detail in Section 4.

3. Scientific cases

One of the main topics of the ELIGANT program at ELI-NP is the in-depth study and understanding of the GDR in the energy region above the neutron threshold. Here, in particular, for stable medium-mass and high-mass nuclei, the decay is dominated by neutron emission, and only a tiny fraction of the decay goes directly via internal γ decay. This tiny fraction of γ decay will, in turn, be dominated by the decay to the ground state in even–even nuclei, and only a tiny fraction of this will go via excited states into a two-step γ-decay process. The assumption that almost the full decay strength above the particle-separation threshold is via neutron decay is justified for heavier nuclei, but this is not necessarily the case in the lower mass region below $A \sim 56$. This mass region is also critically important for astrophysics applications, particularly regarding the photodisintegration of ultra-high energy cosmic rays (UHECRs) [28–30].

In the heavier region of the nuclear chart, however, neutron decay and, to a lesser extent, γ-ray decay are expected to dominate. One of these cases highlighted in the ELIGANT technical design report (TDR) [7] is the case of ^{208}Pb. From an experiment at the Research Center for Nuclear Physics (RCNP), Osaka in Japan [31], using inelastic forward scattering of polarised protons, a fragmentation of the GDR strength is observed in the energy range of approximately 9–13 MeV. Experimental efforts to understand this fragmentation would be an ideal case for ELIGANT day-one experiments. In such a series of experiments, the different excitation strength and decay branchings of ^{208}Pb, as illustrated in Fig. 2, can be explored in detail using narrow-bandwidth γ-ray beams. By selecting a narrow energy region above

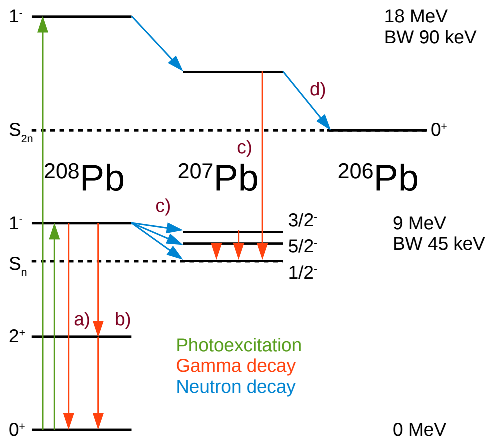

Fig. 2. (Color online) Illustration of the scientific case for the day-1 experiment on ^{208}Pb. Green (up) arrows represent photoexcitation at two different energies, 9 MeV and 18 MeV. Red (down) arrows represent possible γ-ray decay, and blue (diagonal) arrows represent possible neutron decay. The beam's typical bandwidth (BW), assuming 0.5%, is also marked.

the neutron threshold, (S_n), but below the two-neutron threshold, (S_{2n}), with the VEGA beams, illustrated in Fig. 2, the relative branchings of the $J^\pi = 1^- \to 2^+$ and $J^\pi = 1^- \to 0^+$ can be extracted in the ELIGANT-GN $LaBr_3$:Ce and $CeBr_3$ scintillators. This type of branching has recently been shown to be very sensitive to several nuclear structure observables [32]. These branchings can be further compared to the final-state branching following neutron decay from the EJ-301 and GS-20 neutron scintillator detectors. Above the (S_{2n}) threshold, similar measurements can be performed with additional information from the γ-ray branchings in the $A-1$ nucleus ^{207}Pb and the neutron energy and angular distributions to the $A-2$ nucleus ^{205}Pb.

Besides exclusive measurements of neutron and γ decay of the GDR to test microscopic models in great detail, inclusive properties like the GDR total cross section, energy, and width can be measured from the total excitation strength in ELIGANT-TN, assuming all the decay cross section is contained in the (γ, xn)-decay channels. A series of experiments were performed within the context of preparatory ELIGANT experiments performed at NewSUBARU in Japan, see, for example, Refs. [20, 33–37], extracting the photo-neutron (γ, xn) cross sections, directly proportional to the γSFs, for a variety of nuclei. While these individual experiments also had their specific scientific motivations, one overarching theme of these measurements was to resolve the long-standing systematic cross-section discrepancies between the Lawrence Livermore National Laboratory (LLNL) and the Centre d'Études Nucléaires de Saclay (Saclay) data sets. This was achieved using a combination of almost monochromatic LCS γ-ray beams and the then new direct neutron-multiplicity sorting technique using flat-efficiency neutron counters [8, 10], like ELIGANT-TN, and culminated in two major overview publications [38, 39].

With the narrow-bandwidth γ-ray beams at ELI-NP, this type of measurement of γSFs will be possible to continue with even higher precision using the direct neutron-multiplicity sorting technique together with the implemented flat-efficiency neutron counters in the region above the neutron separation threshold. Around and below the neutron separation threshold, the (γ, n) cross-section measurements can be complemented by other techniques. Two ways to extend the γSFs data to cover the full-strength function is by inelastic proton scattering of high-energy protons close to zero degrees using a magnetic spectrometer, as is done at RCNP or lower energy charged-particle scattering and reactions as have been extensively done by the Oslo method [40–43]. A comparison between these different data types is shown in Fig. 3.

4. Complementary measurements at the 9 MV Tandem

At the beginning of 2022, a new series of experiments were initiated at the 9 MV Tandem facilities of IFIN-HH, using the ELIGANT-GN detectors together with the ROmanian array for SPectroscopy in HEavy ion REactions (ROSPHERE) [44] to create a new, anti-Compton shielded, array for high-efficiency detection of high-energy γ rays using charged particle beams [45]. During the first year of this campaign, several exploratory experiments were performed to assess the potential of this type of setup, most notably the isospin mixing [46], the search for the hot PDR [47], rare M3 γ-ray branching in ^{10}B [48–52], as well as astrophysical critical γ-decay channels aiming for the radiative decay of the Hoyle state [53].

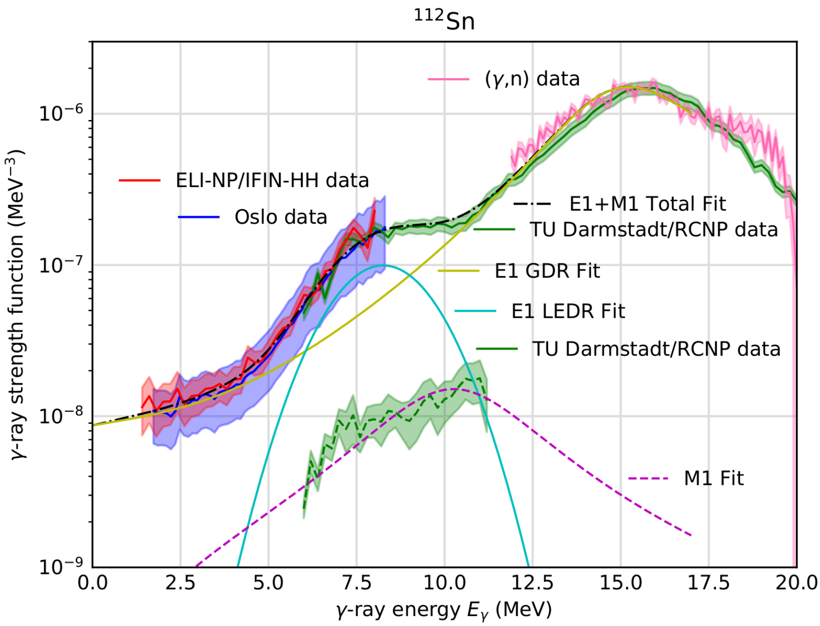

Fig. 3. Comparison of γ-ray strength functions obtained with different methods: (γ, n) cross-section measurements [54], high-energy (p, p') scattering at zero degrees [55], $(p, p'\gamma)$ scattering with the Oslo method at the Oslo Cyclotron Laboratory [56], and $(\mathrm{p}, \mathrm{p}'\gamma)$ scattering with the Oslo method at IFIN-HH with the combined ELIGANT-GN and ROSPHERE setup [57].

For measuring γSFs and nuclear level densities (NLDs) below the neutron separation threshold, complementary experiments to the future γ ray beams at ELI-NP have been performed using the Oslo method [40–43]. In 2023, such an experiment was performed at the 9MV facilities at IFIN-HH for the first time. The choice of targets for this experiment was ^{112}Sn, due to the Sn chain recently being measured at the Oslo Cyclotron Laboratory (OCL) [56, 58–60] making it a good candidate for verification of reliability of the results, and ^{114}Sn, as this was not previously measured [57]. The experiment was performed using the 21 ELIGANT-GN large-volume $LaBr_3$:Ce, and $CeBr_3$ detectors mounted in the ROSPHERE structure. In addition to the γ-ray detectors, the setup included a ΔE–E telescope consisting of two annular double-sided silicon strip detectors (DSSSDs) in the backward direction for scattered charged particles. The results on ^{112}Sn from this experiment are shown in Fig. 3.

An alternative approach to measuring γSFs below the neutron threshold was investigated by Isaak *et al.* [61] using the LCS γ-ray beams available at the High-Intensity γ-ray Source (HIγS) facility in Triangle Universities

Nuclear Laboratory (TUNL), North Carolina. By using an array combining high-purity germanium (HPGe) and $LaBr_3$:Ce detectors and comparing the decay cross section between excited states following the initial nuclear photoexcitation, the authors of Ref. [61] could extract a γSFs of ^{128}Te that was previously unmeasured. With the projected photon beams at the ELI-NP, which are expected to provide users with narrow-bandwidth photon beams for photoexcitation and decay studies, there will be new opportunities to directly measure the γ-ray strength functions. This new methodology provides a solid opportunity to measure γSFs in the region around and just below the neutron separation threshold. Future results from this type of measurement can provide an alternative view of the extracted γSFs and NLD with the Oslo method, which is also impacted by the underlying spin distribution [62]. As the topic of γSFs intimately connects to the foreseen topics to be measured at ELI-NP, this kind of complementary measurement can be used to enhance the ELIGANT physics program strongly. In particular, by comparing the γSFs obtained by charged particle beams and γ-ray beams, topics like the role of the spin distribution and the validity of the Brink–Axel hypothesis can be approached, as well as the model-dependency that appears when extrapolating pNLD to the neutron threshold. Such an experiment was performed on ^{128}Te in 2024 where, by extracting the decay probability $P(E_\gamma, E_x)$ as a function of γ-ray energy, E_γ, and excitation energy, E_x, from the measured data and using a χ^2 minimisation, we can obtain one pair of solutions for the NLD, $\rho(E_x)$, and transmission coefficients, $\mathcal{T}(E_\gamma)$. By normalising the $\mathcal{T}(E_\gamma)$ solution to the $(\gamma, \gamma'\gamma'')$ data, we can extract the parameters corresponding to the absolute values and the slope for the γSFs. With the slope known, we can fix the absolute value of the nuclear level densities from the complete spectroscopy of known states in the energy range of 2–3 MeV and extract the nuclear level densities without the need to invoke model-dependent extrapolations of either the constant temperature model or the back-shifted Fermi gas model. This research direction is ongoing and further detailed investigations and evaluations intended to enhance the ELI-NP physics program for γSFs and NLD are foreseen shortly.

5. Conclusions

The ELIGANT instrumentation at ELI-NP is ready to start the scientific program with the VEGA γ-ray beam currently under construction. We have provided a brief overview of the possibilities for exclusive studies with ELIGANT-GN and inclusive studies with ELIGANT-TN. We have also highlighted some opportunities for a parallel complementary physics program using the facilities existing at IFIN-HH and how these can further enhance the studies of γSFs for the operational phase of ELI-NP.

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