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Colloquia: COMEX7

From implementation to operation and the first measurements with the ELIGANT detectors from ELI-NP

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Summary. — The ELIGANT set of instruments is a dedicated tool being developed at ELI-NP for studying high-energy collective nuclear excitations using gamma beams. The topics of interest in these studies range from fundamental nuclear structure properties of the Giant Dipole Resonance and the low-energy strength enhancement in the Pygmy Dipole Resonance region, to applications in *p*-process nucleosynthesis and propagation of Ultra-High Energy Cosmic Rays. The equipment consists of large-volume $LaBr_3$:Ce and $CeBr_3$ detectors for high-energy γ-rays, liquid scintillators and lithium glass scintillators for high- and low-energy neutron time-of-flight, and a proportional counter system of ^{3}He tubes for cross-section measurements. These instruments have been installed and commissioned with sources and *via* in-beam measurements, in different configurations, at the IFIN-HH Tandem/Tandetron accelerators with terminal voltages of 3 MV and 9 MV. This contribution gives an overview of the present and future activities with ELIGANT.

1. – Introduction

The Extreme Light Infrastructure (ELI) facilities constructed in Romania, the Czech Republic, and Hungary are starting to transition from the implementation phases to the operational phases. At the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) pillar [1-3] in Măgurele, outside of Bucharest, the high-power laser system (HPLS) is currently in the final stages of commissioning, and the first user experiments have begun, while the γ-ray beam system is still under preparation. However, the instrumentation for the γ-ray beam system, in particular, the ELI Gamma Above Neutron Threshold (ELIGANT) equipment, ELIGANT Gamma Neutron (ELIGANT-GN) and ELIGANT Thermal Neutron (ELIGANT-TN), are operational and ready to be used with beams [4-7]. For a complete overview of the potential ELI-NP physics program with γ-ray beams, see, for example, refs. [8, 9]. The specific goals of the ELIGANT setups are basic nuclear physics studies of decay characteristics of the giant dipole-resonance (GDR), including the fine structure and the details of the GDR and pygmy dipole resonance (PDR) wave functions. In addition, applications to astrophysics will be another essential topic by cross-section measurements of *p*-process nuclei [10]. The ELIGANT setups are also one of the key facilities in the Photo-Absorption of Nuclei and Decay Observables for Reactions in Astrophysics (PANDORA) project, together with the Research Center for Nuclear Physics (RCNP) in Osaka and the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) in South Africa, for systematic studies of photodisintegration cross-sections for applications in ultra-high energy cosmic-ray (UHECR) physics [11, 12]. In addition to these, another research direction that has begun to be explored is the higher order nuclear and atomic processes such as competitive double γ decay [13, 14] using the ELIGANT-GN detectors in a well-shielded configuration [15]. While the ELIGANT detectors have their dedicated scientific topics, they are also used in other research directions at ELI-NP [16], as well as reference detectors for further instrumentation development [17].

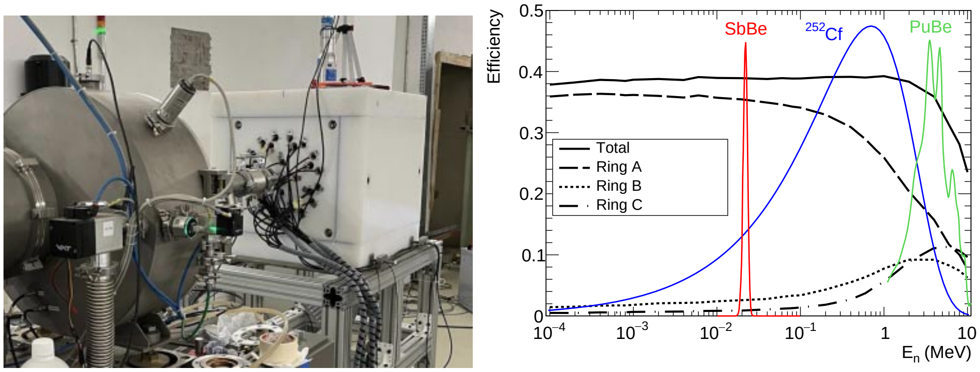

Fig. 1. – (Left) Front view of the ELIGANT-TN rings from the 3 MV Tandem experiment in 2023. (Right) Simulated efficiencies of the three rings of ELIGANT-TN, as well as the total efficiency, compared to the energy spectra from three possible neutron sources.

2. – ELIGANT-TN

ELIGANT-TN is a dedicated setup for photoneutron cross-section measurements, built in collaboration with the Konan University in Japan. An identical setup has been operational there [18], that has been extensively used in a preparatory campaign [19-24] that was performed at the γ-ray beamline NewSUBARU at SPRING-8 as a part of a Coordinated Research Activity by the International Atomic Energy Agency (IAEA), a project that culminated in two review papers [25, 26]. For ELI-NP, one of the main goals of the ELIGANT-TN array is the measurement of photonuclear cross-sections for the p process, as described by Filipescu *et al.* [8], and discussed more in-depth in a recent review paper [10].

ELIGANT-TN consists of 28 ^{3}He gas-filled counters in three rings embedded in a polyethylene matrix for neutron moderation, as shown in fig. 1. The setup is designed to have a flat efficiency up to around 2.5 MeV, which has been verified both with a plutonium-beryllium (PuBe) source [27] as well as ^{252}Cf standard neutron sources. The typical energy spectra of these sources and a proposed but not yet performed source of antimony-beryllium (SbBe) are shown in the right part of fig. 1. The SbBe source is particular in this context. The principle behind this source is that radioactive ^{124}Sb will beta decay with a half-life of approximately 60 days, emitting a gamma-ray with an energy of 1690.971 keV. As beryllium has a neutron separation energy of 1664.54 keV, these γ rays will produce neutrons with around 22 keV energy and an energy spread of approximately 2.6 keV [28]. Due to the short half-life and the low photonuclear cross-section, this source type is complicated to be produced and used, as it has to be activated, typically in a nuclear reactor. This is one of the collaboration points between the National Physical Laboratory (NPL) in the United Kingdom and ELI-NP.

The instrument has been successfully commissioned in-beam at the 9 MV Tandem facility at Horia Hulubei Institute for Physics and Nuclear Engineering (IFIN-HH), where $^{\mathrm{nat}}\mathrm{Cu}(\mathrm{p}, x\mathrm{n})$ and $^{27}\mathrm{Al}(\mathrm{p},\mathrm{n})$ cross-sections were measured to be in agreement with IAEA recommendations and previous data [7]. In addition, a dedicated series of measurements are being performed at the 3 MV Tandetron facility at IFIN-HH, partially in collaboration

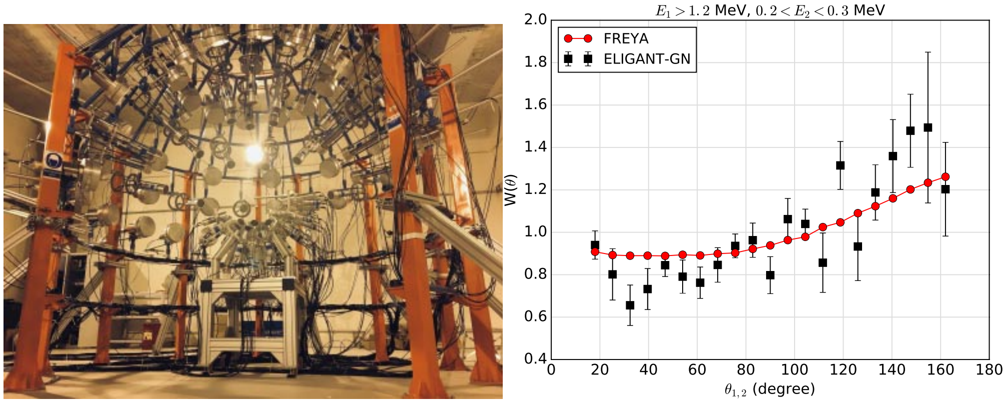

Fig. 2. – (Left) Photograph of the ELIGANT-GN setup with the γ-ray detectors in the southern hemisphere and the neutron detectors in the northern hemisphere. (Right) Neutron angular correlations between high-energy neutrons detected in the EJ-301 liquid scintillators and low-energy neutrons detected in the lithium glass GS-20 detectors from ELIGANT-GN and calculations using the Fission Reaction Event Yield Algorithm (FREYA) code, with $\chi^2/\mathrm{NDF} = 1.58$.

with NPL, to focus on (α, n) reactions in the α energy range of the particles produced from decay in the actinide region. The motivation is to establish and verify experimental cross-sections that are important for background processes in various applications ranging from nuclear fuel tomography to dark matter searches. One specific example, and the first experiment that was performed in this series, is the neutron-production cross-section of $^{19}\mathrm{F}(\alpha, \mathrm{n})^{22}\mathrm{Na}$ reactions in the energy range of α decay from $^{234}\mathrm{U}$ and $^{235}\mathrm{U}$. This is one of the dominant sources of neutrons in uranium hexafluoride [29] and contributes to the background in, for example, neutron tomography measurements of nuclear materials. The analysis of these data is still ongoing.

3. – ELIGANT-GN

For spectroscopic studies, the ELIGANT-GN setup is the main instrument for high-energy collective states at ELI-NP. ELIGANT-GN, shown in left part of fig. 2, consists of 34 large volume $\mathrm{LaBr_3}$:Ce and $\mathrm{CeBr_3}$ detectors for high-energy γ-ray decay from the GDR, 36 liquid scintillators of type EJ-301 for fast neutrons, and 25 lithium glass scintillators of type GS-20 for slow neutrons [4-6]. The γ-ray efficiency of ELIGANT-GN is expected to be around 1% at 10 MeV of γ-ray energy. For high-energy neutrons in the EJ-301 detectors, the efficiency is between 2% and 1% for 2 MeV and 10 MeV neutrons, respectively, while for low-energy neutrons in the GS-20 detectors, the efficiency is around 0.5% in the 200-300 keV range. The data acquisition (DAQ) of ELIGANT-GN is fully digital based on CAEN V1730 digitisers and read out in a self-triggering mode for event reconstruction offline.

This setup will be able to measure photonuclear excitations above the one- and two-neutron separation thresholds and extract nuclear structure details from the different branching between γ-ray and neutron decay properties. For a general overview of the topic, see ref. [30]. In the technical design report (TDR) of ELIGANT-GN [4], the flagship experiment identified is the fine structure of the GDR in $^{208}\mathrm{Pb}$. The excitation cross-section has been measured in detail at RCNP in Osaka [31]. Using ELIGANT-GN, the γ decay measurements can provide valuable information about, for example, the damping mechanisms of the GDR and particle-hole couplings. Additionally, neutron decay characteristics offer information about the population of the excited states in ^{207}Pb, giving detailed information about the wave-function overlap with different states in the daughter nucleus as a function of energy.

With the γ-ray beam system still under construction and with renewed interest in correlations of observables following fission [32], the full commissioning of the array was performed using a 3.7 MBq ^{252}Cf source with the multiplicity and total energy in the γ-ray hemisphere as a fission trigger, calibrated up to 9 MeV using a composite source [33]. In these measurements, angular correlations of both fast and slow neutrons and coincidence with high-multiplicity γ rays were created, proving the performance of the system. The results were compared with the Fission Reaction Event Yield Algorithm (FREYA) fission model [34], developed at Lawrence Livermore National Laboratory (LLNL). With the known data reproduced in ref. [6], we can also examine previously not measured correlations. For example, as ELIGANT-GN consists of both liquid scintillators for high-energy neutron detection and lithium-glass scintillators for low-energy neutron detection, it can be interesting to look at the angular correlations between high-energy and low-energy neutrons, shown in fig. 2, right panel. While the uncertainties are significant due to the lower yield and the lower efficiency in the low-energy neutron region compared to the high-energy neutrons observed in the liquid scintillators, a clear trend that is significantly more asymmetric than the high-energy neutron correlations is visible, which is also reproduced well in FREYA.

The next step in these measurements would be to join the ELIGANT-GN detectors with the ELI Thick Gaseous Electron Multiplier (ELI-THGEM) setup developed for photofission to investigate neutron and γ-ray anisotropies and correlations relative to the fission vector.

4. – Joint experiments with ROSPHERE

In the time between the completion of the ELIGANT-GN implementation and the full ELI-NP operational phase, including the γ-ray beam, an experimental effort has been carried out together with the ROmanian array for SPectroscopy in HEavy ion REactions (ROSPHERE) [35]. The first actual experiment where ELIGANT-GN detectors were used together with ROSPHERE was when the liquid scintillator detectors for high-energy neutrons were added in two neutron wall-type configurations, together with four neutron detectors inside the sphere itself [36]. In this case the ELIGANT-GN detectors only had a minor impact. In contrast, the main gain of including ELIGANT-GN detectors in ROSPHERE comes with the addition of large volume LaBr$_3$:Ce and CeBr$_3$ detectors [37]. In this configuration, two experimental campaigns have already been performed to explore GDR and PDR properties, as well as statistical quantities, and discrete but weak γ-ray transitions in light nuclei like ^{10}B and ^{12}C.

The first of these experiments, carried out in spring 2022, was the study of the isospin symmetry in ^{72}Kr at low temperature through the γ decay of the GDR populated by fusion reactions, following the work in refs. [38, 39]. Here, 21 LaBr$_3$:Ce and CeBr$_3$ detectors were placed in the ROSPHERE frame with four high-purity germanium (HPGe) detectors. Two reactions were performed populating isospin symmetric states in ^{72}Kr *via* using a ^{32}S beam on a ^{40}Ca target, and isospin asymmetric states in ^{71}Rb using a ^{31}P beam with a ^{40}Ca target, with both compound nuclei having a predicted temperature of

$\langle T_{\mathrm{CN-GDR}} \rangle = 1.3$ MeV. The discrimination between neutrons and γ rays from the decay was done *via* time-of-flight (TOF), requiring a pulsed beam from the Tandem accelerator with a full width at half maximum (FWHM) of around 1.5 ns.

The aim of the second experiment with the same configuration was to search for PDR strength in ^{58,60}Ni at finite temperatures, following theoretical predictions of increasing dipole strength in these nuclei with increasing neutron number as well as temperature [40,41]. Three fusion reactions were performed, with ^{32}S beam and ^{24}Mg target producing ^{56}Ni, ^{34}S beam and ^{26}Mg target producing ^{60}Ni, and ^{36}S beam and ^{26}Mg target producing ^{62}Ni, populating the energy region of the PDR in the isotope range from $N = Z$ to $N = Z + 6$. Also, in this case, the neutron separation, which was even more critical due to the lower excitation energy, was obtained *via* TOF and a pulsed beam. Both these experiments were successful, and the gross data shows good agreement with the statistical model, while the analysis and interpretation of the more subtle features that were the main goals of the experiments are still ongoing.

On the light mass side, there has recently been a renewed interest in the characteristics of the weaker decay branches in odd-mass and odd-odd nuclei [42]. Also in the spring of 2022, an experiment was carried out searching for the E2 decay of the first excited 2^+ state, with isospin $T = 0$, to the first excited 0^+ state, with $T = 1$, in ^{10}B. Here, the advantage of the digital electronics for ELIGANT-GN was crucial, as it allowed us to keep the experiment at a total count rate of up to 1 MHz, compared with around 30 kHz which was the limitation of the previous analogue electronics. The details of this experiment are discussed further in another contribution to these proceedings [43].

Another experiment on the lighter region was aimed at understanding the most recent results regarding the radiative decay of the Hoyle state, in particular, related to the ^{12}C(p, p$'$) reaction from ref. [44] resulting in a 50% higher value than the recommended value in ref. [45]. This contrasts another more recent measurement ref. [46] that reported a value consistent with the old data. For this, a $^{12}\mathrm{C}(\alpha, \alpha')$ experiment was carried out, introducing a circular silicon detector of type S1 by Micron Semiconductor Ltd. This experiment required pulse shape analysis for particle identification and, thus, besides the additional analogue software introduced in the DAQ, also the traces from associated CAEN V1730SB 500 MS/s flash digitisers with zero-suppression firmware were recorded, including an external programmable trigger module, showing the scalability of the experimental setup to very complex conditions.

In the spring of 2023, a test experiment was carried out to extract the level densities and γ strength functions *via* the so-called Oslo method [47-49] at the IFIN-HH facilities. This experimental method is based on extracting particle-γ coincidence events in light-ion-induced reactions. The coincidence events are grouped in γ-ray spectra at all excitation energies of a nucleus and further unfolded to correct for the detector response. This unfolded matrix is subject to the iterative first-generation procedure with the main objective of singling out the primary - or first generation - γ-rays for each cascade at each excitation energy of a nucleus below the neutron threshold, as shown in fig. 3. Recently, new experimental results on level densities and γ-strength functions have been published for ^{116,120,124}Sn [50] and ^{120,124}Sn [51] using the LaBr$_3$:Ce Oslo Scintillator Array (OSCAR) at the Oslo Cyclotron Laboratory (OCL) and for ^{112}Sn from the NaI array CACTUS [52]. In addition, high-energy (p, p') data exists down to ~ 6 MeV [53] providing a significant region of overlap up to the neutron threshold that can be used to verify the consistency of the results in the high-energy region. One goal of the 2023 experiment was to verify consistency between IFIN-HH and Oslo data for the Oslo method on ^{112}Sn. Preliminary results for the ^{112}Sn level density are shown in fig. 3. These

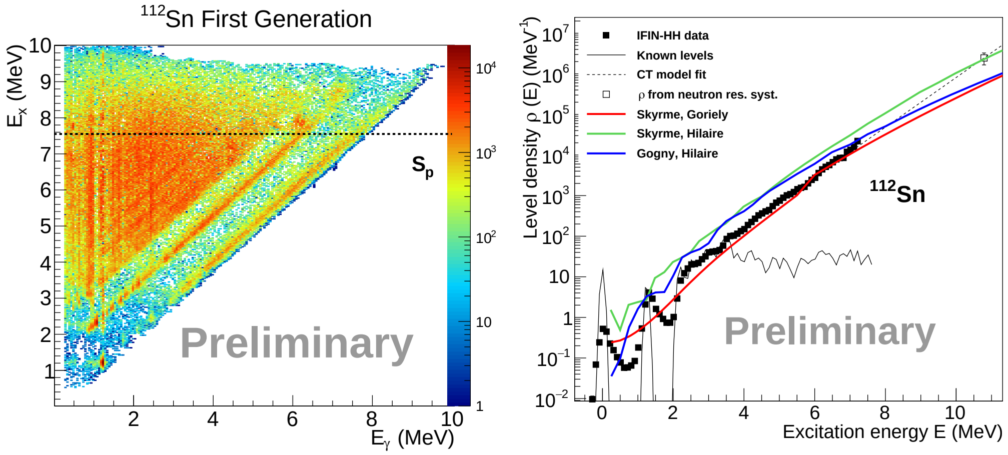

Fig. 3. – (Left) Preliminary first-generation matrix of ^{112}Sn as obtained from the ELIGANT-GN detectors at ROSPHERE. (Right) Preliminary level density extracted from the experimental data, using a fit to the constant-temperature model (CT), compared to three microscopic models.

results can be compared to Hartree-Fock (HF) calculations using the Skyrme force by Goriely [54], Hartree-Fock-Bogolyubov (HFB) calculations using the Skyrme force by Hilaire and Goriely [55], and HFB calculations by Hilarie using the Gogny force [56], as implemented in the reaction code TALYS [57, 58]. A complete data analysis including the extraction of γ-ray strength functions for both ^{112}Sn and ^{114}Sn is in progress.

5. – Conclusions

We have presented the current status of the ELIGANT detectors at ELI-NP and a selection of the measurement carried out during the transition phase from implementation to operation. These measurements are being performed both in the ELI-NP facilities and in collaboration with research groups at IFIN-HH.

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