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Highlights of the day-one experimental program at the gamma-beam system of ELI-NP

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The emerging experimental program with brilliant gamma beams at the Extreme Light Infrastructure – Nuclear Physics facility (ELI-NP) is presented with emphasis on the prepared day-one experiments. Experiments at ELI-NP will cover nuclear resonance fluorescence measurements, studies of large-amplitude motions in nuclei, photo-fission and photonuclear reactions of astrophysics interest, and measurements of photonuclear reaction cross sections. The physics cases of the flagship experiments at ELI-NP and the performance of the related instruments, which are under construction for their realization, are discussed.

Keywords: photonuclear reactions, photo-activation, photo-fission, nuclear resonance fluorescence, giant and pigmy dipole resonances, nuclear spectroscopy.

Introduction

A versatile research program related to physics and applications with brilliant gamma beams at the Extreme Light Infrastructure – Nuclear Physics facility (ELI-NP) has been defined in several Technical Design Reports (TDR) [1] and reviewed periodically [2-5]. Nuclear resonance fluorescence (NRF) experiments, photo-neutron reaction measurements, studies of (γ, α) or (γ,p) reaction cross sections and photo-fission experiments are considered. Gamma-beam applications include the production of intense beams of slow positrons, NRF analytical techniques, γ-ray based radiography and tomography and research related to new medical radioisotopes. Here some of the flagship day-one experiments, which are under consideration, and the expected performance of the instruments, which are constructed for their realization, are discussed. In addition, a family of beam diagnostic detectors is developed, which will monitor the spatial, temporal, spectral and power parameters of the gamma beam, and will provide this information to the experiments upon request.

Ideas for day-one experiments with high-brilliance gamma beams

The experimental program will target NRF measurements which provide a specific research niche for the ELI-NP facility. In particular, the pencil-size gamma beams at ELI-NP will provide access to targets that are available in small quantities and will open the actinide region for studies of low-lying E1 and M1 excitations. Detailed high-resolution studies of the dipole strength distribution in the region of the pygmy dipole resonance (PDR) will be done. Related to this experimental program, the ELIADE detector array of segmented Ge Clover detectors, large-volume $LaBr_3$:Ce detectors and digital data acquisition system is under construction. The array will have eight CLOVER Ge detectors which will be able to detect with high efficiency gamma rays with energies up to several MeV in the presence of the high radiation background produced by the gamma beams. Gamma-ray energies, angular distributions and γ-ray polarization will be measured with high accuracy. The γ-ray photo-peak efficiency of ELIADE is about 6%. A 3D drawing of ELIADE is presented in Figure 1. The Ge Clover detectors are mounted at backward angles in two rings of four detectors each.

A photo-activation measurement of ^{180}Ta with the ELIADE array, i.e. a measurement of the subsequent γ decay as a function of the gamma-beam energy, is discussed. This experiment is closely related to nuclear astrophysics research, since the detailed knowledge of the doorway states and the flux which passes through them, provides a sensitive thermometer for studying the star conditions during the nucleosynthesis. Indications from a bremsstrahlung experiment about the doorway states, through which the $I^{\pi}=9^{-}$, $T_{1/2}>1.2\cdot 10^{15}$ year isomer is de-excited, have been reported [6, 7]. At ELI-NP this measurement can be done with the needed sensitivity and precision. It can be performed already during the commissioning of the GBS.

Extensive photonuclear reaction cross-section measurements were performed during the 1960-1980 at the Lawrence Livermore National Laboratory in USA and the Centre d'Etudes Nucleaires de Saclay in France. The two data bases have inconsistencies, which occur in a non-systematic way. This asks for new more precise measurements, which ideally can be done with a high-resolution gamma beam. Photo-neutron (γ, xn) cross sections with x = 1,2 will be measured using an in-beam neutron multiplicity technique utilizing the high-and-flat efficiency neutron detector ELIGANT-TN. An example for the existing discrepancies is the photodisintegration cross section in ^{9}Be, which has been measured in several experiments. The last three measurements were performed at laser Compton backscattering (LCS) facilities and provide discrepant results within the energy

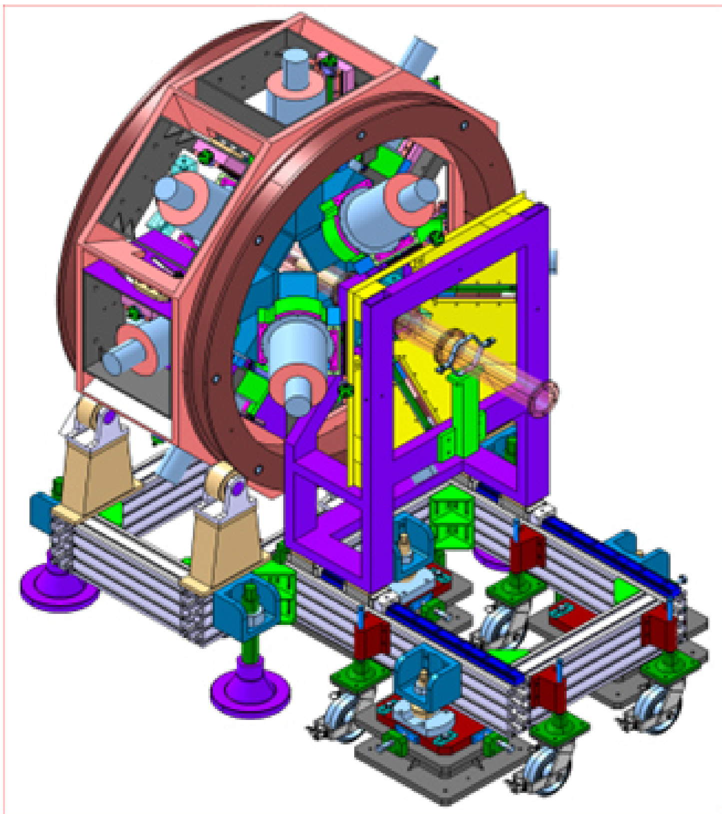

Figure 1. A 3D model of the ELIADE Ge Clover detector array (see details in the text).

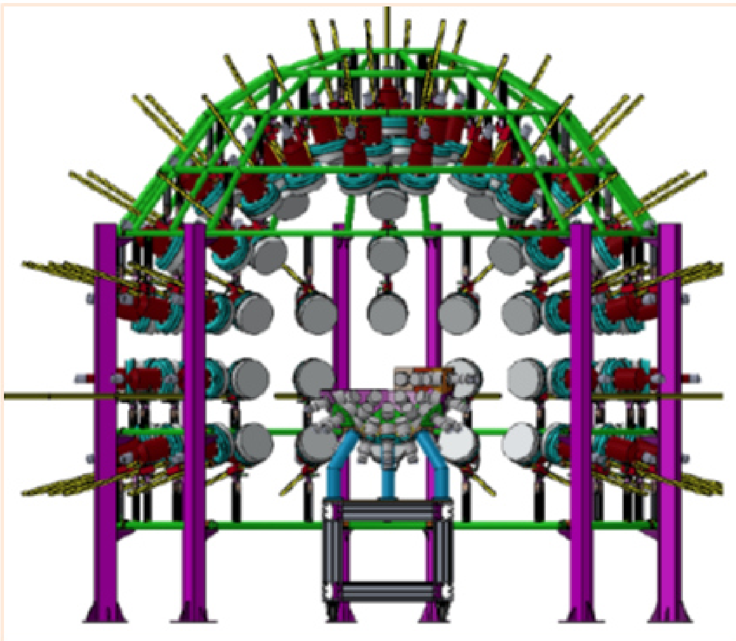

Figure 2. A 3D model of the ELIGANT-GN detector array (see details in the text).

ranges where the cross section varies significantly within the energy spread of the incident γ-ray beam, while for the slow energy variation regions all three data sets are in relatively good agreement [8-10]. The current understanding is that the discrepancies between the three measurements are due to the energy unfolding of the measured cross sections, a procedure which relies on the precise determination of the incident LCS γ-ray beam energy spectra. A day-one experiment at ELI-NP can focus on the ^{9}Be(γ,n) reaction cross section within the 1.6 MeV – 3.0 MeV energy range. The expected narrow bandwidth will allow a complete mapping of the complex ^{9}Be resonant structure with little need for energy unfolding.

Studies above the particle evaporation threshold address open questions related to nuclear structure and astrophysical abundances of nuclear species, e.g. photodisintegration cross-sections for low-abundance nuclei relevant to the p-process nuclear synthesis and nuclear structure of the giant (GDR) and pigmy (PDR) dipole resonances, as well as the magnetic dipole resonances (MDR), from studies of gamma and neutron decays. The ELIGANT-GN detector array will be used for these measurements (see Figure 2). ELIGANT-GN is a 4π spectrometer which consists of 30 $LaBr_3$:Ce and $CeBr_3$ large volume 3"x 3" scintillation detectors mounted at backward angles for detection of γ rays, and of up to 60 BC501A liquid and GS20 ^{6}Li glass scintillators for detection of neutrons [1, 11]. The liquid scintillators will be used for measurements of the neutrons of energies above 1 MeV, while the ^{6}Li glass detectors are the most efficient at lower energies. The energy range below 1 MeV is important because large fraction of the strength of PDR and MDR is observed from neutron threshold up to the first excited states in residual nuclei in the measurement with the neutron threshold technique. The experimental set-up is arranged in such way, as to allow simultaneous γ-ray and neutron measurements, as well as coincidence gamma measurements. The large γ-ray efficiency of the array will enable detailed studies of the fragmentation of the E1 and M1 strength of collective nuclear excitations. The neutron detectors will allow measurements of neutron spectra, which will complement the studies with the ELIGANT-TN array.

The GDR γ decay in ^{208}Pb is a case for a day-one experiment [1, 2] because very detailed measurement on the absorption cross sections with fine structures is available for this case, while only few data with large uncertainties exist for the γ-decay branch. Details related to such measurement with the ELIGANT-GN array were discussed recently and detailed simulations of the detector response were presented [11]. The combination of ELIADE and ELIGANT-GN arrays is ideal for studies of the nuclear dipole polarizability, which is related to the slope of the symmetry term of the nuclear equation of state (EoS) through the neutron skin thickness. Thus, ELI-NP will provide accurate and unambiguous data for the E1 strength below and above the neutron threshold.

Studies of photonuclear reactions with emission of charged particles are related to nuclear astrophysics research. Day-one experiments, which are considered at ELI-NP, are the photodisintegration of ^{7}Li and the $^{16}O(\gamma,\alpha)^{12}C$ reaction at energies close to the Gamow window. The motivation for studying the $^{7}Li(\gamma,t)^{4}He$ reaction is not only a final check on one of the reactions related to the "cosmological Li problem", but also an approach to the recently pointed disagreement between theoretical models and the experimental data. The mirror alpha capture reactions $^{3}H(\alpha,\gamma)^{7}Li$ and $^{3}He(\alpha,\gamma)^{7}Be$ have been at odds in the last five years as the different theoretical models agree very well with the $^{3}He(\alpha,\gamma)^{7}Be$ experimental cross section but could not reproduce the $^{3}H(\alpha,\gamma)^{7}Li$ experimental results. A study of the $^{16}O(\gamma,\alpha)^{12}C$ will help understanding He burning in massive stars.

The cross section of the time-reversal $^{12}C(\alpha,\gamma)^{16}O$ reaction has been measured down to energies around 1 MeV but must be extrapolated to helium-burning energies around 300 keV. There are two energy ranges, which are important for the study of the $^{12}C(\alpha,\gamma)^{16}O$ cross section, at energies below 1 MeV to approach the Gamow peak or at higher energies to constrain the R-matrix extrapolation. Modelling the evolution and explosion of massive stars requires a 10% uncertainty on the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section but recent analysis of the world data estimated this uncertainty at around 20% [12]. The approach for such studies is the measurement of the time-reversal $^{16}O(\gamma,\alpha)^{12}C$ reaction.

Two instruments will be used for the realization of these experiments, a 4π array of Si strip detectors [1, 13, 14] and a time-projection chamber (TPC) with an electronic read-out [1, 15, 16].

Experiments in the field of photo-fission address mapping of the fission barriers, as well as studies of rare fission modes. A flagship experiment is the investigation of fission transmission resonances in the second and third potential minima in the actinides. Studies of the photo-fission cross-section and fragment identification, will result in mapping the fission barrier landscape as a function of the photon-beam energy in the range from 4 MeV to 8 MeV [17].

Pilot experiments on ^{238}U and ^{232}Th [18, 19] have been carried out at the HIγS LBS facility, but the available beams there lack resolution to resolve the resonance states. Further experiments at ELI-NP will profit from the narrow bandwidth of the γ-beam.

The photofission the research programme includes also measurement of kinetic energy, angular, mass and charge distribution of fission fragments, measurements of absolute photofission cross-sections, studies of rare photofission events, such as triple fission, highly asymmetric fission, clusterization phenomena, the predicted cold valleys of fission potential, etc [1].

Conclusion

A diverse research program is been prepared at ELI-NP, which covers all possible directions of photonuclear studies. State-of-the-are instrumentation is constructed for the realization of these experiments. All detector arrays will be ready in time to take first available beams and perform the defined day-one experiments.

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References

[1] ELI-NP Technical Design Reports, Rom. Rep. Phys. **68** (2016).
[2] D. Filipescu et al., Eur. Phys. J. A **51** (2015) 185.
[3] S. Gales et al., Phys. Scr. **91** (2016) 093004.
[4] D.L. Balabanski et al., Europhys. Lett. **117** (2017) 28001.
[5] S. Gales et al., Rep. Prog. Phys. **81** (2018) 094301.
[6] D. Belic et al., Phys. Rev. C **65** (2002) 035801.
[7] D. Belic et al., Phys. Rev. Lett. **83** (1999) 5242.
[8] H. Utsunomiya et al., Phys. Rev. C **63**(2000) 018801.
[9] C.W. Arnold et al., Phys. Rev. C **85** (2012) 044605.
[10] H. Utsunomiya et al., Phys. Rev. C **92** (2015) 064323.
[11] M. Krzysiek et al., Nucl. Instr. Meth. Phys. Res. A **916** (2019) 257.
[12] R.J. deBoer et al., Rev. Mod. Phys. **89** (2017) 035007.
[13] C. Matei et al., J. Phys. Conf. Series **940** (2018) 012025.
[14] S. Chesnevskaya et al., JINST **13** (2018) T05006.
[15] M. Cwiok et al., Acta Phys. Pol. B **49** (2018) 509.
[16] M. Gai et al., Nuclear Inst. and Methods in Physics Research, A (2019), https://doi.org/10.1016/j.nima.2019.01.006.
[17] A. Krasznahorkay, Handbook of Nuclear Chemistry **1** (2011) 281-318.
[18] L. Scige et al., Phys. Rev. C **87** (2013) 044321.
[19] J.A. Silano, H.A. Karwowski, Phys. Rev. C **98** (2018) 054609.