Nucl. Sci. and Tech., Vol.9, No. 3 (2019), pp. 30-37

Nuclear Science and Technology

Journal homepage: https://jnst.vn/index.php/nst

High-resolution fission studies with the planned GBS facility at ELI-NP

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Abstract: The emerging photo-fission experimental campaigne with the gamma beam system at ELI-NP is presented along with the physics cases to be addressed, with emphasis on prepared day-one experiments. The design of the state-of-the-art detector arrays, which are under construction for such experiments, is reported. The results of the performance tests of the constructed prototypes are presented. Plans for further extension of the photo-fission experimental programme at ELI-NP are discussed.

Keywords: *photo-fission, fission barrier, transmission resonance, GBS, ELI-NP, fission detectors.*

I. INTRODUCTION

The complex multi-humped potential energy surface (PES) of the atomic nuclei have focused considerable research interest during the years. In the actinide region, the appearance of a deep, local superdeformed (SD) second minimum in the PES of the nucleus at large quadrupole deformations was already observed experimentally and described within the macroscopic-microscopic theoretical framework in the 1960s [1,2]. A shallow third minimum in the PES at large quadrupole and octupole deformations was suggested theoretically, long ago [3–5]. A deep 3rd hyperdeformed (HD) minimum was suggested experimentally by Krasznahorkay et al. in studies on uranium isotopes in transfer (d,pf) reactions [6]. Recently, experimental evidence for the existence of a HD minimum in the PES of ^{238}U was reported in a sub-barrier photo-fission experiment [7]. However, recent theoretical approaches, like microscopic-macroscopic and self-consistent calculations did not predict the existence of such third minimum [8, 9]. Clear-cut experimental evidence for the existence of a HD minimum in the PES of actinide nuclei is needed, which asks improved performance of the experimental instrumentation. Bottomline, the existence of a third minimum in the PES at hyperdeformed (HD) nuclear shapes in the actinide nuclei is a long-standing problem, which still awaits a solution.

Theoretical considerations also predicted that, in a cluster description, the HD minimum consists of a spherical ^{132}Sn-like component ($N = 82$, $Z = 50$) complemented by an attached elongated second cluster of nucleons [5]. Since the fission mass and charge distributions are

https://doi.org/10.53747/jnst.v9i3.42
Received 08 November 2019, accepted 27 November 2019

distinctly determined by the configuration at the scission point, and the 3rd minimum is very close to the scission configuration, it is expected that the mass distributions originating from the 3rd minimum has a much more remarkably asymmetric nature. Such a dramatic effect of the shell structure has not been observed so far.

Experimentally, the multiple-humped PES can be investigated through observation of transmission resonances in the prompt photo-fission cross section as a function of energy. Such a resonance appears when directly populated excited states in the first potential minimum overlap energetically with states either in the SD 2nd or HD 3rd minimum, respectively [10,11]. The fission channel can thus be regarded as a tunneling process through the multiple-humped fission barrier as the gateway states in the first minimum decay through states in the other minima of the PES. By the angular distribution measurements of the fission fragments, one can get information on the values of the nuclear spin and its projection K on the symmetry axis of such excited states.

The study of transmission resonances was mostly carried out using transfer reactions [10] and photo-fission [12-15]. Transfer reactions provide very good energy resolution, giving better than 0.1% resolution in excitation energy, hence enabling the identification of the members of the SD and HD rotational bands. However, in such reactions, states with various spins and parities are excited, e.g. the reaction mechanism is not sensitive to states of any particular spin and parity, I^{π}, except for the lowest transition state having spin-parity $I^{\pi} = 0^{+}$. Photo-fission measurements are simpler to interpret since photons excite only dipole and quadrupole states with appreciable probability. Hence, photo-fission enables selective investigation of extremely deformed nuclear states in the light actinides and providing better understanding of the multiple-humped fission barrier landscape [16, 17].

In first experiments, sub-barrier photo-fission was studied with bremsstrahlung photons, measuring integrated fission yields. A plateau was observed in the fission cross section, referred to as the isomeric shelf [12,13]. Measurements using bremsstrahlung monochromator [14] and tagged photons [15], pushing the bremsstrahlung technique to its limit, could improve the resolution, but, faced limitations with beam intensities [18]. High statistics experiments in the deep sub-barrier energy region, where cross sections are as low as σ = 1 nb – 10 μb are difficult to be performed with these tecniques. The cross section measurements in such deep sub-barrier energy region can lead to unambiguous determination of the double- or triple humped nature and precise evaluation of the barrier parameters. Relatively recent development of the Compton backscattering (CBS) of eV range photons off a relativistic electron beam, producing brilliant narrow-width photon beams, offers an opportunity to overcome the previous limitations. A recent experiment to explore the multiple-humped fission barrier via subbarrier photo-fission, was performed at HIγS, Duke University, USA. The measurements indicated the existence of three minima in ^{238}U, because the measured sub-barrier cross section was described best by a model assuming a deep HD minimum [6]. However, the γ-beam bandwidth there, 150-200 keV at 5 MeV, could not resolve possible transmission resonances. The sensitivity of this study was limited to resonances with $\Gamma\sigma \approx 10$ eV b.

The high-intensity (~10^4 photons/s/eV), high-resolution (band width ≥ 0.5%) and highly-polarized (>95%), tunable (0.2-19.5 MeV) brilliant gamma-beam system (GBS) to be hosted by ELI-NP [19,20], will be far superior to the photon beam available at HIγS, and will enable the identification of sub-barrier transmission resonances in the fission decay channel with integrated cross sections down to $\Gamma\sigma \approx 0.1$ eVb. The narrow energy-bandwidth will allow for a significant reduction of background from non-resonant processes. The highly collimated γ beams allow the development of compact fission detectors, and permit remarkably improved angular resolution. ELI-NP GBS is expected to allow preferential population and identification of vibrational resonances in photo-fission cros section, ultimately enabling the observation of the fine structure of the isomeric shelf.

II. PHOTO-FISSION STUDIES AT ELI-NP

The photo-fission experimental campaign with the GBS facility at ELI-NP, aims at high resolution measurement of the absolute photo-fission cross sections and transmission resonances in the deep sub-barrier energy region for actinide nuclei, and at studying the properties of fission fragments, like energy, mass, charge and angular distributions, following the decay of states in the different minima of the PES in the region of the light actinides. An important goal is to resolve the so far unobserved fine structure of the isomeric shelf by decomposing it into individual transmission resonances, and to observe the predicted nucleon clusterization phenomena in SD and HD states of the actinides. The polarized γ beams provide an excellent opportunity to study the space asymmetry of the angular distribution of the fission fragments and the correlation between the space asymmetry and the asymmetry of the fission process [21,22].

Another topic, which will be covered by the photo-fission programme at ELI-NP, are studies of exotic fission modes, such as ternary fission, Pb radioactivity and collinear cluster tripartition. Ternary fission has been studied so far in neutron-induced and spontaneous fission experiments, while ternary photo-fission has never been observed, due to the low cross section and the limited intensities of hitherto available photon beams. Fission studies at ELI-NP will be done with highly polarized beams, fixing the geometry of the process, which is advantageous for detailed studies. Ternary particles, being released close to the scission point, provide information about the neck formed between the two heavy fission fragments, and about fission dynamics. Hence, it is very interesting to measure light-particle emission in coincidence with fission fragments.

In order to make these measurements possible, two new detector arrays are being developed based on existing, well-understood cutting-edge technologies [21,22]. These detectors will be shortly discussed in the sections below, along with presenting some test experiments demonstrating their performance.

III. DETECTOR ARRAYS FOR THE PHOTO-FISSION STUDIES AT ELI-NP

For the photo-fission studies with the GBS facility at ELI-NP, two detector arrays are under development: ELITHGEM and ELI-BIC. The arrays will be positioned at the closest possible distance from the γ-beam production point.

A. The ELI-THGEM Array: Measurements of fission cross sections

A multi-target detector array, ELITHGEM is under development, consisting of position sensitive detector modules based on the THick Gas Electron Multiplier (THGEM) technology [23]. The array consistes of twelve THGEM boards inside a low-pressure gas chamber, coupled with a transmission mesh and a segmented delay-line read-out electrode providing a true pixelated radiation localization. It will be used for measurements of fission cross sections and fission fragment angular distributions as a function of the photon energy. The experiments will be carried out as a function of the γ-beam energy. It will be possible to map fission resonances with the array, which can be a day-one experiment within this research program. This detector array covers almost a full solid angle (around 80% of 4π) and has an angular resolution of about 5°. A set of ten target foils will be placed in the centre of the array and tilted at 45° with respect to the beam direction. A performance test of one THGEM detector unit was carried out using spontaneous fission of ^{252}Cf, at MTA Atomki, Hungary. The results demonstrated good position sensitivity and time stability of the detector unit [22].

B. The ELI-BIC Arrays: Measurements of the properties of the fission fragments

For studies of the fission fragment characteristics, such as energy, mass and angular distributions, a highly-efficient four-fold array, ELI-BIC, of Frisch-grid twin Bragg ionization chambers (BIC) [24,25], is designed and developed. A thin (100-200 μg/cm^2) elliptical target foil of dimensions 3 cm × 0.5 cm (major and minor axis, respectively), and tilted at 10° with respect to the γ-beam direction, will be placed in the centre of the cathode of each BIC. The target dimension is based on the simulated beam spot dimensions using the beam parameters with 0.5% photon energy bandwidth [26,27]. The multi-target set-up will increase the photo-fission yield at deep sub-barrier energies with very low cross sections.

Each BIC of the ELI-BIC array will be coupled to eight ΔE-E detectors, consisting of an ionization chamber for registration of the ΔE signal and a double-sided silicon strip detector (DSSD) for the E signal. The array of these eight ΔE-E telescopes covers in total about one □ solid angle. The array will be used for the identification of ternary fission particles and the study of their correlations with the properties of the fission fragments.

IV. PERFORMANCE TESTS OF ONE BIC WITH ONE ΔE-E DETECTOR

So far, several tests have been performed already to demonstrate the sensitivity and performance of the above mentioned detector assemblies. Below we report some first-stage results of two test experiments.

A. In-beam experiment performed at the cyclotron accelerator in Debrecen

The experiment was carried out at the MGC-20 cyclotron facility of MTA Atomki (Debrecen) employing the ^{9}Be(p, n) reaction to produce 18 MeV neutrons. The neutrons were then thermalized by paraffin blocks for the ^{235}U(n$_{th}$, f) reaction. A 230 ug/cm^2 thick target foil was placed in the center of the BIC cathode. One BIC was coupled with one ΔE-E telescope. Signals were collected from both anodes and grids of the BIC for the binary fission fragments, the anode and cathode of the ionization chamber and the two sides of the DSSD for the detection of the energy loss ΔE and the remaining energy E of light charged particles, respectively.

Signals from the BIC and ΔE electrodes, after pre-amplification, were amplified and shaped by using normal analog data acquisition set-up using amplifiers and discriminators. The

DSSD data was acquired using analog read-out with multiplexer (MUX) interfaces. The data was recorded for two days, using an online acquisition software developed at MTA Atomki. Offline analysis of the data was carried out using a ROOT-based [28] analysis program to determine the various properties (mass, kinetic energy and angular distribution) of the fission fragments. The total kinetic energy (TKE) vs. mass distribution of the fission fragments is shown in Fig. 1. The mass distribution of the light and heavy fragments for the so-called cold fission events, with total kinetic energy of TKE>180 MeV and thus very low fragment excitation energies, are shown in Fig. 2. At ELI-NP, the data from the BIC will be acquired using a digital acquisition system consisting of 14-bit 500 MS/s waveform digitizers facilitating both triggerless as well as triggered waveform processing, and better sensitivity of the array.

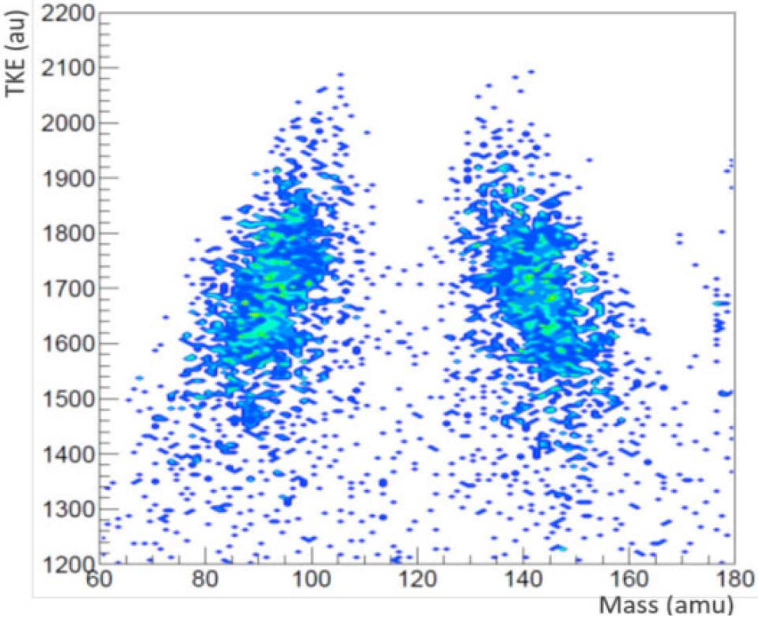

Fig. 1. TKE-mass correlation of fission fragments produced from ^{235}U(n_{th}, f).

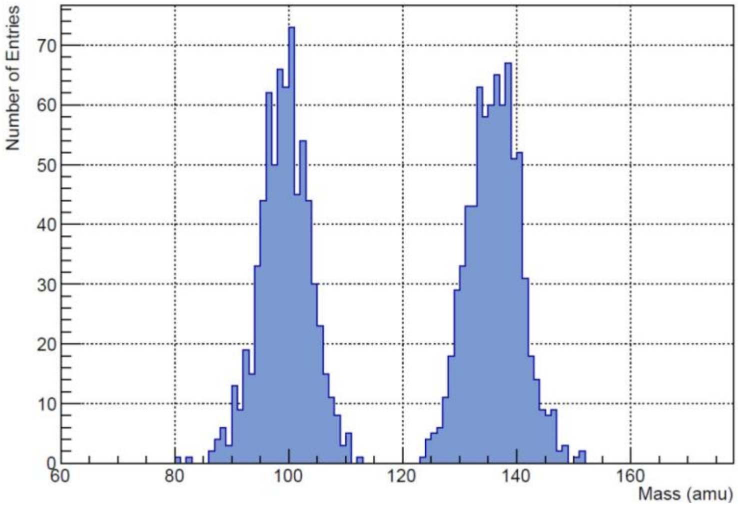

Fig. 2. Pre-neutron mass distribution of fission fragments produced from ^{235}U(n_{th}, f).

B. Performance test using a spontaneously fissioning ^{252}Cf source

Due to the moderate neutron flux and the very small branching ratio of ternary to binary fission, light charged particle accompanied fission could not be studied in detail. Thus, a ^{252}Cf spontaneous fission source with a specific activity of ~30 Bq was placed in the cathode of the BIC to test the capability of the dE-E array, using the same settings of the front-end electronics as in the in-beam experiment.

Preliminary results show a very distinct dE-E correlation of the ternary particles (Fig. 3), measured by one *ΔE-E* telescope. Energy calibration still has to be performed considering the results of on-going GEANT4 simulations: in the present BIC detector configuration and geometry, conventional α sources cannot be used for energy calibration of the dE-E array since alpha particles with a kinetic energy of E=4-5 MeV are fully stopped withing the range of the Bragg section of the array. The shown ΔE-E correlations, where the lines represent fits to guide the eye, are expected to correspond to α and tritons, respectively. A proper energy calibration and more statistics are needed for confirmation. However, the current result clearly indicates that the newly designed Δ*E*-*E* detector array is very promising for the efficient identification and study of ternary fission particles, and hence, ternary photo-fission studies at ELI-NP.

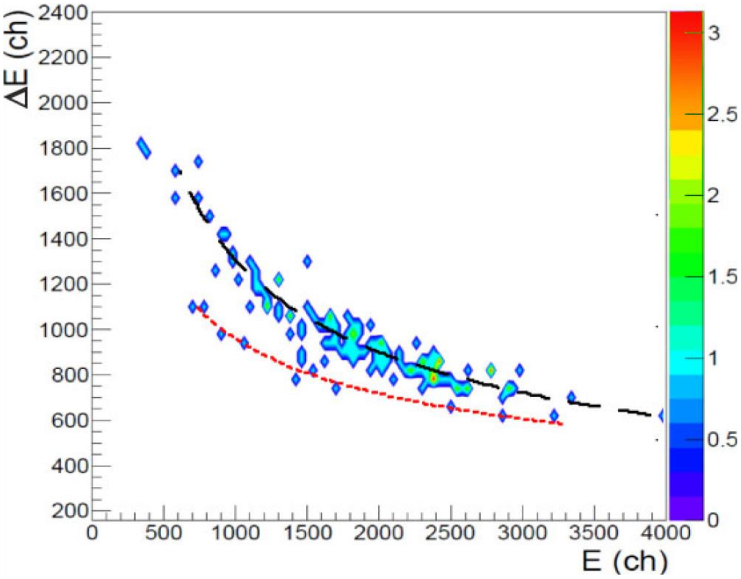

Fig. 3. Uncalibrated ΔE-E correlation of the light charged particles released in fission.

V. CONCLUSIONS AND OUTLOOK

The high-intensity, narrow-bandwidth, tunable, highly-polarized and highly-focussed gamma beams at ELI-NP will enable high-resolution photo-fission studies in actinide nuclei, in the low cross section sub-barrier region. Two detector arrays, have been designed for such studies. Performance tests of the produced prototypes of the instruments demonstrate that the expected performance is achieved. Necessary DSSD detectors and corresponding electronics have been procured and tested. The construction of the arrays is in progress.

The detectors will be further tested with fission sources and used in-beam at existing facilities. The array will be ready for day-one experiments at ELI-NP for measurements of fission fragment charateristics of light actinide nuclei. The study of fission barriers in ^{234,238}U and ^{230,232}Th by high-resolution measurements of transmission resonance in the sub-barrier energy region of 5–6 MeV will be aimed at as day-one flagship experiments at ELI-NP.

The distant vision for photo-fission exeriments at ELI-NP, beyond day-one, includes the coupling the fission arrays with the gamma- and neutron detector arrays called ELIADE [27] and ELIGANT [28], respectively, which are developed under other experimental programmes with the GBS at ELI-NP. This coupling of detectors will enable high-precision measurements of photon-induced prompt-fission gamma-rays and neutron spectra, as well as γ-decay spectroscopy of excited fission fragments. The study of photo-fission, photo-neutron and neutron-fission correlations will become possible using the time-of-flight technique.

ACKNOWLEDGEMENTS

The authors acknowledge the support from the Extreme Light Infrastructure Nuclear Physics (ELI-NP) Phase II, a project co-financed by the Romanian Government and the European Union through the European Regional Development Fund - the Competitiveness Operational Programme (1/07.07.2016, COP, ID 1334)) and by the Hungarian NKFI (OTKA) Foundation No. K124810.

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