PROSPECTIVES OF PHOTOFISSION STUDIES WITH HIGH-BRILLIANCE NARROW-WIDTH GAMMA BEAMS AT THE NEW ELI–NP FACILITY*

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Simulations providing estimates of the ELI–NP gamma-beam energy bandwidths and beam spot dimensions for the collimated beams, and expected fission rates with the narrow-width γ beams of bandwidth 0.3% and 0.5% on actinide targets, ^{238}U and ^{232}Th, are reported. These estimates support the feasibility of precise transmission resonance measurements with the narrow-width ELI–NP γ beams. The status of the design and construction of a state-of-the-art experimental array, consisting of four double-sided, Frisch-gridded Bragg ionization chambers, coupled to ΔE–E detectors, is reported.

1. Introduction

Photofission studies at the Extreme Light Infrastructure–Nuclear Physics (ELI–NP) facility [1–3] aim at a precise investigation of the multiple-humped potential energy surface (PES) of the fission barrier in light actinides, using transmission resonance spectroscopy. Measurements of the absolute cross section, mass, atomic number, angular and kinetic energy distributions of fission fragments following the decay of the states in the different minima of

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the multiple-humped fission barrier in the region of the light actinides will be studied within this research programme. Other topics to be addressed are exotic fission modes, such as true ternary fission, clusterization, *etc.*

In the actinide nuclei, the superdeformed (SD) second minimum in the PES was discovered experimentally [4] and explained theoretically [5] in the 1960s. The existence of a third minimum at hyperdeformed (HD) nuclear shapes has been suggested theoretically [6–8]. However, other models do not predict any third minimum of the PES [9, 10]. Transmission resonance spectroscopy is one of the experimental approaches to study the fission barrier and, in particular, to search for HD nuclear shapes in the light actinides [11, 12]. The experiments were mostly carried out using transfer reactions [12] and photofission [13–16]. The advantage of the transfer reactions is the very good (< 5 keV) energy resolution, which gives better than 0.1% resolution in excitation energy, which is provided by the magnetic spectrometers. Such resolution enabled the identification of the members of the SD and HD rotational bands [12].

Photofission, enabling selective investigation of extremely deformed nuclear states, can explain better the landscape of the multiple-humped PES in light actinides [17, 18]. Photofission studies were carried out with bremsstrahlung photons measuring integrated fission yields [13, 14]. Better resolution was achieved with measurements using bremsstrahlung monochromator [15] and tagged photons [16]. However, high-resolution measurements of transmission resonances with much better statistics are needed for the study of extremely deformed nuclear shapes in the light actinides [11, 12]. A recent experiment to explore the multiple-humped fission barrier via sub-barrier photofission performed at HIγS, Duke University, USA, 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 [19]. The γ-beam bandwidth was not small enough to resolve possible transmission resonances.

The high spectral density, $\sim 10^4$ photons/(s eV), high-resolution, bandwidth $\geq 0.3\%$, and high polarization, $> 99\%$, of the tunable (0.2–20 MeV) ELI–NP gamma-beam system (GBS) [20, 21] overcome the existing limitations and open a new path for the identification of the low cross-section sub-barrier transmission resonances in the fission decay channel with cross sections down to $\Gamma\sigma \sim 0.1$ eVb.

The work reported here includes results from simulations for the ELI–NP beam profile, the beam spots at the planned experimental position, and estimates of fission fragment emission rates for ELI–NP beams at low, medium and high energies for ^{238}U and ^{232}Th targets. The planned spectrometer for transmission resonance spectroscopy, and the status of its design and construction are discussed.

2. Estimates of the conditions for transmission resonance spectroscopy experiments: Beam properties and fission yields

Numerical simulations, performed within the Geant 4 Monte Carlo simulation toolkit [22] for checking the feasibility of high-resolution photofission measurements with the ELI–NP GBS are presented.

2.1. Beam profile and beam spot dimension at the target position

The ELI–NP γ beam will be produced by the inverse Compton backscattering (CBS) of laser photons, off a relativistic electron beam. The beam profile will be characterized by a strong relation of γ rays with the highest energy being emitted at the smallest angle, as demonstrated in Fig. 1 of Ref. [23]. This property is used for producing quasi-monoenergetic γ-ray beams by beam collimation, *i.e.*, by decreasing the collimator aperture [23, 24]. At the ELI–NP, a tungsten collimator, whose aperture can be adjusted precisely in the sub-millimetre range [21], will be positioned at 890 cm from the CBS interaction point (IP). Geant 4 Monte Carlo simulations have been performed to study the beam collimation angle and beam bandwidth as a function of collimator opening. Expected beam bandwidths for different collimator apertures are listed in Table I, for three different beam energies, 5.8, 12.9, and 18.6 MeV. The photofission experiments are planned to be carried out at about 30 m from the interaction point. The expected beam spot dimensions at this position are also listed in Table I.

TABLE I

Beam collimation angle, bandwidth, and beam spot diameter at 30 m from IP for different collimator apertures, for 5.8, 12.9, and 18.6 MeV beam energies.

Coll. aperture [mm]	Beam coll. angle [mrad]	Beam bandwidth for 5.8 MeV [%]	Beam bandwidth for 12.9 MeV [%]	Beam bandwidth for 18.6 MeV [%]	Beam spot diameter [mm]
3.0	0.169	0.65	1.20	1.60	9.3
2.5	0.140	0.50	0.90	1.21	7.7
2.0	0.112	0.39	0.68	0.86	6.2
1.5	0.084	0.30	0.50	0.59	4.6
1.3	0.072	0.27	0.45	0.50	4.0
1.0	0.056	0.24	0.40	0.39	3.1
0.5	0.028	0.23	0.30	0.30	1.6

2.2. Estimates of fission yields

Using the ELI–NP gamma beams with the properties described in the previous section, the fission fragment emission rates have been estimated for actinide targets, ^{238}U and ^{232}Th, within the Geant 4 simulation framework [22]. The implementation of the photofission process in Geant 4 is described in Ref. [23]. Photofission cross sections for these target materials are taken from Ref. [25]. Numerical calculations for three beam energies, 5.8, 12.9, and 18.6 MeV, with 0.3% and 0.5% bandwidths and using target tilt angles of 10° and 45° with respect to the beam direction are presented. The two angles correspond to the target tilt angles for the planned photofission experiments at the ELI–NP. The estimated fission fragment emission rates are shown in Fig. 1, for a 20 mg/cm^2 thick target, the maximum effective target thickness to be used in photofission measurements at the ELI–NP. Thick target experiments will aim at cross-section measurements.
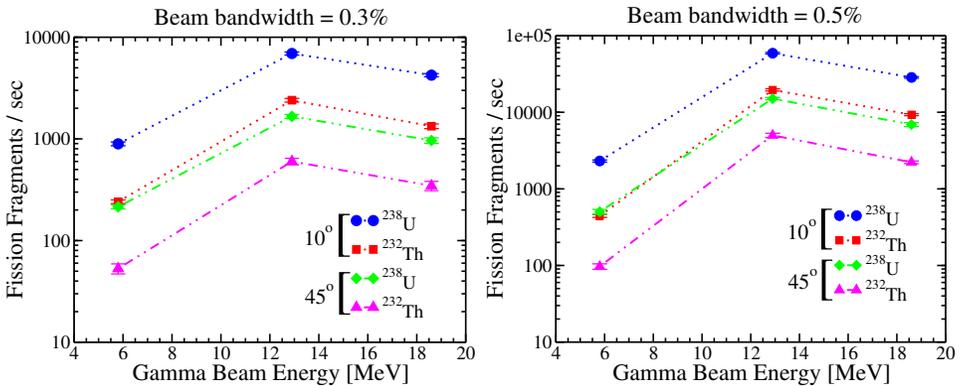

Fig. 1. Estimated fission fragment emission rates for the ELI–NP gamma beam on ^{238}U and ^{232}Th targets of thickness of 20 mg/cm^2, for three γ-beam energies, 5.8, 12.9, and 18.6 MeV. Results for a beam bandwidth of 0.3% (left) and 0.5% (right) are shown. The statistical uncertainties are smaller than the symbols.

From the estimated fission rates for the two target materials, the feasibility of the planned high-resolution photofission measurements with the ELI–NP beam is ensured. In the sub-barrier region, for a thin target of thickness $\sim 200~\mu g/cm^2$, $\sim 10^6$ fission fragments are estimated to be emitted in one week of 5.8 MeV beam with 0.3% bandwidth. Thin target experiments will aim at studying the kinetic energy, mass, atomic number and angular distributions of the fission fragments. With these rates, the high-resolution transmission resonance studies in the 5.5–6 MeV energy interval are feasible in one-week beam time with the ELI–NP GBS. For the envisaged sub-barrier

transmission resonance studies in the excitation energy region of the isomeric shelf, 3.5–4.5 MeV, the expected yield will be scaled with the change in cross section.

3. Setup for sub-barrier photofission measurements

For the study of the kinetic energy, mass, atomic number and angular distributions of the fission fragments, a highly-efficient, Frisch-gridded twin-ionization chamber [26], used as Bragg ionization chamber (BIC) [27], is under development. The chamber will be coupled to eight ΔE–E detectors in order to measure α or light-particle emission probabilities from highly-deformed compound states and to detect any ternary fission. Atomic numbers will be extracted by recording the ion stopping power using a VME digitizer and advanced digital signal processing (DSP) techniques. To improve the statistics, an array of four such chambers, called ELI-BIC, will be constructed. The design of the array is in progress. A prototype of the ΔE–E detector has been designed and constructed. It consists of a gas chamber coupled with a double-sided Si strip detector (DSSD) with 16 strips on each face. The prototype has been tested with a triple α source (^{239}Pu + ^{241}Am + ^{244}Cm). After a proper strip-by-strip energy calibration, an energy resolution of FWHM = 40 keV has been obtained for the ~ 5 MeV α peak. The ionization chamber has been coupled with one ΔE–E detector. The prototype is being tested for feasibility and efficiency.

4. Conclusions and outlook

Simulations for the γ-beam properties and fission yield estimations ensure the possibility of high-resolution measurements in the sub-barrier region for actinide nuclei. A 5.8 MeV collimated beam with $\geq 0.3\%$ bandwidth, impinging on a ~ 200 μg/cm^2 thin ^{238}U target can produce $\sim 10^6$ fission events in one week, which are sufficient for studies of transmission resonance spectroscopy experiments. A spectrometer, called ELI–BIC, which consists of four Frisch-gridded twin ionization chambers, coupled to ΔE–E detectors, is being designed. A prototype of one chamber has been constructed. It is tested with fission sources and will be used in-beam at existing facilities. The array will be ready for day-one experiments in 2018 for the measurements of absolute cross sections, and studies of angular, energy, mass, and atomic number distributions of light actinide nuclei. The ELI–NP will be commissioned in 2018 and start operating as a user facility in 2019. Day-one experiments are being planned for this time scale. The study of fission barriers in ^{234,238}U and ^{230,232}Th, by high-resolution transmission resonance spectroscopy in the sub-barrier energy region of 5–6 MeV will be aimed at for day-one experiments.

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