PERSPECTIVES FOR SPECTROSCOPY OF ACTINIDES WITH HIGHLY BRILLIANT γ BEAMS*

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Presently two new research facilities are either already under construction ('MEGa-Ray' at Lawrence Livermore National Laboratory/US) or soon ready to start construction (ELI-Nuclear Physics in Bucharest/Romania), both aiming to provide highly brilliant γ beams with so far unprecedented properties (*ca.* 10^{13} photons/s, energy resolution $\leq 10^{-3}$) via Compton-backscattering of laser photons from a high-quality relativistic electron beam. With these intense, monochromatic γ beams, a new era of photonuclear physics will be enabled. It is envisaged to exploit the novel beams for highly-selective studies of extremely deformed nuclei in the multiple-humped potential energy landscape of the actinides via photofission. We will be able to populate gateway states in the first potential minimum of nuclei, predominantly originating from collective states in the (superdeformed) second or (hyperdeformed) third potential minimum, tunnelling back into the first well. The γ beam energy resolution of 10^{-3} will allow to resolve individual resonances due to the lower level density in the higher potential minima. Excited states in these minima can be rather selectively populated with much larger intensities than achieved with former methods based on light-ion induced reactions. Also the large background from prompt fission with $\sigma_{\rm isomer}/\sigma_{\rm prompt} \approx 10^{-5}$ is avoided. Hence a detailed γ spectroscopy in the second and third minimum will be enabled.

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1. Introduction

The appearance of a (superdeformed) second minimum (quadrupole deformed with axis ratio 2:1) in the potential energy surface of actinide nuclei between U ($Z = 92$) and Bk ($Z = 97$) ('island of fission isomers') can be described in a macroscopic–microscopic theoretical approach as a superposition of microscopic shell corrections to the nuclear binding energy, varying periodically with deformation, onto the unstructured macroscopic part of the deformation energy described by the liquid drop model [1]. Moreover, in recent years also the existence of an octupole-deformed deep (hyperdeformed) third minimum (axis ratio 3:1) has been established in uranium isotopes [2,3] in agreement with theory [4,5]. This general picture of the triple-humped fission barrier is schematically illustrated in Fig. 1. So far experimental progress was achieved mainly via light-particle induced nuclear reactions

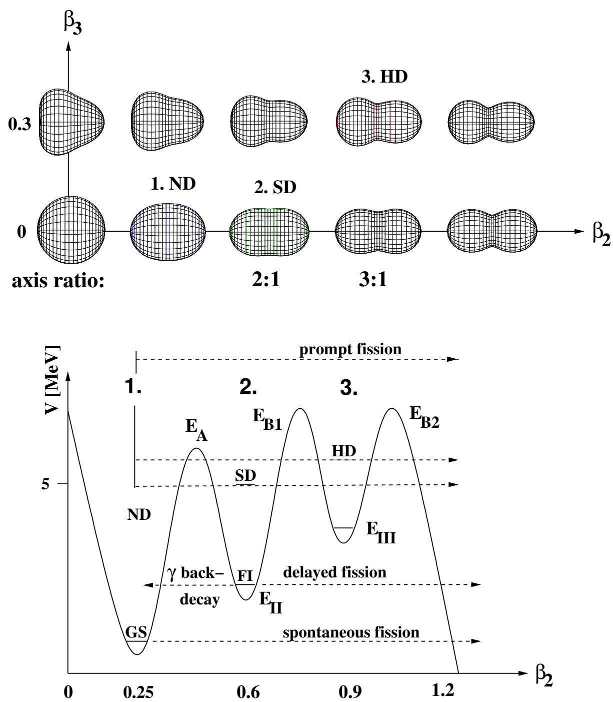

Fig. 1. Schematic view of the triple-humped fission barrier in actinides together with the underlying nuclear shapes. Bottom: cut through the potential energy surface along the fission path with a superdeformed (SD) second minimum at an axis ratio of 2:1 and a hyperdeformed (HD) minimum at an axis ratio of 3:1. Top: corresponding nuclear shapes as a function of the quadrupole and octupole degrees of freedom [2].

studying transmission resonances, or by performing conversion electron or γ-ray spectroscopy [2]. In sub-barrier photofission experiments the so-called 'isomeric shelf' in the fission cross-section was observed [6,7], resulting from a competition between prompt and delayed photofission. Until now nearly all measurements of subbarrier photofission have been performed with bremsstrahlungs photons, measuring integrated fission yields, where the fission cross-section is folded with the increasing γ-ray spectrum, resulting in a typical effective γ band width of only ~ 4–6×10^{-2} (energy resolution 200–300 keV).

Upcoming new γ-beam facilities like MEGa-Ray (Lawrence Livermore National Laboratory [8]) or ELI-Nuclear Physics (ELI-NP) in Bucharest/Romania [9] both aim to provide highly brilliant γ beams with so far unprecedented properties.

The γ source of ELI-NP will produce a very intense and brilliant γ beam with (initially) $E_\gamma \leq 13\,\mathrm{MeV}$, which is obtained by Compton back-scattering of direct laser light from a very brilliant and intense electron beam ($E_e \leq 600\,\mathrm{MeV}$). Presently the following design parameters are pursued for the γ beam: energy bandwidth (BW) $\Delta E/E \leq 10^{-3}$, total flux higher than 10^{13} photons/s at 100% BW (corresponding to 10^6 photons/(s eV) and a peak brilliance higher than 10^{21} photons/mm^2/mrad^2/s/(0.1% BW). Comparing the spectral photon flux envisaged for ELI-NP with the current performance of the presently world leading photonuclear facility, HIγS at Duke University, of 10^2 photons/(s eV) [10] reveals the unprecedented properties of the novel photon beam at ELI-NP.

2. Photofission in the 2$^{\text{nd}}$ and 3$^{\text{rd}}$ minimum of actinide nuclei

With the availability of these highly-brilliant γ-beams completely new perspectives for photofission studies in extremely deformed actinides will be enabled. So far the second and third potential minima could only be accessed for γ spectroscopy via a statistical population with a probability of 10^{-4}–10^{-5} in particle-induced reactions, exhibiting typical isomer intensities of ~ 1/s. Moreover, these γ measurements suffered from a dominating background from prompt fission. With the novel γ beams, providing a spectral flux of about $10^6\gamma$ (eV s), very clean spectra can be achieved at isomeric intensities of $\sim 10^2$–10^6/s (depending on the transmission of the innermost barrier), allowing to identify individual vibrational resonances in the fission decay. Thus, weak sub-barrier resonances with integrated photo-fission cross-sections down to $\sigma\Gamma = 0.1$ eV b can be addressed for resonances with $\Gamma \sim 100\,\mathrm{eV}$–$100\,\mathrm{keV}$, while, so far, in nuclear resonance fluorescence typically resonances with ≈ 10 eV b were studied. This will enable to perform γ spectroscopy at the high resonances energies of the 'isomeric shelf' in the fission yield ($E_\gamma = 3.5$–$4.5\,\mathrm{MeV}$), allowing to test the prediction of Bellia *et al.* [7] that the isomeric shelf consists of 2^+ ($K = 0$) and 1^- ($K = 0$) resonances as indicated in Fig. 2. Such resonances would represent effective gateway states for the population of the second minimum. Several so far unobserved

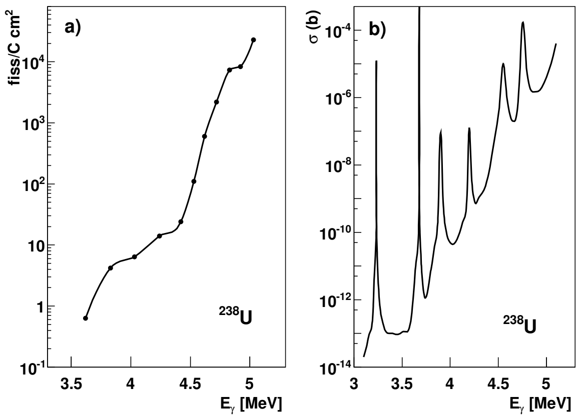

Fig. 2. (a) Measured photofission yield and (b) calculated total photofission cross-section, both displayed as a function of the maximum bremsstrahlung energy for photofission of ^{238}U (according to [7]).

features of the multiple-humped fission barrier in actinides will become accessible. The γ decay in the second minimum of thorium isotopes with its predominant back-decay to the first minimum can be studied with high resolution. Adding up the energies of the γ cascade results in the resonance energy. It will become possible to measure the isomeric excitation energies with a resolution of $< 10^{-3}$ and study the back decay to the first minimum, as well as the fission decay. The $E1$ excitations will have a strong decay branch to quadrupole and octupole bands in the minima, allowing for a measurement of these elementary collective excitations in the deformed potential minima. Identifying the multi-phonon β-vibrational excitation pattern over a wide energy range from the isomeric ground state to the region of the barrier top will provide valuable insight into the harmonicity of the potential in the second well.

This will be of interest also in view of the existence of a triple-humped fission barrier in actinide nuclei, as established in several recent measurements [3], while most older analyses of subbarrier photofission were performed in the picture of only a double-humped fission barrier. Measurements of the ground state of the third minimum via its γ decay will be enabled. Enhanced $E1$ strengths can be expected in the second and third potential well due to the large static dipole moment [11], resulting in γ decay times comparable to prompt fission.

In view of the very intense available photon intensity, trading flux *versus* resolution could be afforded by further monochromatizing the γ beam (*e.g.* by using a crystal spectrometer) to a bandwidth as narrow as 10^{-6}. This way the γ resolution could be matched to the resonance width, thus avoiding atomic background from Compton scattering or pair creation.

2.1. Exploratory experiments

In order to prepare for the described photofission experiments at the γ beams of MEGa-Ray (starting operation in 2013) and ELI-NP (operation envisaged for 2016), exploratory studies of sub-barrier photofission in actinides will be performed at the γ beam of the HIγS facility at Duke University [10]. With an energy resolution of 1–3% and a spectral flux of *ca.* $10^2\gamma(\mathrm{s\,eV})$ a first experiment is envisaged to map the multiple-humped fission barrier landscape in ^{238}U. The experiment will be carried out with an array of Parallel Plate Avalanche gas detectors (PPACs), surrounding 23 ^{238}U targets (overall target thickness 45 mg/cm^2) such that coincidences between the two registered fission fragments can be measured [12]. A similar multi-target array is available for ^{232}Th. Fig. 3 illustrates our expectation for the properties of the triple-humped fission barriers in ^{238}U and ^{232}Th,

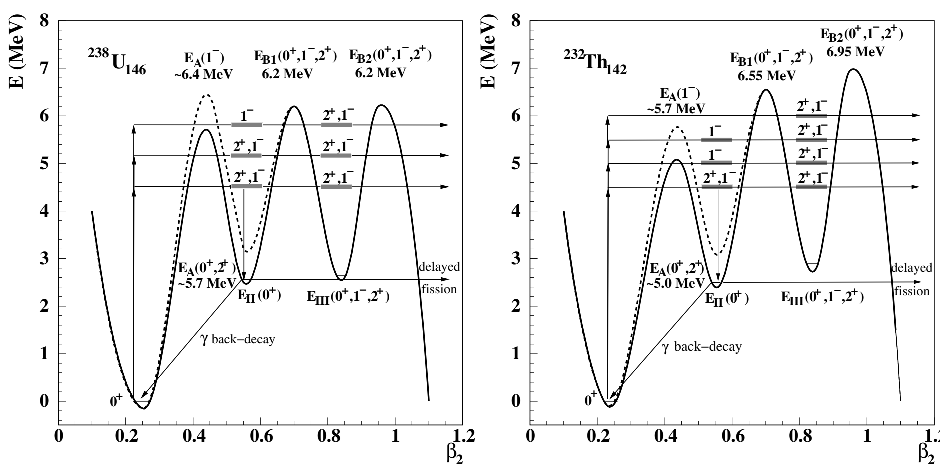

Fig. 3. Schematical view of the expected triple-humped fission barrier in ^{238}U and ^{232}Th as a function of the quadrupole deformation β_2. The solid lines show a parametrization in the harmonic model, where potential barriers and minima are described by joint parabolas. The dashed curves represent the spin-dependent barriers for dipole (1^-) and quadrupole (2^+) excitations, differing at the inner but degenerate at the middle barrier [13]. Expected transmission resonances in the various potential wells are also indicated.

respectively, that will be tested in the experiments. It is particularly interesting to note that Zhang *et al.* [14] report on the determination of the excitation energy of the ground state in the second minimum of ^{232}Th from their measurement of the photofission resonance level density. Their analysis assumed only a shallow third potential well, according to the, at the time, prevailing paradigm [15]. However, from our improved knowledge on the existence of a rather deep third minimum in this mass region we have to re-interpret the result of [14], stating that what they in fact determined was not the ground state of the second, but rather the one of the hyperdeformed third minimum. It will be particularly interesting to directly target this highly deformed ground state via γ spectroscopy and test the underlying picture of the fission barrier in high-resolution photofission experiments.

In conclusion, we state that with the novel highly-brilliant γ beams at MEGaRay and ELI-NP a new era of high-resolution photofission studies in the multiple humped fission barrier landscape of the actinide will be enabled.

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