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PHOTOFISSION OF LIGHT ACTINIDES INDUCED BY NEW GENERATION, QUASI MONOCHROMATIC, HIGHLY-INTENSE γ BEAMS

L. Csige[1], D.M. Filipescu[2], J. Gulyás[1], M.M. Günther[3], D. Habs[3], H.J. Karwowski[4], A. Krasznahorkay[1], G.C. Rich[4], M. Sin[2], P.G. Thirolf[5]

[1]Institute of Nuclear Research, Hungarian Academy of Sciences (MTA ATOMKI), PO Box 51, H-4001 Debrecen, Hungary
[2]H. Hulubei National Institute of Phys. and Nucl. Eng., Bucharest, Romania
[3]Max-Planck-Institute for Quantum Optics, D-85748 Garching, Germany
[4]Triangle Universities Nuclear Laboratory (TUNL), Durham, NC 27708, USA
[5]Ludwig-Maximilians-Universität München, D-85748 Garching, Germany

Abstract

New research facilities like HIγS2 or ELI-NP will provide within the next three years photon beams of unprecedented quality with respect to both photon flux ($10^{13}\gamma/s$) and spectral intensity ($10^4-10^6/eVs$), thus overcoming previous limitations of existing facilities by several orders of magnitude. This remarkable progress will be achieved by Compton-backscattering of an intense laser on a high-quality, relativistic electron beam. With these intense, monochromatic γ ray beams, a new era of photonuclear science begins. In the manuscript, an overview is given on the perspectives for photofission studies, and the first results of an exploratory experiment are presented. In the prototype experiment, the photofission cross section of ^{238}U was measured as a function of the γ ray energy using, for the first time, a monochromatic, high-brilliance, Compton-backscattered γ-ray beam at beam energies between E_γ=4.7 MeV and 6.0 MeV. As a next step, a novel highly-efficient, position-sensitive photofission detector array is under development. The status of the development is reported.

I. Introduction

Using highly-brilliant γ-ray beams, which will be soon available at the HIγS2 facility [1] (Durham, USA) and at ELI-NP [2] (Bucharest, Romania), a new experimental campaign on photo-nuclear physics can be envisaged to investigate extremely deformed nuclear states of the light actinides and their multiple-humped potential energy surface (PES) in a highly-selective way. Photofission measurements enable selective investigation of extremely deformed nuclear states in the light actinides and can be utilized to better understand the landscape of the PES in these nuclei. The selectivity of these measurements originates from the low and well-defined amount of angular momentum transferred during the photoabsorption process.

Most recent theoretical activities in the field also emphasize the importance of spin-selective photofission experiments in the actinide region. The validity of previous theoretical calculations [3] predicting the existence of a deep third minimum in the PES was questioned [4, 5, 6], resulting in a puzzling discrepancy with experimental findings especially in the chain of uranium isotopes.

II. Transmission resonance spectroscopy via photofission

The experimental technique of investigating extremely deformed nuclear states of the light actinides is based on the observation of the transmission resonances in the prompt fission cross section. Transmission resonances appear when directly-populated excited states in the first potential minimum overlap energetically with states either in the superdeformed (SD) 2^{nd} or hyperdeformed (HD) 3^{rd} potential minima [7, 8]. The fission decay channel thus can be expressed as a tunneling process of these gateway states through the multiple-humped fission barrier.

So far mainly light-particle induced nuclear reactions have been performed to study the transmission resonances with charged particle [9, 10], conversion electron or γ ray spectroscopy. These studies did not benefit from the same selectivity of photonuclear excitation and consequently they are complicated by statistical population of the states in the 2^{nd} and 3^{rd}

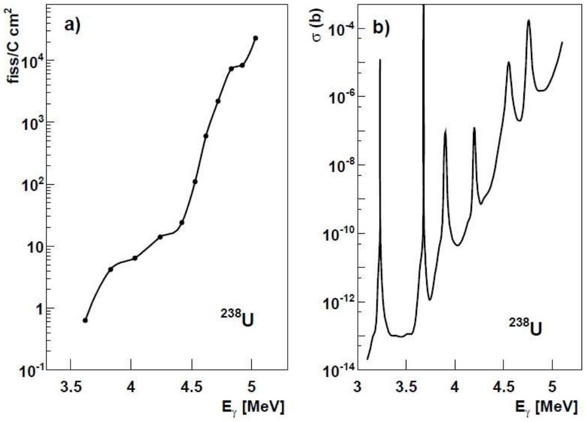

Figure 1: a) Measured photofission yield displayed as a function of the maximum bremsstrahlung energy for the photofission of ^{238}U [11] and b) the calculated photofission cross section.

minima with a very limited probability. Moreover, these measurements suffered from a dominating background from prompt fission. Contrary, by using monochromatic γ-ray beams, the states in the higher-lying minima can be populated directly with considerably increased probabilities, leading to a much suppressed background and due to the strong spin-selectivity very clean spectra can be obtained.

Until now sub-barrier photofission experiments have been performed with bremsstrahlung photons, where the fission cross section was folded with the continuous γ ray spectrum, resulting a typical effective γ bandwidth of only E/E $-$ 10^{3}). In these experiments a plateau (”isomeric shelf”) was observed in the fission cross section (Fig. 1a). With the new generation γ beams, providing a spectral flux of about $10^6\gamma/(\mathrm{eV}\ \ \mathrm{s})$ and an improved energy resolution of E 1 keV, one can aim at identifying individual vibrational resonances in the fission decay, and resolving the fine structure of the isomeric shelf (Fig. 1b).

In order to prepare for the photofission experiments at the γ beams of HIγS2 and ELI-NP, we performed an exploratory experiment on the sub-barrier photofission of ^{238}U at the γ beam of the present HIγS facility at the Duke University (Durham, US).

III. The prototype experiment: photofission of ^{238}U

The aim of our very recent experiment was to measure the ^{238}U(γ,f) cross section at deep sub-barrier energies and to search for transmission fission resonances. The experiment was performed at the HIγS facility with its Compton-backscattered γ-ray beam, having a bandwidth of E=150-200 keV and a spectral flux of about $10^2\gamma/(\mathrm{eV}\ \ \mathrm{s})$. An array of parallel plate avalanche counters, consisting of 23 electrolytically-deposited ^{238}UO$_2$ (2 mg/cm^2) targets [12], was used to measure the photofission cross section. Both fission fragments were detected in coincidence to suppress the -particle background to an extremely low level, which is required by the particularly low counting rates.

The experimental photofission cross section of ^{238}U as a function of the γ-ray energy is shown in Fig. 2a, along with the experimental data of Ref. [13], the only experiment so far measured with bremsstrahlung photons. Due to the large photon flux, the cross section data could be extended by about an order of magnitude into the deep sub-barrier region down to E_γ=4.7 MeV. A clear transmission resonance has been observed at E_γ=5.6 MeV, which is consistent with the observation of Ref. [13].

For the theoretical evaluation of the present ^{238}U photofission experimental data, we performed nuclear reaction code calculations using the EMPIRE-3.1 code [14]. The triple-humped fission barrier parameters of ^{238}U were extracted by tuning the inputs to these calculations and comparing the resulting predictions of the photofission cross section to the experimental data. For comparison, both triple- and double-humped fission barriers were used in the calculations. The experimental data of the present experiment could be reproduced dramatically better with a calculation assuming a triple-humped fission barrier than with a double-humped one. The resonance at E_γ=5.55 MeV was attributed to the HD well. The results of the experiment is presented in Ref. [15] in details.

Due to the energy spacing of the vibrational states in the HD oscillator well, which is determined by the curvature parameter of the 3 potential

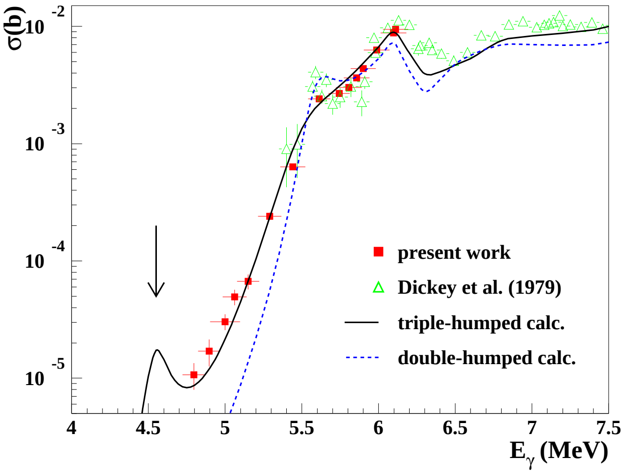

Figure 2: The measured photofission cross section of ^{238}U in the γ ray energy range of E_γ=4.7-6.0 MeV. The result of the present experiment and the experimental data of Ref. [13] are indicated by full squares and open triangles, respectively. The calculated cross sections are shown as solid and dashed lines, assuming a triple-humped and a double-humped fission barrier, respectively.

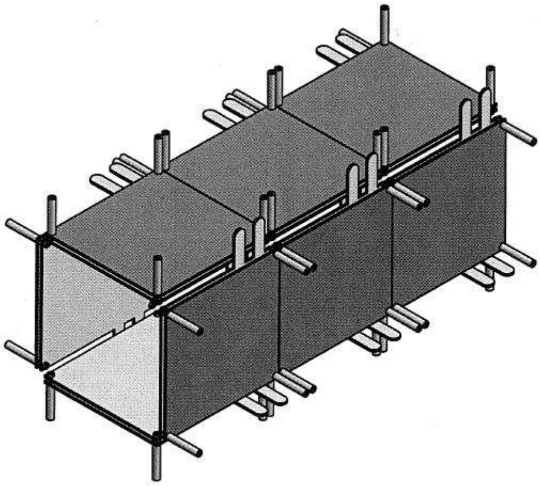

Figure 3: (Color online) Schematic view of the photofission detector array. The actinide targets are aligned along the central axis of the cube.

minimum ($\hbar$ =1.0 MeV), a further resonance should appear at E_γ=4.55 MeV. Experimental evidence for the existence of such a resonance would fully confirm our present theoretical interpretation. Thus, it is crucial to improve the γ-ray beam energy bandwidth and the energy density of data points (requiring a higher γ-ray beam intensity) in order to explore a full set of deep sub-barrier fission resonances and to obtain conclusive evidence for the HD nature of the fission barrier of ^{238}U. It is also highly important to measure the fission fragment angular distribution to identify the total angular momentum of the decaying compound state.

IV. Development of a novel photofission detector-array

Fission fragment angular distribution measurements (in photofission) request a multi-target, position sensitive detector array, which is under development presently at MTA ATOMKI (Debrecen, Hungary). The array consist of 12 units of position sensitive gas detector with dimensions of 10x10 cm and based on the state-of-the-art THick Gasous Electron Multiplier (THGEM) technology [16] (Fig. 3.

The THGEM is a robust, simple to manufacture, high-gain, gaseous electron multiplier. The operation is based on gas multiplication within small, sub-millimeter to millimeter diameter holes drilled in standard double-face Cu-clad printed circuit boards (PCB). The hole structure of the THGEM together with a segmented readout electrode provides a true-pixelated radiation localization. The electron multiplication of the THGEM is based on the large potential difference between the two sides of the board resulting in a strong dipole field within the holes. Electrons, deposited by ionizing radiation in a conversion region above the THGEM, are focused into the holes by the dispersed electric field. Then the electrons are multiplied within the holes under the high electric field (25-50 kV/cm). A small fraction of the resulting avalanche electrons are collected on a bottom electrode, while the significant part is transferred to a collecting anode or to a second multiplier element. Each hole acts as an independent multiplier. Depending on the filling gas a multiplication factor of 10 can be achieved.

At the low-pressure operation mode (typically 10 mbar), the signals are exceptionally fast, having a rise time of 1-2 ns. A position resolution of 2 mm can be achieved by using a segmented anode with 1-2 mm wide anode pads. In the present design, the detector covers almost a full solid angle (80% of 4) and has an intrinsic angular resolution of 5 degrees. The background sensitivity and the radiation damage are negligible, however, the extremely low counting rates in photofission experiments at deep sub-barrier energies require sufficient particle discrimination. This goal can be achieved by the coincident detection of both fission fragments.

The prototype detector unit was characterized by using a ^{2} ^{2}Cf fission source. Figure 4 shows a typical two-dimensional position spectrum of the fission fragments emitted by the source. In these test measurements an intrinsic detector efficiency of 85% could be determined. After the highly efficient operation of the prototye unit was demonstrated, the production of the full array including the anodes and the support frame has been initiated. The electrolytically-deposited actinide targets will be produced at the radioactive target laboratory of the University of Mainz with a thickness of 2 mg/cm^2.

The foreseen unprecedented sub-millimeter γ beam spot size allows to develop considerably more compact photofission detectors than those of be-

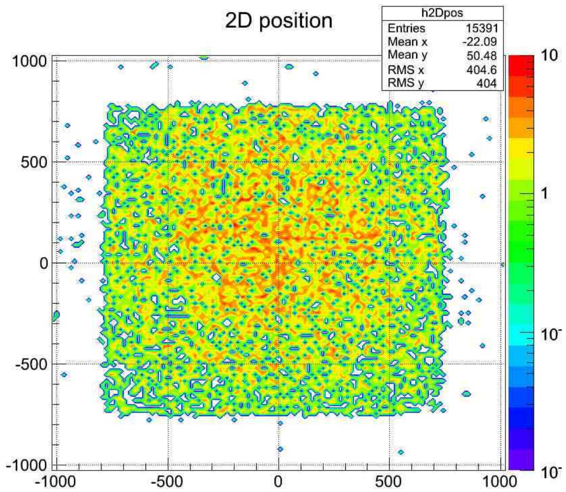

Figure 4: (Color online) Two-dimensional position information of the fission fragments emitted by a $^{2\ 2}$Cf fission source.

fore when only bremsstrahlung γ sources were available with a beam spot diameter of 4-5 cm. Furthermore, due to the small diameter of the targets, highly-radioactive target materials (e.g. ^{23} Pu) can be used without encountering radiation safety problems, which was not possible before. The well-focused γ beam also defines a distinct fission position, so a remarkably improved angular resolution can be achieved compared to previous bremsstrahlung photofission experiments.

V. Outlook

The experiment presented above can be considered as a first step towards the photo-induced nuclear physics at the new facilities HIγS2 and ELI-NP, where 6 orders of magnitude higher beam intensities are expected and new techniques will be developed to narrow the γ beam bandwidth down to $E/E \quad 10^{-4}$. This way the γ resolution could be matched to the natural width of the resonances, so atomic background from Compton scattering and pair creation could be avoided. This excellent bandwidth can be exploited to resolve the fine structure and the level densities of transmission resonances and to identify the individual class-II (SD) and class-III (HD) states with spin , value, and parity, eventually even addressing some class-I states in the first minimum of the PES.

One of our long term goals will be to determine the spin dependent inner barrier heights of ^{232}Th for dipole and quadrupole excitations E (1^{-}) and E $(2$ $)$, respectively, and to determine the depth E of the second minimum from the class-II states via level density arguments. Once E and E is known, the lifetime of the so far unobserved fission isomer in ^{232}Th can be estimated for the first time.

The γ decay in the second minimum of thorium isotopes with its predominant back-decay to the first minimum can also be studied with high resolution. Adding up the energies of the γ cascade results in the resonance energy. As a result, it will become possible to measure the isomeric excitation energies with a resolution of 10^{-3}. In addition, identifying the multiphonon -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. Measurements of the ground state of the 3 minimum via its γ decay will also be enabled. On the other hand, as a result of the strong spin selectivity of the photo-induced reactions, the states in the 2 and 3 minimum can be populated with much larger intensities compared to former methods (light-ion induced reactions). Together with the enhanced E1 strengths in the second and third potential well due to the large static dipole moment (resulting in γ decay times comparable to prompt fission), a detailed γ spectroscopy in these minima will be enabled for the first time.

VI. Summary

As a conclusion, the measurement of the photofission cross section in the deep sub-barrier energy region is a crucial step towards a reliable characterization of the PES, including unambiguous determination of the double- or triple-humped nature of the surface. Next-generation Compton-back-scattering γ-ray sources, such as HIγS2 and ELI-NP, are anticipated to provide beams with spectral fluxes of $10^{6}\gamma/$ eV s and energy resolution of E 1keV, far superior to those currently available at HIγS. These next-generation γ-ray sources are expected to allow preferential population and identification of vibrational resonances in the photofission cross section and ultimately to enable observation of the fine structure in the isomeric shelf as well as unambiguous determination of the structure of the PES. This may open the perspective towards a new era of photofission studies.

As a first, preparatory step, we measured the photofission cross section of ^{238}U in the γ-ray energy region of E=4.7-6.0 MeV with the monochromatic, high-brilliance, Compton-backscattered γ-ray beam of the HIγS facility. With the significantly higher intensity of the beam, when comparing to a tagged-photon facility, the cross section could be measured at deep sub-barrier energies. EMPIRE-3.1 reaction code calculations were performed to extract the fission barrier parameters of ^{238}U. Our present results on the fission barrier of ^{238}U support a deep 3 minimum. Indications of predicted resonance structures have also been observed, however, with moderate amplitudes. The results indicate the need for further investigations at lower γ-ray energies and using smaller-bandwidth, higher-intensity γ-ray beams. In such measurements special type of fission detectors need to be applied. Thus, a multi-target, position sensitive photofission detector array is under development at MTA Atomki based on the novel THGEM technology.

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References

[1] http://www.tunl.duke.edu/higs2.php, (2012).

[2] http://www.eli-np.ro/, (2011).

[3] S. Cwiok et al., Physics Letters B **322**, 304 (1994).

[4] T. Ichikawa et al., Phys. Rev. C **87**, 44326 (2013).

[5] P. Jachimowicz et al., Phys. Rev. C **87**, 44308 (2013).

[6] J.D. McDonnell et al., Phys. Rev. C **87**, 44327 (2013).

[7] P.G. Thirolf and D. Habs, Prog. Part. Nucl. Phys. **49**, 325 (2002).

[8] A. Krasznahorkay, in: Handbook of Nuclear Chemistry, Springer Verlag, 2011, p. 281.

[9] A. Krasznahorkay *et al.*, Phys. Lett. **B461**, 15 (1999).

[10] L. Csige *et al.*, Phys. Rev. C **80**, 011301 (2009).

[11] G. Bellia et al., Z. Phys. **A314**, 43 (1983).

[12] J. Drexler et al., Nucl. Instrum. Methods **220**, 409 (1984).

[13] P.A. Dickey and P. Axel, Phys. Rev. Lett. **35**, 501 (1975).

[14] M. Herman et al., Nucl. Data Sheets **108**, 2655 (2007).

[15] L. Csige et al., Phys. Rev. C **87**, 044321 (2013).

[16] R. Chechik et al., Nucl. Instr. and Meth. A **535**, 303 (2004).

[17] H.X. Zhang et al., Phys. Rev. C **34**, 1397 (1986).