HIGH-RESOLUTION STUDIES OF ISOMERIC STATES IN ^{236}U WITH THE nu-Ball2 SPECTROMETER*

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Received 13 December 2024, accepted 8 March 2025, published online 10 April 2025

* Presented at the 57[th] Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 25 August–1 September, 2024.

Fission shape isomers (SI) are poorly understood metastable states characterized by a second super-deformed potential energy minimum coexisting with normally-deformed states in the low-spin regime. Although many such isomers have been observed in the actinide region, our understanding of the states of the second minimum remains very limited. For most SIs, the only available information is their half-life, determined via their exclusive decay mode, delayed fission. However, the interesting possibility of a competing branch of γ-back decay towards normally-deformed states opens up as the number of protons decreases and the fission barrier becomes harder to penetrate, uranium isotopes being the heaviest candidates. In this context, two experiments were performed to study ^{236f}U using the nu-Ball2/PARIS spectrometer at the ALTO facility of IJCLab. The nu-Ball2 setup consists of 24 High Purity Germanium (HPGe) Clovers and 64 phoswiches ($LaBr_3$/NaI) from the PARIS Collaboration are added to cover more than 90% of the total solid angle. Additionally, a Double-sided Silicon Stripped Detector (DSSD) was used to measure the energy of outgoing light-charged particles. The state-of-the-art fully digital FASTER electronics allowed triggerless data acquisition at high data rates. The selectivity of this setup enabled us to probe rare decays with sub-microbarn cross sections.

DOI:10.5506/APhysPolBSupp.18.2-A25

1. Introduction

Shape isomers (SI) in actinides are poorly understood metastable states characterized by a super-deformed shape, coexisting with normally-deformed states in the low-spin regime. Their existence is predicted by the double-humped fission barrier, initially identified by the micro–macro method calculations [1]. This method incorporates the averaged Nilsson potentials into the liquid-drop fission barrier, revealing two distinct potential wells. The first and deeper one, located at lower deformation with a $1.33:1$ prolate ellipsoid axis ratio, leads to the permanent deformation of the ground state of actinides. The second well corresponds to more elongated shapes with an axis ratio of $2:1$ and lies 2 to 4 MeV above the first well. It leads to the formation of super-deformed states, known as class II states. The super-deformed ground state is meta-stable and fissions spontaneously, making it a shape isomers. Due to this particularity, actinides SIs are also often referred to as fission isomers.

Although many such SIs have been observed in the actinide region, our understanding of the states in the second minimum remains very limited. For most SIs, the only available information is their half-life, determined via their unique decay mode — spontaneous fission. However, an interesting possibility of a competing branch of γ-back decay towards normally-deformed states opens up as the number of protons decreases, because the fission barrier becomes harder to penetrate [2]. This is also supported by the small amount of fission isomers found below the Pu isotopes and their low population cross sections that could be a result of this back decay dominating over spontaneous fission, to which fission detectors are not sensitive. However, the nature of this γ-back decay remains poorly understood [3]. Since the first experiments several decades ago, experimental techniques and nuclear facilities have improved significantly, hence, there has been a renewed interest in study of the γ-back decay [4, 5].

The γ-back decay has been observed in both ^{236f}U and ^{238f}U in the past, in which fission isomers have also been detected. While the various experiments on ^{238f}U are contradictory [3], the ^{236f}U case shows very solid results [6] and has been chosen to be re-investigated using the high-resolution spectroscopy capabilities of the nu-Ball2 hybrid spectrometer. In order to assess the capabilities of this setup, an extensive study of the normally-deformed $K^\pi = 4^-$ isomer with an excitation energy of $E_x = 1052$ keV and a half-life of $t_{1/2} \approx 101$ ns [7] has also been performed.

2. The experimental setup

The experiment took place during the nu-Ball2 experimental campaign in 2023 at the ALTO facility of IJCLab [8]. A deuteron beam with $E_{\mathrm{beam}} =$ 11 MeV from the 15 MV Tandem was pulsed into 2 ns-wide bunches with a 200 ns repetition period. The beam impinged a 4 mg/cm^{-1} highly-enriched ^{235}U oxide target, electroplated onto a thin (1 μm) Al backing to populate the ^{236m}U metastable states through the (d,p) reaction.

The γ-rays emitted in the transitions populating these isomeric states, as well as their later decay transitions, were detected by 24 Compton-suppressed HPGe Clover detectors of the Gammapool consortium and 64 $LaBr_3$ (or $CeBr_3$)/NaI phoswiches of the PARIS Collaboration [9] (see Fig. 1). In addition, a Double-sided Stripped Silicon Detector (DSSD) [10, 11] placed in the reaction chamber at backward angles was used to tag and measure the energy of outgoing light-charged particles. Each detector channel was managed by the state-of-the-art fully digital FASTER electronics [12] that allowed for triggerless data acquisition at high data rates.

The pulsation of the beam allowed for a clear separation between prompt and delayed γ-ray emissions that allows for studying the decay of states with lifetimes between a few nanoseconds and a few hundred nanoseconds. Delayed γ-rays are defined as found in the time window $[+60; +180]$ ns relative to the beam reference time, while the prompt time window depends on the detector type, due to different time resolutions: $[-10; +10]$ ns for Clovers (HPGe and BGO) and $[-5; +5]$ ns for PARIS phoswitches ($LaBr_3$ and NaI). No time condition is set for the DSSD, because every DSSD hit is supposed to be prompt (the dark current has been estimated to be less

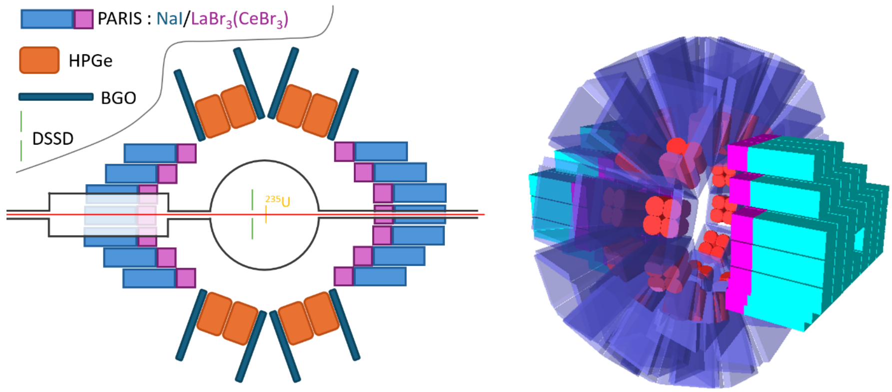

Fig. 1. Left: Schematics of the setup, not to scale. Right: 3D representation from the Geant4 simulation viewer, displaying only the γ-sensitive materials. Two rings of Compton-suppressed High Purity Germanium (HPGe) Clover detectors, each made of four germanium crystals and surrounded by BGO crystals, are placed around the reaction chamber in which a DSSD is placed to detect the light particles emitted in the reactions. Two "walls" of PARIS phoswich detectors are placed in front and back angles to cover in total over 90% of the solid angle.

than 1‰). The selectivity of such a setup comes from the combination of the high resolution of the HPGe detectors, the high-energy efficiency of the PARIS detectors, a charged particle selection, and gamma calorimetry and multiplicity in both prompt and delayed time windows.

3. Data analysis

The resulting prompt and delayed spectra are highly complex due to the unwanted reactions on oxygen and aluminum that are present in the target, prompt fission fragment decays, and fission fragment isomeric and beta decays. Additionally, a significant source of unwanted reactions originated from neutron-induced interactions in the structural and detector materials, neutrons produced in abundance from fission, and break-up of the deuteron beam in the target. Hence, various event conditions were necessary to help select the transitions of interest and reduce the unwanted background. Conditioned prompt and delayed γ–γ matrices are filled and background-subtracted, then used to characterize these highly-complex spectra and identify the hundreds of both intense and weak γ-ray transitions.

One state in ^{236}U is particularly strongly populated in both prompt and isomeric decays: the vibrational band head $K, J^\pi = 0, 1^-$ at $E_{\text{level}} =$ 688 keV, decaying via two transitions emitting γ-rays of energies $E_\gamma =$ 642 keV and $E_\gamma = 688$ keV, with intensities of $I(642) \approx 80\%$ and $I(688) \approx$

20%, respectively. In the reaction used in this work, the $E_\gamma = 642$ keV γ-ray intensity represents 34% of the total decay intensity of ^{236}U. Therefore, it can be used as a good reference for its population since the nu-Ball2 HPGe photo-peak absolute efficiency at this energy is well measured (5.8%) from calibration sources.

The delayed $E_\gamma = 642$ keV γ-ray line represents more than half of the intensity of the decay of the K-isomer (56%)[1]. Therefore, it can be used as a probe to assess the selectivity of the various conditions that were applied to select events most likely to have led to its formation. An example of such selection can be seen in Fig. 2: for each event, a particle must be detected, with at least one prompt γ-ray in either a Clover or a PARIS detector, while the prompt γ calorimetry must not exceed 5 MeV, and the prompt and delayed γ multiplicities must not exceed 4 each.

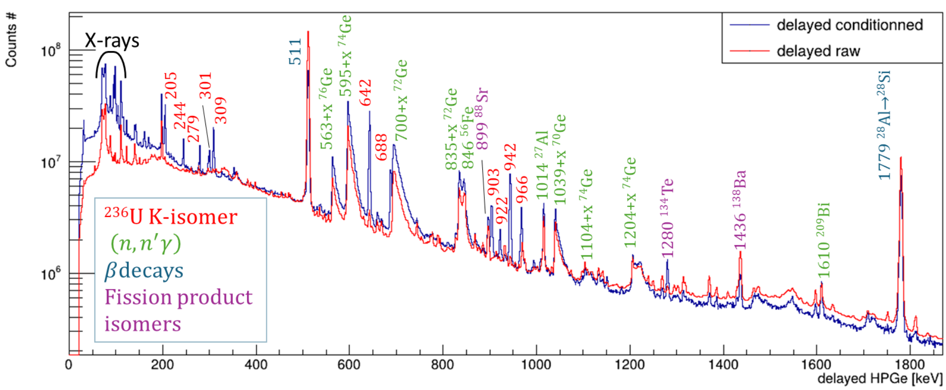

Fig. 2. (Color online) Delayed HPGe spectra, with normalized log Y axis, before (red/gray) and after (blue/dark gray) the conditions selection. The ^{236m}U K-isomer decay lines are enhanced with respect to most other decays by the use of the event-by-event conditions explained in the text: their peak-to-background ratios are increased by approximately a factor 10. Note that other lines are also enhanced, such as the ^{134}Te isomeric decay at $E_\gamma = 1280$ keV, meaning that this selection is also matching the conditions leading to the formation of this $t_{1/2} \approx 164$ ns fission product isomer.

This selection has a coupled effect: the intensities of the γ-ray lines originating from unwanted reactions are reduced, along with their associated Compton background, which increases the peak-over-background ratios of

[1] The adopted levels [7] do not report such intensity. However, the adopted decay of the $E_{\rm level} = 744$ keV is in contradiction with our measured $E_\gamma = 642$ keV intensity: the unobserved highly-converted $E_\gamma = 56.6$ keV transition must feed the $E_{\rm level} = 687.5$ keV level with nearly 100% intensity for the $E_\gamma = 642$ keV to be seen with 56% intensity. This is also supported by the ^{236}Pa β^- decay study [13].

the transitions of interest. This leads to an increased significance of the $E_\gamma = 642$ keV peak, as well as all other peaks associated with the isomeric decay of ^{236m}U (both K-isomer and shape isomer). These conditions are also very close to those leading to the formation of the SI and should increase the significance of the associated γ-back decay. However, because the excitation energy of the SI is 1.5 MeV higher, slight corrections to the calorimetry and multiplicity conditions are applied to maximize the selectivity to the γ-back decay.

The details of decays from the K-isomer, its populating transitions, as well as the search for transitions de-exciting the SI will be the subject of a future publication.

4. Summary

In the present experiment on ^{236}U, the selectivity of the nu-Ball2 setup has been assessed using the intense isomeric decay of the normally-deformed $E_x = 1052$ keV K-isomer, populated by the $^{235}\mathrm{U}(d,p)^{236m}\mathrm{U}$ reaction. The present work responds to a renewed interest in shape isomers in actinide nuclei and will help facilitate possible future experiments with powerful spectrometers such as AGATA.

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