γ-Spectroscopy of the Odd-N Fission Isomers in ^{237f}Pu ◇

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Fission barriers can be calculated more precisely if the single-particle level structure is known at the Fermi surface, however, so far not one single-particle state in strongly-deformed heavy elements has been identified. The identification of Nilsson orbitals will provide an important input for the validation and improvement of theoretical nuclear models and will lead to improved predictions for fission barriers.While so far spectroscopic studies of fission isomers concentrated on even-even nuclei, high-resolution γ spectroscopy of odd-N fission isomers will allow to identify Nilsson orbitals in heavy actinide nuclei [2].

As the first case ever studied for odd-N nuclei in the second potential minimum, the fission isomers in ^{237}Pu ($t_{1/2}$ = 110ns/1.1 μs) were studied using the ^{235}U(α,2n) reaction with a pulsed α beam (E_α =24 MeV, pulse distance 400 ns) from the Cologne Tandem accelerator. A self-supporting thick metallic ^{235}U target (3.7 mg/cm^2) was used, where the ^{237}Pu reaction products were stopped and fission products were emitted in opposite directions. The rare γ-rays from the second potential well in delayed coincidence with fission products were measured with the MINIBALL spectrometer. Due to the small population cross section of about 2 μb a large solid angle coverage both for the γ-rays as well as for the fission fragments was required. A very compact 4π parallel plate detector array (diameter ca. 15 cm) was used for the fission fragment detection, allowing for a discrimination between the dominant prompt fission products and the rare isomeric fission events. In three weeks beam time ≈ 20000 delayed fission events were recorded [3].

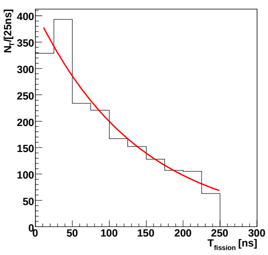

Fig. 1: An example of an individual γ - transition half life. Shown is the measured time difference between the beam pulse and the detected fission fragments gatted on the 209 keV γ - transition. An exponential fit to the decay curve results in a half life of 106 [10]ns, thus qualifying this transition as originating from the short - lived fission isomer.

Following the calibration, event building and subtraction of random background of the experimental data, a two - component exponential fit to the decay curve of the measured fission fragments in coincidence with the α-beam pulse was performed, the two isomeric lifetimes were identified as $t_{1/2}$ = 115[20] ns and 1.12[80] μs, confirming the population of states in the superdeformed second minimum. Furthermore 170 γ-transitions were identified, the individual lifetimes of these γ - tranitions was fitted, Fig. 1 shows the time spectrum of fission fragments, for the 209 keV transition, measured with respect to the prompt α beam pulse. An exponential fit applied to the decay curve in the delayed time region exhibits a half-life of 106[10] ns. The γ - spectrum was disentangled into the two contributions from the short - lived ($t_{1/2}$ = 115 ns) and long - lived ($t_1/2$ = 1.12 μs) fission isomers, for which so far ground state spins of 5/2 and 11/2, respectively were tentatively assigned in literature [5].

Superdeformed fission isomers are well - known to be rigid rotors strictly following the rotational pattern of $E_\gamma = J(J+1)\frac{\hbar^2}{2\theta}$ and $E_{J+1} - E_J = 2(J+1)\frac{\hbar^2}{2\theta}$ (where E denotes the transition energy, J the spin of the state and $\frac{\hbar^2}{2\theta}$ the rotational parameter) [2]. Amongst the multitude of transitions visible in the γ - ray spectra for the two fission isomers, rotational band structures, based on a superdeforemd rotational parameter (ca. 3.3 keV) were searched. Using a peak correlation algorithm 9 rotational bands were identified. For the low - spin isomer 5 bands with band head spins of 3/2 and 5/2 (see Figure 5 a.) were discovered, for the high - spin isomer, band head spins of 9/2 and 11/2 were found (see Figure 5 b.).

The resulting moments of inertia are shown in Figure 2 together with those for the superdeformed shape isomer in ^{240}Pu, the moments of inertia exhibit comparable spin dependent variations as already found in ^{240}Pu.

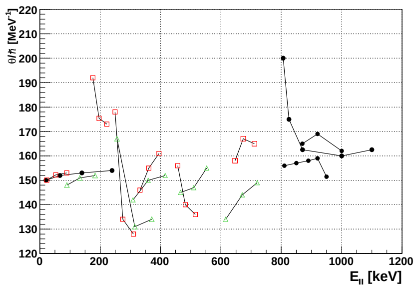

Fig. 2: Moments of inertia of rotational bands in the second minimum of ^{240}Pu (●) and ^{237}Pu (□ for the 115 ns isomer and △ for the 1120 ns isomer) as a function of the excitation energy $E^2{}_{II}$ with respect to the ground state in the second minimum. The spin - dependent moments of inertia for the rotational bands derived in ^{237f}Pu exhibit comparable variations with the excitation energy as found in ^{240f}Pu

Following the identification of rotational bands, using a Ritz combinatorial technique level schemes, for both isomers, could be derived. In a first step isomeric ground state bands were constructed using a rigid - rotor pattern for a superdeformed rotational parameter of ca. 3.3 keV. As the isomers preferably deexcite via in - band transitions to their respective ground states, from which they are depopulated into the ground state rotational band, the ground state decays of the rotational band heads will exhibit the largest decay intensities. This feature was indeed identified in the isomeric γ spectra (see Fig. 5 a. and 5 b.). Thereby the isomeric ground state spins of 5/2 for the short - lived and 9/2 for the long - lived isomer, respectively, could be identified. γ transitions not only from the excited rotational

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bands to the ground state band but also inter - band transitions between excited rotational bands were found for both isomers leading to an even more conclusive picture.

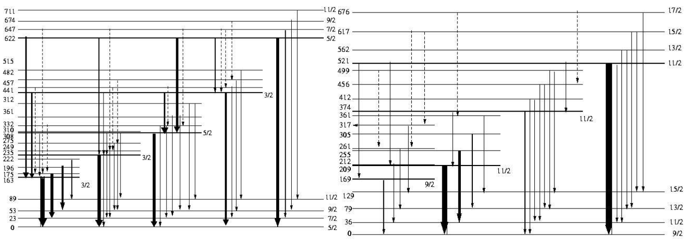

Fig. 3: a.) The decay scheme deduced for the 115 ns isomer. The ground state spin of the low spin isomer was found to be 5/2, as no transitions to a 3/2 or 7/2 ground state were discovered. b.) The decay scheme deduced for the 1120 ns isomer. The ground state spin of the low spin isomer was found to be 5/2, as no transitions to a 7/2 or 11/2 ground state were discovered.

While the relative energetic position of the short - and long - lived isomeric band heads previously were known only with a very large error margin to 300 ± 150 keV, our detailed γ - ray spectroscopy allows to search for a decay pattern that links the long - lived high - spin to the short - lived low - spin fission isomer. The fact of the mere existence of a long - lived fission isomer with a ground state spin of 9/2 points to an excitation energy not too far above the 9/2 state of the low - spin isomer, otherwise fission would be hindered by a strong direct γ - decay branch. Indeed our γ spectrum reveal a series of 4 transitions linking the band heads of the 1.12 μs isomer to the g.s. rotational band for an excitation energy of 54 keV of the 9/2 ground state of the 1.12 μs isomer. Moreover, 4 transitions can be found depopulating the rotational bands of the low - spin isomer into the ground state of the high - spin isomer.It is rather this interwoven consistent network of linking transitions than the obviously limited statistical relevance of the individual transitions that endorses the credibility of this new single - particle picture in the second minimum. Modern theoretical single - particle calculations are presently being performed [4] that will allow to correlate our level scheme with Nilsson single - particle orbitals and thus lead to their first identification in extremely deformed heavy nuclei.

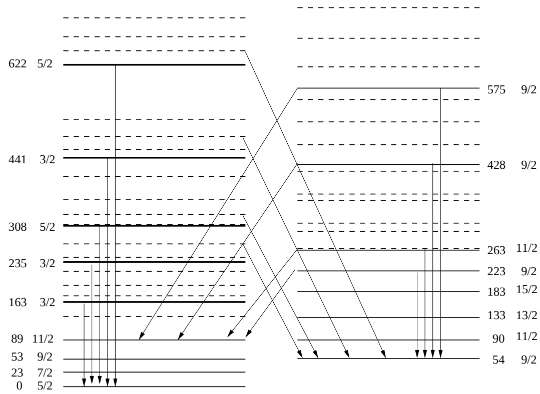

Fig. 4: Level scheme of the second minimum of ^{237}Pu. Indicated are transitions from the low spin isomer to the high spin isomer and vice versa, pinpointing the ground state of the high spin isomer to 54 keV.

In a similar way ^{239}Pu will be studied via the ^{238}U(α, 3n) reaction, where conversion electron spectroscopy in the second minimum has already been performed [1]. Combined with the identified two-quasi-particle bands in ^{240}Pu [2] a rather detailed picture should emerge around the magic neutron number N=146.

References

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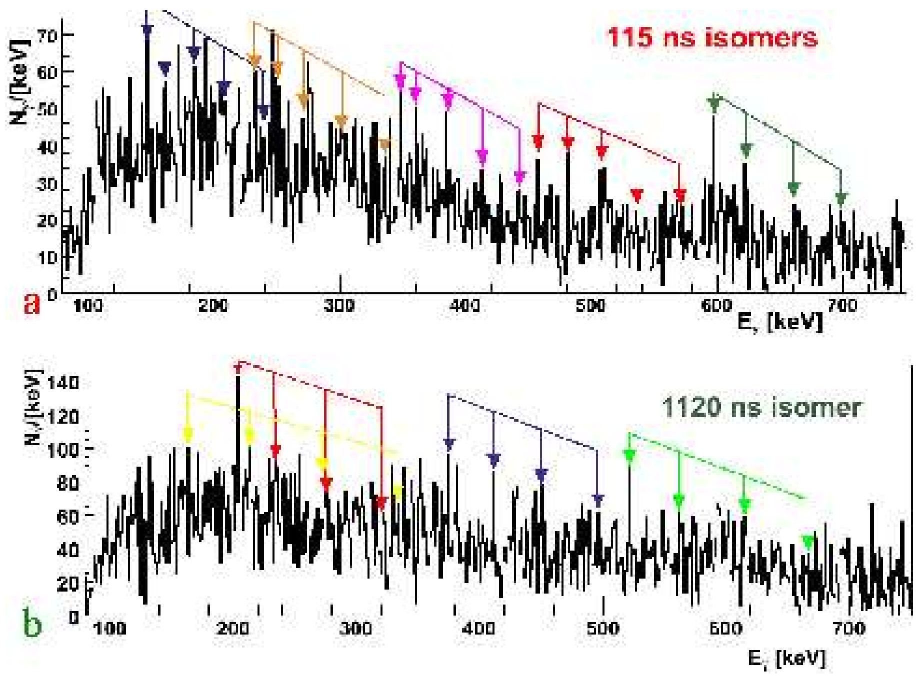

Fig. 5: a.) Energy spectra of γ - rays in coincidence with isomeric fission decay from the 115 ns isomer. Indicated are 5 rotational bands with spin assignments for the band heads of 3/2 and 5/2, the moments of inertia indicate a superdeformed configuration. b.) Energy spectra of γ - rays in coincidence with isomeric fission decay from the 115 ns isomer. Indicated are 4 rotational bands with spin assignments for the band heads of 9/2 and 11/2.