Search for a new Picosecond Fission Isomer in ^{234}U

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The island of fission isomers [1,2] is limited for e-e nuclei and high Z-values by the very short-lived ps-isomers of the Cm isotopes. For low Z values only the isomers with half-lives of 116 ns in ^{236}U and in ^{238}U with 195 ns are known. Their half-lives are predominantly determined by the γ back-decay through the inner barrier. From theory [3] a lowering of the inner barrier is expected for more neutron-deficient isotopes or lower Z-values. At the same time an increase of the excitation energy of the isomer occurs. Both effects increase the penetrability of the inner barrier and lead to the prediction of much shorter half-lives in this region. We therefore started a search for picosecond fission isomers at the lower Z-boundary of the island of fission isomers, resulting in experimental evidence for a new fission isomer in ^{234}U with a half-life of about 170 ps. ^{234}U is of special interest within the picture of the triple-humped fission barrier. Fig. 1 schematically shows our present picture of the triple-humped fission barrier of ^{234}U.

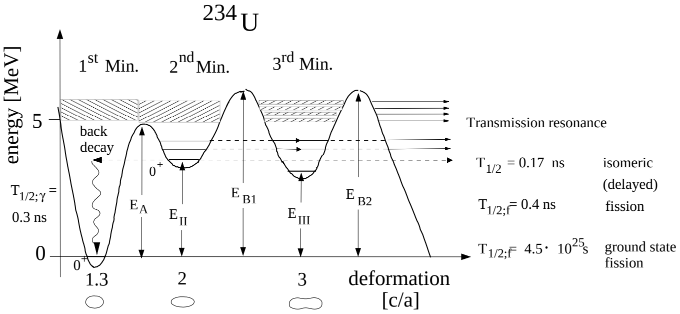

Fig. 1: Potential energy surface as a function of deformation for ^{234}U. The appearance of the triple-humped fission barrier gives rise to the existence of a superdeformed fission isomer with excitation energy E_{II} and a hyperdeformed third minimum with excitation energy E_{III}.

The shape isomer with the excitation energy E_{II} will partially decay by γ back-decay, tunneling through the inner barrier A. The inner fission barrier is characterized by its height E_A and a width characterized by the curvature energy $\hbar\omega_A$, assuming a parabolic shape. The shape isomer also decays by tunneling through the outer barrier B, which is split into two barriers B1 and B2 with the third minimum E_{III} inbetween. This third minimum has been observed in fission transmission resonances [5], but it is too short-lived ($T_{1/2} \leq 1$ fs) for an observation in delayed decays. Within error bars the depth of the second and third minimum is comparable. It may even be the case, as shown in Fig. 1, that the third minimum is deeper than the second minimum. For higher excitation energies transmission resonances in the third well occur, while for lower excitation energies transmission resonances in the second minimum can appear, which decay by tunneling through the double-humped outer barrier without meeting a resonant state in the third minimum. Extrapolating the height of the inner and outer barrier from ^{236}U [4] with the dependence from the theoretical predictions by Howard et al. [3], one obtains $E_A \approx 4.6$ MeV and $E_B \approx 5.8$ MeV for ^{234}U. A linear extrapolation of the fission isomer excitation energy E_{II} from ^{238}U and ^{236}U gives $E_{II} \approx 3.1$ MeV. With these energies a partial fission half-life of 1.6 ns and a γ back-decay half-life of 1.6 ns are predicted, in good agreement with the experimental upper limits of 2 ns [6]. The increased isomer excitation energy leads to much shorter half-lives for the γ back-decay and the fission mode. Since the split outer barrier B is about twice as thick as the inner barrier A, the branching ratio shifts towards fission and total half-lives below 1 ns are predicted. This explains why earlier searches for this isomer in the ns-range were unsuccessful [7]. We therefore performed an experiment, searching for the fission isomer half-life in the time region between 5 ps and 30 ns with a special recoil distance projection method [8], which is explained by the schematical picture of Fig. 2.

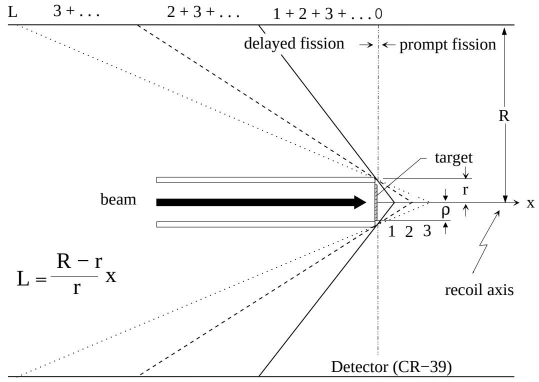

Fig. 2: Schematic picture of the projection method introduced by Metag et al. [8] (see text).

Isomers decay at different distances x in front of the target into two fission fragments, which can reach the backward hemisphere with the detectors. Via the enlargement factor P =(R-r)/r short decay lengths x along the beam axis become enlarged lengths L on the detector plates. The radius r of the projection edge and the radius R, where the detector plates are mounted, determine the projection factor P. In order to convert decay lengths into fission isomer half-lives we measured at the same bombarding energy the known 3.8 ns fission isomer of ^{240}Pu in the ^{238}U(α,2n) reaction. These isomers within 3% have the same recoil velocity distribution as the ^{234}U fission isomers from the ^{232}Th(α,2n) reaction. Since fission isomers which have travelled further away from the target can still give contributions to detector areas close to the projection edge of prompt events on the detector plates, the fission fragment distributions represent integral yield distributions, which still have the same exponential decay length. The deviations from the exponential behaviour due to different efficiencies are rather small [8]. Due to the shielding of the detector plates by the target area, the detection efficiency $\epsilon \propto \frac{\tau}{r}$ is reduced proportional to the lifetime τ for short half-lives. Since all evaluations are done relative to ^{240f}Pu, absolute fission cross sections can also be determined.

30 μg/cm^2 oxide targets of ^{232}Th and ^{238}U were bombarded for typically 6 hours with 22-26 MeV α-particle beams (beam current about 150 nAmp). The (α,2n) reaction was used to populate the fission isomers of ^{234}U and ^{240}Pu. In our exploratory experiment fission fragments

were detected using CR-39 plastic nuclear track detectors (width: 5 cm, length: 10 cm). The detector plates were arranged cylindrically around the target, parallel to the beam, covering mainly the upstream hemisphere. The closest inner radius of the six detector plates forming a hexagon was 44 mm. The detector plates started 3 mm in front of the target in order to also register the downstream prompt fission. Specially designed plunger targets were used [8]. The outer tube, carrying the Ni target backing foil had a radius r of 1.4 mm. An inner tube was used to stretch the target, reaching a very flat surface. Only a target spot with 1.1 mm radius ρ was covered with ^{238}U or ^{232}Th target material. The radii of the target arrangement were minimized in order to reduce the shielding of fission fragments decaying in a short distance in front of the target.
In order to calibrate the recoil velocity of the fission isomers and the efficiency of detecting the fission fragments, in parallel the measurement of the known 3.8$\pm$0.3 ns fission isomer in ^{240}Pu with a known production cross section [10] was performed. After the irradiation the CR39 detector plates were etched in a six-molar NaOH at 60^{o}C for $\approx$ 220 minutes. For track counting an automated track counting system, developped by the University of Siegen, was used [11]. The system consists of a high-precision microscope with an autofocus, a positioning stage and a CCD-camera. The camera and the positioning stage are coupled to a computer with a special pattern recognition software. For the analysis of the nuclear tracks the program SAMAICA version 2.2.0 [12] was used, which analyses the video images and searches for ion tracks. To each recognized track an ellipse is fitted and a number of parameters is stored such as position, semi-axis, angle, enclosed area and central brightness. Afterwards the program moves the microscope by one image and the process is repeated until the whole track detector is scanned. For a 10 cm x 5 cm plate this typically takes 20-30 hours at a 50-fold magnification.

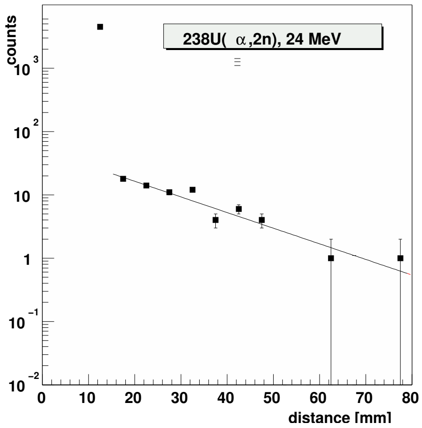

Fig. 3: Fission yield for the reaction ^{238}U(α,2n) for 24 MeV α particles. The decay of the 3.8 ns fission isomer of ^{240}Pu is used to convert the length scale along the detector plates into a decay time.

Fig. 3 shows the observed fission tracks along the CR-39 plates when a ^{238}U target was irradiated with 24 MeV α-particles. In the ^{238}U(α,2n)^{240}Pu reaction the 3.8 ns fission isomer of ^{240}Pu is produced with a maximum cross section of 11 μb for 24 MeV α-particles [10]. Fig. 4 shows the fission tracks when irradiating ^{232}Th with 24 MeV (a) and 26 MeV α-particles (b). The delayed tracks correspond to a fission isomer in ^{234}U with a half-life of (170$\pm$60) ps. Here we converted the length scale of the track detector into a time scale using the data of the 3.8 ns ^{240}Pu of Fig. 3.

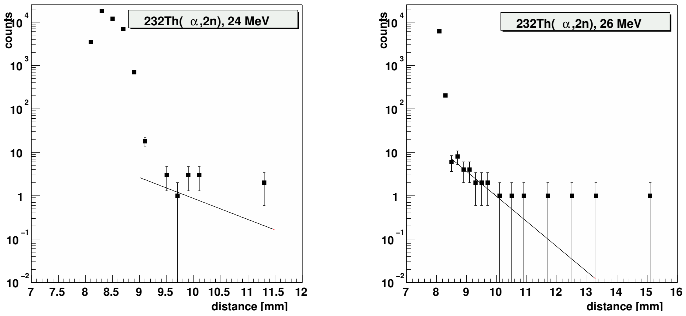

Fig. 4: Fission yield for the reaction ^{232}Th(α,2n) for 24 MeV and 26 MeV α particles. Behind the prompt fission edge the decay of a fission isomer with a half-life of 170 $\pm$60 ps is observed.

Fig. 5 shows the measured excitation functions of the fission isomers ^{234f}U and ^{240f}Pu. From the known excitation energy of the fission isomer in ^{240}Pu of (2.48$\pm$0.2) MeV and the shift between the two excitations functions of 1.3$\pm$0.5 MeV the excitation energy of the ^{234}U isomer of E_{II}=(3.8$\pm$0.5) MeV was determined independently from the results obtained with the half-lives.

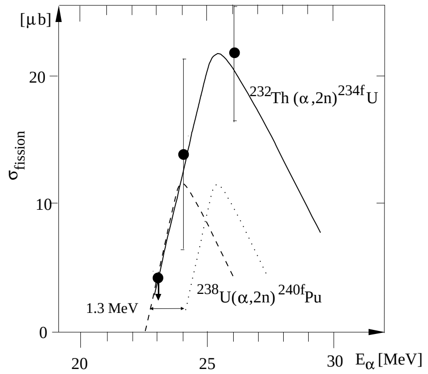

Fig. 5: Excitation functions for the ^{238}U(^{4}He,2n)^{240f}Pu and the ^{232}Th(^{4}He,2n)^{234f}U reactions. The measured cross sections of Ref. [10] were used to obtain absolute cross sections of ^{234f}U from the relative measurements. Normalizing both excitation functions to the same maximum heigth resulted in a relative shift in excitation energy of (1.3$\pm$0.5) MeV.

While in the first experiment background problems from scattered α projectiles occurred, we plan to repeat the experiment with increased statistics using BG-24A phosphate glass nuclear track detectors (width and length: 5 cm) [9]. The phosphate glass detectors have a threshold in detecting only ions with Z$\geq$6 and in this way they are insensitive to scattered α-particles.

References

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