Hyperdeformed Sub-barrier Fission Resonances Observed in ^{232}U ◊

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The existence of hyperdeformed (HD) states in the third minimum of the fission barrier in Th and U isotopes has firmly been well-established both experimentally and theoretically [1,2,3,4]. Observing transmission resonances as a function of the excitation energy caused by resonant tunneling through excited states in the third minimum of the potential barrier allows to identify the excitation energies of the HD states. On the other hand, calculations of potential energy surfaces [2] have predicted that HD minima correspond to reflection asymmetric shapes with large quadrupole ($\beta_2 = 0.9$) and octupole deformations, while the depth of the third well was estimated to be much larger than previously believed. However, in contrast to the ^{234,236}U isotopes, where sharp HD fission resonances have been identified in Refs. [4,5], in ^{232}U no clear resonance structures have been observed so far [6].

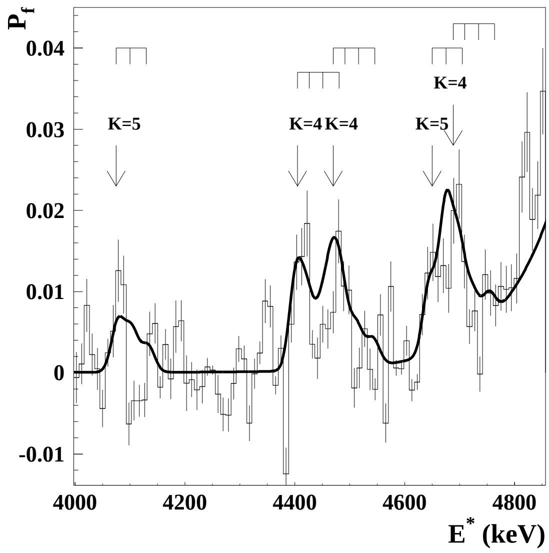

Fig. 1: Fission probability with error bars as a function of the excitation energy between E^*=4.0 MeV and E^*=4.85 MeV. The observed fission resonances are indicated by arrows, while the result of the fitting procedure assuming five rotational bands with overlapping band members as described in the text is indicated by the continuous line. The picket fence structures indicate the positions of the rotational band members used in the fit.

The aim of our experiment was to search for such sub-barrier fission resonances in ^{232}U and to determine the fission barrier parameters of ^{232}U. The experiment was carried out at the Tandem accelerator of the Maier-Leibnitz Laboratory (MLL) at Garching, employing the ^{231}Pa(^{3}He,df) reaction with a ^{3}He beam of $E = 38.1$ MeV to investigate the fission probability of ^{232}U in the excitation energy region of $E^* = 4.0 - 6.5$ MeV. An enriched (99%) 70 μg/cm^2 thick radioactive target of ^{231}Pa was used on a 20 μg/cm^2 thick carbon backing. The kinetic energy of the outgoing deuterons was analyzed by the Q3D magnetic spectrograph set at $\Theta_{lab} = 35°$ relative to the beam direction with a solid angle coverage of 10 msr. The experimental energy resolution was deduced to be $\Delta E = 11$ keV (FWHM). Fission fragments were detected in coincidence with the outgoing deuterons by two position sensitive avalanche detectors (PSAD), allowing for a detection of the fission fragment angular correlation with respect to the recoil axis ($30° < \Theta_R < 90°$) and a solid angle coverage of 10% of 4π.

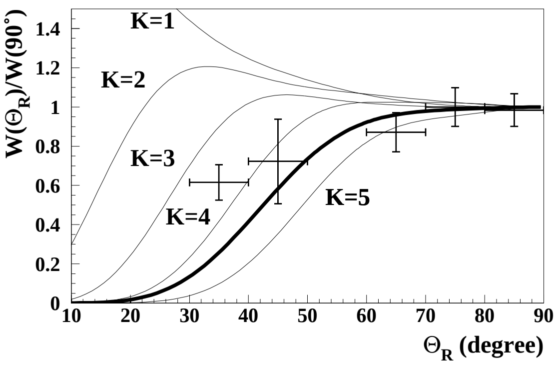

Fig. 2: Comparison of theoretical and experimental fission fragment angular distributions $W(\Theta_R)/W(90°)$ with respect to the recoil axis. The theoretical curves were obtained by assuming different K values for the rotational bands. The thick line was calculated using those K values which were assigned to the experimentally identified rotational bands during the fitting procedure.

Figure 1 shows the high resolution fission probability spectrum of ^{232}U as a function of the excitation energy of the compound nucleus. A number of sharp transmission resonances have been observed for the first time in the excitation energy region of $E^* = 4.2 - 4.8$ MeV and with widths of $\Delta E \approx 30$ keV. In order to describe the rotational structure of these resonances, overlapping rotational bands were assumed with the same moment of inertia (θ) and intensity ratio for the band members, as described in [4]. During the fitting procedure the energy of the band head and the absolute intensity of the band were used as free parameters, while a common rotational parameter was adopted for each band. On the other hand the angular distribution of the fragments was determined for the energy region of the observed resonances with respect to the recoil axis (Fig 2). The measured angular distribution was compared to calculated ones in order to derive information on the K value of the rotational bands. The results of these calculations assuming different K values are displayed in Fig.2 as continuous lines and suggested us to assign $K = 4, 5$ to the rotational bands. We have obtained a rotational parameter of $\hbar^2/2\Theta \approx 2.1$ keV, which is far

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smaller than the corresponding values characterizing SD shapes ($\hbar^2/2\Theta \approx 3.3$ keV). Our results have been deduced assuming $K = 5, 4, 4, 5$ and 4 for the five rotational bands at band head energies $E^* = 4080, 4402, 4468, 4651$ and 4678 keV, respectively. In Fig 2 the thick line represents the resulting angular distribution obtained from the measured resonances which have been assigned to rotational bands with their respective K values as derived from the fitting procedure. The experimental and calculated values are in a very good agreement, which also supports our conclusion to assign the measured fission resonances as being hyperdeformed transmission resonances.

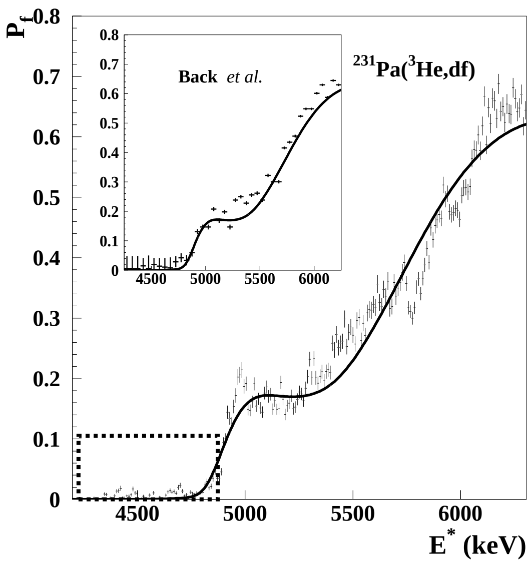

Fig. 3: Fission probability of ^{232}U as a function of the excitation energy measured with 11 keV resolution (FWHM). The result of the fitting procedure assuming five joint parabolas corresponding to a triple humped fission barrier is indicated by a continuous line. The spectrum shown in the insert was measured by Back *et al* [6] with a resolution of FWHM=95 keV. The small box surrounded with a dashed line is (equivalent to the data shown in Fig 1).

For the determination of the fission barrier parameters we have deduced an analytical expression for the fission probability that has been fitted to our experimental values. Within the calculation we used the optical model for fission [6], which was extended by Sin *et al* [7] to the light actinides, featuring a triple-humped fission barrier. Following the concept of Ref. [7] to deduce the fission width, our final analytical expression depends on the heights (E_{1-5}) and the curvature energies ($\hbar w_{1-5}$) of the barrier. Because of the strong correlation of the parameters E_i and $\hbar\omega_i$, only the barrier heights have been treated as free parameters during the fitting procedure for a given set of $\hbar\omega_i$ values. Using this method ≈ 3500 sets have been examined for the most realistic values of $\hbar\omega_i$ of a triple-humped fission barrier [7].

The result of the fitting procedure is presented in Fig 3, while the potential energy curve of ^{232}U using the deduced fission barrier parameters is displayed as a function of the quadrupole deformation (β_2) in Fig 4. The experimental value for the third well was compared to the the one calculated by Ćwiok *et al* [2] for a less reflection asymmetric ($\beta_3 \sim 0.36$) hyperdeformed nuclear shape and the more reflection asymmetric case ($\beta_3 \sim 0.6$). Our result on the depth of the third potential well ($E_{III} = 3.2 \pm 0.2$ MeV) suggests that in the case of ^{232}U fission proceeds via more reflection asymmetric shapes. The excitation energy region of the observed HD transmission resonances between the barrier heights of the inner and middle barrier is indicated by an arrow. The fission probability of ^{232}U measured by Back *et al* [6] using the same reaction but with a much reduced energy resolution of 95 keV (FWHM) is also displayed in Fig.3.

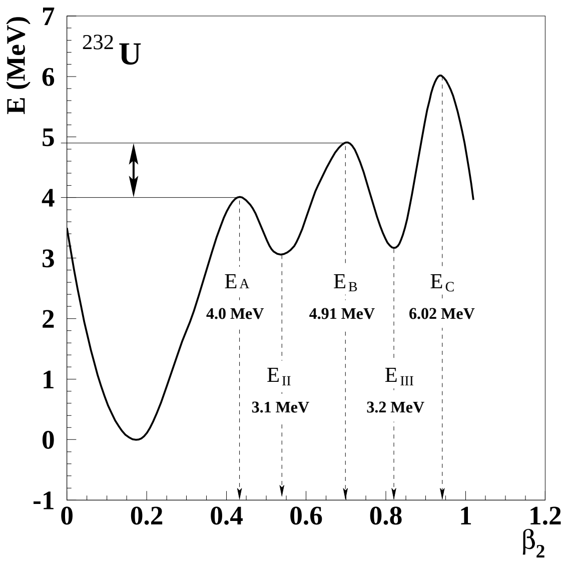

Fig. 4: Potential energy of ^{232}U as a function of the quadrupole deformation parameter (β_2). The excitation energy region above the first barrier and below the second barrier, where HD transmission resonances have been observed, is indicated by an arrow.

Our present result on the inner barrier height (E_A) of ^{232}U together with previous experimental results on the inner barrier heights of ^{234}U [8], ^{236}U [5] and ^{238}U [9] reveal a clear trend of decreasing E_A within the isotopic chain with decreasing neutron number. This trend complements the observed drop of E_A with decreasing proton number in actinides above $Z \approx 90$, giving rise to expect so far unobserved short lived fission isomers in low-Z as well as low-N actinide nuclei, respectively, due to the increasing probability of back decay to the first minimum with lower E_A.

All of these new results have been recently submitted to Physical Review C.

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