Resonant Tunneling through the Triple-Humped Fission Barrier of ^{236}U

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An experiment was performed at the MLL, where the ^{235}U(d,pf) reaction (E_d = 9.75 MeV onto a ≈100 μg/cm^2 $^{235}U_2O_3$ target (99.89 % enriched) on a 30 μg/cm^2 C backing) was used to study hyperdeformed transmission resonances [1]. The energy of the proton ejectiles was analyzed by the Q3D magnetic spectrograph. The Q3D was placed at $\Theta_L = 125^o$ relative to the beam. The position of the analyzed particles in the focal plane was measured with a light-ion position sensitive focal-plane detector [2] achieving an energy resolution of about 8 keV. Fission fragments were detected by two position-sensitive avalanche detectors (PSAD) placed at 55° and 125° with respect to the beam.

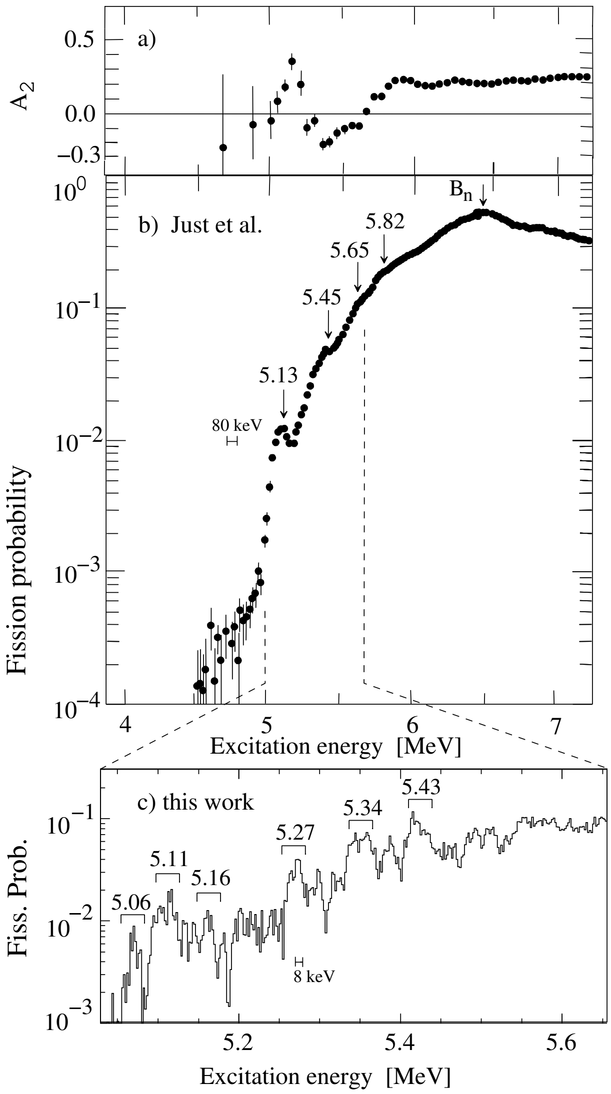

Fig. 1: a) Angular correlation coefficient A_2 for prompt fission following the reaction ^{235}U(d,pf). b) Prompt fission probability of ^{236}U from [3]. c) Prompt fission probability measured with high resolution in this work. The energy resolution of both measurements is indicated by a horizontal bar.

The measured high-resolution fission probability in terms of the excitation energy in ^{236}U is shown in Fig. 1c). Fig. 1b) shows for comparison the same fission probability measured by Just et al. [3] with a $\Delta E - E$ telescope, reaching an energy resolution of 80 keV. From the angular distribution of the fission fragments the angular correlation coefficient A_2 was calculated as a function of the excitation energy as shown in Fig. 1a). The resonances at 5.27, 5.34 and 5.43 MeV previously had been identified as hyperdeformed resonances [4], but without resolving any rotational structure. The resonance structure around 5.1 MeV formerly was interpreted as a vibrational resonance in the second minimum, however without knowledge of the existence of the third minimum [5,3].

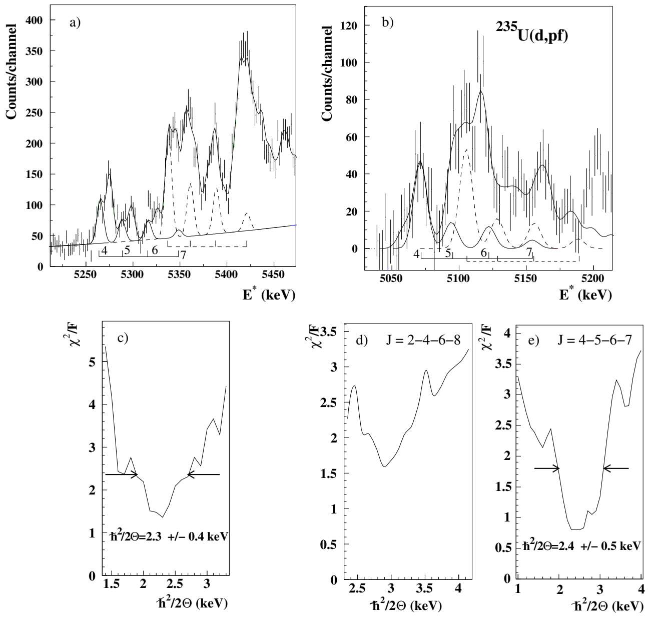

Fig. 2: a) Proton energy spectrum in coincidence with fission fragments following the ^{235}U(d,pf) reaction for $E^* \geq 5.2$ MeV. b) Excitation energy spectrum for the energy range below 5.2 MeV. In both regions the spectrum has been fitted with rotational bands (solid lines) with a variable rotational constant $\frac{\hbar^2}{2\Theta}$. The best fit in both cases has been obtained by hyperdeformed rotational bands, as indicated by panel c) and e). Panel d) shows an alternative scenario assuming a (superdeformed) spin sequence of J=2-4-6-8.

In order to describe the rotational structure, overlapping rotational bands were assumed with the same moment of inertia, inversion-splitting parameter and intensity ratio for the band members. Gaussians were used for describing the different band members, leaving the energy of the band head and the absolute intensity of the band as free parameters. A common rotational parameter ($\hbar^2/2\theta$) and inversion-splitting ($\Delta E_\pm$) parameter were adopted for each band. Due to the target spin of $\frac{7}{2}^-$ mainly J = 3^- and J = 4^- states were excited. Supposing alternating parity bands with K=4 band heads, the fission probability was fitted between 5.2 and 5.52 MeV, resulting in the fit superimposed to the data in Fig. 2a). The normalized χ^2 values are presented in Fig. 2c) as a function of $\hbar^2/2\theta$. The deduced rotational parameter is $\hbar^2/2\theta = 2.3^{+0.2}_{-0.45}$ keV and for the inversion parameter $\Delta E_{\pm} = 0^{+8.8}_{-5.5}$ keV, consistent with values characterizing HD rotational resonances.

Fig. 2b) shows the result of a similar fitting procedure for the proton spectrum below 5.2 MeV, where so far no conclusive experimental high-resolution data was available. The spectrum could not be reproduced assuming superdeformed bands, however, the experimental data could be described with 10 hyperdeformed rotational bands starting with spin J=4 (Fig. 2b) and e)). The rotational parameter deduced from this fit is $\hbar^2/2\theta = 2.4^{+0.4}_{-0.6}$ keV, corresponding to a hyperdeformed configuration, in contrast to the initial assumption (represented by the χ^2 assuming a superdeformed spin sequence J=2-4-6-8 in panel d)).

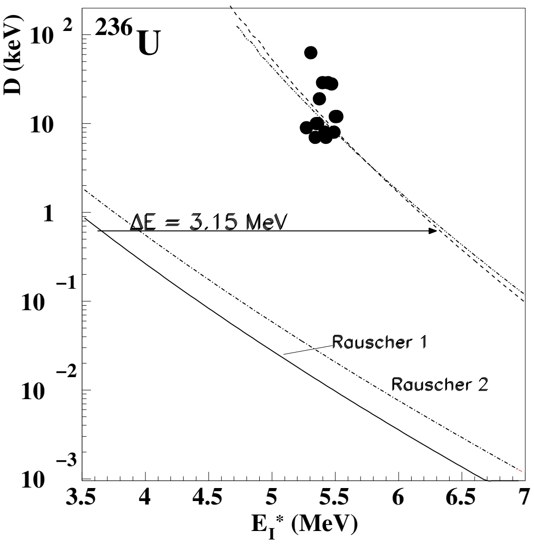

Fig. 3: Average distances of the J=4 levels in the third miminum of ^{236}U as a function of excitation energy. The solid curves show calculated values by different formulae, the full points correspond to experimental values.

Similar to our previous work on ^{234}U [6], the depth of the third well has been determined by comparing the experimentally obtained average level distances of the(J=4) band heads in the third well with the calculated ones using the back-shifted Fermi-gas description [7]. In order to find the best fit of the experimental level distances, the calculated distribution for the first well had to be modified with an energy shift corresponding to the excitation energy E_{III} of the ground state in the third minimum as shown in Fig. 3, resulting in a value of $E_{III} = 3.15\ \pm 0.35$ MeV. The theoretical prediction for the depth of the third minimum in ^{236}U according to Ćwiok et al. is 3.8 MeV [8]. Our result is in a good agreement with this prediction and also with the so far only experimentally determined value of E_{III} for ^{234}U as obtained in our previous work [6].
The new interpretation of the 5.1 MeV transmission resonance in ^{236}U as a resonance in the third well leads to a determination of the parameters of the inner barrier. Formerly the interpretation as a resonance in the second minimum led to the requirement that the inner barrier height E_A was larger or equal to the outer barrier E_B, because a strong resonance required penetrabilities of both barriers with rather comparable values. With the new interpretation the inner barrier has to be reduced to the excitation energy of the lowest transmission resonance in order to achieve the strong mixing between class-I and class-II compound states required for the occurrence of hyperdeformed transmission resonances. Thus an inner barrier height E_A smaller than 5.2 MeV can be deduced. On the other hand we can obtain a lower limit for E_A from the measurement of the isomer population probability. This is shown in Fig. 4 with data from Goerlach et al. [9,3]. The data show a clear exponential rise. At an excitation energy of 5.1 MeV the isomer population probability starts to saturate, because the compound states of the first and second minimum become largely mixed. Above 6 MeV we observe a drop of the isomer population probability because the competing fission and neutron channels open up. From the exponential rise of the isomer population probability for low energies we can deduce that E_A has to be larger than 5.1 MeV. ¿From both limits we obtain for the first time a precise value for the height of the inner barrier $E_A = 5.15 \pm 0.1$ MeV. The new method to limit the height of the inner barrier can be carried over to other nuclei like ^{234,238}U, thus reaching a much better understanding of the potential energy landscape of Uranium nuclei and resolving the long-lasting puzzle of the 'Thorium anomaly' in the picture of the triple-humped fission barrier.

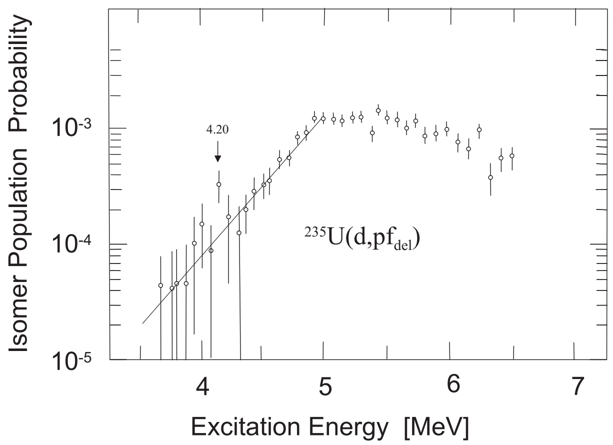

Fig. 4: Isomer population probability from Goerlach et al. [9,3].

In Fig. 5 we show the potential energy surface of ^{236}U as a function of the deformation with the triple-humped fission barrier as deduced in this work.

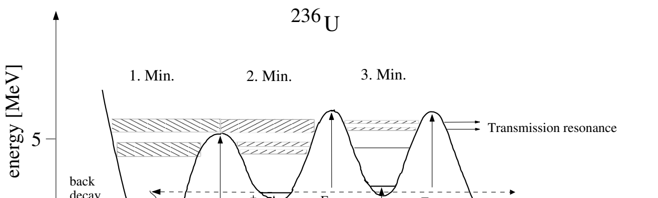

Fig. 5: The triple-humped potential energy surface of ^{236}U. Also damped class-I, class-II and class-III compound states are shown in the three minima. For strongly mixed class-I and class-II states transmission resonances of class-III states can occur in fission.

It is interesting to note that in the data of Goerlach et al. [9] a resonance in the isomer population probability could be observed at E* =4.20±0.05 MeV (Fig. 4). It agrees with the sum of the isomer energy and the energy of the second phonon $E_{II} + 2 \cdot \hbar\omega_{II} = (2.814 + 2 \cdot 0.685)$ MeV = 4.184 MeV. This shows that the second well at lower excitation energies is rather harmonic. A similar observation was made for the second well of ^{240}Pu [10]. The barrier heights (E_A =5.15 MeV, E_{B1} =E_{B2} =6.1 MeV) and the potential minima (E_{II} =2.814 MeV, E_{III} =3.15 MeV) approximately agree with predicted values of E_A=5.46 MeV, E_{B1}=6.0 MeV, E_{B2}=6.0 MeV, E_{II}=2.2 MeV and E_{III}=3.8 MeV from [8] and [11].

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