New Insights into the Fission Barrier Landscape of Light Actinide Nuclei

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Main outcome of our transmission resonance studies on ^{236}U presented in detail in the previous annual report [1] was the identification of rotational structures in the (hyperdformed) third minimum, thus allowing to prove the existence of a deep third minimum ($E^*_{III} = 3.3(4)$ MeV) [2] and to deduce the parameters of the inner and outer fission barriers as shown in Fig. 1.

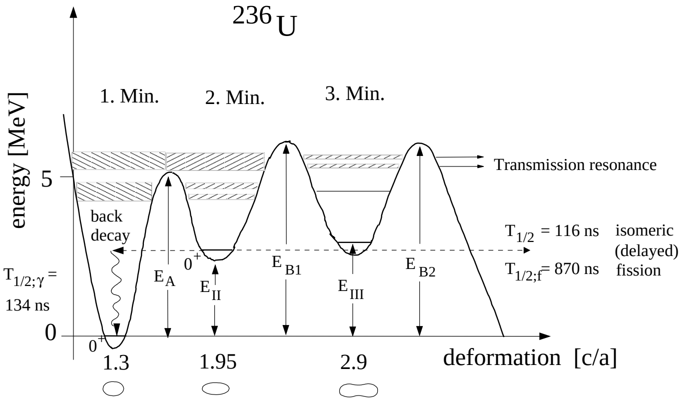

Fig. 1: Potential energy surface of ^{236}U as a function of the nuclear deformation. The fission barrier heights and the excitation energy of the ground state in the third well have been determined in our recent experiment [1,2] to be $E_A = (5.15 \pm 0.1)$MeV, $E_{B1} = E_{B2} = (6.1 \pm 0.2)$MeV and $E_{\rm III} = 3.3(4)$MeV. The energy of the ground state in the second minimum lies at $E_{\rm II} = 2.81(2)$MeV above the ground state of the first minimum [6]. In addition partial halflives are given for the ground state fission decay as well as for the isomeric decay from the second minimum towards the first well (γ back decay) and the delayed fission, respectively. ^{236}U is the only case where experimental information exists both for the fission isomer as for hyperdeformed resonances in the third well and where the coupling between the second and third well can be studied.

Significant information on the barriers is obtained from the ground state decay of the second minimum. It has an excitation energy of 2814±17 keV and a total half-life of 116±3 ns [6]. The partial half-life for delayed fission is t_{IIf}= 870±95 ns and the partial half life for the γ-back decay to the first minimum is $t_{II\gamma}$=134±4 ns. From the fission half-life the common penetrability of the outer two barriers $P_{B1} * P_{B2}$ can be calculated as:

$$t_{IIf} = \frac{ln2 \cdot 2\pi\hbar}{\hbar\omega_{II} \cdot P_{B1} \cdot P_{B2}} \,. \qquad (1)$$

The β-vibrational phonon energy in the second minimum $\hbar\omega_{II}$=685 keV has been measured in conversion electron spectroscopy [7]. Thus we obtain: $P_{B1} \cdot P_{B2} = (4.5 \pm 0.4) \cdot 10^{-15}$. From the half-life of the γ back-decay a rough estimate of the penetrability P_A of the inner barrier can be deduced: $P_A = \frac{t_{I\gamma}}{t_{II\gamma}}$. The typical half-life $t_{I\gamma}$ of the γ decay in the first minimum with an energy close to the isomer energy can be obtained from the Weisskopf estimate: $T_W(E1) = 6.76 \cdot A^{-2/3} \cdot E_\gamma^{-3}[\mathrm{MeV}] \cdot 10^{-15} sec$ combined with a typical Weisskopf hindrance factor F_W= 100 leading to: $t_{I\gamma} \approx 10^{-15} sec$. In this way we obtain a penetrability of the inner barrier $P_A \approx 1 \cdot 10^{-8}$, which is about 7 orders of magnitude larger than the one of the two outer barriers.

Whereas for the inner fission barrier E_A of ^{236}U largely-varying parameters have been published (E_A=5.98±0.15 MeV, $\hbar\omega_A$=1.32±0.1 MeV [3]) or (E_A=5.6±0.2 MeV, $\hbar\omega_A$=1.04 MeV [8]), in our new experiment it could be proven that a better choice of parameters is: (E_A=5.15±0.2 MeV, $\hbar\omega_A$=1.2 MeV) allowing for a full damping of the class-II compound states in the region where transmission resonances for the third minimum are observed.

With our new knowledge on the existence of a deep third minimum in the actinide mass region a revised picture on the fission barrier landscape can be given. From our understanding of the triple-humped barrier of ^{236}U we can now further limit the barrier parameters of ^{234}U. For the outer symmetrically-split barrier a height $E_{B1} = E_{B2} =$ 6.1 MeV and $\hbar\omega_{B1} = \hbar\omega_{B2} = 1.2$ MeV can be deduced from the prompt fission probability [3], identical to the values of ^{236}U. However, again the observation of hyperdeformed transmission resonances down to energies of 4.8 MeV [13] requires the inner barrier height $E_A \leq$4.8 MeV.

From the general half-life systematics of fission isomers [9] $(E_B - E_{II}) = 3.0$ MeV was obtained for ^{234}U, if adjusting the systematics to the $(E_B - E_{II})$-values of ^{236}U and ^{238}U of 3.3 MeV and 3.5 MeV. In this way a rough prediction for the E_{II}-value of ^{234}U with $E_{II} \approx 3.1$ MeV could be obtained. Assuming the same $\hbar\omega_A$ and $\hbar\omega_B$ as in ^{236}U, we roughly by scaling can predict a half-life of about 3 ns for the γ-back decay and about 45 ns for the fission decay in ^{234}U. An upper limit for the half-life of the fission isomer in ^{234}U of 2-4 ns has been given in studies with light-ion induced reactions. Thus the half-life could be a little shorter. Using this approach we again have a rather weak fission branch (1:12), which might explain why the fission isomer has not been observed yet. The search for this isomer with standard projection techniques [9] looks rather promising and will consolidate this global picture.

Also in ^{238}U low-lying transmission resonances are observed at 4.9 MeV and 5.1 MeV in the ^{236}U(t,pf)^{238}U reaction [14]. Again in high-resolution spectroscopy one could clarify if these transmission resonances are due to superdeformed or hyperdeformed states. If they originate from hyperdeformed states like in ^{236}U, which is very probable, they would allow to limit the inner barrier height for ^{238}U. The high-energy end of the isomeric shelf in photofission of ^{238}U leads to a lower limit for the inner barrier ($E_A \geq$4.6 MeV) for ^{238}U. Thus $E_A = (4.8 \pm 0.3)$ MeV would be a good estimate for ^{238}U.

The discussion presented in this section shows that the described new technique will allow to clarify the problem of the inner barrier for all even-even Uranium isotopes with fission isomers.

If we compile all presently available information on fission barrier parameters in the actinide mass region including the new information obtained in our experiments, the resulting plot is shown in Fig. 2.

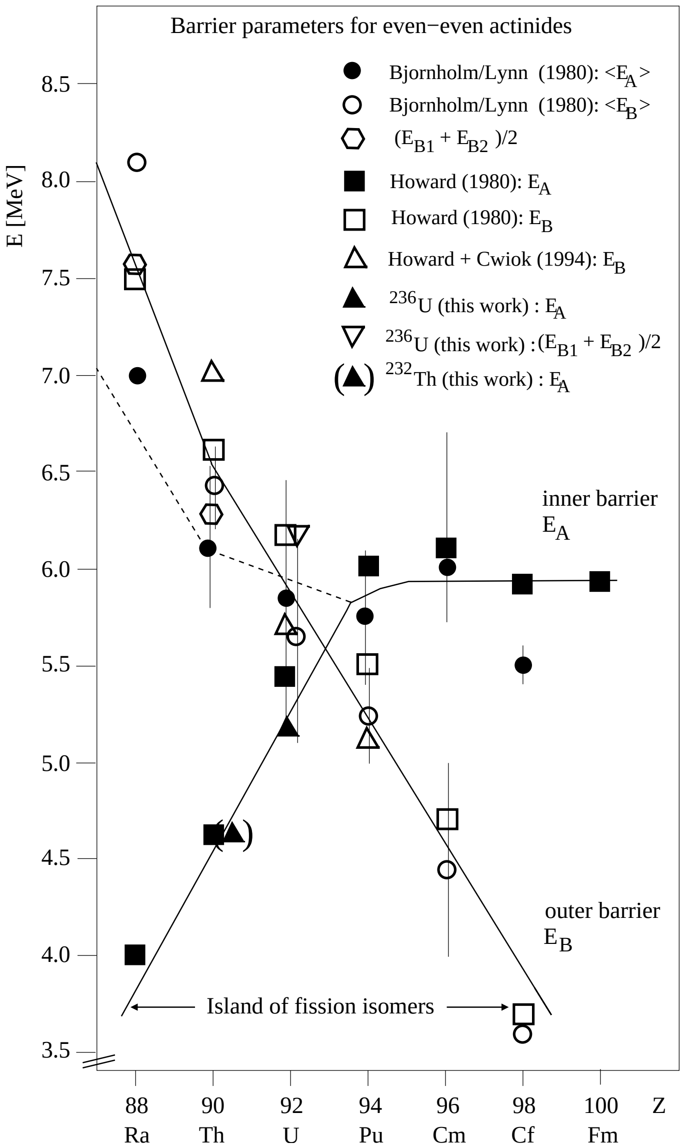

Fig. 2: Fission barrier parameters of actinide isotopes. Open symbols indicate the height of the outer fission barrier E_B, while full symbols correspond to the height of the inner fission barrier E_A. The circular symbols mark the centroid of experimental barrier parameters for given actinides as compiled by Bjørnholm and Lynn [8] with the error bar denoting the respective range of barrier heights. Open polygons indicate the average value of the two outer barriers for the triple-humped barrier in Ra and Th. Rectangular symbols show calculated barrier heights from Howard [12], while open triangles contain in addition to the calculations from Howard information on the depth of the third potential well according to Ćwiok et al. [11]. Triangular symbols display the barrier heights for ^{236}U as derived in our recent work as well as an estimate for the inner barrier in ^{232}Th. The solid lines visualize the trends visible in the data (see text).

Open symbols indicate the outer fission barrier E_B, while full symbols stand for the inner barrier E_A. The experimental data points from the compilation by Bjørnholm and Lynn [8] are given by the circular symbols, indicating the centroid of the barrier parameters for a given Z with the error bars denoting the respective range of barrier heights. Open polygons indicate the average value of the two outer barriers for the triple-humped barrier in Ra and Th. Rectangular symbols show calculated barrier heights from Howard [12], while open triangles contain in addition to the calculations from Howard information on the depth of the third potential well according to Ćwiok et al. [11]. Triangular symbols display the barrier heights for ^{236}U derived in our recent experiment as well as an estimate for the inner barrier in ^{232}Th. The solid lines visualize the trends visible in the data. While previous publications [15,16] favoured the increase of E_A with decreasing Z as shown by the dashed line, our new experimental information, in agreement with earlier calculations, indicates a lowering of E_A as illustrated by the solid line below Pu. This discrepancy can be understood remembering the fact that at the time of Ref. [15] and [16] the existence of a deep third minimum was not known, so that the observation of transmission resonances at comparable excitation energies in different nuclei led to the interpretation of similar heights of the fission barriers. In the paper of Britt et al. [17] an unease about the obvious discrepancy to the theoretical expectations for E_A in ^{228}Th is explicitly expressed, however the interpretation of the experimental data was misguided by the assumption of an only double-humped fission barrier. In view of our present knowledge the theoretical trend of a drastic lowering of the inner barrier height with decreasing Z is clearly confirmed by our experimental findings.

Fig. 2 impressively allows to illustrate the occurrence of the island of fission isomers in the mass region of the light actinides. With the continuous decrease of the outer barrier height E_B with increasing Z the corresponding halflife of isomeric fission drops below the picosecond region for $Z > 98$. Quite similar the decrease of the inner barrier height E_A with decreasing Z results in sub-picosecond halflives for the γ back-decay in the region of $Z < 88$, thus both cases marking the upper and lower limits for the island of shape isomers.

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