SUPERDEFORMATION, HYPERDEFORMATION AND CLUSTERING IN THE ACTINIDE REGION*

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Excited states in the second minimum of ^{240}Pu were populated by the ^{238}U$(\alpha,2n)$ reaction at E_α=25 MeV. Conversion electrons from electromagnetic transitions preceding the fission of the 3.7 ns ^{240f}Pu shape isomer have been measured. In a combined analysis of e$^-$ and high resolution γ-ray spectroscopy data previously established octupole bands could be studied in more detail. In order to study higher lying states in the second and third minimum the ^{239}Pu$(d,pf)^{240}$Pu, and the ^{233}U$(d,pf)^{234}$U reactions have been studied with high energy resolution. The observed fission resonances were described as members of rotational bands with rotational parameters characteristic to super- and hyperdeformed nuclear shapes. The level density of the most strongly excited states has been compared to the prediction of the back-shifted Fermi-gas formula and the energy of the ground state in third minimum has been estimated for the first time in ^{234}U. The fission fragment mass distribution of the hyperdeformed states in ^{236}U has also been measured. The width of the mass distribution, coincident with the hyperdeformed bands, is significantly smaller than the ones obtained in coincidence with background regions below and above the resonances, which suggests a pear-shaped di-nuclear configuration of ^{236}U in the third well of the potential barrier.

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1. Introduction

Studying nuclei with exotic nuclear shapes is one of the most vital fields in modern nuclear structure physics and especially in the last few years studying super- and hyperdeformed states in the actinide region became one of the frontiers of this field.

The nuclear fission in this region presents a very rich variety of nuclear shapes which can be described by a continuous sequence of nuclear surface shapes from a more or less spherical to one which elongates, becomes super- and/or hyperdeformed than necks in and splits into two fission fragments.

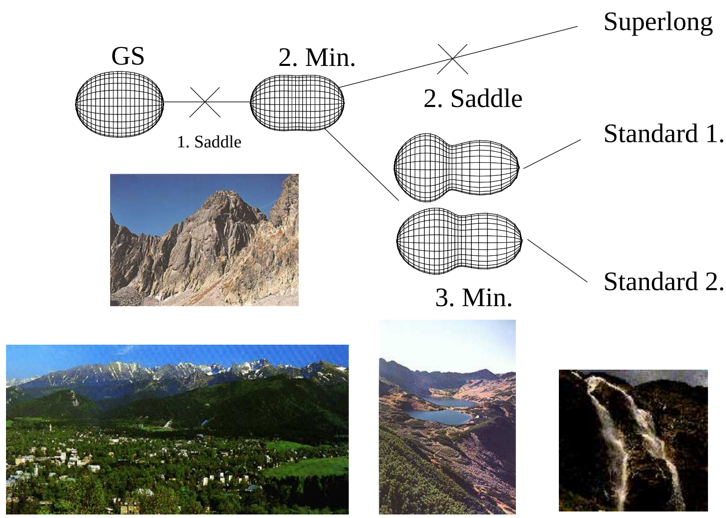

Fig. 1. Schematic representation of the fission pathes of ^{236}U according to Hambsch [1].

A very schematic representation of the energy surface of ^{236}U is shown in Fig. 1. At this beautiful place we may compare the potential energy surfaces to the best places of the Tatra mountain. We may characterize the fission process in the following way. From the ground state minimum a common path climbs to the inner first saddle point and then descends to the second minimum. On further elongation the nucleus may choose to stay either reflection symmetric or asymmetric. The symmetric path has to coast over a second saddle point and slopes down a long valley until the scission point is reached. For the asymmetric path there is, to start with, a second saddle, which contains two third minima. Again the nucleus has to decide which way to go. One path is moderately asymmetric and rather short, while the other path is more pronounced asymmetric and somewhat longer.

The main aim of this work is to study the excited states in the second and third minimum of the potential barrier but in addition to these exotic shapes it is also an interesting and longstanding question, at which points of the fission path the mass and energy distributions of the fission fragments are determined [1]. Can we get different mass distributions after the fission of the super- and hyperdeformed states as suggested by Ćwiok *et al.* [2]?

2. γ and conversion electron spectroscopy in the second minimum

The first superdeformed (SD) states have been found in the actinide region. They were the so called fission isomeric states discovered by Polikanov *et al.* [3] almost 40 years ago. Their half-lifes go from a few ns's to a couple of ms's. Ten years after the discovery of these interesting isomeric states Specht and coworkers [4] were able to prove spectroscopically that they are really SD states. They measured the first conversion electron spectrum containing a SD rotational band. Their interpretation of being the result of microscopic shell corrections on top of the macroscopic liquid drop potential was given by Strutinsky [5]. Up till now the second minimum of the potential energy surface is well established both theoretically and experimentally [6, 7].

The γ-spectroscopic studies of the SD states turned out to be very difficult in the actinide region because of the low cross sections and the high background produced by the fission fragments. In spite of that, recently nice results have been obtained using six EUROBALL-type cluster detectors [8, 9].

For an unambiguous interpretation of these data, especially for the determination of the multipolarity, a conversion electron measurement was carried out in Munich. We used the same ^{238}U$(\alpha, 2n)$ reaction at $E_\alpha = 25$ MeV as Specht *et al.* [4] in their pioneering conversion electron work, which led to the identification of the rotational ground state band built on the fission isomer.

The main experimental challenge was to isolate an efficient trigger on delayed fission events against a huge background of prompt fission dominating by 5 to 6 orders of magnitude. This was achieved by using the recoil shadow technique introduced by Specht *et al.* [4], where the target was placed inside the 4mm hole of an annular Si-surface barrier detector. The $(\alpha, 2n)$-reaction takes place where the detector cannot see the prompt fission products, while the recoils in the isomeric state fly on the average 1.8 mm out of the target and then decay in front of the detector. The conversion electrons are guided with Mini-Orange magnetic transport and filter systems to nitrogen-cooled Si(Li) detectors.

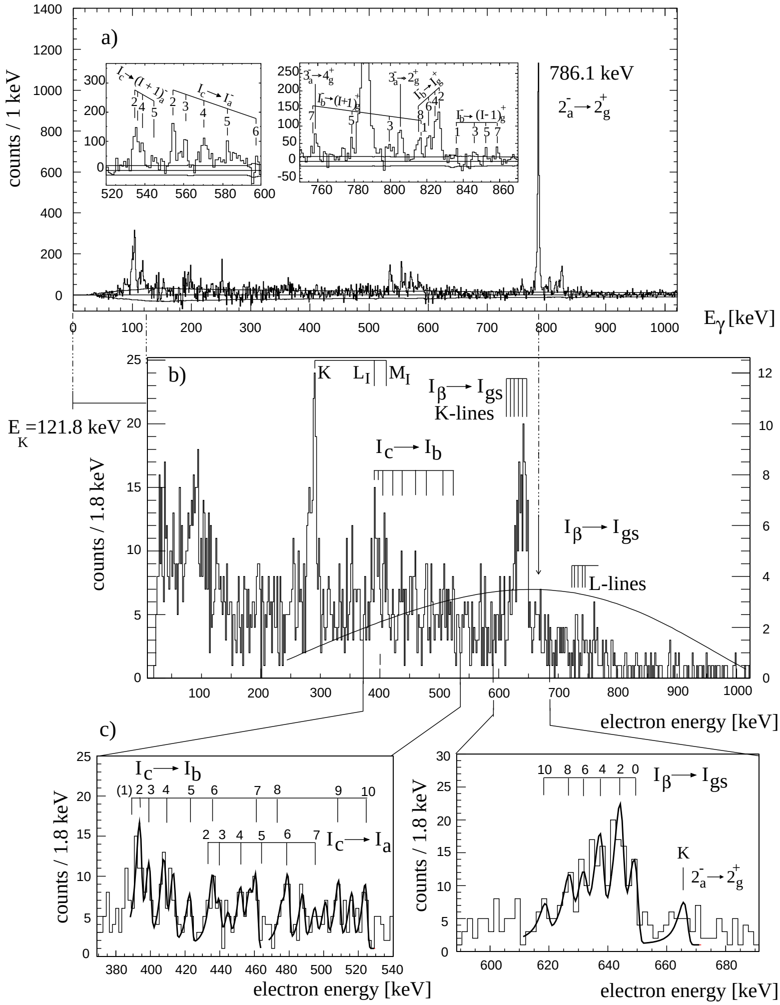

Fig. 2. (a) γ-ray spectrum in coincidence with delayed fission of ^{240f}Pu from [9]. The inserts show enlarged regions of transitions connecting the c- and a-band and the a- and ground-state-band, respectively. (b) Conversion electron spectrum from the present work in coincidence with delayed fission of ^{240f}Pu shifted by the electron binding energy of E_K=121.8 keV. The summed transmission efficiency (weighed average of the two experiments) of the 3 Mini-Orange spectrometers is represented by the solid line. (c) Enlarged parts of the electron spectrum with fitted line spectra and transition assignments.

The prompt γ-ray spectrum from Ref. [9] and the electron spectrum shown in Fig. 2(a) and 2(b), respectively, were measured in coincidence with delayed fission of ^{240f}Pu.

The same reaction and beam energy was used in both experiments. Electron lines from K-conversion are lower in energy as compared to the corresponding γ-ray transitions by the K-binding energy of 121.8 keV. This shift is taken into account by the displacement of Fig. 2(b).

The deduced level scheme based on the γ-ray and conversion electron spectroscopic studies is shown in Fig. 3.

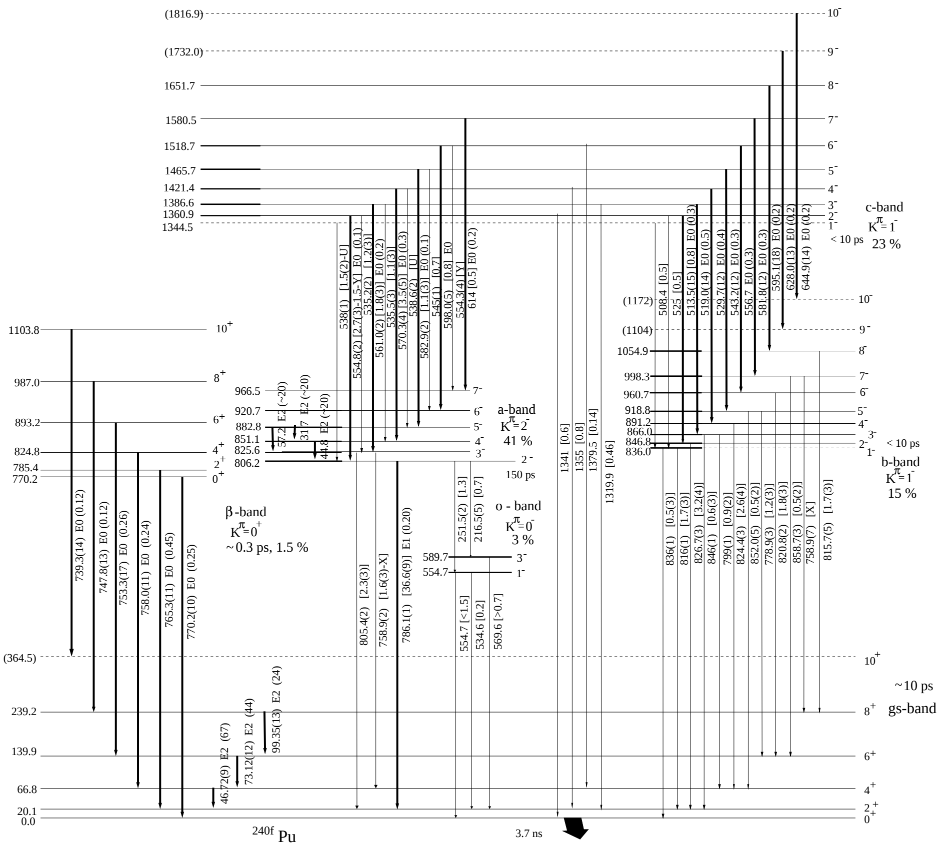

Fig. 3. Level scheme of ^{240}Pu in the second minimum. The accuracy of the Doppler corrected transition energy is given in round parenthesis ( ), the absolute γ-ray intensity with respect to the isomeric fission decay in rectangular parenthesis [ ] and the dominant multipolarity together with the absolute electron intensity in round parenthesis ( ). Transitions observed in the electron spectrum are marked by thick arrows. Levels with energies in parenthesis were introduced by a smooth extrapolation of the moment of inertia.

3. Study of the higher-lying states by measuring transmission resonances

In a program which aims at studying the super- and hyperdeformed states in the actinides we have already studied the SD states in ^{240}Pu [10] and the HD ones in ^{231}Th, ^{234}U [11] and in ^{236}U [12]. We are presenting now two examples for the SD and HD states in ^{240}Pu and in ^{234}U.

Our method of studying the above exotic states is based on the resonance tunneling through the fission barrier. The fission probability as a function of excitation energy shows sub-barrier transmission resonances in the range close to the top of the fission barrier at energies of quasi-bound states in the second and third minimum of the potential barrier. By measuring this function one can map the SD and HD states. Early attempts of studying these transmission resonances critically suffered from either a limited energy resolution or statistical significance.

In order to study the transmission resonances proton–fission fragment coincidence measurements have been performed in (d,pf) reactions. The energy of the outgoing protons from the different (d,p) reactions was analyzed with high energy resolution in coincidence with the fission fragments.

The experiments were carried out at the Debrecen 103 cm isochronous cyclotron with deuterons of $E_d = 9.73$ MeV and in Munich with deuterons of 12.5 MeV obtained from the Munich Tandem accelerator. Enriched (97.6%–99.89%) 30–250 μg/cm^2 thick targets were used.

The energy of the outgoing protons was analyzed by a Split-pole magnetic spectrograph in Debrecen and by a Q3D magnetic spectrograph [13] in Munich, which were set at $\Theta_L = 130°$ and $140°$ with respect to the incoming beam direction [12].

The fission fragments were detected by two Position Sensitive Avalanche Detectors (PSAD) [14] having two wire planes (with delay-line read-out) corresponding to the horizontal and vertical directions. The solid angle of the detectors varied between 10% and 30% of 4π in the different experiments.

The mass distribution of the fission fragments has been determined by using the time difference method. The fission fragments were detected with two PSAD's having active areas of 16x16 cm^2 and distances of 23 cm from the target resulting in a relatively large solid angle of 4% of 4π. The angle of the detectors was 55° and 125° with respect to the beam direction.

3.1. High-lying super deformed states in ^{240}Pu

In order to study higher-lying multi-phonon vibrational resonances the fission probability of ^{240}Pu has been measured with high energy resolution using the (d,pf) reaction. The spectrum of outcoming protons in coincidence with the fission fragments is shown in Fig. 4(a).

Two enhanced structures of highly damped vibrational resonances at $E^* = 4.5$ MeV and 5.1 MeV excitation energies have been resolved with good statistics into sub-states due to the underlying compound states coupled to the β-vibrations. For the first time rotational bands with spins 0^+, 2^+, 4^+ could be identified for transmission resonances in ^{240}Pu [10, 15].

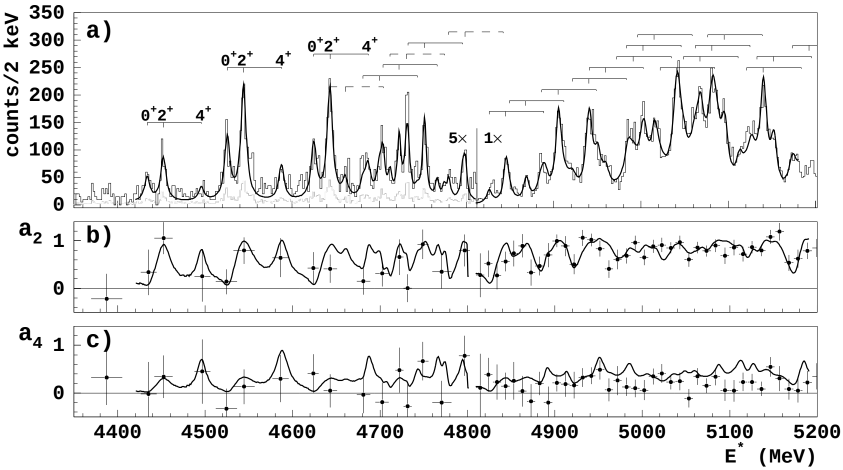

Fig. 4. (a) Proton energy spectrum from the ^{239}Pu(d, pf)-reaction at E_d = 12.5 MeV. The superimposed solid line is the result of the fit to the observed resonance structures with $K^\pi = 0^+$ rotational bands, dashed markers indicate the ambiguous presence of some additional bands. (b) and (c) Experimental and calculated a_2 and a_4 coefficients of the fission fragment angular correlation as a function of the excitation energy. The calculated values resulted from combining theoretical coefficients with the obtained fit from the spectrum. See Ref. [10, 15] for details.

Their moment of inertia is typical for a superdeformed nuclear shape and close to that of the ground state rotational band in ^{240f}Pu. The assignment of $K^\pi = 0^+$ as the quantum number of the rotational bands is supported by the analysis of peak distances, intensity ratios and fission fragment angular correlations. The level density of the most strongly excited 2^+-states has been compared to the prediction of the back-shifted Fermi-gas formula and the energy of the ground state in the second minimum has been estimated to be $E_{\rm II}$ =2.25±0.2 MeV in good agreement with the value known from excitation function measurements.

3.2. High-lying hyperdeformed states in ^{234}U

In order to investigate the HD bands the excitation energy was chosen between the energy of the inner and outer barriers of the second well (Fig. 5). In this energy range the widths of the SD resonances in the second well should be much broader than those of the HD states due to the strong coupling to the normal deformed states. The widths of the HD states due to the higher outer barriers of the third well remain below the actual experimental resolution of ∼5 keV.

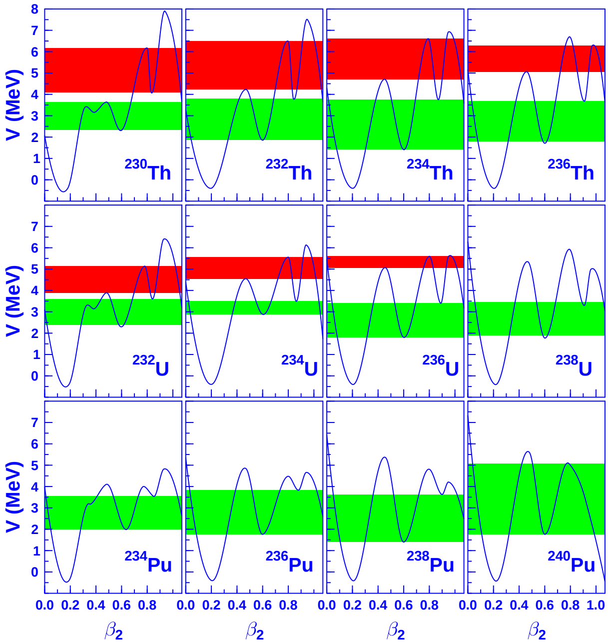

Fig. 5. Potential energy as a function of the quadrupole deformation parameter for a few U isotopes. The energy and location of the saddle points and minima (except for the third one) were taken from Ref. [16] while the energy of the third minimum for the less reflection — asymmetric HD minimum ($\beta_3 \approx 0.4$) was taken from Ref. [2]. The whole energy scale was slightly shifted in order to reproduce the energy of the ground states in the first well. The best excitation energy region for studying the hyperdeformed states is marked by the darkest shadowed regions.

Part of the proton spectrum measured in coincidence with the fission fragments is shown in Fig 6(a).

Assuming overlapping rotational bands with the same moment of inertia, inversion parameter and intensity ratio for the members in a band, we fit our spectrum using simple Gaussians for describing the different band members in the same way as we did it previously [12]. The result of the fit is also shown in Fig. 6(a). In order to get information on the spins and K values of the observed rotational bands, or to check our assumptions made for fitting the energy spectrum, the angular distribution coefficients of the fission fragments have been calculated and compared to the experimental ones (Fig. 6(b)). For details of the fitting procedure see our previous work [11].

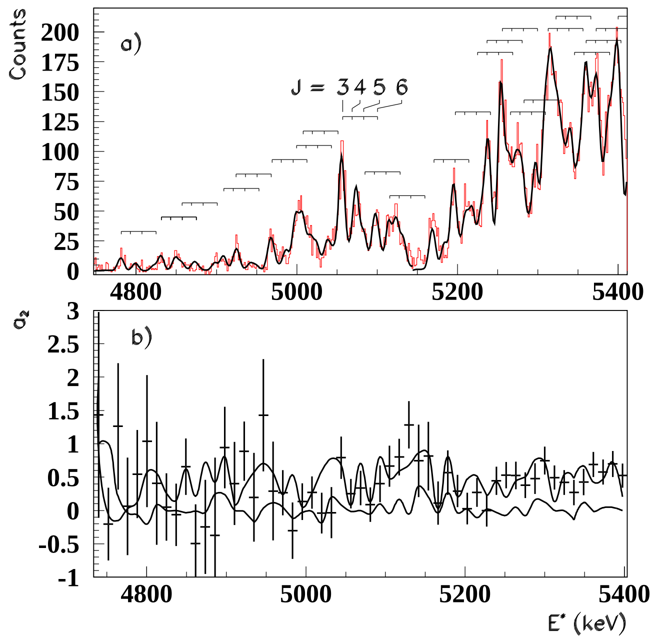

Fig. 6. (a) Part of the measured proton energy spectrum from the ^{233}U(d,pf) reaction fitted with 24 rotational bands with a common rotational parameter. The spectrum was divided into two parts at $E = 5150$ keV for the fitting; (b) Experimental fission fragment angular-distribution coefficients as a function of excitation energy compared to the calculated ones using $K = 1$ (upper curve) and $K = 3$ (lower curve) for all of the bands.

The density of $J = 3$ states has been determined from our experimental data and calculated as a function of the excitation energy using the back-shifted Fermi-gas description with parameters determined by Rauscher *et al.* [17]. In order to estimate the depth of the third well we compared the experimentally obtained and calculated densities. We assumed that the same parametrization of the level density formula is valid in the third well, as it was determined by Rauscher *et al.* [17] by fitting the level densities in the first well of the potential barrier and which we have already checked also in the second well in case of ^{240}Pu. By comparison we find a value of 3.1 ± 0.4 MeV for the energy of the ground state in the third well.

Ćwiok *et al.* [2] predicted two different HD minima for ^{234}U with very different β_λ ($\lambda = 3$–7) values. The experimental value of $E_{\rm III} = 3.1 \pm 0.4$ MeV obtained in the present work is between two predicted values with an error bar, which overlaps both theoretical values. Recently, Shneidman *et al.* [18] found the depth of a potential well keeping the two clusters together to be 3.4 MeV. This value agrees also very well with the depth of the third well which we have determined experimentally.

4. Clustering in the actinide region

The clustering phenomenon is a dramatic manifestation of the shell structure at very large deformations. From such a di-nuclear system one may expect a strong fission decay to the components similarly to the case of the enhanced α decay of the light α-particle nuclei.

Recently, we have repeated the $^{235}\mathrm{U}(d,pf)^{236}\mathrm{U}$ experiment [12] in Debrecen and measured the mass distribution in coincidence with the HD bands found previously at 5.28, 5.37 and 5.47 MeV.

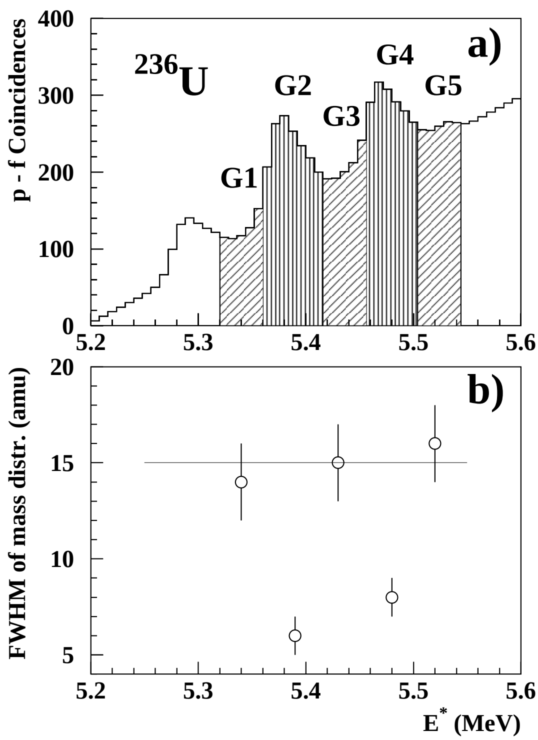

Fig. 7. The observed HD resonances of ^{236}U. The marked regions selected the resonant and non-resonant parts of the spectrum, whose mass distributions were fitted by two Gaussians. The resulted widths of the mass distributions are shown in the lower figure.

The mass distribution in coincidence with the HD bands has been found significantly sharper (FWHM $\approx$ 5 amu) compared to the other distributions measured above and below the peaks (FWHM $\approx$ 15 amu). The width of the mass distributions in coincidence with the HD bands is mostly caused by our mass resolution. Better mass resolution is required to determine the real widths of the mass distributions.

The HD states lying in the third well of the fission barrier may play a role of a doorway-like state before fission, from which states the fission can only occur through a limited number of fission paths resulting in a sharper mass distribution.

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REFERENCES

[1] F. Habsch *et al.*, *Nucl. Phys.* **A491**, 56 (1989).
[2] S. Ćwiok *et al.*, *Phys. Lett.* **B322**, 304 (1994).
[3] S. M. Polikanov *et al.*, *Sov. Phys. JETP* **15**, 1016 (1962).
[4] H. J. Specht *et al.*, *Phys. Lett.* **41B**, 43 (1972).
[5] V.M. Strutinsky, *Nucl. Phys.* **A95**, 420 (1967).
[6] S. Bjørnholm, J.E. Lynn, *Rev. Mod. Phys.* **52**, 725 (1980).
[7] V. Metag *et al.*, *Phys. Rep.* **65**, 1 (1980).
[8] D. Pansegrau, Ph.D. Thesis, Universität Heidelberg 1998; D. Pansegrau, Diploma Thesis, Universität Heidelberg 1994.
[9] D. Pansegrau *et al.*, *Phys. Lett.* **484B**, 1 (2000).
[10] M. Hunyadi *et al.*, to be published.
[11] A. Krasznahorkay *et al.*, *Phys. Lett.* **B461**, 15 (1999).
[12] A. Krasznahorkay *et al.*, *Phys. Rev. Lett.* **80**, 2073 (1998).
[13] H.A. Enge, S.B. Kowalsky, Proc. 3rd Int. Conf. on magnet technology, Hamburg 1970.
[14] P.C.N. Crouzen, PhD Thesis, Rijksuniversiteit Groningen 1988, unpublished.
[15] M. Hunyadi, PhD Thesis, Lajos Kossuth University Debrecen 1999, unpublished.
[16] W.M. Howard, P. Möller, *At. Data Nucl. Data Tables* **25**, 219 (1980) and references therein.
[17] T. Rauscher, F.K. Thielemann, K.L. Kratz, *Phys. Rev.* **C56**, 1613 (1997).
[18] T.M. Shneidman *et al.*, *Nucl. Phys.* **A671**, 119 (2000).