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Experimental Evidence for Hyperdeformed States in U Isotopes

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Sharp transmission resonances have been observed in the $^{235}U(d,pf)^{236}U$ reaction. The shapes of the resonances as well as the angular distributions of the associated fission fragments are analyzed together with the data obtained previously for ^{234}U. The resonances are interpreted as being hyperdeformed rotational bands with $\hbar^2/2\theta = 1.8^{+0.5}_{-0.7}$ and $1.6^{+1.0}_{-0.4}$ keV and K values of 1, 2, and 4 for ^{234}U and ^{236}U, respectively. [S0031-9007(98)05574-4]

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One of the most exciting aspects of research on nuclear shapes in recent years is the study of superdeformed (SD) and search for hyperdeformed (HD) nuclear shapes with a ratio of 2:1 and 3:1 for the long to short axis in deformed nuclei, respectively [1–3]. Although one of the main goals of a very large community with 4π γ-arrays such as GAMMASPHERE or EUROBALL is to search for HD states, up to now only some signs of HD rotational bands have been found, but no discrete HD levels have been identified.

In the actinide region a third minimum in the potential energy (which contains HD states) was predicted already more than 20 years ago by Möller *et al.* [4]. In these nuclei the so-called third minimum of the potential barrier appears at $\beta_2 \approx 0.90$ and $\beta_3 \approx 0.35$ [5–8].

Experimentally, the very large quadrupole and octupole moments of the HD states manifest themselves by the presence of alternating parity bands with very large moments of inertia [9]. With the aim of delineating new HD structure Blons and co-workers [10,11] measured the subbarrier resonances of the fission probability for several Th and U isotopes with high energy resolution. For ^{230}Th, ^{231}Th, and ^{233}Th they were able to describe the microstructure of the resonances as being HD rotational bands. However, for the U isotopes they encountered rather puzzling results [12].

In order to understand the large deformation observed for the fission isomers, Strutinsky [13] developed a macroscopic-microscopic method for calculating the potential energy of nuclei as a function of shape. In his approach the potential energy is given as a sum of a rather smooth barrier described by the liquid-drop model and an oscillating shell correction term. The macroscopic-microscopic models and the various steps involved in the calculations are extensively discussed in the literature [14]. These calculations resulted in a very shallow ($\Delta E \approx 0.5$ MeV) third minimum which can accommodate only a few very low-energy excitations.

A new impetus was given to the experimental studies of HD states by Ćwiok *et al.* [7], who predicted a much deeper ($\Delta E \approx 2.5$ MeV) third well for the actinide nuclei. Interestingly, this well splits into two distinct minima with very different β_3 values. The minimum with $\beta_3 \approx 0.6$ is almost as deep as the superdeformed minimum. In such a deep third well many excited hyperdeformed states might be accommodated and the interplay of large deformation and magicity may be studied [7].

Following Glässel *et al.* [15] the vibrational states of a nucleus having a complex potential energy surface (as discussed above) might be classified as class I, class II, or class III states, depending on whether the amplitude is the greatest in the ground state, the second, or the third minimum, respectively.

Higher-lying states in the second or third well could be studied by measuring the fission probability as a function of excitation energy. The states must be predominantly of β-vibrational type, i.e., the stretching mode, which leads to fission. If the levels in the first well are populated, e.g., by (d,p) reactions, one will observe an enhanced fission probability (transmission resonances) for those excitation energies in the first well which coincide with vibrational states in the second or third well.

In this paper we report the first high resolution study of the transmission resonances in ^{236}U. These results are interpreted together with the ^{234}U results obtained by Blons *et al.* [12] as a consequence of the hyperdeformed states lying in the third well of the fission barrier. Information on the spins of the above transmission resonances excited in the (d,p) reaction has been obtained from comparing the measured fission-fragment angular distributions with the results of PWBA calculations [15]. In PWBA calculations, the m-state population amplitudes with respect to the recoil axis are all zero except for $m = 0$. This implies axial symmetry for the measured fission-fragment angular distribution around the recoil axis.

Subbarrier resonances at about 5 MeV excitation energy have been observed previously in many actinide nuclei [9,16]. Based on the modest energy resolution measurements, these were believed to arise from the coupling of compound nuclear states in the first potential well to vibrations of the fission degree of freedom of the second potential well. Goldstone *et al.* [17] proposed that the observed transmission resonances in ^{234}U and in ^{236}U might be due to states in the second well, which consist of a fission vibration coupled to low-lying states in the second well such as rotations and $K^{\pi} = 0^+, 0^-, 2^+, 1^- \ldots$ collective vibrations. Blons *et al.* [12] were able to resolve the fine structure of the resonances in ^{234}U and they measured also the angular distribution of the fission fragments, but their results were not consistent with the angular distributions calculated with the assumption of single pure J resonances.

If the excitation energy is higher than the inner barrier of the second well, but lower than the barriers of the third well, then the transmission resonances corresponding to class II and class III states could in principle be distinguished according to their width. The width of class II resonances should be much broader due to the strong coupling to class I states, while the damping of class III resonances is hindered by the higher barriers of the third well. According to the above considerations the best energy region for studying the hyperdeformed states by measuring the transmission resonances in the actinides is indicated in Fig. 1, illustrating the ^{232,234,236}U potential barriers.

The experiment on ^{236}U was carried out at the Debrecen 103-cm isochronous cyclotron at $E_d = 9.73$ MeV and at $E_d = 13.0$ MeV at the Munich Tandem accelerator. Enriched (97.6% – 99.89%) 88 – 250 μg/cm^2 thick targets of ^{235}U were used.

The energy of the outgoing protons was analyzed in Debrecen by a split-pole magnetic spectrograph [18], which had a solid angle of 2 msr and was set at $\Theta_{\rm lab} = 140°$ with respect to the incoming beam direction. The position and energy of the protons were analyzed by two Si solid-state, position-sensitive, focal-plane detectors. The overall proton energy resolution of the system including the effects of the target thickness and long term stability was estimated to be less than 20 keV.

In Munich the energy of the outgoing protons was analyzed by a Q3D magnetic spectrograph [19], which was set at $\Theta_{\rm lab} = 130°$ relative to the incoming beam and the solid angle amounts to 10 msr. The position in the focal plane was measured by a light-ion, focal-plane detector of 1.8 m active length using two single-wire proportional counters surrounded by two etched cathode foils [20]. Using that detector with the spectrograph, a linewidth of $\leq$3 keV has been observed for elastic scattering of 20 MeV deuterons.

Fission fragments were detected in both experiments by two position-sensitive avalanche detectors (PSAD) [21] having two wire planes (with delay-line readout) corresponding to horizontal and vertical directions. Protons were measured in coincidence with fission fragments. Typical proton energy spectra are shown in Fig. 2 as a function of excitation energy.

A highly damped superdeformed (SD) vibrational resonance, which is very close to the top of the first barrier is clearly seen at 5.1 MeV [17]. Above this resonance we observed some sharper peaks (FWHM $\approx$ 30 keV) similar to the modest energy resolution work (FWHM = 60 – 70 keV) of Goldstone *et al.* [17] and to our previous results [22,23]. These resonances do not appear to be appreciably damped although they are above the top of the inner barrier, so these sharp resonances cannot be associated to SD states lying in the second well. These results support the presence of a deep HD minimum as predicted by Ćwiok *et al.* [7].

In the third well of the potential barrier the reflection-asymmetry permits almost degenerate levels of both parities in the rotational spectrum. These kinds of rotational

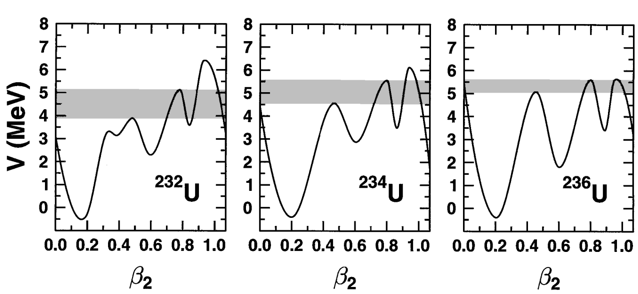

FIG. 1. Potential energy as a function of the quadrupole deformation parameter for a few U isotopes. The energy and location of the saddle points and minima (except for the third one) were taken from Ref. [14], while the energy of the third minimum for the less reflection—asymmetric HD minimum ($\beta_3 \approx 0.4$) was taken from Ref. [7]. 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 horizontally shadowed regions.

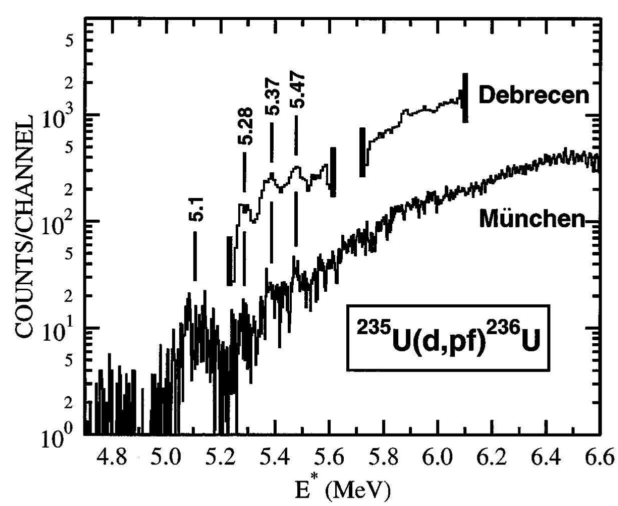

FIG. 2. Proton spectra in coincidence with the fission fragments measured in Debrecen and Munich.

levels have been nicely observed in the experimental fission probability of ^{231}Th [10]. Assuming that each of the observed resonances also contains a whole rotational band, we fit our experimental results by using simple Gaussian functions for describing the different members of the band following the same procedure of Blons *et al.* [10].

The relative excitation probabilities for members of the rotational band were taken from the work of Back *et al.* [16] who performed DWBA calculations for the (d, p) reaction at the same bombarding energy. The width of the Gaussians was fixed by our experimental resolution.

We have used the following free parameters: (1) Energy of the band head, (2) absolute intensity of the band, and (3) rotational parameter of the band. The last parameter was kept identical for all of the groups, i.e., the 5.28, 5.37, and 5.47 MeV groups. A fit to the measured spectrum was performed with the above parameters using least χ^2 method. The nonresonant part of the fission probability was taken into account as an exponential "background."

Assuming that we saw a rotational band built on an excited state rather than on the ground state in the HD potential well, we varied the K value of the band head as well during the fitting procedure. The same K value was assumed for all the groups observed. Assuming K values differing by one unit for the neighboring group did not change the χ^2 value much. The best fit was obtained with $K = 4$ as shown in Fig. 3(a). The K value of the target was $K = 7/2$. At the low bombarding energy we used (9.73 MeV) the $l = 0$ transfer is the most probable which implies the excitation of mainly $K = 3$ and 4 states in agreement with our results.

The calculated χ^2/F values as a function of $\hbar^2/2\theta$ are plotted in Fig. 3(b). The predicted values of $\hbar^2/2\theta$ for the hyperdeformed and superdeformed states are indicated by HD and SD, respectively. From our best fit we get $\hbar^2/2\theta = 1.6^{+1.0}_{-0.4}$ keV in good agreement with the value predicted for the hyperdeformed state $(\hbar^2/2\theta)_{\mathrm{theor}} = 2.0$ keV [6].

Fission-fragment angular distributions were generated for the 5.47 MeV line as well as for the continuous nonresonant part of the fission probability and normalized to the known (d, f) angular distribution [24]. The angular distribution is shown in Fig. 3(c). All distributions were fitted with even Legendre polynomials (LP) up to fourth order. For the nonresonant region our LP coefficients are in good agreement with the previously published data [25–27]. The measured angular distribution was compared to the calculated ones assuming different K values, in order to get information on the K value of the hyperdeformed rotational band. From the comparison the most probable K value of the band is $K = 4$ [see Fig. 3(c)], which is in perfect agreement with the analysis of the proton spectrum.

We also reanalyzed the results of Blons *et al.* [12] concerning ^{234}U in a similar way to that for ^{236}U. We

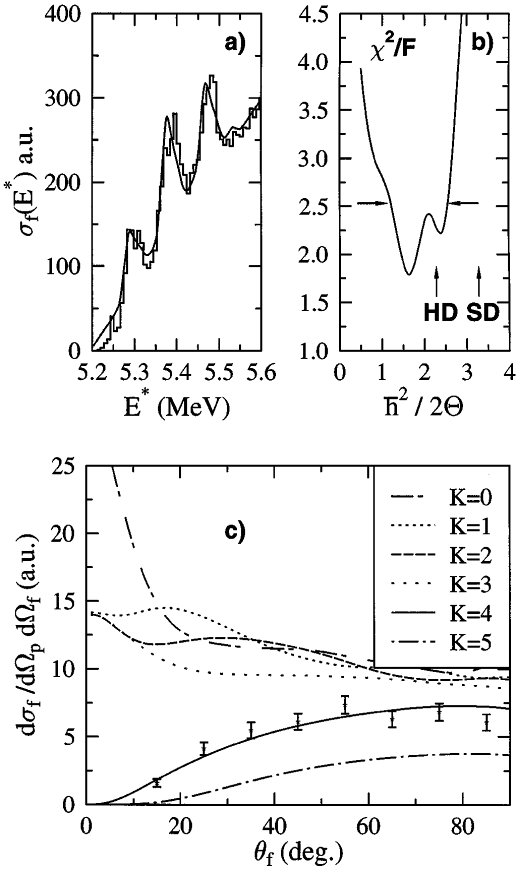

FIG. 3. (a) Proton spectrum measured for ^{236}U in coincidence with the fission fragments as a function of excitation energy, compared to the fitted rotational band; (b) the results of the χ^2 analysis; the theoretical predictions for the HD and SD rotational parameters are indicated by arrows; (c) experimental fission-fragment angular distribution for the 5.47 MeV resonance with respect to the recoil axis (z axis) compared to the calculated ones.

assumed that each of the resonances observed (see Fig. 4) consists of a complete rotational band.

The energy of the band heads, the absolute intensity of the bands, and an inertia parameter $(\hbar^2/2\theta)$ were fitted to the experimental data. The obtained inertia parameter is $\hbar^2/2\theta = 1.8^{+0.5}_{-0.7}$ keV, which is the average of the values at the equivalent χ^2 minima, and again agrees well with the predicted value for the HD states.

The angular distribution of the fission fragments was also calculated and compared to the experimental data [see Fig. 4(c)]. Good agreement has been obtained, which also supports that each of the peaks observed contains a complete rotational band with $K = 1$ or 2, instead of one definite state with a well defined J^π as assumed by Blons *et al.* [12]. The K value of the target was $5/2$, which implies the excitation of $K = 2$ or 3 states with $l = 0$ transfer.

We note that Blons *et al.* [12] observed many more resonances at higher energy up to $E^* \approx 5.5$ MeV, which corresponds to the energy of the inner barrier of the third well shown in Fig. 1. Their widths are very similar to

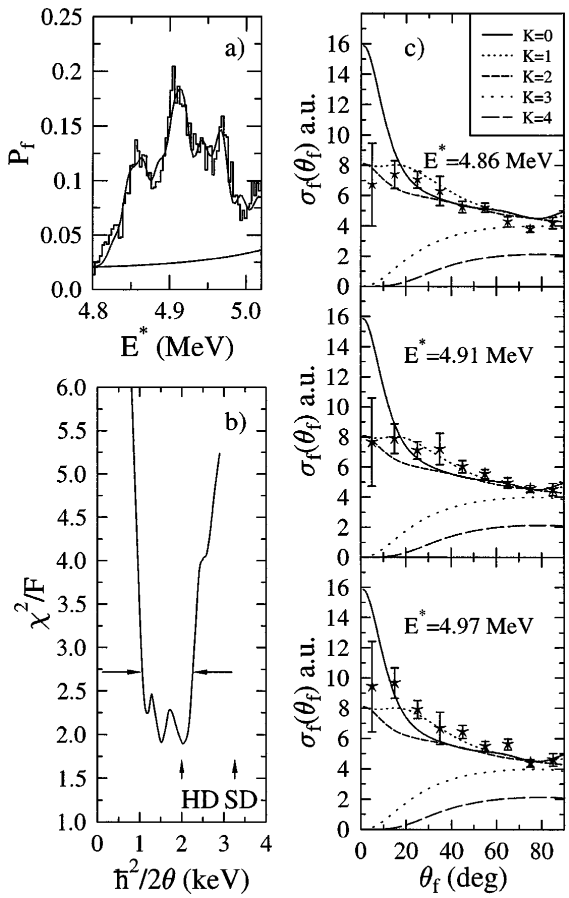

FIG. 4. (a) Fission probability of ^{234}U as a function of excitation energy. The full curve is a result of the fit with $\hbar^2/2\theta = 2$ keV according to the deepest χ^2 minimum; (b) the results of the χ^2 analysis; (c) fission fragment angular distributions for the 4.86, 4.91, and 4.97 resonances in ^{234}U compared to the theoretically calculated curves assuming different K values for the rotational bands.

the ones we analyzed here, but for the present analysis we chose only the resonances for which the angular distributions of the fission fragments were also published.

In summary, we have measured the fission probability of ^{236}U as a function of excitation energy with the (d, pf) reaction in order to search for the presence of a third minimum of the fission barrier. Our deduced moments of inertia and K values of the rotational bands observed in ^{234}U and ^{236}U support the existence of a deep HD minimum predicted by Ćwiok *et al.* [7]. In this potential well the transmission resonances observed in the fission probability might correspond to some higher-lying (e.g., two-neutron) states built on the basic vibrational states.

Another signature of the HD states could be their highly characteristic fission-fragment mass distribution [7]. In order to demonstrate an enhanced mass yield for masses around 134 and 100 we plan to measure the fission-fragment mass distribution of the HD states.

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