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NEW EXCITED STATES AND FISSION RESONANCES IN THE ACTINIDE REGION*

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The fission probability has been measured in the ^{231}Pa$(d,pf)^{232}$Pa and ^{231}Pa(^{3}He,df)^{232}U reactions as a function of the excitation energy. In the fission probability of ^{232}Pa new resonance groups were found and were interpreted as hyperdeformed rotational bands with a preliminary rotational parameter of $\hbar^2/\theta = 2.0^{+1.5}_{-1.0}$ keV. However, in the case of ^{232}U the fine structure of transmission resonances was not observed.

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1. Introduction

One of the most exciting aspects of research in nuclear structure physics in recent years is the study of nuclei having extremely large deformations. In the actinide region a third minimum in the potential energy, which contains hyperdeformed (HD) states, was predicted more than three decades ago. The authors have been investigating the excited states in this third minimum for a decade by measuring the microstructure of sub-barrier fission resonances [1–7]. Recently, we performed experiments on ^{232}U and ^{232}Pa nuclei. In these experiments we measured the fission probability as a function of the excitation energy and the angular distribution of the fission fragments in order to determine the moment of inertia, the spin and K-values of the rotational bands of the fission resonances.

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2. Experimental setup

The experiments were performed at the Tandem accelerator of the Maier-Leibnitz Laboratory (MLL) at Garching using ^{231}Pa(d, pf) and ^{231}Pa(^{3}He,df) reactions at a bombarding energy of 12 MeV and 38.1 MeV, respectively. The kinetic energy of the ejectiles was analyzed by a Q3D magnetic spectrometer [8], set to 139.4° for (d, pf) and 35° for (^{3}He,d). An energy resolution of $\Delta E = 11$ keV was achieved. Fission fragments were detected by a position sensitive avalanche detector (PSAD) [6], which consisted of two perpendicular wire planes, thus allowing for a detection of the fission fragment angular correlation with respect to the recoil axis. The fission detector covered a wide range of $\Theta_{\rm R} = 0°$–$100°$ relative to the recoil axis with a solid angle coverage of 10% of 4π.

3. Experimental results

3.1. Searching for hyperdeformed fission resonances in ^{232}Pa

Besides the thorium and uranium isotopes with respect to hyperdeformation the double-odd nucleus ^{232}Pa is of great interest. The fine structure of the fission resonances of this nucleus have been studied so far only via the (n, f) reaction [9] but the results of these experiments showed no conclusive evidence for the existence of a triple-humped fission barrier of ^{232}Pa.

Using the ^{231}Pa(d, pf) reaction on a radioactive ^{231}Pa target the fission probability of ^{232}Pa as a function of the excitation energy has been measured in order to search for hyperdeformed (HD) rotational bands. In contrast to the (n, f) reaction, the (d, p) reaction can transfer considerable angular momentum. The angular distribution of fission fragments was also studied to get information on spin and K-values of the rotational bands.

Fig. 1(a) displays the fission probability spectrum between $E = 5.7$ MeV and $E = 5.9$ MeV. In order to describe the rotational structure, overlapping rotational bands were assumed with the same moment of inertia (θ), and intensity ratio for the band members. Gaussians were used for describing the different band members. 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, see Ref. [2, 5] for the details. The angular correlation was analyzed by fitting it with even Legendre-polynomials up to fourth order: the angular coefficients a_2 and a_4 were determined for the most prominent structures parameterized by a series of rotational bands with K-value assignments as indicated in the figure. Fig. 1(b) shows the a_2 values only: the a_4 values contain much less information on the K-values due to the relatively poor experimental statistics. The high-resolution excitation energy spectra deduced from the

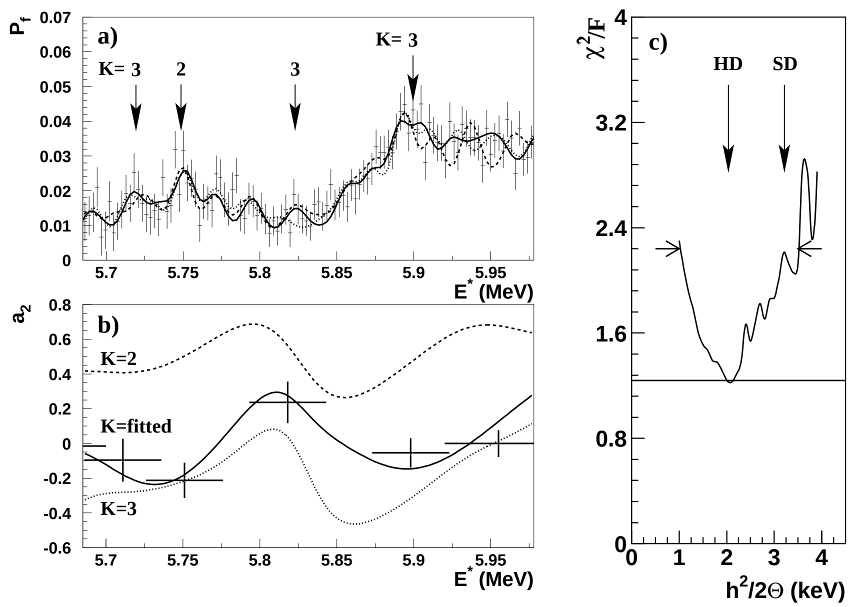

Fig. 1. (a) Fission probability of ^{232}Pa fitted with rotational bands. Dashed lines indicate the fitted rotational bands with $K = 2$ and $K = 3$ for all members, respectively. (b) Fission fragment angular correlation data calculated for rotational bands with different K-values on the experimental a_2 points. (c) Result of the χ^2-analysis indicating the HD structure of these resonances.

proton spectrum in Fig. 1(a) in combination with the analysis of the angular distribution measurement in a consistent description indicate the interpretation of the transmission resonance structures around 5.7 and 5.9 MeV as hyperdeformed rotational bands.

The rotational parameter was determined as $\hbar^2/\theta = 2.0^{+1.5}_{-1.0}$ keV based on the χ^2 test shown in Fig. 1(c).

3.2. Searching for hyperdeformed transmission resonances in ^{232}U

According to the most recent calculations the depth of third minimum for U isotopes is predicted to be much deeper than previously believed [10]. Fig. 2(a) shows the calculated potential energy [10] as a function of the nuclear deformation. Calculations performed in Ref. [10] predicted two deep third minima for different values of the reflection-asymmetry (the deeper minimum predicted for the more reflection-asymmetric configuration indicated by dashed line).

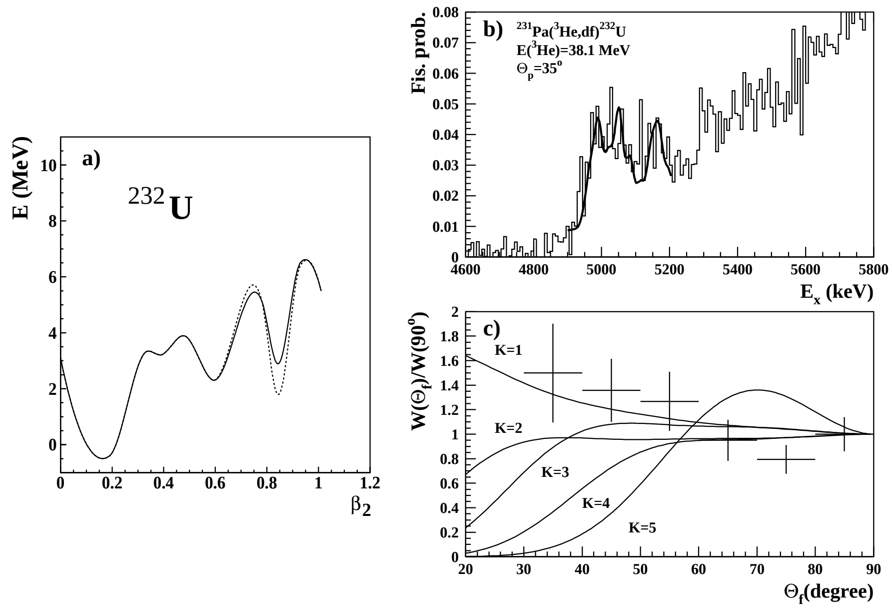

Fig. 2. (a) Potential energy curve of ^{232}U as a function of the nuclear deformation. (b) Fission probability spectrum measured in ^{231}Pa(^{3}He,d)^{232}U. (c) Experimental angular distribution for the 4.9 MeV–5.2 MeV energy region with angular distributions calculated for rotational bands with different K-value.

In our most recent experiment the fission probability of ^{232}U was measured as a function of the excitation energy, using the ^{231}Pa(^{3}He,df)reaction in order to get information about the third minimum of ^{232}U. The measured fission probability spectrum is shown in Fig. 2(b). In contrast to our previous results obtained so far for ^{240}Pu [6], ^{234}U [1] and ^{236}U [7] similar resonance structure has not been observed. This may partly be explained by the asymmetry of the inner and outer fission barrier heights which does not favor the occurrence of the transmission resonances and may be attributed to the reduced rotational energy differences due to the lower target spin in ^{231}Pa ($3/2^-$) compared to $7/2^-$ in ^{235}U. A comparison of the experimental angular distribution to the calculated ones (for bands with different K-values) confirms the appearance of rotational bands with low K-values (Fig. 2(c)). The reduced, present energy resolution of FWHM = 20 keV caused by the larger energy loss of ^{3}He, compared to the previously used deuterons and the non optimal target angle may also inhibit the resolved observation of rotational states. Due to the limited energy resolution of the angular correlation data the a_2 angular correlation coefficients for states with different spins cannot be extracted. Instead of that, Fig. 2(c) shows the angular correlation extracted for the whole resonant structure between $E_x = 4900$ keV and 5100 keV. The result of the same fitting procedure as described in the previous section suggests the interpretation of the structure as being hyperdeformed fission resonances (three rotational bands with $K = 1$). However, a superdeformed description of the structure cannot be excluded due to the result of the χ^2-analysis. Further experiments with better energy resolution and higher statistics is planned to study this interesting phenomenon in ^{232}U.

4. Conclusion

In summary, we have measured the prompt fission probability of ^{232}Pa and ^{232}U as a function of the excitation energy using the (d,pf) and $(^3\mathrm{He},df)$ reaction, respectively, in combination with the measurement of the angular correlation of the fission fragments in order to study the nature of the high-lying rotational bands. For the rotational bands of ^{232}Pa the rotational parameter was determined to be $\hbar^2/\theta = 2.0^{+1.5}_{-1.0}$ which is an indication of being hyperdeformed rotational bands. The fission probability of ^{232}U was measured for the first time. The energy and angular correlation data can be described by assuming HD rotational bands with $K = 1$, which is consistent with our recent data obtained for ^{234}U and ^{236}U and also with the theoretical prediction of Cwiok *et al.* However, better quality data is needed for the unambiguous assignments of the rotational bands for the extraction of the parameters of the fission barrier.

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