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Evidence for Rotational Bands near the $^{232}Th(n,f)$ Fission Threshold

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The $^{232}Th(n,f)$ cross section and the angular anisotropy of fission fragments have been measured up to 5 MeV. The broad vibrational levels located above 1 MeV are resolved into sharp structures which are interpreted as rotational states. The rotational constants $\hbar^2/2\mathcal{J}$ of highly deformed ^{233}Th are found to be 2.46 and 2.73 keV at 1.5 and 1.6 MeV, respectively. Our results are interpreted in terms of a hypothetical third minimum in the fission barrier.

The double-humped fission barrier, as calculated with the Strutinsky prescription,[1] has proved very fruitful in explaining most of the fission results. It is now possible to calculate potential energies of deformation which in general agree with the experimental results within 1 MeV. However, for the thorium isotopes, the calculated heights of the first maximum and the second minimum are substantially lower than the experimental values. These thorium isotopes are known to present sub-barrier resonances which are currently interpreted as evidence of vibrational states in the second well of the fission barrier.[2] In order to study the above thorium anomaly, we decided to measure the $^{232}Th(n,f)$ cross section in the threshold region with the best resolution obtainable with the 60-MeV Saclay linear accelerator. Futhermore, the angular anisotropy of the fission fragments, which is sensitive to the values of the total angular momentum J and its projection K on the symmetry axis of the nucleus undergoing fission, has also been measured.

The experiment was performed on a 51.9-m flight path providing a resolution of 3 keV at 1.6 MeV. The fission events were detected in a large-volume gas scintillator containing 803 mg of ^{232}Th in the form of 2-mg/cm^2 layers of ThO_2. A separate cell of the scintillator was loaded with 384 mg of ^{235}U in order to allow the normalization of the ^{232}Th data relative to the ^{235}U cross section from version IV of the evaluated nuclear data file (ENDF/BIV).

In a second experiment a grid placed against the thorium layer was used to stop the fission fragments emitted at an angle greater than 30° relative to the neutron direction. By comparison with the data provided by a cell without a grid it was thus possible to measure the anisotropy of the fission fragments. Because of the smaller counting rate, this experiment had to be done on a smaller flight path (22.4 m), with a resolution of 6 keV at 1.6 MeV. Figure 1 shows the angular anisotropy of the fragments: The number of fission fragments detected in the cell with the grid relative to the number detected in the cell without the grid is plotted versus the neutron energy. This ratio has been corrected for the transmission coefficient of the grid ($\frac{1}{32}$). In Fig. 1, we also indicate the calculated values of the ratio

$$a(K,J)=\frac{\int_0^{30^\circ} w(K,J;\theta)\sin\theta\,d\theta}{\int_0^{90^\circ} w(K,J;\theta)\sin\theta\,d\theta}$$

where $w(K,J;\theta)$ is the angular distribution for a

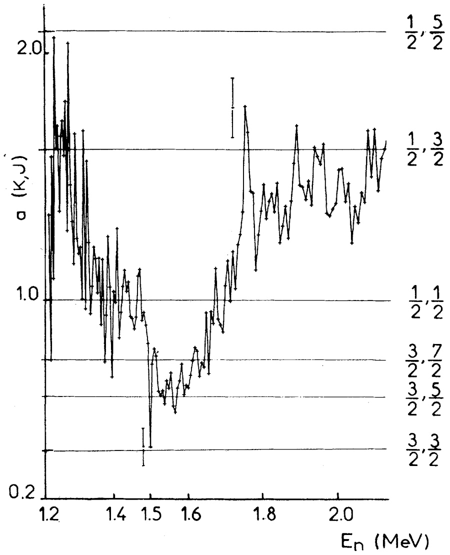

FIG. 1. Experimental fission-fragment anisotropy in the ^{232}Th(n,f) reaction with an energy resolution of 6 keV at 1.6 MeV and theoretical evaluations for some specific K and J values.

set of fixed K,J values.

A comparison of the experimental results with these theoretical predictions indicates that, although several values of K contribute to the fission cross section at any fixed energy, a certain predominance of $K=\frac{1}{2}$ at 1.4 and 1.7 MeV and $K=\frac{3}{2}$ at 1.5 and 1.6 MeV can be discerned in Fig. 1.

In the fission cross section shown in Fig. 2, the 1.6-MeV resonance is resolved into four narrow peaks. Similarly, the resonance at 1.7 MeV displays three peaks; one can also distinguish a group of three peaks slightly above 1.4 MeV and a group of four peaks above 1.5 MeV. A broad resonance similar to the one at 1.6 MeV has been studied by James *et al.*[3] in the ^{230}Th(n,f) cross section and, although they were unable to resolve the different components, the authors have analyzed this resonance in terms of a rotational band of the standard form:

$$\epsilon(J,K)=\epsilon_K+(\hbar^2/2\mathcal{J})[J(J+1)-K(K+1)+\delta_{K,1/2}a(-1)^{J+1/2}(J+\tfrac{1}{2})],$$

where $\mathcal{J}$ is the moment of inertia and a the decoupling parameter for $K=\frac{1}{2}$.

The calculated energy interval $\Delta\epsilon(J)_{\text{calc}}$ between two consecutive peaks in a rotational band,

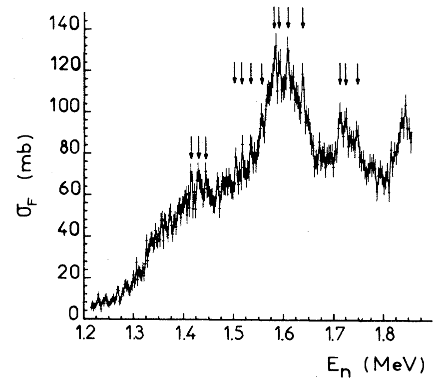

FIG. 2. ^{232}Th(n,f) cross-section values and statistical error bars obtained with a resolution of 3 keV at 1.6 MeV. The arrows indicate the position of the peaks listed in Table I.

for $K\neq\frac{1}{2}$, is

$$\Delta\epsilon(J)_{\text{calc}}=\epsilon(J+1,K)-\epsilon(J,K)=(\hbar^2/2\mathcal{J})2(J+1).$$

Least-squares fits to the experimental values $\Delta\epsilon(J)_{\text{exp}}$ for the $K=\frac{3}{2}$ resonances are plotted in Fig. 3. The rotational constants $\hbar^2/2\mathcal{J}=2.46\pm0.11$ and 2.73 ± 0.11 keV for the 1.5- and 1.58-MeV groups, respectively, are less than half the values usually observed in the first well. The experimental energies of the peaks $\epsilon(J,K)_{\text{exp}}$ obtained by a least-squares fit to the cross-section data are given in Table I.

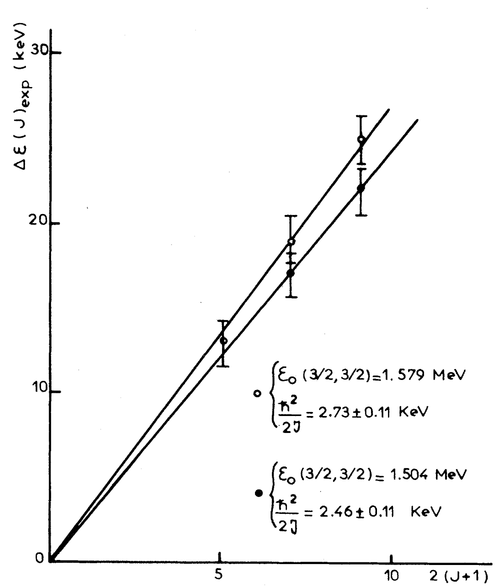

FIG. 3. Least-squares fits to the energy intervals $\Delta\epsilon(J)_{\text{exp}}$ for the $K=\frac{3}{2}$ resonances.

TABLE I. Experimental and calculated values for rotational bands.

$[K, J]$	$\epsilon(J,K)_{exp}$ (MeV)	$\epsilon(J,K)_{calc}$ (MeV)
[1/2,]	1.415	...
[1/2,]	1.429	...
[1/2,]	1.444	...
[3/2, 3/2]	1.504	1.504
[3/2, 5/2]	1.517	1.516
[3/2, 7/2]	1.534	1.533
[3/2, 9/2]	1.556	1.555
[3/2, 3/2]	1.579	1.579
[3/2, 5/2]	1.592	1.593
[3/2, 7/2]	1.611	1.612
[3/2, 9/2]	1.636	1.637
[1/2,]	1.711	...
[1/2,]	1.724	...
[1/2,]	1.748	...

It should be noted that J values are determined from the energy intervals, whereas the anisotropy experiment, being unable to resolve individual peaks, allows a determination of K values only.

If the rotational levels were located in the second well of the fission barrier, their width (about 10 keV) would indicate that this well is much shallower than expected. By introducing mass-asymmetric deformation, Moller and Nix have found that for $N < 146$ the second saddle point is split into two individual saddle points separated by a "third minimum."[4] They proposed this third minimum (which is very shallow) as a simple explanation of the thorium anomaly; but this would not explain the existence of so many rotational bands. One may even question whether the third miminum is deep enough to trap a level at all, but one may think that the second saddle region is broad and almost flat topped. Moreover, since the calculations have been made for the even-even ^{232}Th nucleus, we have to add, for ^{233}Th, the quasiparticle energy of the last neutron. The specialization energy of the $\frac{3}{2}$ state, for instance, will result in the crossing of a few $\frac{3}{2}$ single-particle levels and will show up as peaks and valleys in the second saddle region. Since there are not many $\frac{3}{2}$ single-particle states, each valley is probably deep enough to trap one vibrational state and its associated rotational band. Such a behavior would explain qualitatively the existence of several rotational bands with slightly different moments of inertia.

It is worth noticing that our experimental determinations of the moments of inertia $2\mathcal{I}/\hbar^2 = 407 \pm 26$ and 366 ± 22 MeV^{-1} for the 1.5- and 1.58-MeV groups, respectively, are significantly greater than the value of 300 MeV^{-1} reported by Specht *et al.*[5] for the ^{240}Pu fission isomer in the second well of the fission barrier. They are however very close to the 400 MeV^{-1} value calculated by Sobiczewski *et al.*[6] for the second saddle point. This agreement gives some confidence in the above third-minimum interpretation.

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