Isomer shells in the cross section of deep subbarrier photofission of heavy nuclei

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For the isotopes ^{232}Th, ^{237}Np, and ^{238}U, in the deep subbarrier region, we observed an abrupt decrease of the slope of the energy dependence of the photofission cross section, called the isomer shelf. An investigation of this phenomenon uncovers a number of new possibilities for the refinement of our concepts concerning the structure of the fission barrier of heavy nuclei.

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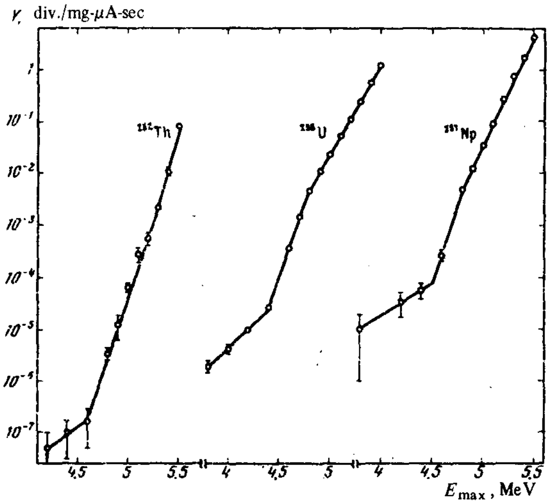
The reaction (γ,f) is apparently the most favorable for the study of nuclear fission at low excitation energies. The energy region up to 1 MeV below the fission threshold was investigated in detail in[1]. Bowman has shown recently,[2] on the basis of the double-hump barrier concept, that at still lower excitation energies there should be observed the phenomenon of "isomer shelf," which consists in a sharp decrease of the slope of the energy dependence of the photofission cross section. Bowman[3] has also obtained the first experimental data on the existence of such a shelf in the cross section of the reactions ^{238}U(γ,f). We have undertaken investigations of this phenomena for a larger group of nuclei.

The measurements were performed with the bremsstrahlung beam of the microtron of our Institute, at maximum γ-ray energies from 3.8 to 5.5 MeV and at an average electron current 60–80 μA. The target was made up of plates of tungsten 1 mm thick and aluminum 12 mm thick. The time of bombardment of the fissioning samples was 30 hr. The samples were placed directly behind the decelerating target, along the axis of the electron beam. Mica fragment detectors were used. To increase the fragment yield, the fissioning samples were foils of thorium and uranium (the ^{235}U content was decreased by a factor 200) and the ^{237}Np layer was ~1 mg/cm^2 thick. To estimate the background of the fission induced by the neutrons, control measurements were performed at 4.0 MeV with a ^{238}U sample located outside the γ-ray beam. The fragment tracks obtained in this case coincided with the activity of the spontaneous fission of the investigated uranium sample.

The measured yields of the (γ,f) reaction are shown as in the figure functions of the end-point energy of the bremsstrahlung spectrum. Since the γ-ray bremsstrahlung spectrum is described by a function that decreases with energy, while the cross section of the photofission in the subbarrier region is an exponentially increasing function, the observed integral yield of the fragments practically duplicates the energy dependence of the cross section, but with an approximate shift of 0.2 MeV to the left along the abscissa axis. The isomer shelf appears clearly for all three investigated isotopes, although the statistical errors of the low-energy points are quite large in the case of ^{232}Th and ^{237}Np.

The origin of the "isomer shelf" is interpreted within the framework of the double-hump barrier model in the following manner. Nuclei that fall in the second well



Energy dependence of the photofission yield of ^{232}Th, ^{238}U, and ^{237}Np.

with probability $P_A(P_A + P_{\gamma_1})^{-1}$ experience prompt fission with probability $P_B(P_a + P_B + P_{\gamma_2})^{-1}$ and delayed fission with probability $kP_{\gamma_2}(P_A + P_B + P_{\gamma_2})^{-1}$, the delay being determined by the time of the spontaneously fissioning isomers produced as a result of the γ transitions in the second well. Accordingly, the fission cross section can be represented in the form

$$\sigma_f = \sigma_c \frac{P_A}{P_A + P_{\gamma_1}} \frac{P_B + kP_{\gamma_2}}{P_A + P_B + P_{\gamma_2}}, \qquad (1)$$

where σ_c is the cross section for the production of the compound nucleus, P_A and P_B are the penetrabilities of the barriers A and B, P_{γ_1} and P_{γ_2} are the radiative penetrabilities of the decay in the first and second wells, and $k \le 1$ is the branching coefficient and determines the average ratio of the probabilities of the spontaneous fission and the radiative decay to the first well for isomeric states. For a parabolic barrier we have $P_i(E) \approx \exp[2\pi(E - E_{fi})/\hbar\omega_i]$; $E - E_{fi} \gg \hbar\omega_i/2\pi$, where E_{fi} and $\hbar\omega_i$ are the height of the i-th barrier and its curvature parameter.

At $P_B \gg kP_{\gamma_2}$, the predominant contribution to the observed fragment yield is made by prompt fission, and if the inequality is reversed the contribution is made by delayed fission. From the structure of (1) it follows that the cross section of the delayed fission can be obtained from the prompt cross section by multiplying by the factor kP_{γ_2}/P_B, and the quantity $d\ln\sigma_f/dE$, which characterizes the curvature of the energy dependence of the cross section, is obtained by decreasing by the factor $[(2\pi/\hbar\omega_B) - (d\ln P_{\gamma_2}/dE)] > 0$, which indeed explains the shelf effect.

The results obtained above can be easily understood also on the basis of simple physical considerations: in delayed fission, unlike in prompt fission, the penetrability of the barrier B from the isomeric states remains the same with changing energy, and all that changes is their population probability, which is proportional to P_{γ_2}; in other words, the barrier B plays no part.

Measurements of shelves in deep subbarrier fission cross sections can be an effective means of studying spontaneously-fissioning isomers with very low yields and short lifetimes. The shelf in the cross section for the ^{232}Th photofission is the first experimental indication of the existence in it of a spontaneously fissioning isomer with a yield that is smaller that that of ^{238}U by at least two orders of magnitude. Identification of this isomer by traditional procedures would encounter very great difficulties. An investigation of isomer shelves is also of interest in a much wider context, as a new source of information on the structure of the barrier. Realization of this possibility calls for a thorough discussion, which is beyond the framework of this communication.

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