^{238}U and ^{232}Th Photofission and Photoneutron Emission near Threshold*

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Variable-energy photons defined to 100 keV were used to study ^{238}U and ^{232}Th from 5 to 8 MeV. The inferred fission transmission indicates (a) that the lowest 1^- fission barrier is about 6.5 MeV in ^{238}U and 6.3 MeV in ^{232}Th, and (b) that there is an energy gap before the rapid opening of additional fission channels above 7 MeV in ^{238}U.

Fission seems to be governed by the spectrum of transition states that exists at nuclear deformations corresponding to the fission saddle point, as predicted by Bohr.[1] We now know[2,3] that many actinide nuclei have two saddle points; as the deformation increases, the potential energy rises to a maximum, E_A, falls to a minimum, $E_{\rm min}$, and rises to a second maximum, E_B. Transfer reactions have been used to learn about fission-barrier parameters,[4] but because these reactions excite states with many spins and parities they are not very sensitive[4] to states of any particular spin and parity except for the lowest transition state which has $J^\pi = 0^+$. Our data provide, for the first time, a relatively direct determination of the lowest 1^- transition states. The relative spacing of 1^- and 0^+ states at A and B helps show how deformation affects the relative energy of different states. The rapid opening of many 1^- states suggests the size of the pairing gap at B.

Photofission is particularly revealing, as is well known,[1,2,5] because the dominance of electric dipole excitation produces essentially only 1^- states in even-even nuclei. However, previous attempts to find the energy dependence of photofission suffered as a result of the lack of either variable-energy γ rays[6-9] or good enough energy resolution.[10-16]

Our improved energy resolution was obtained with a bremsstrahlung monochromator[17]; incident electrons with energy E_i emerge from a very thin converter with energy E_e after producing a photon of energy $E_\gamma = E_i - E_e$. The detection of the electron of energy E_e tags the photon, determining its energy and formation time. The electrons came from a new accelerator[18] which recirculates electrons through a superconducting linac; the electron-beam energy and duty cycle were either 9.7 MeV and 40% or 8.4 MeV and 60%.

The energy of neutrons produced when these photons interacted in thick targets was determined by timing the flight of the neutrons over a 70-cm path at 135°. The neutrons were detected in liquid scintillator, NE 213; pulse-shape dis-

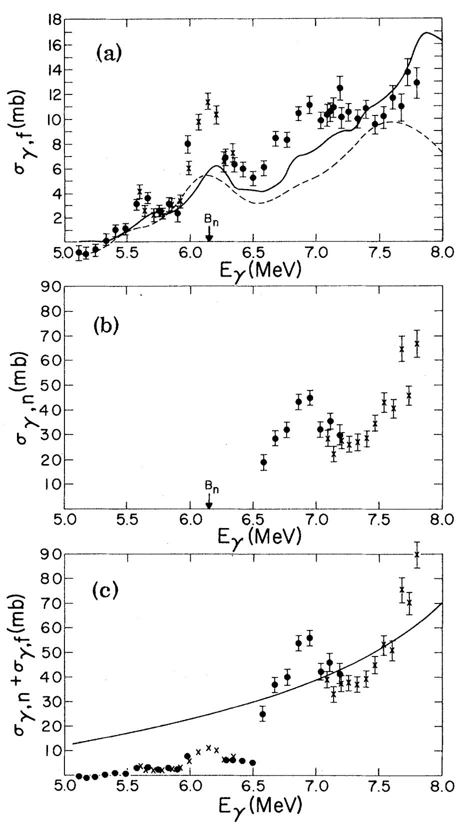

FIG. 1. Photon-induced cross sections for ^{238}U. All of the points come from this experiment. In (b), (c), and the low-energy portion of (a) the different symbols identify different runs; the spacing of points in a single run is equal to the photon-energy resolution. (a) Photofission cross sections. The curves correspond to measurements with poorer resolution; the solid curve is from Ref. 12 and the dashed curve is from Ref. 14. (b) Photoneutron cross sections inferred by measuring only those neutrons with energy above 300 keV. (c) Below 6.6 MeV the points represent $\sigma_{\gamma f}$ only. Above 6.6 MeV, the points are the sum, $\sigma_{\gamma f} + \sigma_{\gamma n}$, with statistical errors shown. The line is the extrapolation of the Lorentzian curves which have been fitted to the giant dipole resonance as reported in Ref. 19.

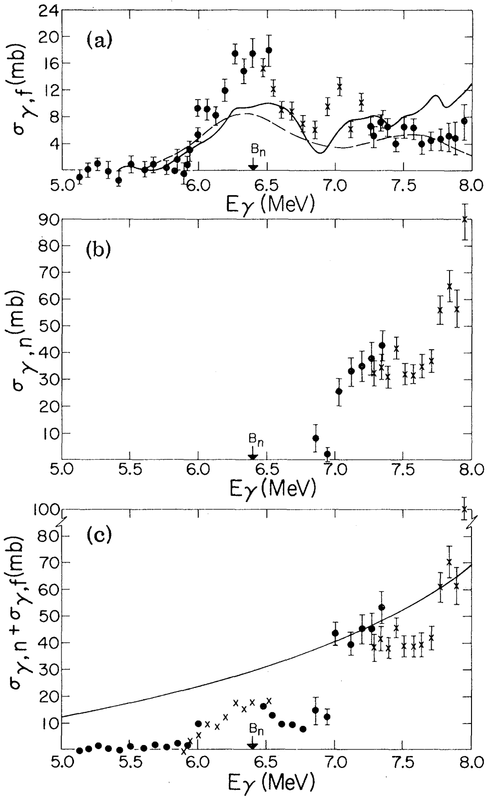

FIG. 2. Photon-induced cross sections for ^{232}Th. All of the points come from this experiment. In (b), (c), and the high-energy portion of (a), the different symbols identify different runs. The spacing of the points in a single run is equal to the photon-energy resolution. (a) Photofission cross sections. The curves correspond to measurements with poorer resolution; the solid curve is from Ref. 12 and the dashed curve is from Ref. 13. (b) Photoneutron cross sections inferred by measuring only neutrons with energy above 300 keV. (c) Below 6.9 MeV the points represent $\sigma_{\gamma f}$ only. Above 6.9 MeV, the points are the sum, $\sigma_{\gamma f}+\sigma_{\gamma n}$, with statistical errors shown. The line is the extrapolation of the Lorentzian curves which have been fitted to the giant dipole resonance as reported in Ref. 19.

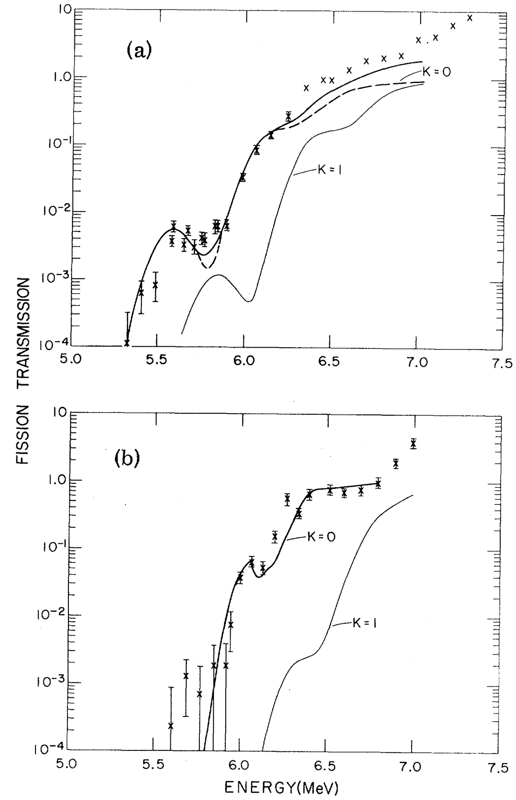

FIG. 3. Fission transmissions: (a) ^{238}U. The upper solid curve is the sum of the $K=0$ and $K=1$ transmissions calculated with the parameters in Table I. The dashed curve shows the $K=0$-barrier contribution when it is noticeably lower than the sum. (b) ^{232}Th. The curves are calculated transmissions for $K=0$ and $K=1$ using the barrier parameters listed in Table I.

crimination was used to distinguish neutrons from γ rays. Neutrons whose energy exceeded the maximum energy possible for photoneutrons indicated photofission; photoneutrons were apparent as an excess of low-energy neutrons above that measured for fission spectra.

The photofission cross sections, shown in Figs. 1 and 2, assume the average neutron multiplicities[2] $\bar{\nu}_U = 2+0.13E_\gamma$ and $\bar{\nu}_{Th} = 1.4+0.13E_\gamma$; these cross sections would be 15% higher if the multiplicities of Caldwell, Dowdy, and Worth[20] are correct. The experimental errors indicated in Figs. 1 and 2 include only the statistical uncertainties; the data were obtained in eight runs each of which lasted about 36 h. The systematic errors are probably less than 15%.

We calculated absolute fission transmission factors by comparing our photofission values with the photon interaction cross section, as explained in Ref. 12. At energies more than 600 keV above the photoneutron threshold, we used as the photon interaction cross section the sum of our measured values for $\sigma_{\gamma f}$ and $\sigma_{\gamma n}$. At lower energies, the photon interaction cross section was assumed to be that predicted by extrapolating the giant resonance[19]; this extrapolation is shown by the solid lines in Figs. 1(c) and 2(c). The γ ray competition was obtained from page 122 of Ref. 2. The neutron competition was calculated[21] by summing optical-model transmission coefficients[22] to known states in the residual nuclei ^{237}U and ^{231}Th. The inferred fission transmissions are shown in Fig. 3.

At an energy above the barriers of several transition states, the fission transmission is expected to be equal to the number of open fission channels. Figure 3(a) implies that between 6.7 and 6.9 MeV only two channels are open, presumably corresponding to two collective 1^- transition states. The fission channels begin opening rapidly only above 7 MeV. If this rapid increase is due to 1^- states made of two quasiparticles, Fig. 3(a) provides graphic evidence for the pairing gap in transition states; the two-quasiparticle states begin to appear 0.9 MeV above the 0^+ barrier[4] at E_B.

The continuous rise of the data points in the neighborhood of the neutron threshold in Fig. 3(a) indicates that the decrease in photofission just above 6.2 MeV [Fig. 1(a)] can be attributed to neutron competition, as previously suggested.[5] This conclusion is based on the observation that the photon interaction cross section follows the curve in Fig. 1(c) rather than having a local peak[16] near 6.2 MeV.

Although it is impractical in this brief report to discuss adequately the precision with which these data determine the different fission-barrier parameters, it is worthwhile to compare some calculated transmissions with the data, particularly because the barrier parameters for ^{238}U are quite different from some that have been used.[15,23] A double-humped fission barrier was constructed by smoothly joining parabolas which go through E_A, $E_{\min}$, and E_B; the curvature of each parabola is described, as usual[2], by $\hbar\omega$.

A bump in the transmission, such as can be seen near 5.6 MeV in Fig. 3(a), is attributed to an excited vibrational level in well II, between A and B. The sub-barrier transmission through a double-humped barrier has very sharp resonances. In order to simulate the spreading that would be caused by the mixing between a vibrational level and its neighboring levels in well II, a Gaussian line was folded over the pure-barrier transmissions in order to spread the resonances in energy. We used one energy-independent spreading width for each barrier. We originally chose 200 keV for all of the spreading widths but changed the lowest barrier to 230 keV in ^{238}U and to 160 keV in ^{232}Th to match the data better.

The curves in Fig. 3 show the calculated transmissions for the barrier parameters given in Table I. The K quantum numbers were assigned on the basis of ^{238}U angular distributions[24] which can be matched if the lowest barrier was $K=0$ and if there is a second barrier with $K=1$. The

TABLE I. Fission-barrier parameters (energies given in MeV).

	J^π	K	E_A	$E_{\min}$	E_B	$\hbar\omega_A$	$\hbar\omega_{\min}$	$\hbar\omega_B$
^{238}U	0^+	0	5.9[a]	2.0	6.1[a]	1.0[a]	0.9	0.6[a]
	1^-	0	6.5	2.35	6.1	1.0	0.9	0.6
	1^-	1	6.7	2.55	6.6	1.0	0.9	0.6
^{232}Th	0^+	0	< 5.5[a]	3.0	6.1[a]	0.9[a]	1.5	0.5[a]
	1^-	0	6.3	3.1	6.3	0.9	1.0	0.45
	1^-	1	6.5	3.3	6.9	0.9	1.0	0.5

[a]Values taken from Ref. 4.

$K=1$ barrier was chosen so that the fission transmission through it increases much more rapidly with energy near 6.2 MeV than does the transmission through the $K=0$ barrier; this may provide an explanation for the different energy dependences of different components of the angular distributions.[24] The transmission through the $K=1$ barrier is not given the double weighting that would be appropriate in a statistical treatment of nonzero K values at higher excitation.[25] The 1^--barrier parameters were also guided by the 0^+-barrier parameters in Table I, and by the expected near degeneracy[26,5] of the 0^+ and 1^- $K=0$ barriers at B. Because this near degeneracy need not apply to the 1^- $K=1$ barrier, its shape was chosen to be more similar to the 0^+ barrier. For ^{232}Th, the points in Fig. 3(b) are fitted as well by the $K=0$ 1^- barrier alone as by the combination including $K=1$. The ^{232}Th barrier parameters are similar to those suggested[27] to explain qualitatively angular-distribution results.[11]

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High-Spin Anomalies in Yb: Coriolis Antipairing versus Pair Realignment with a Realistic Interaction

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The Hartree-Fock-Bogoliubov cranking equations are solved for ^{168}Yb and ^{170}Yb with an effective interaction obtained from the Reid soft-core nucleon-nucleon potential. Coriolis antipairing in ^{168}Yb and pair realignment in ^{170}Yb explain their anomalous high-spin spectra.

A realistic description of the anomalous high-spin spectra of rare-earth nuclei[1] involves the following program: First, the calculation of an effective interaction based on a realistic nucleon-nucleon potential. Second, a reasonable description of the nuclear ground state, where both deformation and pairing properties are obtained from the same interaction. Third, the application of a unified formalism general enough to encompass the various mechanisms proposed to explain the "backbending" phenomenon. These mechanisms are the Mottelson-Valatin Coriolis