Quantum effects in low-energy photofission of heavy nuclei

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The article is devoted to quantum effects in highly deformed nuclei and the related features of the fission mechanism in the low-energy photofission of heavy nuclei. The following questions are considered: the spectrum of transition states (fission channels), the symmetry of the nuclear configuration in the deformation process, the features of the passage through the barrier due to the existence in the second well of quasistationary states of fissile and nonfissile modes, the isomeric-shelf phenomenon in deep sub-barrier fission, and the relation between the fragment mass distribution and the structure of the fission barrier.

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"The thing that seems best to each person is that for which he has an inclination."
Koz'ma Prutkov

INTRODUCTION

More than 40 years have passed since the discovery of fission by Otto Hahn and Fritz Strassman, a period of time which, it would seem, is sufficient to almost exhaust any field of investigation. Nevertheless the physics of fission, which has undergone several rises and falls during its history, remains the subject of intensive study by experimenters and theoreticians, not to mention the tremendous practical value of fission as a source of nuclear energy.

Today it is hard to imagine the perplexity and disbelief with which physicists received the report of fission of nuclei by slow neutrons, since it was well known that to remove a nucleon from a nucleus requires an energy of millions of electron volts. In the words of Robert Leachmen,[1] this is equivalent to a solid rock being split by the light tap of pencil. Nevertheless the first explanation of the observed process was advanced by Niels Bohr and J. A. Wheeler[2] and independently by Ya. I. Frenkel'[3] only a few months later on the basis of an analogy between the fission of a nucleus and the fission of a charged drop of liquid during deformation. It should be noted that the liquid-drop model remains up to the present time one of the principal models of fission, describing a number of aspects of this astonishing phenomenon. It was assumed for a long time that the correct inclusion of the electrical forces of repulsion of the two fission fragments and the attraction as the result of the surface energy would give the possiblity of describing in detail all characteristics of fission, including the fission barrier which arises as the result of the competition of these forces and the properties of which are closely related to the subject of the present review. Even among universally respected theoretical physicists there was the opinion that the study of fission was a specialized area without scientific promise. for example, H. A. Bethe in 1947 wrote, "After all this process is a specialized phenomenon in nuclear physics."[4]

Therefore it was with complete surprise that experimenters in the early 1950s observed an anisotropy of the angular distribution of fission fragments near the barrier.[5] The origin of this phenomenon was hard to understand in the framework of the classical ideas of the liquid-drop model. The orientation of nuclei in space is determined by the alignment of their angular momenta **J** with respect to the only distinguished direction—the direction of the incident beam. It was necessary to find a mechanism which would provide a nonuniformity of the distribution of K—the projection **J** on the nuclear asymmetry axis, which is also the direction of emission of the fragments, and thus would provide an anisotropy of their angular distribution (the latter is isotropic if the distribution of K is uniform). The nature of this mechanism was then associated with the existence of a discrete structure of the so-called fission channels—transition quantum states of the fissioning nucleus at the top of the barrier. Thus, the discovery of the angular anisotropy of fragment emission led for the first time to a realization of the influence of the quantum properties of the fissioning nucleus on the fission process.

Beginning in the middle 50s, physicists began to realize the futility of attempting to explain in the framework of the liquid-drop model another remarkable property of the fission of heavy nuclei—the asymmetry of the fragment-mass distribution. They began to pay attention to the influence of shell effects on the fission process. It is true that at one time it appeared that these effects hardly play an important role, since their contribution, for example, to the nuclear deformation energy (a few MeV) is insignificant in the background of the total energy released in fission (about 200 MeV). However, the development of the statistical description of the asymmetry of fission[6] refuted this opinion: just ths scale of variation of the deformation potential energy at the moment of separation, due to the exponential energy dependence of the level density, leads to changes of the mass yield by orders of magnitude. The energetic advantage of fission into fragments one of which is close to the doubly magic $Z=50$, $N=82$ results in dominance of fission into unequal parts with the most probable masses rather close to those observed. The role of the shell structure of the fragments showed up still more clearly in their other properties: the kinetic energy and the yield of neutrons and γ rays.

The influence of shell effects was felt not only in the later stages of fission. The barrier heights and the spontaneous-fission half-lives plotted as a function of the principal parameter of the liquid-drop model Z^2/A revealed a structure distinctly correlated with the shell corrections to the liquid-drop mass formula.[7] At the same time the theory for a long time did not give a correct answer to an important question: is the influence of shells preserved in the intermediate deformation region in the fission process—the region from the ground state of the nucleus to the point of separation (scission) into fragments?

The shell structure of nuclei is a fundamentally quantum phenomenon associated with the discrete structure of the single-particle levels near the Fermi level. The properties of this spectrum depend strongly on the number of nucleons in the nuclei (the filling of the shells). For spherical nuclei with a magic number of nucleons 8, 20, 28, 50, 82, 126 . . . (the gross shells) a significant rarefaction of the spectrum of single-particle levels as the result of degeneracy is characteristic. On deformation this degeneracy is lifted, as a result of which it is usually assumed that under deformation corresponding to a ratio of the major semiaxis of the nucleus to the minor semiaxis $c/a=1.2$–1.3, when levels from neighboring gross shells cross, shell effects disappear. The top of the liquid-drop fission barrier (the saddle point) of a heavy nucleus such as ^{236}U corresponds to a much more elongated configuration $c/a\approx1.8$, which is still rather far in deformation from the scission point. In this way arose the subsequently refuted opinion that shell effects play a role in fission only in the earliest and latest stages, but are not important in the region of intermediate deformations.

The rapid development of electronics and of experimental techniques in general at the beginning of the 1960s and the coming into operation of a number of new accelerators of high intensity led, in fission as in all of nuclear physics, to the setting up of qualitatively new experiments and, as a conseqence, to the appearance of a large number of results which did not fit into the framework of the previously existing ideas (spontaneously fissile isomers, resonances in the cross section for near-threshold fission, grouping of sub-barrier neutron resonances, and anomalies in the fragment angular distribution). These facts, which at first appeared to be separate and unrelated, were explained in a unified manner by the two-humped barrier model of fission constructed in 1966–1967 by V. M. Strutinskiĭ.[8–10] Strutinskiĭ's calculations, which were based on a theoretical approach[8,9] developed by him and which has been named the method of shell corrections, established for the first time that the idea of disappearance of phenomena of the gross-shell type in highly deformed nuclei was unjustified. It was observed also that in the region of the heavy actinides (uranium-curium) a deep minimum in the deformation potential energy appears for a substantial elongation of nuclei, characterized by a ratio of the axes $c/a\approx1.8$, i.e., at a place where according to the liquid-drop model there is only one broad maximum. The energy of the second minimum (the first corresponds to the ground state of the nucleus) was predicted to be 2–2.5 MeV above the ground state, while the heights of the barriers which surround the second minimum also amount to several MeV, i.e., a value of the same scale as the liquid-drop fission threshold. The two-humped barrier model not only turned out to be very productive in the interpretation of many properties which were not understood in the framework of the earlier ideas, but also stimulated investigators to search for and investigate new phenomena due to the structure of the fission barrier, thus resulting in a great rise in the study of the physics of fission all over the world.

The present review is devoted primarily to an analysis of experimental studies of the low-energy photofission of heavy nuclei carried out over the last 15 years jointly by the Institute of Physics Problems of the USSR Academy of Sciences and the Physics and Power-Engineering Institute of the State Commission on the Use of Atomic Enegy. These studies encompass the active period of investigation of quantum effects in highly deformed nuclei and in our opinion have led to the understanding of many features of the fission mechanism which are related to them. The success of this work, as we now understand, was the result of the fortunate occurrence of three circumstances: 1) the construction at the Institute of Physics Problems of a new type of electron accelerator—the high-current microtron—which advantageously combines high intensity and monochromaticity of the beam; 2) the appearance of a simple method of detecting fission events by solid-state track detectors, which is completely insensitive to γ rays, and (3) a rapid advance in the level of theoretical ideas which we have mentioned above.

Photoabsorption has an important advantage over other means of excitation of near-threshold and sub-barrier fission. This is first of all the simplicity of the spectrum of angular momenta transferred to the nucleus ($l=1, 2$), which creates very favorable possibilities for study of the properties of the lowest fission channels. In fission of even-even nuclei a dominant role is played by states with the two spin-parity combinations $J^{\pi} = 1^-$ and 2^+, the contributions of which can be easily distinguished on the basis of the form of the angular distribution of the fission fragments. In addition, with use of γ rays there are no fundamental limitations on energy such as exist in fission induced by neutrons or charged particles. Only the exponential nature of the barrier transmission and the resulting drop in the statistics of the detected induced fission events limit the possibilities of experimental study of deep sub-barrier phenomena. And although, in view of the limitations on the spectrum of angular momenta, we cannot investigate by means of γ rays complicated types of nucleon motion in the nucleus, in the case of fission this deficiency (or simplicity) is an advantage which provides the possibility of studying the probability of fission through states with definite combinations of spin and parity over a wide range of excitation energy.

1. THE TWO-HUMPED FISSION BARRIER

As was pointed out above, Strutinskiĭ in 1966–1967 invented a method of making a shell correction to the deformation energy in the liquid-drop model,[8,9] by means of which it was possible for the first time to overcome the difficulties in the theoretical calculation of fission barriers with inclusion of the shell structure of the nuclei. In this method, which is also called the micromacroscopic method, the deformation potential of a nucleus $V(\varepsilon, Z, N)$ is represented in the form of two components: a smooth macroscopic part $\widetilde{V}(\varepsilon, Z, N)$ which corresponds to a uniform distribution of the nucleons and in the calculations is replaced by the solution in the classical liquid-drop model, and a shell correction which oscillates with change of the deformation ε and the number of nucleons Z and N, $\delta W(\varepsilon, Z, N)$, which is calculated by a microscopic method on the basis of the spectrum of single-particle states for a real quantum distribution of the nucleons in the shell model. Nuclei with a filled shell, i.e., with a smaller than average density of single-particle levels at the Fermi energy, have an increased binding energy[1)] in comparision with the average, since the nucleons occupy deeper and therefore more highly bound states. On the other hand, a high density of these levels is associated with a reduction of the binding energy. The oscillations of $\delta W(\varepsilon)$, which are related in this way to the nuclear property of alternation of rarefaction and compression in the spectrum of single-particle states as a function of deformation, are the most important regularity established by the shell correction method. Three results which follow from this fact have fundamental significance for nuclear physics:

a) the existence of a new type of magic number—that of deformed shells;

b) a quantitative description of the deformation of nuclei in the ground state;

c) prediction of a second minimum of the deformation potential energy and a two-humped fission barrier in the actinide region.

In Fig. 1 we have given an example of the shell corrections to the liquid-drop energy of the nucleus as a function of its deformation for ^{240}Pu. The oscillating nature of the shell correction, first of all, leads to the appearance of two minima in the potential energy—one corresonds to the ground state and the other, at large deformation, corresponds to a quasistationary state. The population and decay of quasistationary levels in the second well are responsible for the occurrence of spontaneously fissile isomers (or of delayed fission), and the interaction of these levels with the levels in the first well is responsible for various resonance structures in the cross sections for sub-barrier fission. In the second place, two humps (A and B) arise in the path of the fissioning nucleus—two saddle points with their own spectra of transition states. Note that completely microscopic calculations according to the Hartree-Fock model[11] confirm the characteristic features of the dependence of the nuclear energy on the deformation shown in Fig. 1.

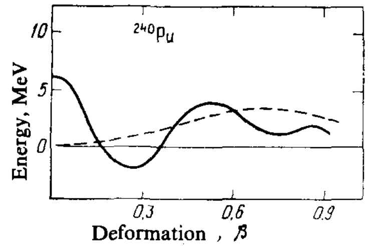

FIG. 1. Shell correction to the potential energy of the ^{240}Pu nucleus. The dashed line is for the liquid-drop model.

Detailed calculations of fission barriers carried out by Miller and Nilsson[12] and by Pashkevich[13] have shown that at the saddle point of the outer hump B in a mirror-asymmetic pear-shaped configuration of the fissioning nucleus is energetically more advantageous, while in the process of traversing the inner hump A and in the second well the configuration retains reflection symmetry. Figure 2 shows how the deformation energy of the ^{240}Pu nucleus changes when the asymmetry of its shape is taken into account (the parameter α_3). The calcuations of Pashkevich[14] show also that in the region of the inner hump A the fissioning nucleus

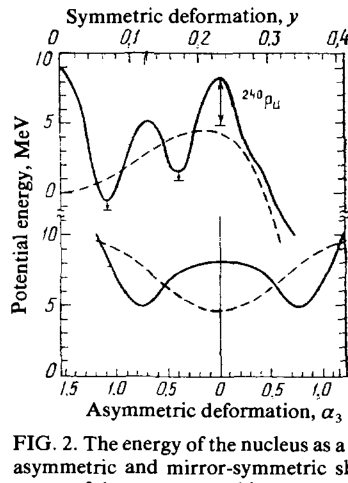

FIG. 2. The energy of the nucleus as a function of deformation for axially asymmetric and mirror-symmetric shapes.[16] The arrows show the decrease of the energy on taking asymmetric deformations into account. In the lower part of the figure is shown the dependence of the energy on the mass-asymmetry parameter α_3 for a fixed longitudinal deformation $y = 0.23$ corresponding to barrier B. The dashed line shows the potential energy in the liquid-drop model.

[1)]It must be kept in mind that the changes of the deformation potential energy and the binding energy of a nucleus have opposite signs.

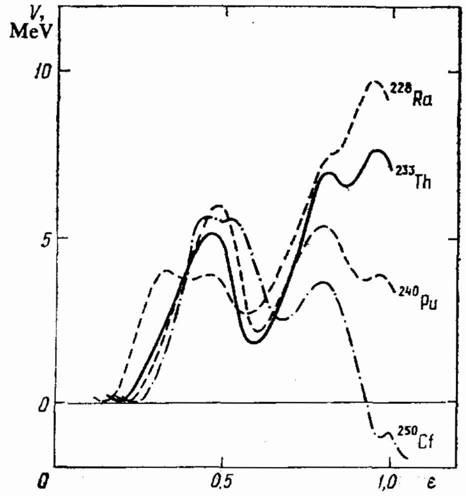

FIG. 3. Deformation potential energies $V(\varepsilon)$ of several actinides, established from the extremal values given in Ref. 15.

loses stability against axially asymmetric deformations. Thus, the theory predicts that the second minimum is separated from the ground state by an axially asymmetric hump A and from the scission point by a mass-asymmetric hump B. Of course, this one-parameter picture must be considered to be a section of the potential energy surface along the trajectory of the nucleus in the direction of fission.

The ideas discussed above enable us to understand Fig. 3, in which we have plotted as a function of the quadrupole deformation ε the result of one of the most recent calculations of the deformation potential energy[15] for several actinides near the valley of greatest stability. This figure gives an idea of the Z-dependence of the barrier shape expected by the theory, which, as will be seen from the further discussion, has a fundamental influence on the pattern of the quantum effects observed in photofission. We shall mention the most important features of this dependence:

a) a weak dependence on nucleon composition of the height of the higher of the humps ($\gtrsim 6$ MeV), which determines the threshold observed in the fission cross section;

b) an increase of the difference in the heights of the inner and outer humps of the barrier $E_{fA} - E_{fB}$ with increase of Z, which changes sign in the vicinity of uranium;

c) the existence of structure of the outer hump in the light actinides (thorium–uranium).

The fission barrier of heavy nuclei has been studied experimentally by various means of excitation. The group of questions associated with investigations of the barrier shape is significantly broader than is discussed in the present article. The experimental and theoretical material on this subject is presented most completely in the recent review by Bjornholm and Lynn.[16]

2. EXPERIMENTAL VERIFICATION OF AAGE BOHR'S HYPOTHESIS OF FISSION CHANNELS

The idea of fission channels—quantum states of the fissioning nucleus at the saddle point which arise as a consequence of excitation of all degrees of freedom except fission (β vibrations) is contained in the work of Niels Bohr and J. W. Wheeler.[2] The method of transition states was suggested by them on the basis of theoretical ideas regarding the fission probability in analogy with the description of phenomena associated with dissociation of molecules.

In 1955 Aage Bohr, in connection with the explanation of the angular anisotropy of fission observed in 1952 by Winhold, Demos, and Halpern[5] in photofission of ^{232}Th, made the following more detailed suggestion[17]: "At excitation energies not too far above the fission threshold, the nucleus transversing the saddle point is essentially cold, since the greater part of its energy is potential energy of deformation. The quantum states in which the nucleus can exist at the critical point of the fission channels are strongly separated and represent a relatively simple type of motion of the nucleus. We can expect that the spectrum of these channels will be similar to the spectrum observed at low excitations of the ground state of the nucleus."

Thus, fission channels are quantum levels of the nucleus in an anomalously deformed transition state corresponding to the energetically narrowest stage of the fission process—the top of the barrier. Each fission channel corresponds to its own deformation potential energy surface determined by the set of quantum numbers J (the angular momentum of the nucleus), K (its projection on the direction of fission, which coincides with the symmetry axis), and π (the parity of the states). In nuclear physics we have for a long time been familiar with the dependence of the barrier on the total angular momentum J, in particular, in α decay. However, according to Aage Bohr in fission the barrier (the channels) are determined also by the quantities K and π. The dependence which arises of the barrier height E_f^λ on the quantum numbers $\lambda = (J, K, \pi)$ results in a nonuniformity of the distribution of K, which in the presence of a certain alignment in space of the angular moment J of the compound nucleus, as we have already mentioned, leads to an angular anisotropy of fragment emission with respect to the direction of the incident beam. If the K distribution given by the spectrum of E_f^λ is preserved during the descent from the saddle point to the scission point, then the angular anisotropy of the fission cross section $d\sigma_f/d\Omega$, or in other words, the angular distribution of the fragments $W(\vartheta)$, arbitrarily normalized, can be calculated in accordance with the formula

$$W(\vartheta) \sim \frac{d\sigma_f(\vartheta)}{d\Omega} = \sum_{JMK} \sigma(J, M)\, P(J, K)\,(|D^J_{M,K}(\vartheta)|^2 + |D^J_{M,-K}(\vartheta)|^2), \tag{1}$$

where $\sigma(J, M)$ is the cross section for production of the compound nucleus with angular momentum J and its projection M on the direction of the incident beam, $P(J, K)$ is the fissility in the given channel, and $D^J_{M,K}(\vartheta)$ is the Wigner function.

A basic difficulty associated with this interpretation of fission angular anisotropy and with the concept of fission channels in general has been noted repeatedly. For example, Griffin[18] says "The assumed spectrum at the saddle point is in the best case quasistationary, and actually the concept of such a spectrum is correct only in the case in which the nucleus is at the saddle point for a longer time than the period of excitation." Geĭlikman[19] goes still further: "This point of view (Aage Bohr's hypothesis) is hardly correct, since the time of descent from the barrier $\tau \approx (1-3)\cdot 10^{-20}$ sec is less than the period of rotation $\hbar/\Delta\, E_{rot} \approx 10^{-19}$ sec." The question of fulfillment of the condition of quasistationarity of the spectrum of transition states is closely related to the more general questions of the space time picture of fission, the dynamics of the process, the viscosity of nuclear matter, and so forth, and cannot be solved in the framework of the theory (at the present time there is no satisfactory answer to this question). Therefore the adequacy of our ideas regarding the spectrum of fission channels can be established only experimentally.

A number of authors[19-21] have advanced an alternative to the channel interpretation of the anisotropy in the form of the model-free description discussed by Strutinskiĭ,[20] in which the distribution of K is given not at the top of the barrier, but at the moment of formation of the fragments. In connection with this possibility, I. M. Frank[21] wrote "To explain the angular anisotropy there is no need of resorting in all cases to such model representations. A qualitatively correct nature of the angular anisotropy should arise if the orbital angular momentum associated with the motion of the emitted fragments is obtained as the result of the orbital angular momentum brought into the fissioning nucleus by the bombarding particle . . . this result is a direct consequence of the conservation of angular momentum."

The direct means of solution of this dilemma and also of verification of Bohr's hypothesis itself, consists of experimentally establishing those uniquely interpreted properties of the fission angular anisotropy which are not present in the alternative (fragment) description. Obviously these properties should be the most concrete consequences of the discrete structure of the fission channels, which appear only in a characteristic energy region—near the threshold (the saddle point). In the alternative description the threshold region is not identified.

Concrete predictions follow from Aage Bohr's hypothesis only for the spectrum of fission channels of even-even nuclei, in which in the deformation process as the result of pairing among the nucleons the quantum numbers of the ground state $J = K = 0$, $\pi = +1$ and the energy gap in the spectrum of internal excitations are preserved. From theoretical and experimental studies of the spectrum of low-lying excitations of even-even axially symmetric deformed nuclei such as the actinides it follows that for $K = 0$ there is a rotational band of positive parity $J = 0, 2, 4 \ldots$ and a negative-parity band $J = 1, 3, 5 \ldots$ located about 0.5–0.7 MeV higher. Levels with $K \neq 0$ located still higher (≈ 1 MeV) correspond to more complicated types of excitations. Therefore the photofission of even-even nuclei represents a unique possibility for direct verification of Bohr's hypothesis. If the γ-ray energy is close to the threshold, then the dominant role in fission will be played by the channels $J^\pi = 2^+$ and 1^-, $K = 0$, which are excited in electric quadrupole (E2) and dipole (E1) absorption. These are the first excited states, which belong just to the lowest rotational bands of fission channels which were predicted by Bohr. The partial contribution of each of these states can be established reliably in experiments on the basis of the shape of the angular distribution $W_{JK}(\vartheta)$; specifically $W_{20}(\vartheta) \sim |D^2_{10}(\vartheta)|^2 \sim \sin^2 2\vartheta$ has the form of a symmetric bell with a maximum at the angle $\vartheta = 45°$, and $W_{10}(\vartheta) \sim |D^1_{10}(\vartheta)|^2 \sim \sin^2\vartheta$ with a preferential direction of fragment emission in the plane perpendicular to the beam. In the general case the distribution of the fragments from photofission can be described by the expression

$$W(\vartheta) = a + b\sin^2\vartheta + c\sin^2 2\vartheta, \tag{2}$$

where the isotropic component a is due to the states with $K \neq 0$, mainly $K^\pi = 1^-$.

The transmission of a fission barrier in the form of an inverted parabola has the simple analytical dependence

$$T(E, E_f^\lambda) = \left\{1 + \exp\left[\frac{2\pi}{\hbar\omega_\lambda}(E - E_f^\lambda)\right]\right\}^{-1}, \tag{3}$$

where $\hbar\omega_\lambda$ is the curvature parameter for a barrier with quantum numbers $\lambda = (J, \pi, K)$ and E_f^λ is its height. The ratio of the cross sections for quadrupole and dipole photo absorption, which characterizes the means of formation of the compound nucleus but not of its decay, according to an estimate of electrodynamics is

$$\frac{\sigma_\gamma^{E2}}{\sigma_\gamma^{E1}} \approx \left(\frac{R}{\lambda}\right)^2 \approx 0.05 \quad (\text{for} \;\; E_\gamma \approx 6\text{MeV}), \tag{4}$$

where R is the radius of the nucleus and λ is the wavelength of the γ ray. If there is actually at the saddle point an appreciable energy gap between the rotational bands of positive and negative parity, then in view of the exponential dependence of the barrier transmission on the energy, below the negative-parity band one should observe a rapid increase of the relative fraction of quadrupole fission. This mechanism of sub-barrier enhancement of the probability of quadrupole fission was discussed for the first time by Griffin.[18]

Figure 4 shows the results of an experiment[22,23] set up in the bremsstrahlung beam from electrons accelerated in the microtron, in which the sub-barrier enhancement of the quadrupole component of $W(\vartheta)$ was observed for the first time for ^{238}U. Figure 4 shows how the contribution of the quadrupole component, which is insignificant ($\approx \sigma_\gamma^{E2}/\sigma_\gamma^{E1}$) in the super-barrier region $E_{max} \gtrsim 6$ MeV, rises rapidly with increase of the γ-ray energy, and at $E_{max} = 5.2$ MeV becomes approximately equal to the dipole component. The region of the exponential increase of the ratio c/b corresponds to a reasonable parameter value $\hbar\omega \approx 0.9$ MeV.

The ratios of the angular-distribution coefficients a, b, and c can be expressed in terms of the barrier transmission $T(E,E_f^\lambda)$ for the individual channels:

$$2\frac{b}{a} \approx \frac{T(E, E_f^{10})}{T(E, E_f^{11})} - 1, \tag{5}$$

$$\frac{c}{b} \approx \frac{5}{4}\frac{\sigma_\gamma^{E2}}{\sigma_\gamma^{E1}}\frac{T(E, E_f^{20})}{T(E, E_f^{10})}. \tag{6}$$

The sharp rise of c/b below the threshold of dipole photofission E_f^{10} means that the channel $2^+, K = 0$ corresponds to a lower barrier E_f^{20}, and the distance between the two barriers can be estimated from Eqs. (3) and (6) with use of the charac-

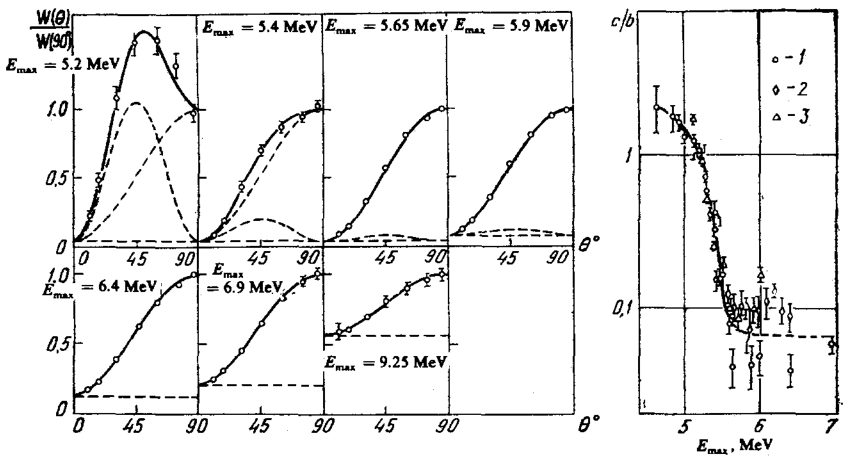

FIG. 4. Angular distributions of fragments in photofission of ^{238}U in the range of bremsstrahlung maximum energies $E_{max} = 5.2$–9.25 MeV.[22,23] At the right is a set of experimental data on the energy dependence of the ratio c/b: 1—from Refs. 22, 23, 25, and 26; 2—from Ref. 27; 3—from Ref. 28.

teristic parameters of the barrier for the U nucleus,

$$E_f^{10} - E_f^{20} \approx \frac{\hbar\omega}{2\pi}\ln\frac{T_{20}}{T_{10}} \approx \frac{\hbar\omega}{2\pi}\left(\ln\frac{c}{b}\Big|_{E_{max}\leqslant 5\,\mathrm{MeV}} - \ln\frac{c}{b}\Big|_{E_{max}\geqslant 6\,\mathrm{MeV}}\right) \approx 0.6-0.7\,\mathrm{MeV}, \tag{7}$$

i.e., it is approximately the same as in nuclei in the equilibrium state. The dominance and the behavior with energy of the anisotropic components of the angular distribution $W(\vartheta)$ in the threshold region not only demonstrate the specific structure of the spectrum of channels (J, π, K) of photofission of even-even nuclei $(2^+, 0)$, $(1^-, 0)$ and $(1^-, 1)$ but also are an important indication that the quantum number K is conserved in the fission process, i.e., it is a rather good quantum number: one observes practically pure D functions

$$|D^1_{10}(\vartheta)|^2, \quad |D^2_{10}(\vartheta)|^2. \tag{8}$$

It should be emphasized that the observation of the subbarrier enhancement of the quadrupole component of $W(\vartheta)$ in the (γ, f) reaction in even-even nuclei is nontrivial as is also experimental information on the symmetry of the shape of the nucleus in the transition state—on a question closely related to the fundamental problem of the formation of the asymmetry of fission of heavy nuclei (see Section 6). The point is that the difference of the barrier heights $E_f^{10} - E_f^{20}$ depends strongly on the static mass-asymmetric deformation. In this connection we shall turn again to Aage Bohr, who in his pioneering work[17] said "For nuclei whose shape has mirror symmetry, the spectrum will contain for $K = 0$ only rotational levels for which the values $J = 0, 2, 4, \ldots$ all have positive parity. However, the observed relation between the masses of the fission fragments indicates the absence of mirror symmetry in the shape of the nucleus at the critical point. In this case the rotational band will contain also levels with large values of J characterized by negative parity." A still more definite statement is given in the book by Bohr and Mottelson[24]: "If a system had a static deformation of this type (mirror asymmetry), then the states $J^\pi = 1^-$ and 2^+ would belong to the same band with $K = 0$, and then dipole photofission would dominate in the entire threshold region."

Experiment shows that we have both situations characteristic of mirror-symmetric and mirror-asymmetric configurations of the nucleus at the saddle point: in six even-even nuclei ^{234}U, ^{236}U, ^{238}U, ^{238}Pu, ^{240}Pu, and ^{242}Pu (Refs. 22, 23, 25–29) the mechanism of the quadrupole component in $W(\vartheta)$ is present but it is absent in the case of ^{232}Th (Refs. 23 and 30) where down to energies ≈ 5 MeV at which the fissility is decreased to a negligible value $\approx 10^{-4}$ the ratio c/b remains at the level

$$\frac{\sigma_\gamma^{E2}}{\sigma_\gamma^{E1}} \approx 5\cdot 10^{-2}. \tag{9}$$

As will be shown below, the nature of the anomaly in the transition from the heavy actinides to the light actinides is explained by the properties of the two-humped fission barrier.

3. CHANNEL EFFECTS IN THE (γ, f) REACTION AND THE SHAPE OF THE FISSION BARRIER

Up to this time we have carried out the discussion of the angular distributions of the fragments in photofission in the framework of the one-humped barrier model. From the point of view of the factors which determine the fragment angular distribution, the new thing in the two-hump barrier model lies in the existence of not one, but two systems of channels E^λ_{fA} and E^λ_{fB} corresponding to the two humps (saddle points), between which at the minimum (the second well) the nucleus can stay for a rather long time. If this time is large in comparison with the period of migration of the value of K, then the nucleus will essentially forget with what K it passed through the inner barrier, and the angular anisotropy of fragment emission will be determined by the spectrum of channels in the outer barrier B.

Since the threshold observed in the fission cross section is determined by the height of the higher of the barrier humps, the pattern of near-threshold effects in the angular distributions of the fragments will depend on the sign of the difference $E^\lambda_{fA} - E^\lambda_{fB}$. If the outer hump is higher, then a situation typical of a single-humped barrier is realized: the channel effects appear in the energy region above threshold. If the threshold in the cross section is determined by a higher inner hump A, and the fragment anisotropy is determined by the outer hump B (as a consequence of the forgetting or mixing of K), then an unusual situation arises: the channel effects are displaced into the subthreshold region and the more so, the greater is the difference in the heights of the humps $E_{fA} - E_{fB}$. As follows from the theoretical calculations (see Fig. 3), the ratio between them is reversed (from greater than one to less than one) in a narrow range of nuclei: in thorium $E_{fB} > E_{fA}$, and in plutonium $E_{fB} < E_{fA}$.

From the discussion above it is easy to predict the pattern of the near-threshold photofission of heavy nuclei. The coefficient ratio b/a determined in accordance with Eq. (5) by the contribution of dipole channels $J = 1$ with two different values $K^{\pi} + 0^-$ and 1^- is exactly the characteristic by experimental study of which we can hope to clear up the question of the adequacy of the idea of K mixing in the second well. The displacement expected in this case of the rise of b/a with respect to the threshold observed in the cross section with change of the sign of $E_{fA} - E_{fB}$ is shown schematically in Fig. 5.[30]

As a consequence of the conservation of J and π, this mechanism has no effect on the ratio c/b, which is determined by channels with different spins and parities ($K = 0$), but at the same time there is an influence of the difference in the symmetry of the fissioning nucleus at the two saddle points. At the first saddle point the nucleus is stable against the mirror–asymmetric deformation α_3, and at the second it is not stable (Fig. 2). The loss of reflection symmetry by the fissioning nucleus in passing through hump B, as has been discussed above, should be accompanied by a rapid decrease of the distance between the channels $J^{\pi} = 2^+$ and $J^{\pi} + 1^-$ ($K = 0$).[17,24] For the sake of simplicity we shall assume, as is shown in Fig. 5, that in hump B these states are degenerate. In this case the mechanism of sub-barrier fission of the quadrupole component will be provided only by the energy splitting of the channels with $K^{\pi} = 0^+$ and 0^- in hump A. The

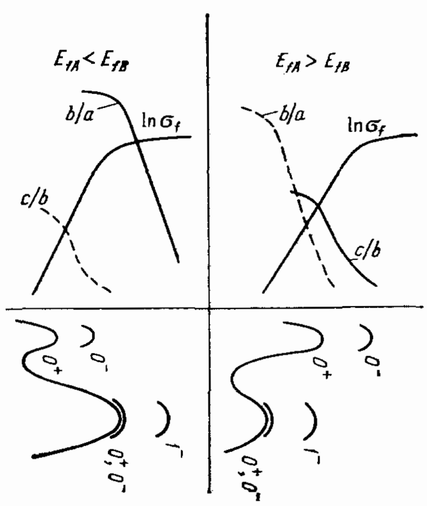

FIG. 5. Structure of the low-lying channels of K^{π} in humps A and B (below) for $E_{fA} < E_{fB}$ and $E_{fA} > E_{fB}$ and the behavior of the photofission cross section and the principal characteristics of the fragment angular distribution b/a and c/b due to this structure. The solid lines show the characteristics determined by the higher of the humps.

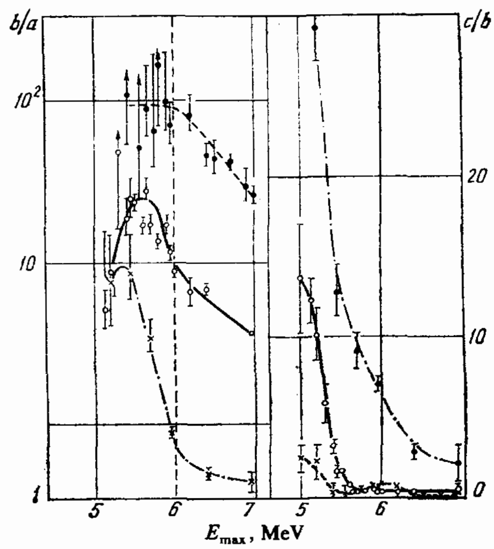

FIG. 6. Energy dependence of the ratios b/a and c/b for the nuclei ^{232}Th (dashed curves), ^{238}U (solid curves), and ^{240}Pu (dot-dash curves).[22,23,25,26] The vertical dashed line shows the location of the observed threshold.

expected dependence of c/b on the sign of $E_{fA} - E_{fB}$, like that of b/a, is shown n Fig. 5.

Thus with increase of the difference $E_{fA} - E_{fB}$ the rise of the ratio c/b associated with the channels of barrier A is displaced to the threshold observed in the cross section, while the increase of the ratio b/a associated with the channels of barrier B, on the other hand, is displaced into the subthreshold energy region. The experimental results, which completely confirm these qualitative discussions, are given in Fig. 6 in the form of the dependence of the ratios b/a and c/b on the maximum energy of the bremsstrahlung spectrum for the nuclei ^{232}Th, ^{238}U, and ^{240}Pu. The dashed line shows the location of the observed threshold, which is practically the same in these nuclei. It is clearly evident that in ^{232}Th the channel effects in the angular anisotropy appear in the energy region of the fission cross section above threshold, and with increase of Z they shift to the sub-barrier region in accordance with the change of the height of the hump. At the same time the contribution of the quadrupole component (the ratio c/b) in the case of ^{240}Pu becomes significant already in the threshold region, while in ^{232}Th it is small ($\approx \sigma_{\gamma}^{E2}/\sigma_{\gamma}^{E1}$) even well below threshold.

At this stage of the studies of photofission, which were carried out mainly at the end of the sixties, it was apparently possible for the first time to obtain experimental confirmation of two important theoretical predictions regarding the fission barrier of heavy nuclei: the strong dependence of the heights of the humps A and B on the Z of the fissioning nucleus, and the loss by the nucleus of stability with respect to mass-asymmetric deformations on traversing barrier B.[23,31] The first of these predictions was subsequently confirmed by a large amount of experimental data obtained mainly from analysis of the excitation functions of spontaneously fissile isomers, including data obtained by means of photonuclear reactions.[32] New indications favoring the second prediction were obtained comparatively recently in study of the resonance structure of the cross sections and angular anisotropy of ^{230}Th and ^{232}Th (see Section 5),[16,33] and also from analysis of effects due to parity violation in fission induced by polarized neutrons.[34]

Thus, experimental study of the near-threshold photofission of heavy nuclei has confirmed Aage Bohr's concept not only in general, but also in such important details as the dependence of the spectrum of fission channels on the symmetry of the nucleus in the transition state. It is nevertheless necessary to acknowledge that although Bohr's hypothesis is based on rather general considerations regarding the quantum nature of the energy spectrum of the system in its cold state, the model of fission channels has never been systematically justified theoretically. We mentioned above that the interpretation of fission channels as specific quantum states not in the potential well, as usual, but at the saddle point, where the potential energy of deformation does not have a minimum, but a maximum, encounters difficulty in satisfying the condition of quasistationarity. This difficulty persists. In the question of the analogy of fission channels with ordinary quantum levels of nuclei, as almost thirty years ago, apparently one should not go further than Aage Bohr, i.e., further than the similarity of their spectra. To our astonishment, experiment shows that this similarity is detailed.

In conclusion we shall note an important feature of the investigations of channel effects which was also perceived only with the development of the two-humped barrier idea, but which we have not yet touched upon. Quantum effects in fission, which we have been discussing up to now, arise against the background of other effects, also associated with discrete levels, and not at the top of the barrier but at its minima. The latter effects can lead to still more rapid variations of the fission cross sections and fragment angular distribution, which in contrast to channel effects have a resonance nature and consequently are localized in narrow energy intervals $\lesssim 0.1$ MeV. For this reason we have up to now attempted to consider only characteristics averaged over the continuous spectrum of electron bremsstrahlung. As a consequence of the falloff of the fission probability with reduction of the energy, the region of averaging below the threshsold is 0.3–0.4 MeV.[23] This natural averaging which occurs in our experiments greatly suppresses the resonance structure of the cross sections, simplifying the observed pattern and facilitating the manifestation in it of properties due to the discrete spectrum of fission channels.

The example given above of the positive role of low energy resolution is a rather rare exception to the general rule, which is confirmed also by the history of the establishment of the ideas of fission and resonance effects in fission. For more than ten years after the appearance of the ideas of the model of fission channels, all irregularities observed in the energy dependence of the cross sections and the angular anisotropy of fission, mainly in the (n, f) and (d, pf) reactions, were associated with channel effects, and this blunder found its way into the pages of many reviews and monographs of past years (see for example Refs. 35 and 36). With improvement of the energy resolution of experiments and with development of the theory it became clear that resonances of the fission probability are another type of quantum effect which has no direct relation to the Bohr channels. The next two sections are devoted to the discussion of the role of these quantum effects; of course, the (γ,f) reaction.

4. THE ISOMERIC SHELF IN PHOTOFISSION CROSS SECTIONS

The existence of a second minimum of the deformation energy of heavy nuclei and the quasistationary states associated with it can lead to the very interesting phenomenon known as isomeric shelf, which was pointed out for the first time by Bowman.[37] The essential features of the phenomenon are easily understood with the aid of a qualitative discussion (Fig. 7).

In the deformation process the nucleus can occupy one of the quasistationary states in the second well. Its subsequent fate is determined by the competition of three processes: two of them involve change of the deformation—the return of the first well, and fission; the third process involves γ decay to the bottom of the second well (the ground state of the fissioning isomer) with no change in deformation. The ratio of the probabilities of these competing processes changes rapidly with decrease of the excitation energy in the second well, since in the sub-barrier region the widths of the processes associated with change of the deformation are determined by the very strong exponential dependences of the transmission of the fission barrier humps (T_A and T_B), whereas the radiative width depends comparatively weakly on energy. If the second well is sufficiently deep, we can have a situation in which the fission width, dropping rapidly with decrease of the energy, is comparable to the width of radiative decay in the second well ($\sim T_{\gamma 2}$), and at still lower energies the fission width becomes much less than the width of radiative decay. If in this situation a return to the first well is strongly forbidden, the nucleus will preferentially make a transition from the excited state of the second well to the ground state of the shape isomer and will undergo spontaneous fission from this state. The fission half-life of the nucleus in the isomeric state is determined by the transmission of the outer hump T_B, but if experimentally fission events are recorded without separation in time (as for example in the

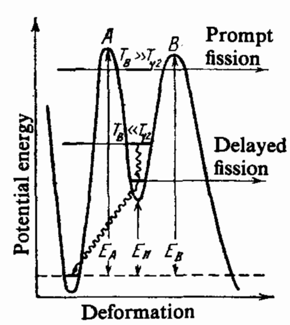

FIG. 7. Schematic representation of the predominating possibilities of traversal of a two-humped barrier in the near-threshold and deep sub-barrier energy regions of excitation energy (the radiative decay in the first well is not shown in the scheme).

track technique used by Bowman and by us), the intensity of the observed delayed fissions will be determined only by the probability of passage into the second well, i.e., by the transmission of the inner hump T_A. Thus, in the sub-barrier region the yield of prompt fission ($\sim T_A T_B$) drops much more rapidly in comparison with delayed fission ($\sim T_A$) and at sufficiently low excitation energies, namely when one has the relation $T_B \lesssim kT_{\gamma 2}$ ($k \leqslant 1$ is the branching coefficient of decay of the isomer characterizing the fraction of fissions in the total number of decays), delayed fission will become more probable than prompt fission. In observation of the combined effect this shows up as a rather sharp slowing down of the rate of falloff of the yield with decreasing energy. Continuing the qualitative discussion, we can expect that on reaching the bottom of the second well the rate of change of the yield should return discontinuously to the dependence characteristic of fission from the states of the first well through the broad liquid-drop barrier. Thus, in the energy dependence of deep sub-barrier fission of heavy nuclei with a deep second well one can observe the step which has received the same isomeric shelf.

Indeed, in 1975, first Bowman's group in the USA[38] and then our group[39,40] observed in the photofission yields of ^{238}U at electron energies $\lesssim 4.5$ MeV a rather rapid decrease of the rate of falloff with a subsequent still more rapid increase of the rate. These results, which are shown in Fig. 8, were interpreted as confirmation of the picture described above: the break in the integrated yield corresponds to the condition $T_B \approx kT_{\gamma 2}$, and the subsequent rapid drop of the field is due to the approach to the bottom of the second well. Subsequently we undertook similar studies of deep sub-barrier photofission of ^{236}U,[40,41] the results of which are also shown in Fig. 8. In the lower part of the figure we have shown the fission cross sections $\sigma_f(E_\gamma)$, which were obtained from the yield, as a function of the γ-ray energy.

Comparison of our more detailed measurements with the data of Bowman *et al.*[38] reveals a number of differences in the behavior of the yields $Y(E_{max})$ and in particular of the cross sections $\sigma_f(E_\gamma)$, which are important for development of adequate ideas regarding the phenomenon under study.[40,41] In the first place, the rapid drop in the yield in the low-energy part of the shelf for the two uranium isotopes is observed at $E_{max} \lesssim 3.5$ MeV, i.e., not in the immediate vicinity of the bottom of the second well as in Ref. 38, but approximately 1 MeV higher. In the second place, the edge of the step in $Y(E_{max})$ in the fission cross sections $\sigma_f(E_\gamma)$ corresponds to resonances. Both of these consequences, as well as the absolute value of the yield in the shelf region which were obtained in our measurements, were confirmed for ^{238}U in 1980 by the Italian group,[28,42] whose experimental data are also shown in Fig. 8. Third and finally, it has become clear that the idea of a characteristic breaking point in the function $Y(E_{max})$ and in $\sigma_f(E_\gamma)$, where $T_B = kT_{\gamma 2}$, which determines the upper limit of the isomeric shelf region, was highly idealized in the early studies.[38,39] Data which are especially indicative of this are those for ^{236}U, in which there is not such clearly expressed energy dependence.

Measurements of the angular distributions of the fragments of deep-sub-barrier photofission carried out using the microtron at the Institute of Physics Problems, USSR Academy of Sciences,[30,41,43] made possible the next step in the study of the isomeric shelf. If the observed deep sub-barrier anomalies of the (γ,f) reaction yield are actually due to the contribution of delayed fission, then the anisotropy of fragment emission should decrease substantially as the result of the disorientation of the angular momentum of the nucleus on emission of γ rays in the second well, and also as a consequence of its interaction with the magnetic field of the atom. In addition, if the main contribution to delayed fission of even-even nuclei is from decay of the shape isomer from the lowest state $J^\pi = 0^+$, then in principle there should be no angular anisotropy. The expected effect is very strong: the angular anisotropy of prompt photofission of the even-even isotopes of uranium in the threshold region amounts to factors of ten, and the isotropic component $a(E_{max})$ in the fragment angular distribution should change by just this factor in transition to the isomeric-shelf region.

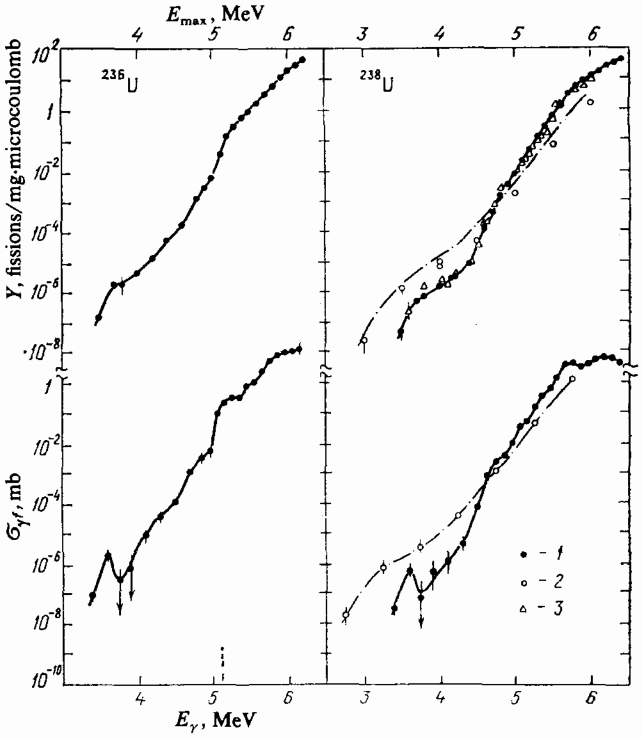

FIG. 8. Yield Y and cross section σ_f in photofission of ^{236}U and ^{238}U. 1—from Refs. 39–41, 2—from Ref. 38, 3—from Refs. 28 and 42.

The results of an experimental verification[43] of this prediction in the reaction ^{238}U(γ, f) are shown in Fig. 9. Here we can easily see that the fragment angular distribution, which is highly anisotropic (prompt fission is still dominant) becomes practically isotropic on reaching the isomeric-shelf region ($E_{max} = 4.15$ MeV). These results provide major support for the interpretation of the isomeric shelf. The experimental proof (although an indirect one) of the nature of the isomeric shelf had special value at that moment, because detailed measurements of the yields and cross sections, as we have seen, had placed in doubt most of the postulates of the

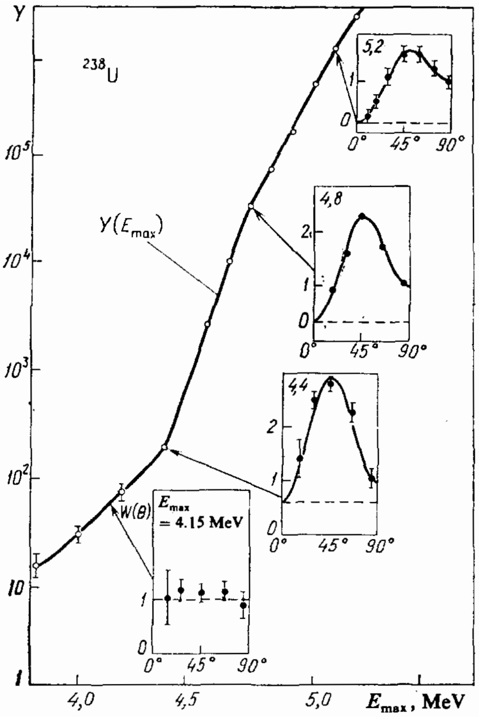

FIG. 9. Change in the nature of the angular distribution $W(\vartheta)$ of fragments in photofission of ^{238}U (in the inserts),[43] with decrease of the excitation energy and approach to the isomeric-shelf region in the yields $Y(E_{max})$. The dashed lines in the inserts show the isotropic component of the angular distribution.

simplified description in the early studies.

The experiments which have been carried out show also that the isotropy of photofission of even-even nuclei through an isomeric state is a remarkable behavior, using which it is possible to trace the contribution of delayed fission over a broader region—not in the total yield as in previous studies, but in the background of its much less intense isotropic prompt-fission component, the contribution of which is determined by the highly placed channels J^π, $K+1^-$, 1. For this purpose we made detailed studies of the fragment angular distributions in the deep sub-barrier region for three nuclei: the isotopes ^{238}U and ^{236}U in which the isomeric shelf has been reliably established, and the isotope ^{232}Th which was the subject of the discussion given above. From the data obtained in these experiments and from earlier studies which are listed in the caption to Fig. 10, we can draw the following conclusions.

In the uranium isotopes with approach to the isomeric-shelf region the contribution of the isotropic component a in the angular distributions of the fragments rises rapidly and becomes dominant at the boundaries of this region. In the reaction $^{232}Th(\gamma,f)$, on the other hand, the coefficient a is small over the entire sub-barrier energy region studied, where the yield drops clearly below the level at which a rise of the isotropy is observed in ^{238}U and ^{236}U. Both these facts are naturally explained from a single point of view. The decrease of the angular anisotropy of sub-barrier photofission in ^{236}U and ^{238}U and the isotropy of fission in the isomeric-shelf region are a consequence of increase of the contribution of delayed fission to the total yield with decrease of the probability of passing through the outer barrier in comparison with the probability of radiative de-excitation in the second well. Being guided by these considerations, one can easily understand also the absence of this effect in photofission of ^{232}Th; in that nucleus delayed fission is less probable, both as the result of the depth of the second well and as a consequence of the high transmission of the inner hump A, which facilitates the return to the first well (see Fig. 3).

A convenient picture of the competition of delayed and prompt fission can be obtained by means of the angular com-

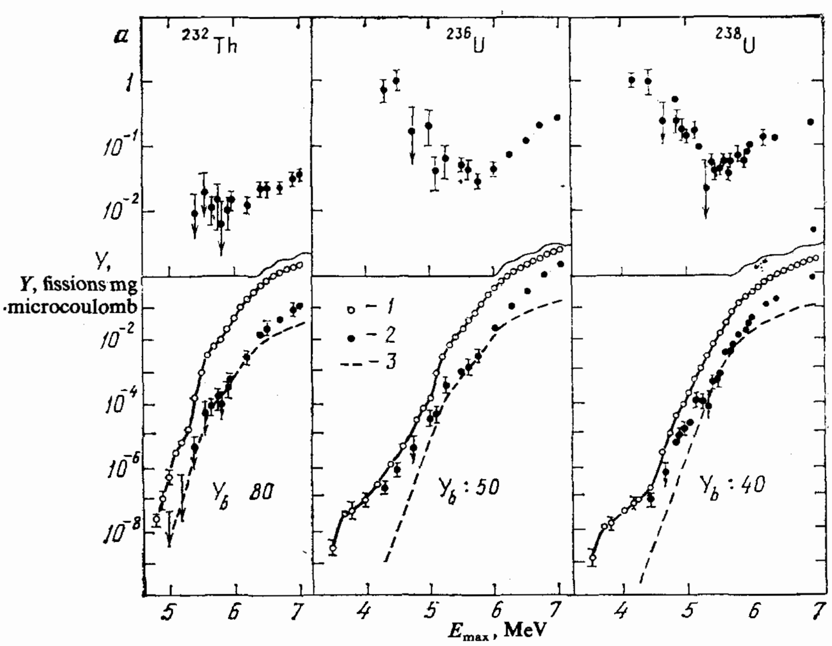

FIG. 10. Upper figures: Dependence of the coefficient a in the isotropic component of the angular distribution of fragments from photofission of ^{232}Th, ^{236}U, and ^{238}U on E_{max}.[25,26,30] Lower figures: 1—total photofission yield of the respective nuclei,[40,50] 2—isotropic component Y_a of the yield, 3—dipole component Y_b, equated to Y_a in the region of minimal values of the coefficient a.

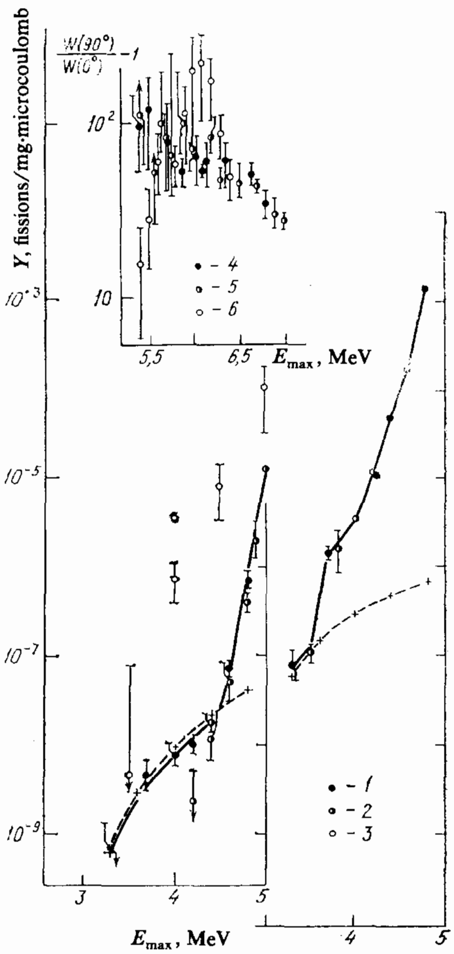

FIG. 11. Yield of the fission of ^{232}Th (left figures) and ^{236}U (right figures) induced by bremsstrahlung. 1—from Ref. 47, 2—from Ref. 40, 3—from Ref. 38. The dashed line shows the level of background from neutrons produced in the reaction Be(γ, n); the insert shows the angular anisotropy of fission of ^{232}Th by bremsstrahlung: 4—from Ref. 47, 5—from Ref. 26, 6—from Ref. 46.

ponents of the total yield—the isotropic component Y_a and the dipole component Y_b. In Fig. 10 the isotropic component is given in the same units as the total yield, while the dipole component has been reduced so as to achieve agreement of the curve of Y_b with the experimental data in the region of minimal values of the coefficient a. It is evident that for ^{236}U and ^{238}U the curves diverge considerably, while in the case of ^{232}Th there is no such discrepancy explainable by the contribution of delayed fission to Y_a.

The question of the presence (or absence) of the isomeric shelf in photofission of ^{232}Th has particular significance. In the first place, as we have already mentioned, a study of the isomeric shelf could provide experimental information independent of other methods on the parameters of the inner hump A, which would be very important for solution of one of the most burning questions of the present day regarding the shape of the fission barrier of the light actinides, which is known as the "thorium anomaly" (see for example Refs. 16 and 33). In the second place, in the case of observation of the feature under discussion in the photofission yield one could hope to observe shape isomerism in the same light actinides. The region of occurrence of spontaneously fissile isomers, studied by other methods, in the direction of light nuclei is limited so far to the uranium isotopes ^{236}U and ^{238}U. In the third place, a very contradictory state of the experimental data on the isomeric shelf has developed for just the reaction ^{232}Th(γ, f).

The deep sub-barrier yield of ^{232}Th photofission has been studied by two groups—by our group[39,40,44] and by Bowman and co-workers.[45] The results of these groups disagree by two orders of magnitude: in Ref. 45 a significant effect was observed, agreeing in value with that for ^{238}U; in our measurements at the same energy region $E_{max} \lesssim 4.5$ MeV the yield was so small that it was hard to say if the isomeric shelf exists at all in the case of ^{232}Th. This contradictory situation became still more interesting when the Italian group reported in 1981 observation in the reaction ^{232}Th(γ,f) of a sharp drop in the fragment angular anisotropy with decrease of the energy in the immediate region of the threshold ($E_{max} = 5.5$–6.3 MeV), the origin of which was related by the authors of Ref. 46 to delayed fission and specifically to the possibility of observing the production of a shape isomer in a third well of the fission barrier. In Fig. 11 we have given the results of our two latest experiments,[40,47] which confirm the data of Refs. 45 and 46. In the main part of the figure we have shown the deep sub-barrier portions of the energy dependence of the photofission yield of ^{232}Th and ^{236}U, in measurement of which we were able to increase the number of recorded events in comparison with our previous experiments by more than an order of magnitude. The new series of measurements confirmed the strong discrepancy with Ref. 45 and also revealed a rapid change of the energy dependence of the yields in ^{232}Th at $E_{max} < 4.4$ MeV and in ^{236}U at $E_{max} < 3.5$ MeV, which in the first case is easy to take for the effect being investigated. In fact, as was shown in Refs. 40 and 47, this is a side effect (the dashed line in Fig. 11) due to the neutron background which arose in photodisintegration of the beryllium contained as a small impurity in the mica of the detectors and in the construction materials of the target. For this reason there is extreme doubt regarding the result of Ref. 45, in which an isomeric shelf was observed for ^{232}Th with yield values 2–3 orders of magnitude greater than the background level recorded by us at the same energies in the absence of the effect. A negative result (in the sense of the isomeric shelf) which does not agree with Ref. 46 was also given by new measurements of the angular anisotropy of photofission.[47] The set of experimental data from Refs. 23, 25, 26, 30, 46, and 47 is given in the insert of Fig. 11.

Thus, the experimental study of the properties of deep sub-barrier photofission of nuclei has given a picture of the ratio of the probabilities of delayed and prompt fission which is in reasonable agreement with what is known regarding the barrier shape in these nuclei, and the combined interpretation of the anomaly of the isotropic component of $W(\vartheta)$ already noted in the early studies[25,26] and of the isomeric shelf in the yields has made it possible to combine into a single consistent qualitative picture such apparently unrelated properties as the fission angular anisotropy and shape isomerism. Certain questions of the quantative description of the isomeric-shelf phenomenon are discussed in the next section.

5. INFLUENCE OF QUASISTATIONARY STATES IN THE SECOND WELL ON THE FISSION PROBABILITY

One of the most interesting consequences of the complicated shape of the fission barrier is the possibility of formation of quasistationary states in the second well. A special role among such states is occupied by β vibrations—longitudinal oscillations of the nucleus. The close connection between β vibrations and the fission mode provides in principle the possibility of distinguishing them with the aid of the fission reaction and observing them over a wider range of excitation energy, since ordinary spectroscopic methods enable us to obtain data only on the zeropoint vibration and on the one-phonon β state of even-even nuclei. However, in the case of a one-humped barrier we would be prevented from accomplishing this by the strong damping of the β vibrations by spreading over the compound states in the near-threshold region, and observation of lower undamped vibrations would be prevented by the rapid falloff of the fission probability at deep sub-barrier excitation energies. The existence of the second well changes the situation. As a result of the fact that it is raised by 2–3 MeV above the ground state, for even-even nuclei even in the near-threshold region the damping of the β vibrations in the second well frequently turns out to be incomplete. Furthermore the inner hump of the barrier prevents strong damping of the vibrations by spreading over the compound states of the first well. In addition the large fission width of the β states in the second well makes possible the study of very low β-phonons. An example is the resonances of the photofission cross section of ^{236}U and ^{238}U at $E_\gamma \approx 3.6$ MeV (see Fig. 8), which lie only 1–1.3 MeV above the ground state in the second well.

In this case we may be dealing with practically pure vibrational resonances, i.e., manifestations of vibrational motion which is very weakly mixed with collective and single-particle excitations of a more complicated type. However, for experimental confirmation of this assumption it would be necessary to have an energy resolution much better than actually achievable so far in this energy region.

However strange it may be, the first candidates for the role of resonances close to pure vibrational were the very strongly expressed structures observed more than twenty years ago in the cross section for near-threshold neutron fission of the nuclei ^{230}Th (Ref. 48) and ^{232}Th (Ref. 49). The paradox of this situation lies in the fact that the existence of practically pure vibrational resonances in odd nuclei according to the existing ideas regarding the damping mechanism could be expected only in the very close vicinity of the bottom of the well, whereas similar resonances are observed at excitation energies of the compound nucleus near 5.85 MeV for ^{231}Th and above 6 MeV for ^{233}Th. Similar structures were observed later in the cross section for fission of the odd-odd fissioning nucleus ^{232}Pa at excitation energies above 5.7 MeV.

A reasonable explanation consistent with existing ideas on the damping mechanism is that such resonances possibly can be found in the framework of the hypothesis of a third minimum which appears as the result of splitting of the outer hump of the actinides on inclusion of mirror-asymmetric deformations[16,33] in the calculation of the fission barrier (see Fig. 3). If the bottom of the third minimum is located sufficiently high, then the observed structures in the cross section for neutron fission of ^{230}Th, ^{232}Th, and ^{231}Pa can be related to the lowest vibrational states in this minimum. The significant effort which has been expended recently in study of the complicated shape of the outer fission barrier of the light actinides in neutron experiments still has not given a definite answer, although the hypothesis of a third minimum remains the most reasonable means of explaining the results.

Somewhat inconsistent with this at first glance are the data obtained by us on the sub-barrier photofission of ^{232}Th,[50] which indicate the existence of a sequence of resonances which occur in an interval of about 1 MeV from the observed threshold in the cross section up to about 5 MeV (Fig. 12). If all these resonances correspond to vibrational states in the third well, it will turn out to be too deep for damping effects not to appear near its upper edge (at least in neutron fission). We can suppose, however, that the low-lying resonances correspond to states already in the second well. It is possible to discover the assignment of a resonance to the second or third well on the basis of the differing symmetry properties of the states in these wells: states in the second well correspond to mirror-symmetric configurations, and those in the third well to mirror-asymmetric ones. As a result the resonances of the quadrupole and dipole components of the photofission cross section corresponding to vibrational states with $K^\pi = 0^+$ and $K^P = 0^-$ in the third well should be almost degenerate in energy, in contrast to resonances corresponding to similar states in the second well, where the splitting between them of several hundred keV characteristic of the first well should be preserved. In order to distinguish between these two possibilities it is necessary to have data on the behavior of the angular compo-

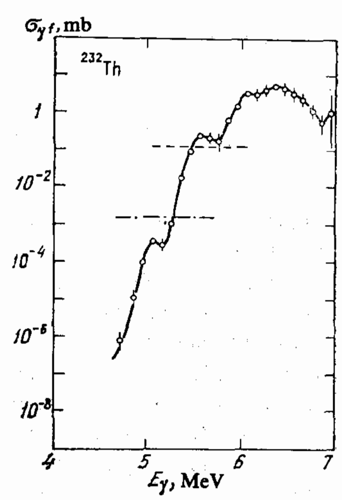

FIG. 12. Cross section for sub-barrier photofission of ^{232}Th obtained in experiments with bremsstrahlung.[50] The dashed and dot-dash lines show the lower limits of the ranges studied by means of quasimonochromatic photons and the (t, pf) reaction, respectively (see the text).

nents of the yield—the dipole and quadrupole components, with a detail and an accuracy at least as good as for the information presently available on the total yield. Solution of this problem presents substantial experimental difficulties since the fraction of the quadrupole component of photofission of ^{232}Th over the entire near-threshold region, as was mentioned above, does not exceed a few percent of the total yield. Here it may turn out to be very useful to use fission by accelerated electrons, in which there is no suppression of the quadrupole component in the entrance channel.

From the point of view of study of the resonance structure of the photofission cross section, obvious interest is presented by improvement of the energy resolution of the experiments. Recently a group of Canadian and American physicists reported the first measurements of the ^{232}Th photofission cross section carried out by the tagged-photon method with a high energy resolution, 12–14 keV.[51] These data (Fig. 13) confirm the resonances previously observed by us in the sub-barrier region and contain an indication of some structure in these resonances. By using methods of γ-ray monochromatization it is possible to supplement substantially our knowledge of near-threshold fission. However, advance to the region of lower excitation energies by this means will be greatly hindered by the poor statistics in experiments with coincidences. Here as before the promsing approach remains through the use of intense bremsstrahlung sources. For the same reason for the region of light actinides with a rather low probability of spontaneous fission ($Z < 94$) they are out of the running also in comparison with direct

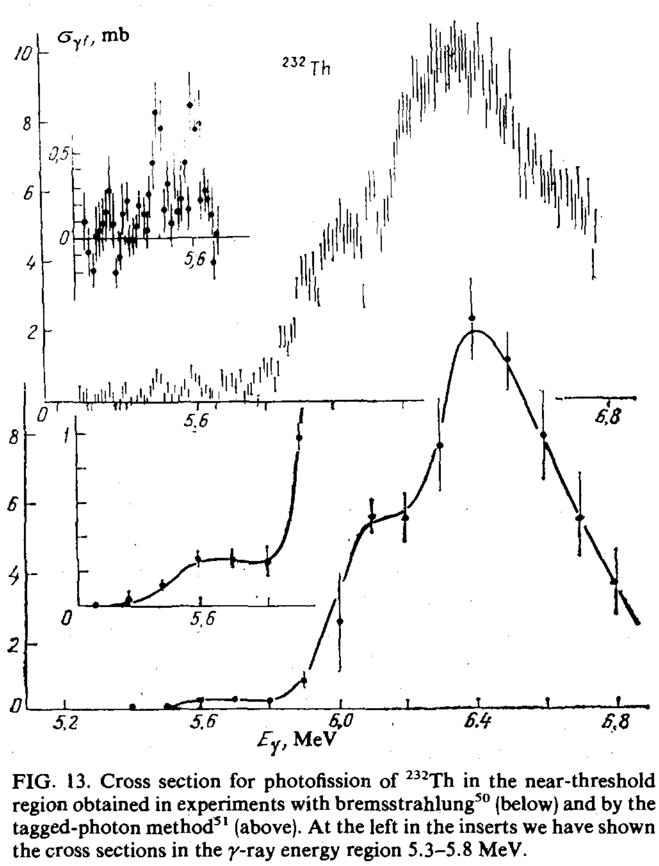

FIG. 13. Cross section for photofission of ^{232}Th in the near-threshold region obtained in experiments with bremsstrahlung[50] (below) and by the tagged-photon method[51] (above). At the left in the inserts we have shown the cross sections in the γ-ray energy region 5.3–5.8 MeV.

reactions. The levels of fissility of such nuclei which can be reached in the sub-barrier region by means of direct reactions and various means of monochromatization of γ rays are shown for the case of ^{232}Th in Fig. 12 (for more detail see Ref. 50).

The study of quadrupole photofission of ^{232}Th well below threshold can play a decisive role also in answering the very important question of the height of the inner hump A: the splitting of the lowest bands of channels of positive and negative parity at the mirror-symmetric inner hump, as we have mentioned above, should lead to an increase of the quadrupole component at energies below the negative-parity channel. The first indications of this increase for ^{232}Th were observed by us at an energy near 5 MeV (see Fig. 6). However, an unambiguous answer will require a further advance downward in energy in this region which is already difficult for experimental study. Here also, perhaps, use of the electrofission reaction will facilitate success.

If the second well is sufficiently deep, as in the case of uranium and the heavier actinides, with increase of the excitation energy it is possible to have formed in this well other sufficiently complicated states which we can arbitrarily call compound states of the second well (states of class II). The interaction of the vibrational states with the compound states leads to a distribution of the fission properties of a vibrational state among the compound states. The density of the levels in the second well will depend on the excitation energy in about the same way as in the first well.[52] Therefore even for even-even nuclei at excitation energies in the second well above the energy gap, the density of compound states substantially exceeds the density of vibrational states, and damping of the latter by spreading over the compound states in the second well can be described by means of a strength function. If the width of this strength function turns out to be less than the distance between the vibrational levels, a partially damped fission resonance will appear in the cross section. A classic example of a partially damped resonance is the resonance of ^{240}Pu at an excitation energy of 5.05 MeV. It has been studied most completely in the reaction ^{239}Pu(d, pf) with an energy resolution of 3 keV.[53] In this experiment an intermediate structure was found for the damped vibrational resonance, which is interpreted as a breakup of the vibrational state into the compound states of the second well. There are many other examples of partially damped resonances in the fission cross section of even-even nuclei excited in transfer reactions[16] and in photoexcitation.[50] The compound states of the second well in turn, as a result of the finite transmission of the inner hump, interact with the states of the first well and we see experimental confirmation of this in the grouping of the compound-nucleus resonances which have an increased fission width.[16]

Thus, in the case of a partially damped vibrational resonance we can obtain a complete picture of the hierarchy of states of an excited nucleus according to their fission properties: in the resonance region among compound-nucleus states with intervals equal to the distance between the levels in the second well there will appear groups with increased fission width, and the vibrational resonance itself will appear as the envelope of the distribution of the total fission width over these groups.

Such a hierarchical structure will not always appear in its entirety. Depending on the density of states and the strength of the interaction between them, it is possible to have, for example, cases of pure vibrational resonances in which near the vibrational state there are no compound states over which the damping could occur, or cases of one state in a group, in which the width of the interaction of the states of the first well with the states of the second well is less than the distance between the levels in the first well.

For the theoretical description of such diverse situations, various approaches have been developed, which have been used to investigate in particular the influence of the intermediate structure of the resonances on the averaged fission probability measured in experiments with moderate resolution, and it has been shown that this influence cannot be neglected in the sub-barrier region.[54] The most detailed apparatus for describing the fission probability with inclusion of the structure of states of various natures has been developed by Lynn in the framework of the R-matrix theory.[16,55] A less detailed and more approximate, but much simpler and more convenient approach for description of the fission probability averaged over intermediate structure over a very wide range of sub-barrier excitation energies was developed in Refs. 56 and 57. This approach takes into account in a unified way the physical situations discussed above which change with excitation energy. In the near-threshold region for description of broad partially damped vibrational resonances the ideas of the doorway-state model are used. At low excitation energies when the width of damping of the vibrational state becomes less than the distance between the compound levels, perturbation theory is used for description of a pure vibrational resonance.

Let us make clear in what sense we are using here the term doorway states. The source of the fission width of an excited state of a compound nucleus is the admixture of the fission mode in its wave function, which appears as the result of interaction between the fission vibrational modes and the states of a nonfission nature which are excited in the initial stage of the raction. The fission mode is usually associated with β vibrations and their comnbinations with simple collective motions of the nucleus—rotation, octupole vibrations, γ vibrations, and so forth. The density of such states in most cases is much lower than the density of neighboring more complicated states of internal excitation; thus, states of a fission nature can be considered as doorway states for the fission process.

Here it is worth recalling the idea lying behind doorway states. In a statistical model it is assumed that the energy of a particle entering a nucleus is rapidly distributed among all the nucleons, forming a very complicated structure, and the nucleus lives so long as to essentially forget by what means it was formed. However, if in the spectrum of states of the nuclear system even at high excitation energies there are states of rather simple configuration which are weakly coupled with the set of complicated compound states, then the interaction of the incident particle with the nucleus can be considered initially as excitation of these simple types of motion (doorway states), which subsequently decay into the more complicated structures. Genrally speaking, we are interested in the reverse process—the separation from the complex structures already produced in the compound-nucleus formation stage of a simple β-vibrational mode which carries the excited nuclear system to fission. In this sense the term "exit state" would be more suitable, but it is clear that the entire discussion and the mathematical apparatus do not change at all if this is done.

As a result of interaction of a doorway state $|A\rangle$ with unperturbed compound states $|a\rangle$ there are formed new compound states $|\alpha\rangle$. The distribution of the strength of the doorway state over the compound states is determined by the ratio of the spreading width Γ_{Aa} and the distance D_a compound levels. In the case $\Gamma_{Aa} \gg D_a$ the squares of the amplitudes of the wave functions $(C_{\alpha A})^2$ which describe the admixture of the doorway state $|A\rangle$ in the diagonalized states of the doorway state are determined by the relation

$$(C_{\alpha A})^2 \approx \frac{D_a}{2\pi}\Gamma_{Aa}\left[(E-E_A)^2+\frac{\Gamma_{Aa}^2}{4}\right]^{-1}. \tag{10}$$

In the limit of very weak damping $\Gamma_{Aa} < D_a$ the doorway state preserves the nature of a practically pure doorway state, and only a small part of its strength is admixed into the other compound states. The distribution of this residual strength can be obtained in first-order perturbation theory:

$$(C_{\alpha A})^2 \sim \frac{D_a}{2\pi}\Gamma_{Aa}(E_\alpha - E_A)^{-2}. \tag{11}$$

Formally this expression is equivalent to a Lorentz distribution with a width $\Gamma \approx 2D_a/\pi$ and therefore the smooth part of the distribution of $(C_{\alpha A})^2$ in the two cases of strong and weak damping can be described by a single Lorentz function with a width

$$\Gamma_A = \sqrt{\Gamma_{Aa}^2 + \left(\frac{2D_a}{\pi}\right)^2}. \tag{12}$$

The practically pure doorway states $|\alpha_0\rangle$ which remain in the case of very weak damping must be taken into account individually. The coefficient $(C_{\alpha 0a})^2$ for such a state can be found by means of the sum rule

$$(C_{\alpha_0 A})^2 = 1 - \sum_{\alpha \neq \alpha_0}(C_{\alpha A})^2 \approx 1 - \sqrt{\Gamma_A^2 - \left(\frac{2D_a}{\pi}\right)^2}\,\Gamma_A^{-1}. \tag{13}$$

In the general case the total width of the doorway state, in addition to the damping width, is determined by the intrinsic decay widths of the state $|A\rangle$ (for example the fission width Γ_{Af}, the radiative width $\Gamma_{A\gamma}$, and so forth).

In the model of a two-humped barrier the states of the nucleus naturally are divided into two classes of doorway and compound states: $|A\rangle$ and $|a\rangle$ in the first well and $|B\rangle$ and $|b\rangle$ in the second well, respectively. Thus, it is necessary to take into account the interactions of the doorway states with the compound states both inside each class and between states of different classes. It is assumed that the interaction between the fission mode and the compound states will depend directly on the overlap of their wave functions in deformation space. Since interactions between states of different classes are suppressed by the transmission factor of the inner hump, the problem is solved approximately. First one considers individually the interaction of compound states of class I ($|a\rangle$) with the doorway states $|A\rangle$ and $|B\rangle$ and individually the interaction of the state $|b\rangle$ with $|A\rangle$ and $|B\rangle$. As a result of these interactions new compound states $|a'\rangle$ and $|b'\rangle$ are formed which belong to the same classes as the unperturbed states $|a\rangle$ and $|b\rangle$, respectively. The states $|a'\rangle$ and $|b'\rangle$ contain an admixture of the fission mode, and in states of class II this admixture is substantially stronger as a result of the larger fission width of the doorway states $|B\rangle(\Gamma_{Bf} \sim T_B, \Gamma_{Af} \sim T_A T_B)$ and as a result of the lower density of compound states in the second well. Therefore the states $|b'\rangle$ play the role of doorway states for $|a'\rangle$.

The main consequences of this discussion reduce to the following. The nonuniformity of the distribution of the strength of the doorway states over the compound states (in the case in which Γ_B is less than the distance between the state $|B\rangle$) results in a gross structure of the fission width of the state $|a'\rangle$. The result of interaction of the states $|b'\rangle$ which have an increased fission width is an intermediate structure of the fission width of the states $|a'\rangle$.

This pattern is destroyed in the deep sub-barrier region. With reduction of the excitation energy and the approach to the bottom of the second well, the average distance between the levels $|b\rangle$ rises exponentially and can become greater than the spreading width of the states $|B\rangle$. That is, a situation of strong damping goes over to a situation of very weak damping, and the width of the gross structures will now be determined not by the spreading width, but by the distance between the levels $|b\rangle$. However, only a small fraction of the strength of the doorway state will be distributed in this way. The main part of the strength of this state is concentrated in the state $|b_0\rangle$ closest to $|B\rangle$, forming a very narrow resonance in the fission width of the states $|a'\rangle$. Since the total width of the compound states of class II $\Gamma_{b'}$ is made up of the width of the interaction with states of class I $\Gamma_{b'a'}$ and the fission width $\Gamma_{b'f}$ (the radiative width $\Gamma_{b'\gamma}$ gives a small contribution to $\Gamma_{b'}$) and both these components fall off exponentially with energy ($\sim T_A$ and $\sim T_B$ respectively), then for the interaction of $|b'\rangle$ with $|a'\rangle$ there is also realized rapidly a case of very weak damping, and the width of the resonance, which is due to the practically pure fission vibration $|b_0\rangle$, will be determined by the distances between compound levels in the first well: $\Gamma_{b0} \approx 2D_a/\pi$.

A similar structure in the deep sub-barrier region is found also in the isomer-population width. However, the probability of delayed fission, as in the qualitative discussion in the preceding section, depends on the energy on the average more weakly ($\sim T_A$) than does the probability of prompt fission ($\sim T_A T_B$). Therefore at low energies ($\lesssim 4.5$ MeV for the nuclei ^{236}U and ^{238}U) the probability of delayed fission becomes predominant, and in the curve of the energy dependence of the total probability of prompt and delayed fission this leads to the appearance of a break due to the transition from the steeper dependence ($\sim T_A T_B$) to the weaker dependence ($\sim T_A$) (the isomeric shelf).

Let us consider now how this description agrees with the experimental results for the isotopes ^{236}U and ^{238}U. As the result of mathematical processing of the angular components of the yield we obtained the cross sections σ_a, σ_b, and σ_c, with which in the approximation $\sigma_\gamma^{E2} \ll \sigma_\gamma^{E1}$ and with inclusion of the delayed fission cross section σ_f^d we can relate the fission cross sections $\sigma_f^{J\pi K}$ for channels with quantum numbers (J, π, K):

$$\sigma_f^{2^+0} = \sigma_c, \quad \sigma_f^{1^-0} = \sigma_b + \frac{1}{2}\sigma_f^{1^-1}, \quad \sigma_f^{1^-1} + \frac{2}{3}\sigma_f^d = \frac{2}{3}\sigma_a. \qquad (14)$$

These cross sections are shown in Fig. 14.

In making the model calculations we assumed degeneracy of the lowest channels $J^\pi = 2^+$ and $1^-(K=0)$ in the outer hump B and used a model in which K is forgotten in the second well. The details of the calculations can be found in Ref. 58. The results of these calculations of the photofission cross sections are shown in Fig. 14, and as can be seen on the whole there is satisfactory description of the experimental data.

It must be emphasized that as a result of the large energy range studied experimentally, the barrier parameters $E_{fA}^{K\pi}$, $E_{fB}^{K\pi}$, and $\hbar\omega_{AB}$ are determined in rather narrow intervals of the order 0.1–0.15 MeV, beyond which the description of the cross sections gets considerably worse. Over the entire sub-threshold region, as can be seen from Fig. 14, resonances are distinctly observed in the cross-section components. It is true that in view of the large distance between the

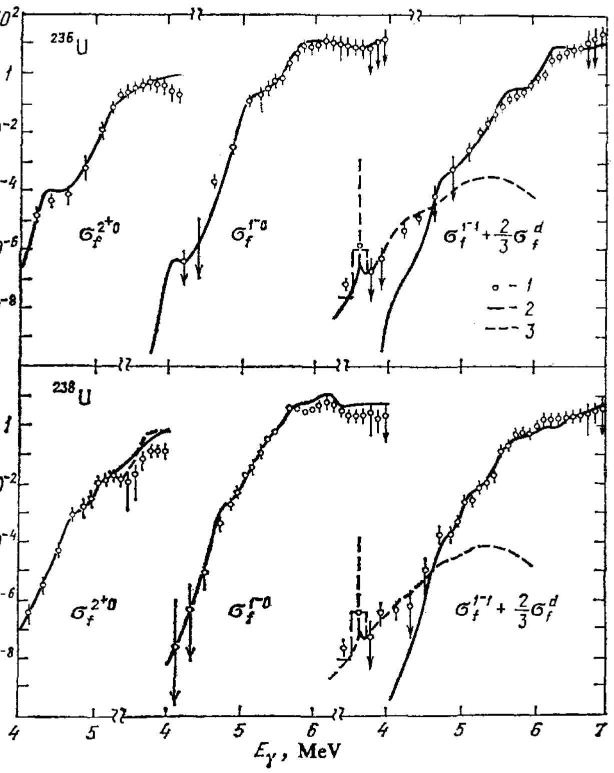

FIG. 14. Results of analysis of the components of the cross section for photofission of ^{236}U and ^{238}U. 1—experiment, 2—calculation of prompt photofission according to the doorway-state model, 3—calculation of the combined contribution of delayed fission from an isomeric state. The histogram near the lowest resonance shows the result of averaging the theoretical curve over the experimental resolution (100 keV).

experimental points it is difficult to draw definite conclusions regarding the width of these resonances and especially regarding the energy dependence of the damping width $\Gamma_{Bb}(E - E_{\rm II})$. In calculation of the curves shown in Fig. 14 we used the following spectra of doorway states $E_B^{k\pi}$ (MeV):

	^{236}U	^{238}U
E_B^{0+} :	3.6; 4.3; 5,35	3.6; 4.7; 5.1
E_B^{0-} :	4.0; 5,1; 5,85	4.7; 5.35; 5.7
E_B^{1-} :	4.7; 5.6; 6,3	4.7; 4.8; 5,1; 5.55; 5.75

A fraction of these resonances, for example the resonance at 4.0 MeV in $\sigma_f^{0^-}$ for the nucleus ^{236}U, appear less distinctly in the experiment, but without taking them into account it is impossible to maintain the calculated dependence at the level required by experiment. In a number of cases it has been necessary for the same purpose to take into account two closely spaced states, the difference between which is substantially less than the average distance between the fission levels, which amounts to about 0.6 MeV, i.e., it has been necessary to introduce a fragmentation of the doorway states (4.7 and 4.8 MeV, 5.5 and 5.7 MeV in $\sigma_f^{1^-}$ of the ^{238}U nucleus).

The resonance which is lowest in energy in the cross sections for ^{236}U and ^{238}U is in the region of the isomeric shelf, and the major contribution to this resonance is from delayed fission. This resonance belongs to the category of resonances whose width, as a consequence of the conditions $\Gamma_B < D_b$ and $\Gamma_b < D_a$ is determined not by the damping width Γ_{Bb} but by the value of $D_a \ll \Gamma_{Bb}$. This width is too small in comparison with the distance between the experimental points $\Delta E_{\max} = 0.1$–0.2 MeV in the integrated yield $Y(E_{\max})$. Since in establishing the cross sections from the data on $Y(E_{\max})$ one actually obtains information only on the number of fissions in the interval $E_{\max}^{i+1} - E_{\max}^{i}$, the representation of the theoretical dependence which is most adequate to the content of the mathematical analysis of the experimental data is representation in the form of a histogram which averages the theoretical curve within a measurement step. The result of such averaging is shown in Fig. 14 by the dashed line.

Thus, the doorway-state model permits description in a unified manner of the probability of sub-barrier fission over the entire energy region studied experimentally, and this is its principal advantage over other more widely used approaches to description of the same properties, which as a result of simplifications have limited applicability (see for example Refs. 44 and 58). The present model is also a step forward in the detailing of our ideas regarding the mechanism of fission, especially in such questions as the quantum aspects of the interaction of the collective and nucleonic degrees of freedom in the fissioning nucleus, the role of quasi-stationary states in the second well, and so forth.

It must be emphasized again that the observed resonance in delayed fission of ^{238}U and ^{236}U at $E_\gamma = 3.6$ MeV is extremely interesting in its quantum aspect: this resonance is a purely vibrational state in the second well, which does not overlap other levels of the first and second wells. We are dealing with a unique quantum-mechanical situation in which excitation of a collective state occurs as a result of overlap of the wave functions of the nucleus in states with different deformations.

6. THE BARRIERS OF SYMMETRIC AND ASYMMETRIC FISSION

In completing this review we shall dwell briefly on the study of fragment mass distributions, or more precisely on those aspects of this question which are directly related to the structure of the fission barrier of heavy nuclei. At the present time investigators have formed the unanimous opinion that the shell structure of the fissioning nucleus in the later stages of its evolution is responsible for formation of the asymmetry of fission, and as to just what stage—this question, which is the subject of a discussion which has gone on for many years, still remains open. In the widely used statistical model[6] only the final phase of the process is considered—the configuration in which individual fragments have been formed but are still in contact. In other approaches[13,15–62] a significant role in formation of the fragment mass distributions is assigned to the saddle point, in particular, in fission of heavy nuclei—passage over the outer barrier B, in the course of which, as we have seen, the fissioning nucleus loses its stability against mass-asymmetric deformation (see Fig. 2). Up to this time we have been concerned with other consequences of this important property: the influence of the symmetry of the nucleus on the spectrum of low-lying fission channels and the occurrence of a third well.

The existence of a difference in the potential energy of deformation for mass-symmetric and asymmetric configurations of the nucleus in the region of the top of the outer hump of the barrier still does not mean that there are two paths to separation which can be distinguished experimentally. Everything will depend on how and to what extent the configuration of the nucleus formed at the saddle point changes in the course of the descent from the barrier to the scission point. Both points of view regarding the "place" of formation of the fragment mass distribution are supported by theoretical calculations. They differ in a number of initial assumptions regarding the properties of the fissioning nucleus, which at this time are poorly known, and in view of this a choice between them is impossible without experimental information.

The point of view that the fragment mass distribution begins to be formed at the rather distant approaches to the scission point is supported by a number of experimental facts and theoretical results. In Refs. 13 and 59, among others, the authors note a correlation between the calculated value of mirror-asymmetric deformation at the saddle point and the observed ratio of the most probable fragment masses. A correlation has been established between the experimental ratios of the yields of symmetric and antisymmetric fission Y_s/Y_a (Refs. 60 and 63) and the theoretical predictions regarding the difference of the heights of the hump B for mass-symmetric and mass-asymmetric deformations.[64] In Ref. 65 it was observed that in the region of the pre-actinides, which

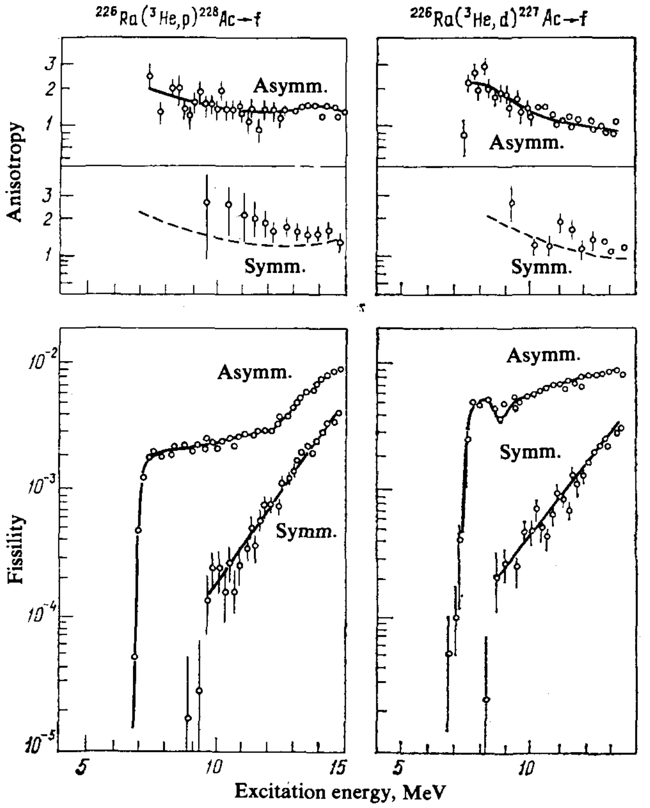

FIG. 15. Fissility and angular anisotropy of symmetric and asymmetric fission in the reaction $^{226}Ra(^3He, pf)$ and $^{226}Ra(^3He, df)$.[59] The dashed line shows the angular anisotropy of asymmetric fission.

undergo primarily symmmetric fission, the dependence of the dispersion of the mass distribution on the parameter Z^2/A corresponds to the prediction of the liquid-drop model for the saddle point, and not for the scission point.[66]

To solve this question one needs experiments which would establish a direct connection between the fragment mass distributions and the fission barrier, for example, differences in the thresholds for symmetric and asymmetric fission. The light actinides, in which the near-threshold region of the fissility is determined by the higher outer barrier, provide the possibility of demonstrating the existence of a difference in these thresholds in a rather direct experiment.

Extensive experimental studies of the properties of symmetric and asymmetric fission in the vicinity of the threshold for the Ra–Th region have been carried out by means of direct reactions.[59,67] In these experiments two characteristics sensitive to the barrier height have been measured for the two modes of fission—the fissility and the fragment angular anisotropy, examples of which are shown in Fig. 15. The differences in the energy dependence of the yields of symmetric and asymmetric fission expected in the near-threshold region have been observed systematically, which cannot be said regarding the fragment angular anisotropy. Measurements of both quantities have poor statistical accuracy, especially the fission angular distribution. Therefore there is no unified opinion as to their interpretation.

Similar studies of the fragment mass distributions in fission in the (γ, f) reaction have been carried out for three isotopes: ^{238}U (Refs. 68–70) and ^{232}Th (Ref. 68) by radiochemical methods, and ^{226}Ra by means of track detectors.[71,72] Figure 16a shows experimental data on the yield ratio Y_s/Y_a for symmetric and asymmetric fission of ^{238}U and ^{232}Th as functions of the bremsstrahlung maximum energy E_{max}. From the data presented, in particular from the regions of a rapid drop of Y_s/Y_a with decrease of the energy, the rate of which (in an interval of the order $\Delta E_{max} < 0.5$ MeV) is typical of tunneling effects, we can conclude that the threshold of symmetric fission for both nuclei has been reached and passed in the measurement, and this effect, like other features of the observed dependence of Y_s/Y_a on E_{max}, is guaranteed by the statistical accuracy achieved and by the agreement of three experiments for the reaction $^{238}U(\gamma, f)$.

In Fig. 16b we have shown data on the absolute total

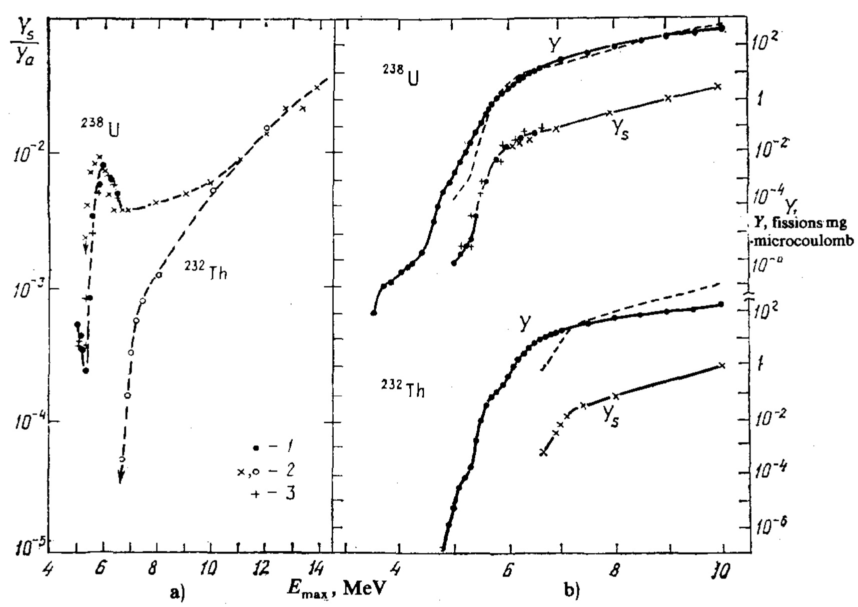

FIG. 16. Yields (b) and ratios (a) of symmetric and asymmetric photofission of ^{232}Th and ^{238}U induced by bremsstrahlung. 1—from Ref. 71, 2—from Ref. 68, 3—from Refs. 70 and 73; Y is the total yield[50] and Y_s is the symmetric yield; the dashed line shows the dependence $Y_s(E_{max})$ normalized to the total yield in the threshold region (see the text).

yields $Y = Y_a(Y_s/Y_a \ll 1)$ (Ref. 50) and on the symmetric-fission yields calculated as YY_s/Y_a. The differences in the symmetric and asymmetric barriers of ^{232}Th appear directly in the difference of the observed thresholds ≈ 0.6 MeV. In the case of ^{238}U it is less noticeable, and this is due to the presence of a strong resonance in the energy dependence of the symmetric component of the photofission cross section (see for example Ref. 73), which in Fig. 16a corresponds to the maximum of the ratio Y_s/Y_a.

It is possible that other such resonances are responsible for the rise in Y_s/Y_a and the break in Y_s revealed by the experimental data at the very lowest γ-ray energies in Fig. 16. These two effects—the shift of the observed thresholds of symmetric and asymmetric fission in the reaction ^{232}Th(γ, f) and the differences in the resonance structure of their cross sections in the reaction ^{238}U(γ, f)—indicate a significant influence of the fission barrier on formation of the fragment mass distribution, and in particular on the ratio of the yields of the main modes of fission.

For the reaction ^{226}Ra(γ, f) measurements have been made of the yield and angular anisotropy of both modes of fission,[72] unfortunately only in the superbarrier energy region. This circumstance and the substantial errors in the measurements for the symmetric component make it difficult to interpret this experiment, which, like experiments with direct reactions, did not reveal statistically significant differences in the fission angular anisotropy. At the same time the entire set of existing experimental data on the angular anisotropy of symmetric and asymmetric fission, including the results of Ref. 72, is consistent with the estimates of the thresholds for these components.[2)]

Thus, experiment gives an affirmative answer to the first question of whether or not there are differences in the potential energy of deformation for mass-symmetric and asymmetric configurations of the nucleus which show up in the observed yields of the corresponding fission modes. At the same time the question of the existence of a correlation of asymmetry and anisotropy of fission, which should be expected in the presence of a difference in the thresholds of symmetric and asymmetric fission, must be considered open. This question undoubtedly deserves the carrying out of new and more accurate experiments, and in this connection it must be emphasized that the possibilities of the (γ, f) reaction have still been only poorly utilized. These possibilities are unqiue from the point of view under discussion: the ratio of the heights of the hump B for the lowest channels $J^\pi = 2^+$ and 1^-, $K = 0$, which dominate in low-energy photofission, is determined just by the mass-asymmetric deformation of the nucleus. Particular interest is presented by the experimental verification of the prediction which follows from the properties of the spectrum of these states regarding the enhancement of the quadrupole component of the fragment angular distribution in symmetric fission. For this purpose it is promising to make use of the (e, f) reaction.

We have considered here only one aspect of the problem of the asymmetry of fission and are compelled to state that so far experiment raises more questions than it gives answers. The state of this problem as a whole is that the group of unsolved problems in it would encompass a rather extensive field of knowledge. This is not surprising, since in this case we are discussing not a small change in the nucleon composition of the nucleus, as in most reactions, but a radical rearrangement, regarding which the development of ideas apparently involves almost all of nuclear physics. At the present time the main thing that is clear is the dominant role in the mechanism of the phenomenon discussed of structure (quantum) properties of the fissioning nucleus.

[2)]In Refs. 71 and 74 the opposite statement is made, that it is not possible to explain in a single consistent picture the properties of the fragment mass distribution and the anisotropy of photofission. However, the data of Ref. 72 and consistent with the estimates of a difference of the thresholds of symmetric and asymmetric fission $\lesssim 1$ MeV for the radium isotopes close to ^{226}Ra with mass numbers $A = 225, 227$, and 228 (Refs. 67 and 75) if one takes into account the error in the measurements and the difference in the location of the channels $K^\pi = 0^-$ for mirror-symmetric and asymmetric configurations (see Section 3).

CONCLUSIONS

Having begun with an analogy with such a purely classical macroscopic object as a liquid drop, physicists have slowly comprehended the quantum features of fission which distinguish the microscopic world of nuclear processes. Today we understand very well that quantum effects in the physics of fission have an all-embracing nature. In the confirmation of this view a dominant role has been played by the creation of the micro-macroscopic method of Strutinskiĭ, which serves not only as a theoretical tool of exceptional effectiveness, but also as a principle which has combined in a single consistent picture important properties of matter which in the past have frequently contradicted each other (the liquid-drop model and the shell model).

The formulation and organization of the present review, which are related to a method of experimental investigation in the excitation-energy region considered, have undoubtedly narrowed the group of questions related to the problem of what is quantum and what is classical in the physics of fission. In particular, we have not been able to discuss the properties of such a typical quantum phenomenon as spontaneous fission, although the characteristics of this phenomenon for decay from the equilibrium state and from the state of a spontaneously fissile isomer contain considerable information regarding the fission barrier of heavy nuclei. We were compelled to deal in a similar manner with the manifestations of quantum properties in fission at significant excitations of the nuclei. We omitted such interesting questions as the fission of cold and hot nuclei and the rearrangement of the shells with energy. A comparative analysis of fission processes at different excitations reveals a picture which is common with other physical phenomena: quantum properties are present in sufficiently cold nuclei, while with heating the nuclei rapidly begin, at energies of the order of 50 MeV, to be described by the quasiclassical liquid-drop model.

We have concentrated our attention in only one direction of experimental studies; here in the course of recent achievements of theory it has been possible to advance very greatly by studying the photofission of heavy nuclei. The possibility of this advance is due to the exceptional simplicity of the kinematics of this reaction. The possibilities of the (γ, f) reaction are far from exhausted, and we have attempted to identify those directions in which the use of this reaction and the related (e, f) reaction will provide new information on the fission process.

Studies of quantum effects (collective and nucleon excitations, and nuclear shell structure) in practice determine the level of our knowledge of the fission process, since the "alternative" properties have been studied in extreme detail in the framework of the homogeneous liquid-drop model twenty years ago. This level is high enough that we can obtain unambiguous experimental information on the structure of anomalously deformed nuclei—properties which at present are accessible only in the study of fission, and at the same time it is still too low to satisfy practical requirements, which increase with increase of the scale of use of the nuclear energy which is liberated in fission.

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