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NUCLEAR FISSION

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CONTENTS

1. INTRODUCTION

SINCE the discovery of nuclear fission by neutron bombardment of uranium[1] and spontaneous fission of uranium nuclei[2] numerous investigations were made of this new type of nuclear reaction.* Even the first experiments revealed that when uranium nuclei are fissioned a large amount of energy is released in the form of kinetic energy of the fission fragments[7], and that an average of 2—3 neutrons are emitted per fission[8]. These features of nuclear fission served as the basis for the realization of the nuclear-fission chain reaction and the creation of a new industry—nuclear power.

Construction of charged-particle accelerators increased the number of fissioning nuclei. By now, nuclei in a wide range of mass numbers have been fissioned by bombardment with neutrons, gamma quanta, and charged particles ranging from protons and mesons to neon ions.

The present article is devoted to a review of the experimental data on nuclear fission. Owing to the limited space in a journal article, we could not present a sufficiently complete bibliography of the work done on nuclear fission†, and were also forced to exclude from consideration some fission problems, such as nuclear fission by meson bombardment, the distribution with respect to the number of neutrons emitted by a given fragment, etc., for which no essentially new data have been recently published. References to most earlier papers are not included in our bibliography can be found in the published review articles, article collections, and monographs devoted to nuclear fission[3-5,9-19].

2. NUCLEAR FISSION CONCEPTS

The liquid-drop model. The fission of a nucleus into two fragments of comparable mass can be effected only as a result of the collective motion of a large number of nucleons of the nucleus. At the time when fission was discovered, the only nuclear model which took into account the collective motion of the nucleons was the model of a charged liquid drop. Therefore, following the discovery of nuclear fission, Meitner and Frisch proposed to regard this process as the fission of a charged liquid drop[20], and soon Bohr and Wheeler[21], and Frenkel[22] performed the first quantitative calculations of this process.

In the case of heavy nuclei, the mutual repulsion of the electric charges compensates to a strong degree for the action of the nuclear attraction forces which hinder the change of the nuclear shape, in analogy with surface tension of a liquid drop. As shown by Bohr and Wheeler[21] and by Frenkel[22], a uniformly charged incompressible drop of spherical form is unstable against small axially-symmetrical deformations if the Coulomb energy of the interaction of the charges E_C^0 is more than double the energy of the surface tension E_S^0, when

$$x=\frac{E_c^0}{2E_s^0}=\frac{\frac{3}{5}\,\frac{Z^2e^2}{R}}{2\cdot 4\pi R^2O}=\frac{3e^2}{40\pi r_0^3O}\;\frac{Z^2}{A}\geqslant 1. \tag{1}$$

The condition of instability against fission is satisfied by nuclei with $Z^2A \geq (Z^2/A)_{cr} = 10 \times (4\pi/3)(r_0^3O/e^2)$, where r_0 and O are the constants in the expressions relating the nuclear radius and the surface-tension energy with the mass number, $R = r_0A^{1/3}$ and $E_S = 4\pi r_0^2A^{2/3}O$, respectively.

*For more details on the discovery of fission see [3-6].

†The cited bibliography includes papers published mainly up to 1966.

For a charged drop with $x = (Z^2/A)/(Z^2/A)_{cr} < 1$ a spherical shape is stable against small deformations. Since for $x > 0$ the potential energy of the initial drop (surface plus Coulomb energies) exceeds the potential energy of its two equal fission fragments when the latter are removed to infinity, it follows that for a charged drop with x in the interval from 0.35 to 1 the potential energy should have a maximum at a certain critical deformation. In order for a nucleus with $0.35 \leq x < 1$ to fission, it is necessary to introduce into it, in the framework of such a classical interpretation, at least a certain minimum excitation energy, an activation energy, the magnitude of which is equal to the potential barrier E_f, the difference between the potential energy of the nucleus at critical deformation and the potential energy of the initial nucleus.

A description of the arbitrary deformation of a liquid drop is a difficult problem. For simplicity, one usually confines oneself to a description of axially-symmetrical deformations of the drop, by expanding the radius vector of the drop in Legendre polynomials

$$R(\theta) = \frac{R_0}{\lambda}\left[1 + \sum_{1}^{N} \alpha_n P_n(\cos\theta)\right], \qquad (2)$$

where the series of N coefficients α_n determines the shape of the drop, and the parameter λ normalizes its volume to the initial value $(4/3)\pi R_0^3$. By investigating the potential energy of the deformed drop as a function of N variables α_n, it is possible to find the shape of the nucleus at critical deformation, which corresponds to the smallest potential energy (saddle point on the potential-energy surface). Bohr and Wheeler[21] considered the symmetrical deformation of a charged liquid drop, confining themselves in the expansion of the radius vector (2) to the first terms P_2 and P_4. This made it possible for them to determine the fission barriers only for nuclei close to the stability limit $(Z^2/A)_{cr}$. Later investigations[23,24] dealt with symmetrical nuclear deformations corresponding to a large number of terms in the expansion (2). Thus, in the numerical calculations of Cohen and Swiatecki[24] the number of expansion terms N was equal to 18, making it possible for them to determine the shape of the nuclei at critical symmetrical deformation and the corresponding barriers for nuclei that are far from the stability limit. The calculated values of the fission barriers[24] can be approximately represented by

$$\left.\begin{aligned} E_f &= 0{,}83\,(1-x)^3 E_s^0 \quad \text{for} \quad \tfrac{2}{3} < x < 1, \\ E_f &= 0{,}38\,(0{,}75-x)\,E_s^0 \quad \text{for} \quad \tfrac{1}{3} < x < \tfrac{2}{3}. \end{aligned}\right\} \qquad (3)$$

Figures 1a and 1b show the fission barriers calculated by Cohen and Swiatecki and the corresponding shape of the nuclei at critical symmetrical deformation for several values of x.

A number of investigations[23,24] dealt with the stability of the symmetrical form of a charged liquid drop at critical deformation, relative to the asymmetrical deformations of the type α_3, α_5, etc. It was found that addition of an asymmetrical deformation component to the symmetrical critical deformation of the drop leads to an increase in the potential energy of the drop when $x > 0.39$. Thus, in the liquid drop model, for nuclei with $x > 0.39$ the potential barrier for symmetrical deformation is the lowest barrier on the potential-energy surface (saddle point).

Cohen and Swiatecki[24] calculated also the potential energy of two identical uniformly-charged ellipsoids in contact. They found that when $x < 0.7$ the minimum potential energy of such a system corresponds to the calculated values of the fission barriers and the form of the fragments at the instant of separation is close to the form of the future fragments in the saddle point, unlike heavy nuclei with $x > 0.7$, for which the form of the nucleus at critical deformation (Fig. 1) differs greatly from two ellipsoids in contact.

Strutinskiĭ et al.[25,26], by solving the variational equation for the surface of a charged liquid drop and minimizing the potential energy of the drop at each stage of its deformation, found that during the entire course up to the instant of separation of the drop, the minimum of its potential energy corresponds to symmetrical configuration of the drop, with the exception of nuclei with $x \simeq 0.8$, for which, at critical deformation, an instability against asymmetrical deformation can possibly appear[26]. It was found in these calcula-

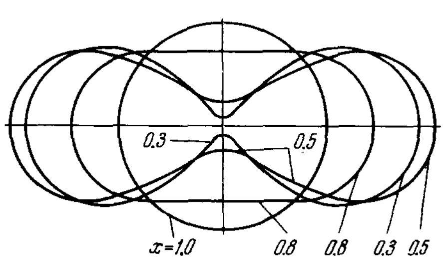

FIG. 1a. Shape of nuclei at the saddle point in the liquid-drop model.[24]

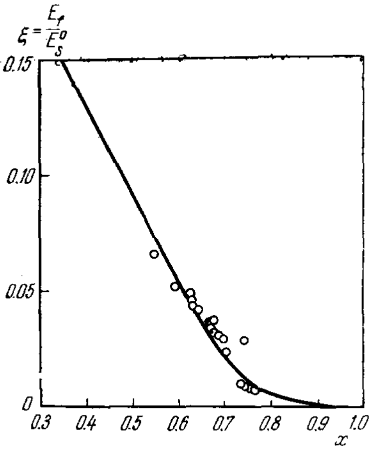

FIG. 1b. Calculated [24] and experimental [52,78,97] values of the fission barrier in relative units E_f/E_s^0 as functions of $x = (Z^2/A)/(Z^2/A)_{cr}$. The experimental values assumed are $E_s^0 = 17.8\ A^{2/3}$ MeV and $(Z^2/A)_{cr} = 48.0$.

tions that the form of the nucleus at the saddle point and the fission barriers are close to values obtained by Cohen and Swiatecki. Strutinskiĭ also performed a variant of the calculation of the nuclear deformation with a variable surface tension that depends on the curvature of the surface of the nucleus[26]. He found, for example, that the calculated values of the nuclear shape at the saddle point (more accurately, the values of the moment of inertia) agree better in this case with the experimental values (see Sec. 7) than the calculated values for a nucleus with a constant surface tension.

Fission channels; A. Bohr's hypothesis. According to Bohr and Wheeler[21], the nuclear fission probability is determined by the ratio of the number of states of the nucleus at critical deformation N_f, which are attainable at the given excitation energy, to the number of states of the initial nucleus, so that

$$\Gamma_f = \hbar A_f = \frac{D}{2\pi} N_f, \tag{4}$$

where A_f is the probability per unit time of the decay of a given level of the compound nucleus by fission, Γ_f is the fission width of the level under consideration, and D is the average distance between the levels of the compound nucleus.

By regarding fission as a quantum mechanical process wherein the fragments tunnel through the potential barrier, Hill and Wheeler[27] connected the nuclear fission probability with the difference between the nuclear excitation energy E and the height E_f of a parabolic barrier (inverted potential-energy curve of a harmonic oscillator)

$$\langle \Gamma_f \rangle = \frac{D}{2\pi} \left\{ \frac{1}{1+\exp\left[2\pi (E_f - E)/\hbar\omega\right]} \right\}, \tag{5}$$

where ω is the oscillation frequency of the harmonic oscillator. The expression in the curly brackets (penetrability of the barrier) is 0.5 at a nuclear excitation energy $E = E_f$ and decreases exponentially with decreasing E, becoming equal to unity when the excitation energy of the nucleus greatly exceeds the height of the barrier. In the most general form, the average value of the fission width of a number of closely-lying levels of a compound nucleus with spin I and parity π[28] is

$$\langle \Gamma_f^{I,\pi} \rangle = \frac{D^{I,\pi}}{2\pi} \sum_{\lambda} \frac{1}{1+\exp\left[(E_{f,\lambda}^{I,\pi} - E)/\hbar\omega\right]} = \frac{D^{I,\pi}}{2\pi} N_{\text{eff}}, \tag{6}$$

where the summation is over all the possible states of the nucleus at the saddle point (fission channels) with spin I and parity π, each of which has its own fission barrier $E_{f,\lambda}^{I\pi}$, and N_{eff} is the effective number of the fission channels.

In 1955, A. Bohr[29] proposed that at a nuclear-excitation energy not too much higher than the fission barrier, when the greater part of the excitation energy is transformed at the saddle point into the nuclear deformation energy, there is, for a nucleus at the saddle point, only a small number of admissible states (fission channels). He proposed further that the spectrum of the states of the nucleus at the saddle point, the spectrum of the fission channels, is similar to the spectrum of the excited states of the same nucleus near equilibrium, i.e., the spectrum of the states corresponding to excitation of the collective degrees of freedom of the nucleus (rotational and vibrational) and the nucleon degrees of freedom. Thus, for example, the spectrum of the excited states at the saddle point of an even-even fissioning nucleus, as expected in accordance with this hypothesis, consists of the rotational band of levels of the ground state with K = 0, $I^\pi = 0^+, 2^+, 4^+$, etc., of the second band by several hundred keV above the levels with K = 0, $I^\pi = 1^-, 3^-, 5^-$, etc.* At still higher energies, more complex rotational-vibrational states are possible, and finally, at energies near 2 MeV (see Sec. 7) single-particle states due to the appearance of the first two unpaired nucleons in the nucleus are possible[28].

The fission-channel hypothesis turned out to be fruitful, as will be shown below, in explaining many aspects of the fission process, especially in explaining the energy dependence of the fission cross sections and the angular anisotropy of nuclear fission.

3. SPONTANEOUS FISSION OF NUCLEI

In the case of spontaneous fission of nuclei, we deal with a quantum-mechanical effect of the penetration of fragments through a potential barrier, as predicted by Bohr and Wheeler[21] and discovered by Flerov and Petrzhak[2]. The penetrability of the fragments through the potential barrier should increase, and the lifetime of the nucleus relative to spontaneous fission should decrease with increasing fissility parameter Z^2/A, for according to the liquid-drop model, the potential barrier decreases in this case. Figure 2 shows the presently available data on the dependence of the half-life for spontaneous fission of the nuclei, $T_{1/2}$, on Z^2/A. The main regularity observed in this relation, as expected from the liquid-drop model, is the decrease[34] of $T_{1/2}$(sp) with increasing Z^2/A. However, as seen from Fig. 2, this dependence is not universal: for even-even isotopes of a given element, $T_{1/2}$(sp) first increases with increasing mass number of the isotope (with increasing number of neutrons), reaches a maximum, and then decreases[35]. Another deviation from the simple dependence lies in the increase[34,36], by a factor 10^3—10^6, of $T_{1/2}$(sp) of nuclei with odd mass number, as compared with even-even nuclei having the same values of the parameter Z^2/A. Both deviations indicated above are connected, apparently, with the fact that the height of the fission barrier depends not only on Z^2/A of the nucleus, as predicted in the liquid-drop

*K – projection of the angular momentum of the nucleus I on its symmetry axis.

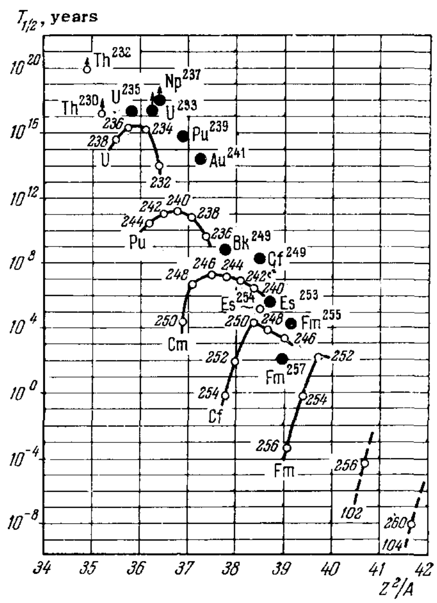

FIG. 2. Half-life of nuclei for spontaneous fission, $T_{1/2}$ (sp), vs. Z^2/A – the fissility parameter of the nucleus [30-33].

model, but also on the relation between the number of neutrons and protons in the nucleus, and in final analysis on the structure of the nucleus.

Swiatecki[37] obtained an empirical relation between $T_{1/2}$(sp) and Z^2/A, in which the deviation of $T_{1/2}$(sp) from the value expected in accordance with the liquid-drop model is connected with the deviation δm of the mass of the nucleus from the value given by the semi-empirical mass formula of the liquid-drop model. The latter deviation leads to a fluctuation of the height of the barrier, and in final analysis to a deviation of the half-lives. Another explanation proposed within the framework of the simple unified model of the nucleus for the anomalously large lifetimes, relative to spontaneous fission of nuclei with odd mass numbers, is as follows[38,39]. Owing to the conservation of the nuclear spin and parity during the fission of the nucleus with odd mass number, the odd nucleon cannot go over during the course of deformation to other levels, even if this leads to a gain in energy, and consequently, the state of such a nucleus, on going through the potential barrier, does not coincide with the lowest energy state. On the other hand, in the case of even-even fissioning nuclei, the paired state with zero spin is apparently the lowest state in all deformations, including the critical one. Johansson[40], proposing that the Nilsson level scheme is effective up to the nuclear deformation in the saddle point, extrapolated the position of the levels at the saddle point and estimated the influence of the single-particle effect on the height of the fission barrier. With allowance for these effects, we obtained a smooth dependence of $T_{1/2}$(sp) on Z^2/A, as follows from the liquid-drop model. However, the values of $T_{1/2}$(sp) predicted by Johansson for the elements 102 and 104 deviate greatly from the experimental values[32,33], this being apparently the consequence of the liberal approximations made in the determination of the position of the nucleon orbits and in the estimate of the deformations of the ground state of the nucleus and of the nucleus at the saddle point.

Fong[41] indicated a possible connection between the difference of $T_{1/2}$(sp) for even-even and A-odd spontaneously-fissioning nuclei and the dependence of the energy of the nucleon pair correlation on the nuclear deformation. To explain the observed difference in $T_{1/2}$(sp) it is necessary to postulate a difference in the pairing energy at the saddle point and in the ground state of an even-even nucleus, amounting to ~ 0.4 MeV. As was recently obtained in experiments on the angular anisotropy of fission[42] (see Sec. 7), the energy gap $\Delta_0^{\mathrm{s.p.}}$ of the fissioning even-even nucleus Pu^{240} is almost twice the energy gap Δ_0 of the nucleus Pu^{240} in the ground state. The fission barrier of the even-even nucleus, E_f (e-e) = E_f (odd) + $(\Delta_0 - \Delta_0^{\mathrm{s.p.}})$ is consequently approximately 0.7 MeV lower than the fission barrier of the neighboring odd nucleus, corresponding to an increase in the lifetime of the odd nucleus relative to the spontaneous fission, compared with the even-even nucleus, by a factor of approximately 2×10^3[42], and is close to the experimentally observed deviations.

In recent years, an interesting phenomenon was observed, namely an anomalous rapid decay of spontaneously fissioning nuclei obtained by bombardment of heavy nuclei with particles. The first fraction that decays rapidly by spontaneous fission was observed[43] in 1962 when uranium was bombarded with accelerated O^{16} and Ne^{22} ions, and later in the irradiation of plutonium and americium with neutrons, deuterons, and alpha particles[44-46]. It was established[44] that the half-life of Am^{242} nuclei is smaller by $\sim 10^{19}$ than the time expected in accordance with the half-life systematics (see Fig. 2). This anomalously rapid decay is connected with the spontaneous fission of the Am^{242} nucleus from the isomer state with energy 2–3 MeV[44,45]. By now, spontaneous fission was observed in a number of nuclei from the isomer state, with half-lives from 0.8 msec to 60 sec[46]. It was recently found[47] that spontaneous fission from the isomer state of Am^{242} nuclei is predominantly asymmetrical, similar to the ordinary spontaneous fission of nuclei (see Sec. 5.1). Apparently these are only the first examples of investigations of the spontaneous fission of nuclei from the isomer state.

4. CROSS SECTION FOR INDUCED NUCLEAR FISSION

4.1. Fission of Nuclei at Low Excitation Energies

In the case of fission of heavy nuclei by neutron bombardment, the target nuclei can be arbitrarily subdivided into two groups: nuclei that become fissioned

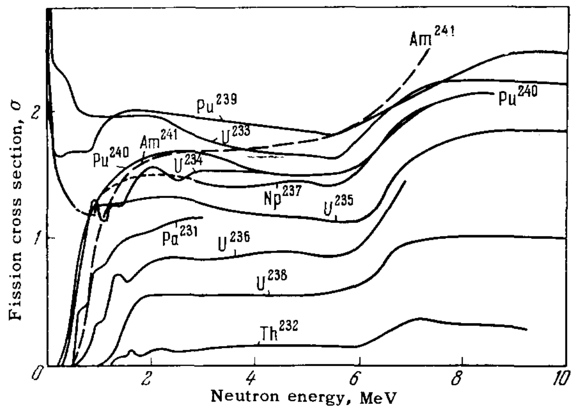

FIG. 3. Dependence of the nuclear fission cross section on the neutron energy (the compilation of the data and references to the original sources are given in the article of Henkel [48]) (σ is in barns).

by thermal-neutron irradiations, and nuclei that do not (Fig. 3 and Table I). In the former case the fission barrier (E_f) of the compound nucleus is lower than the binding energy of the neutron (B_n) in the compound nucleus, and in the second case it is larger. The fission cross sections of the nuclei of the first group first decrease with increasing neutron energy, exhibiting a number of resonant peaks[49], and form the first plateau at a neutron energy 1—5 MeV (see Fig. 3). The nuclei of the second group begin to fission only at a certain threshold neutron energy, their fission cross sections first rise steeply, and then reach saturation, namely the first plateau. When the neutron energy rises above 5 MeV, the character of variation of the fission cross section of the two groups of nuclei is similar (Fig. 3).

Fission of nuclei near the barrier. For nuclei of the type U^{238} and Th^{232}, a study of the fission excitation function at excitation energies lower than the fission barrier is possible by bombarding these nuclei with neutrons[49] (see Fig. 3), photons[51], and neutrons produced by deuteron stripping in the (d, pf) reaction[52]. For the similar nuclei U^{233}, U^{235}, and Pu^{239}, such a study is possible only in the last two cases, for the fission cross sections of these nuclei amount to several hundred barns even when thermal neutrons are used for the irradiation (see Table I). The general law governing nuclear fission at excitation energies E^* lower than the fission barrier is a rapid exponential increase of σ_f with increasing E^*.

When U^{238} was bombarded with neutrons[53] in the (n, f) reaction, and U^{233}, U^{235}, and Pu^{239} were bombarded with neutrons from deuteron disintegration, in the (d, pf) reaction[52], irregularities were observed in the fission excitation cross section; these irregularities are connected with the appearance of a discrete structure of the nuclear levels at the saddle point, of the fission channels. With increasing excitation energy, in the region below the fission barrier, the excitation cross section increases whenever the next effective fission barrier appears. According to (5), the probability of penetration through the potential barrier is 0.5 when the excitation energy is equal in magnitude to the height of the fission barrier. Accordingly, one assumes E_f to be equal to the value of E^* at which the fission cross section amounts to one-half the value on the first plateau. The values of the fission barrier determined in this manner by Northrop et al.[52] for the compound nuclei U^{239}, U^{236}, U^{234}, and Pu^{240} are respectively 6.34, 5.79, 5.27, and 4.77 MeV.

There are a number of uncertainties in the determination of the fission barrier from the energy E^* at which the fission cross section is half the value on the first plateau. Thus, by definition, the height of the barrier is connected with the accuracy at which the first plateau in the fission cross section is determined. A number of the kinks in the excitation function can be disregarded, owing to the insufficient measurement accuracy. Some of the observed kinks can be due to competition from neutron emission. This pertains to the case when the fission barrier of nuclei with $E_f > B_n$ is determined. Owing to the lack of detailed information on the probability of neutron emission from the compound nucleus, it is difficult to establish in this case which of the kinks in the excitation function are

Table I. Nuclear fission cross sections σ_f upon irradiation by thermal neutrons

Target nucleus	σ_f	Literature	Target nucleus	σ_f	Literature	Target nucleus	σ_f	Literature
Th^{229}	32±3	49	Pu^{239} *)	740.6±3.5	49	Am^{244}	2300±300	49
U^{232}	77±10	«		742.4±3.5	50		2300±300	«
U^{233} *)	524.5±1,9	«	Pu^{241} *)	950±30	49	Cf^{249}	1735±70	«
	527.7±2,1	50		1009±9	50	Cf^{250}	350	«
U^{235} *)	577.1±0,9	49	Am^{242g}	2900±1000	49	Cf^{251}	3000±260	«
	579.5±2,0	50	Am^{242m}	6000±500	«			

*Recommended [49,50] average universal values of σ_f for 2200 m/sec neutrons.

due to the fission barrier. As indicated by Usachev et al.[54], there is one more uncertainty in the determination of the height of the fission barrier. For nuclei for which $E_f < B_n$ and for which the only process competing with fission when $E^* < E_f$ is photon emission, the fissility reaches half the fissility on the plateau, when the fission width Γ_f becomes equal to the radiation width Γ_γ, corresponding to an excitation energy lower than the height of the fission barrier by several hundred keV in the case of fission of the compound nuclei U^{234}, U^{236}, and Pu^{240}.

Measurements of sufficiently high precision[49,55-58] have shown that the fission cross section of a number of nuclei with threshold $E_n > 0$ in the far subthreshold region does not decrease exponentially with increasing E^*, but remains approximately constant in a rather broad region $E^* < E_f$. This may be due to the fact that when, say, Pu^{240} is bombarded by neutrons, the fission takes place in this energy region through channels with $K = 1/2^-$ or $3/2^-$. For the compound nucleus Pu^{241} these channels lie apparently lower[57] than the channels with $K = 1/2^+$. The fission cross section is approximately constant in a broad energy region, since the increase in the penetrability of the barrier with increasing energy of the p-neutrons is compensated for by the decrease in the cross section for the formation of the compound nucleus when these neutrons are absorbed.[57,58].

Resonances in the fission cross section. Characteristic features of the resonant structure of the cross section for the fission of U^{233}, U^{235}, Pu^{239}, and Pu^{241} are the large deviations from the fission widths Γ_f of the resonances from the mean value, and, to a considerable degree, the asymmetrical form of a large number of resonances[49]. These singularities in the behavior of the nuclear fission cross section are connected with the limited number of the nuclear states at the saddle point, fission channels, which are possible at the given energy. In the analyses performed to date of the fission cross sections in the resonance region, account was taken of the interference of the closely-lying levels[59,60], but it was assumed at the same time that the position of the maximum of the resonance in σ_f coincides with the position of the level of the compound nucleus. According to the Porter-Thomas statistical treatment[61] the fluctuations of the fission widths Γ_f can be described by a χ^2 distribution with a number of degrees of freedom (ν) which coincides with the number of the effectively open fission channels N_f, from ~ 2 to 4. The number of channels determined directly with the aid of formula (4), $N_f = 2\pi\langle\Gamma_f\rangle/D$, gives much lower values of N_f, from 0.18 to 0.65[62]. On the other hand, on the average for the two spin states $I = I_0 \pm 1/2$, in accordance with the systematics of the possible states of the nuclei[28], the number of open fission channels, in the case when U^{233}, U^{235}, and Pu^{239} are bombarded with s-neutrons, is equal to approximately 1.5 in the first two cases and 0.5 in the last case.

As indicated by Lynn[63], the disparity in the number of fission channels determined from experiment in accordance with formula (4) and the number of fission channels predicted by the theory can be the consequence of the underestimate of the mean fission width of the resonances $\langle\Gamma_f\rangle$, which in turn is the consequence of the treatment of the resonances, which in many cases actually are quasiresonances, results of level interference. Lynn[63] modelled the interference of the nuclear levels, specifying a number of fission channels close to that predicted by the theory, and found as a result that many of the levels of the compound nucleus do not "appear" in the modelled quasiresonances (22 instead of 34), and in many cases the quasiresonances do not coincide in position with the levels of the compound nucleus and have an asymmetrical form. An analysis of the quasiresonances in accordance with the Breit-Wigner formula for an isolated level yields for the fission channels a number $N_f = 0.8$, which is close to the experimental value[62] for U^{233}, and a comparison of the distribution of the quasiresonances with respect to Γ_f with the χ^2 distribution yields $\nu = 4$. Thus, by specifying parameters close to those expected in accordance with the fission-channel theory, Lynn[63] obtained the main features of the observed resonances in the nuclear fission cross section.

4.2. Nuclear Fission at Medium Excitation Energies

Fission induced by neutrons. At neutron energies higher than ~10 keV, the average fission width of the levels of the produced compound nucleus is much larger than the average distance between levels, so that the individual levels no longer appear in the fission cross section of the nuclei that are fissioned by irradiation with thermal neutrons; the fission cross sections of such nuclei decrease rapidly with increasing neutron energy, as we have already seen in Fig. 3, and are approximately constant between 2 and 5 MeV. For nuclei with $Z \geq 90$, for which $E_f > B_n$, the fission cross section has likewise a plateau in this region of E_n. When the neutron energy increases above 6 MeV, and nuclear fission after emission of a single neutron, (n, n′f), becomes energetically feasible, the cross sections of nuclei with $Z \geq 90$ change jumpwise (see Fig. 3), reaching a second plateau. Such jumps in the fission cross section are observed also after the emission of the second, third, etc. neutrons prior to fission, at bombarding-neutron energies close to 12, 17 MeV etc.[48,49].

The main features in the behavior of the excitation function of heavy nuclei were predicted by Bohr and Wheeler[21]. The fission cross section on the first plateau can be represented by

$$\sigma_f = \sigma_c \frac{\Gamma_f}{\Gamma_f + \Gamma_n}, \quad (7)$$

where σ_c is the cross section for the formation of the compound nucleus, and Γ_f and Γ_n are the fission and

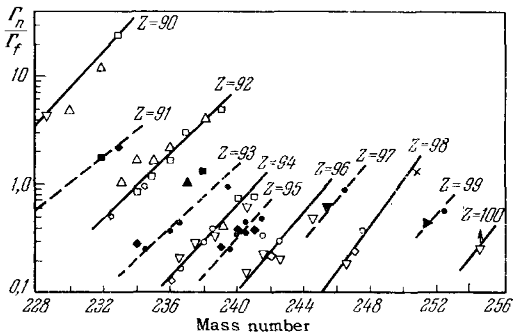

FIG. 4. Values of Γ_n/Γ_f as functions of the mass number of the fissioning nucleus [64]. The squares pertain to data obtained from the fission cross sections of nuclei irradiated with neutrons of energy 3 MeV, and correspond to excitation energies 8 – 10 MeV. The triangles pertain to data obtained from photofission, and correspond to excitation energies 8 – 12 MeV. The circles, diamonds, and inverted triangles pertain to mean values of Γ_n/Γ_f obtained from an investigation of the excitation function of the disintegration reaction products, and correspond to an average excitation energy close to 13, 18, and 23 MeV. The cross corresponds to an excitation energy of approximately 44 MeV.

neutron widths averaged over many levels of the compound nucleus. At such excitation energies it is possible to neglect the photon and charged-particle emission probabilities. Knowing σ_f and σ_c in the region of the first plateau, it is possible to determine Γ_f/Γ_n with the aid of (7). Such calculations were made for a number of nuclei[64]. The results offer evidence that the fission probability increases with increasing nuclear fissility parameter Z^2/A, and, for a given element, the probability increases with decreasing mass number of the isotope* (Fig. 4). Knowing the ratio Γ_f/Γ_n in the region of the first plateau and assuming that it does not change with excitation energy, we can estimate the nuclear fission cross section at neutron energies in the region of the second plateau (center of the second plateau—at neutron energies close to 10 MeV) at

$$\sigma_f(10) = [\sigma_f(10)_{A+1} + \sigma_f(10)_A] = \sigma_c(10)\left\{\left(\frac{\Gamma_f}{\Gamma_f+\Gamma_n}\right)_{A+1} + \left[1-\left(\frac{\Gamma_f}{\Gamma_f+\Gamma_n}\right)_{A+1}\right]\frac{\Gamma_f}{\Gamma_f+\Gamma_n}\right\}. \quad (8)$$

With the aid of equations such as (8) we can, knowing Γ_f/Γ_n in the region of the first plateau and the experimental fission cross section, to calculate successively the values of Γ_f/Γ_n for excitation energies in the region of the second plateau, third plateau, etc.

The results offer evidence that Γ_f/Γ_n for heavy nuclei does not depend or depends weakly on the nuclear excitation energy in this region.

Fission induced by photons. Near the photon energy 14 MeV, the cross section for fission of heavy nuclei passes through a maximum due to the giant resonance in the cross section for inelastic photon interaction[51,66]. Since the contribution of the (γ, γ') reaction can be neglected in this energy region, it is possible to calculate the values of Γ_n/Γ_f from the measured cross sections for the fission and emission of photoneutrons or from the relative fissility of the nuclei. The values of Γ_n/Γ_f obtained in this manner[64] are shown in Fig. 4. They are sufficiently close to the values calculated from the nuclear fission cross section on the first plateau in the case of neutron bombardment of the nuclei.

Nuclear fission induced by charged particles. The Coulomb barrier of the nucleus for charged particles causes both the total cross section for the formation of the compound nucleus and the fission cross sections of the heavy nuclei, which are small at particle energies below the Coulomb barrier, to increase rapidly with increasing charged-particle energy[67-72]. Then, at particle energies below the Coulomb barrier, the cross section for the fission of heavy nuclei increases slowly (Fig. 5). For weakly-fissioning nuclei, such as bismuth, the total cross section of the disintegration reactions of the type (He^4, xn) almost coincides with the cross section for the compound-nucleus formation (see Fig. 5). For well fissioning nuclei, the competition of fission leads to a considerable decrease in the cross section of the disintegration reactions, and from the magnitude of this decrease it is possible to estimate the degree of competition of the fission. Analytic calculations of the competition of nuclear fission and particle evaporation, carried out with certain simplifications, have yielded average values of Γ_n/Γ_f, obtained by comparing the calculated and experimental values of the disintegration reaction cross sections[67,68]. These values of Γ_n/Γ_f are shown in Fig.

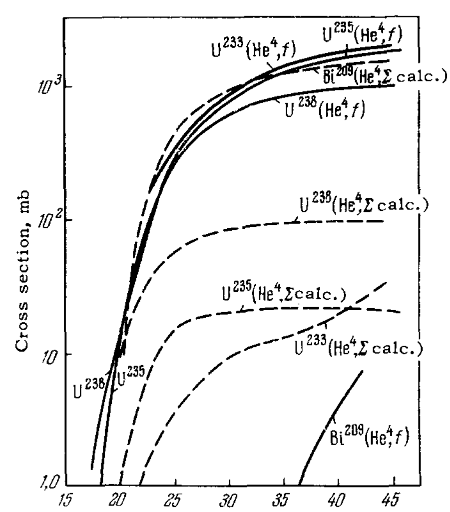

FIG. 5. Dependence of the nuclear fission cross section σ_f and of the total cross section for the formation of the disintegration products in the reaction (He^4, xn, yp) in bombardment of U^{233}, U^{235}, U^{238}, and Bi^{209} by alpha particles [67,69,70,78].

*A detailed analysis of the dependence of Γ_n/Γ_f on the height of the fission barrier and on the neutron binding energy E_f and B_n was made by Huizenga and Vandenbosch [17].

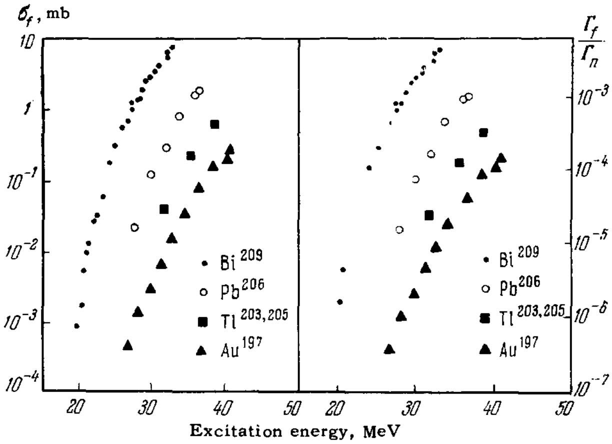

FIG. 6. Dependence of nuclear fission cross section σ_f and of the ratio Γ_f/Γ_n on the excitation energy in bombardment of Au^{197}, $Ti^{203,205}$, Pb^{206}, and Bi^{209} by alpha particles [78].

4, and one can see sufficiently good agreement with the values of Γ_n/Γ_f calculated from the values of the nuclear-fission cross sections upon bombardment with neutrons and photons. Thus, the results of the study of the dependence of the fission cross section of heavy nuclei with $Z \geq 90$ on the energy of the neutrons, photons, or charged particles offer evidence that Γ_n/Γ_f for these nuclei depends weakly or not at all on the excitation energy, up to ~40 MeV.

For nuclei with $Z < 90$ bombarded with charged particles of medium energy, the energy dependence of the fission cross section differs from that for nuclei with $Z \geq 90$. *A rapid increase of the fission cross section was observed for nuclei with* $Z < 90$ bombarded with neutrons[74], protons[75], deuterons[76], and alpha particles[77-79] (Fig. 6). The rapid increase of the fission cross section offers evidence that the fission of these nuclei occurs in the overwhelming majority of cases prior to the neutron emission[77,78]. From the measured fission cross sections, or more accurately, from σ_f/σ_c, it is possible to obtain Γ_f/Γ_n (see Fig. 6), since $\sigma_f/\sigma_c = \Gamma_f/(\Gamma_f + \Gamma_n) \simeq \Gamma_f/\Gamma_n$, owing to the small value of Γ_f compared with Γ_n for these nuclei. We see that Γ_f/Γ_n for compound nuclei from astatine to thallium increases with increasing excitation energy, unlike heavy nuclei, where we have seen that Γ_f/Γ_n does not change or changes little with increasing excitation energy in the same energy interval.

Huizenga and Vandenbosch[17] obtained the following expression for Γ_f/Γ_n:

Table II. Height of the fission barrier E_f and values of the level density parameters a_n and a_f[78].

Compound nucleus	E_f, MeV	a_n, MeV^{-1}	a_f, MeV^{-1}	Compound nucleus	E_f, MeV	a_n, MeV^{-1}	a_f, Mev^{-1}
Tl^{201}	19.83	21.63	25.12	Po^{210}	19.73	21.90	26.25
$Bi^{207,209}$	20.57	22.23	26.0	At^{213}	15.81	21.44	26.62

$$\frac{\Gamma_f}{\Gamma_n} = \frac{k_0 a_n [2a_f^{1/2}(E^*-E_f)^{1/2}-1]}{4A^{2/3} a_f (E^*-B_n)} \times \exp[2a_f^{1/2}(E^*-E_f)^{1/2} - 2a_n^{1/2}(E^*-B_n)^{1/2}], \tag{9}$$

where $k_0 = \hbar^2/gmr_0^2$ is a constant, E_f and B_n are the fission barrier and the binding energy of the neutron in the compound nucleus, a_n and a_f are constants in the dependence of the level density on the excitation energy, $\rho(E) \sim \exp[2(aE)^{1/2}]$ of the initial nucleus and of the nucleus at the saddle point respectively. The derivation of (9) is based on Bohr and Wheeler's definition of the nuclear fission probability as the ratio of the number of states of the nucleus at the saddle point to the number of states of the initial nucleus[21]. Huizenga et al.[78] found that the experimental dependence of Γ_f/Γ_n on the excitation energy in Fig. 6 can be reproduced with the aid of (9) only if $a_f > a_n$. By varying the values of the parameters a_n, a_f, and E_f under the condition $a_f > a_n$, Huizenga et al.[78] attained best agreement between the experimental and calculated values of Γ_f/Γ_n at the parameter values given in Table II. The fission barriers of these nuclei are also shown in Fig. 1. Recently Burnett et al.[79] obtained similar results for the irradiation of gold by He^4 nuclei. Burnett et al. took additional account of the effect of the penetrability of the potential barrier of the nucleus, and found that the best agreement between the experimental and theoretical dependences of Γ_f/Γ_n on the excitation energy can be obtained for this nucleus at E_f = 22.5 MeV.

The fact that the condition $a_f > a_n$ is necessary to obtain agreement between experimental and calculated dependences of Γ_f/Γ_n on the excitation energy can be attributed[78] to the influence of the shell structure of the initial nucleus on the value of a_n. With increasing excitation energy of the initial compound nucleus, one can expect the influence of the shell structure of the nucleus to decrease, the values of the parameters a_n and a_f to come closer together, and the growth of Γ_f/Γ_n, and consequently of the fission cross section σ_f for these nuclei, to slow down.

4.3. Nuclear Fission at High Excitation Energies

Fission induced by neutrons, protons, deuterons, and ions of high energy. If the nuclear fission probability Γ_f/Γ_n were to remain approximately constant with increasing excitation energy, as found in the region of medium energies for heavy nuclei with $Z \geq 90$, or if it were to increase, as was found for nuclei with $Z \leq 90$, then the cross sections for nuclear fission would asymptotically approach the cross section of inelastic interaction with increasing energy of the bombarding particles. This is not observed in fact. The cross section for the fission of heavy nuclei such as uranium and thorium bombarded by neutrons[80,81], protons[73,82,82], deuterons[73,82], and alpha particles[84] changes negligibly in the bombarding-particle energy

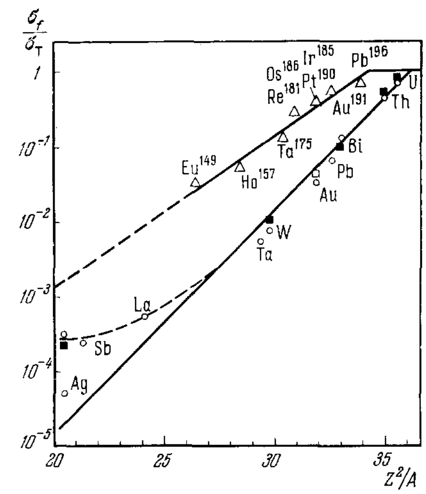

FIG. 7. Dependence of the fissibility σ_f/σ_T in the fission saturation region on Z^2/A in bombardment by high-energy protons [86], photons [104,106], and oxygen ions [97]. ○ – p; ■ – γ; △ – O^{16}.

interval 100—600 MeV,* remaining smaller than the inelastic interaction cross section. The fission cross section of nuclei lighter than thorium, such as bismuth or gold bombarded with neutrons[80,81], protons[82,85], or alpha particles[84] of high energy increases with increasing particle energy to 460—660 MeV, where it exhibits saturation. Figure 7 shown the fission cross sections of the series of nuclei from uranium to silver as a function of Z^2/A, when bombarded with high-energy protons in the saturation region. This dependence of the fission cross section can be represented analytically in the form[86]

$$\sigma_f/\sigma_T = \exp\{0{,}682\,[(Z^2/A) - 36{,}25]\}. \tag{10}$$

As seen from Fig. 7, the experimental values of the fissilities σ_f/σ_T as a function of Z^2/A lie well on a straight line when plotted on a semilog scale for nuclei heavier than lanthanum.

The fact that the fission cross section of most nuclei does not become equal to the total cross section of inelastic interaction with increasing bombarding-proton energy can be due to two main causes: 1) the change in the character of the interaction between the bombarding particle and the nucleus as the energy of the bombarding particle increases, and 2) the possible change in the energy dependence of Γ_f/Γ_n in the region of high excitation energies compared with the dependence in the region of medium excitation energies.

At sufficiently high bombarding-particle energy, when its mean free path in the nucleus becomes comparable with the diameter of the heavy nucleus, the interaction between the particle and the nucleus can be regarded as collisions with individual nucleons of the target nucleus[87]. Following the nucleon-nucleon collision cascade, the nucleus remaining after the emission of several fast nucleons, neutrons, or protons acquires only a fraction of the excitation energy that would be acquired by the compound nucleus. As a result of such an interaction between the fast protons and the nuclei a set of nuclei is produced with a wide range of A, Z, and excitation energies after the cascade stage[88]. The exponential decrease of the fissility of the nuclei upon saturation (σ_f/σ_T) with decreasing Z^2/A (see Fig. 7) is apparently connected in part with the fact that the fission cross sections of heavy nuclei such as uranium are comparable in magnitude in a wide spectrum of excitation energies of the nuclei produced as a result of the cascade, whereas the fission cross sections of nuclei of the bismuth type and of the lighter ones are vanishingly small at low excitation energies. The partial decrease of the charge of the nucleus as a result of the emission of the cascade protons also leads to a decrease in the fissility of the nuclei (σ_f/σ_T), a stronger decrease than in the case of the lighter nuclei.

Several calculations of the yield of the disintegration and fission products were made for nuclei bombarded by high-energy protons. In these calculations, the distribution of the nuclei with respect to the excitation energy following the cascade stage of the interaction was specified, and the Monte Carlo method was used to calculate the chains of the competition between nuclear fission and particle evaporation under various assumptions concerning the character of the competition. It was found as a result that the best agreement between the calculated and the experimental values of the disintegration-products yields, in the case of irradiation of uranium by protons with energy 460 MeV[64,89] and 2 BeV[90], or of thorium with protons of energy 155 MeV[91] is obtained under the assumption that Γ_f/Γ_n is independent of the excitation energy. At the same time, in the calculations[92] made under the assumption that most fissions occur at the end of the evaporation-fission chain (Γ_f/Γ_n in accordance with formula (9) with $a_f = a_n$), there was likewise satisfactory agreement between the calculated and the experimental values of the fission and disintegration cross sections.

Fission of nuclei bombarded by high-energy ions. By now, the fission cross sections of a number of nuclei, from uranium to cesium, bombarded with heavy ions from boron to neon, have been measured[93-97]. Figure 8 shows by way of an example the fission cross sections of nuclei bombarded with C^{12} ions. In the case of uranium bombardment, the fission cross section is close to the calculated value of the cross section for the production of a compound nucleus in the entire bombarding-ion energy region, whereas in the case when lighter nuclei are bombarded with ions, the fission cross section increases rapidly at low ion energies,

*Carvalho et al. [85] found that the fission cross section of uranium, thorium, and bismuth decreases to approximately one-third when the bombarding-proton energy increases from 600 MeV to 25 BeV.

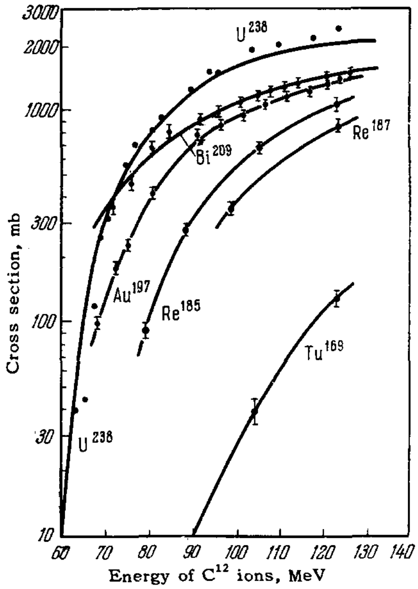

FIG. 8. Fission cross section of U^{238}, Bi^{209}, Au^{197}, Re^{185}, Re^{187}, and Tu^{169} bombarded by carbon ions [94-96].

reaches saturation, but does not become equal to the calculated cross section for the formation of the compound nucleus. A characteristic feature of the fission of light nuclei bombarded with heavy ions is their increased fissility as compared with the fission upon bombardment by lighter charged particles. It was shown experimentally[96,97] that this increase in the fissility of light nuclei bombarded with heavy ions is due to the effect of the large acquired angular momenta. In the case of fission of heavy nuclei bombarded with ions, there is no direct evidence of increased fissility of the nuclei with increasing acquired angular momentum. Tarantin[98], in an investigation of the disintegration reaction yields (C^{12}, xn) of uranium, found that the values of Γ_n/Γ_f, calculated for this case, fit within the systematics of Γ_n/Γ_f (from Z to A), obtained in the study of the disintegration reactions produced by He^4 ions.

The rapid growth of the fission cross section of relatively light nuclei with increasing energy of the heavy ions on the rising section of this dependence offers evidence of the fission of these nuclei prior to the emission of the neutrons, and also of the increased ratio Γ_f/Γ_n with increasing energy of excitation of the nucleus[97]. In calculations of the fission of a charged liquid drop with a large angular momentum it was shown[99,100] that the fission barrier decreases in this case compared with the fission barrier of the nonrotating drop. It was also shown[100,101], that the form of the rotating liquid drop in the initial equilibrium state and on passing through the saddle point differs from the form of the nonrotating drop in the corresponding states. An exact evaluation of the effect of the rotation of the nucleus, of the change of the height of the barrier and of the form of the rotating nucleus on its fissionability is difficult. Under certain simplifications[97], however, in the case of the fission of a rotating nucleus, it is possible to use for Γ_f/Γ_n, in place of (9), the formula

$$\frac{\Gamma_f}{\Gamma_n}=\frac{k_0 a_n\,[2a_f^{1/2}(E^*-E_f-E^{\text{s.p.}}_{\text{вр}})^{1/2}-1]}{4A^{2/3}a_f\,(E^*-B_n-E^0_{\text{rot}})}\exp[2a_f^{1/2}(E^*-E_f-E^{\text{s.p.}}_{\text{rot}})^{1/2}-2a_n^{1/2}(E^*-B_n-E^0_{\text{rot}})^{1/2}], \qquad (11)$$

where E_f is the fission barrier of the non-rotating nucleus, E^0_{rot} and $E^{s.p.}_{rot}$ are, respectively, the rotation energies of the nucleus in the initial equilibrium state and in the saddle point at the shape of the non-rotating nucleus. As shown by Sikkeland[97], the experimental dependence of Γ_f/Γ_n on the excitation energy for compound nuclei from Eu^{149} to Po^{198} can be represented by (11), as was also the case when light nuclei are bombarded by He^4 ions (Sec. 4.2), if it is assumed that $a_f > a_n$ ($a_f \simeq 1.2a_n$). The fission barriers E_f of a number of nuclei, calculated from a comparison of the experimental and calculated Γ_f/Γ_n dependences, are shown in Fig. 1.

Great interest attaches to the fact that when the bombarding-ion energy increases the fission cross sections σ_f of relatively light nuclei do not become equal to the total inelastic-interaction cross section σ_T (see Fig. 8). Figure 7 shows the values of σ_f/σ_T at saturation as a function of Z^2/A of the compound nucleus, for a number of nuclei from W to Cs bombarded with O^{16} ions. The obtained dependence can be represented analytically by the formula

$$\sigma_f/\sigma_T = \exp[0.455\,(Z^2/A-34.43)]. \qquad (12)$$

From a comparison with the similar dependence obtained for fission induced by protons[86] it follows directly that the fissility of nuclei at saturation is larger in the case of ion bombardment than in the case of proton bombardment; this difference in the fissility increases for these two cases with decreasing Z^2/A of the fissioning nuclei.

Nuclear fission produced by bombardment with high-energy photons. When the photon energy increases above 14—16 MeV, the fission cross section of heavy nuclei decreases with increasing distance from the giant-resonance region, but then, at energies higher than 20—50 MeV, it again increases[102,103]. This second increase in the cross section can be connected with the photoproduction of mesons and their subsequent absorption. In the case of photofission of nuclei with Z < 90, the measured yields of the fissions were observed at a photon energy greatly exceeding the photon energy in the region of the giant resonance, and therefore the fission cross section of these nuclei increases monotonically with energy, reaching apparently a maximum value[104]. In recent years, U, Th, Bi, W, and Ag were bombarded with bremsstrahlung photons with maximum energy from 300 to 1000 MeV[105], but no reduction was observed in the nuclear fission cross section with increasing energy

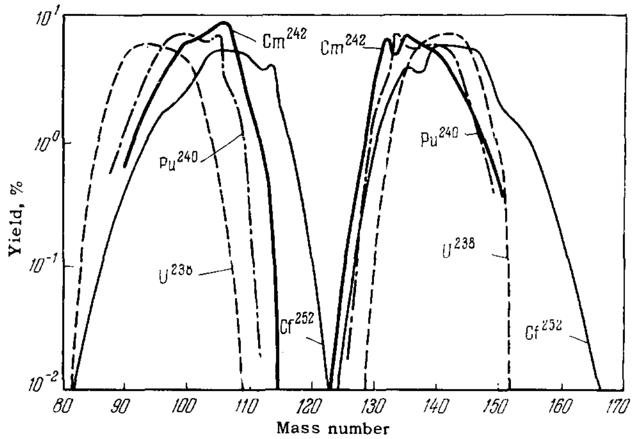

FIG. 9. Mass distribution of spontaneous-fission products of the uranium[109], plutonium[110], curium[111], and californium[112].

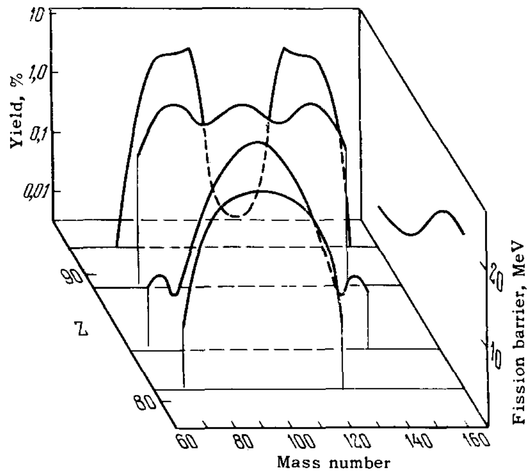

FIG. 10. Mass distribution of the fission fragments obtained by bombarding U^{235} with thermal neutrons [114], Ra^{226} with 11-MeV protons [143], Bi^{209} with 36-MeV protons [75], and Au^{197} with 45-MeV He^4 ions [136]. The values of the fission barriers of the nuclei are also given.

in this region, as was proposed earlier[104]. It is interesting to note that the fissility of the nuclei $(\sigma_f/\sigma_T)'$ in photofission depends to a considerable degree[106] on the fissility parameter Z^2/A, almost as in the case of fission induced by high-energy protons[86] (see Fig. 7).

5. MASS DISTRIBUTION OF FRAGMENTS

The nucleus fissions predominantly into two fragments of commensurate mass.* After the emission of the prompt neutrons ($\nu \simeq 2$—3 in the fission of heavy nuclei near threshold), neutron-excess fission products experience a number of β^- transitions and are transformed into stable nuclei. The primary nuclear-fragment mass distribution prior to the emission of the prompt neutrons can be obtained by measuring the velocities of the fragments during the time of flight or by measuring the kinetic energy of the paired fragments, if the dependence of the number of prompt neutrons on the fragment mass is known[108]. Radiochemical and mass-spectroscopic methods make it possible to obtain only the secondary mass distribution of the fission fragments after the emission of the prompt neutrons. To this end one measures the cumulative yield of the isobar at the end of the β^- transformation chain, which constitutes the sum of the yields of all the fission fragments having a given mass number A.

5.1. Mass Distribution of Fragments in the Fission of Low-excitation Nuclei

Both in the case of spontaneous fission and in the case of fission of U^{233}, U^{235}, Pu^{239}, and Pu^{241} bombarded by thermal neutrons[114,115], the mass distribution of the fission fragments is described by a two-hump curve with a deep minimum in the region of the symmetrical fission (Figs. 9 and 10). A similar fission-fragment mass distribution was obtained when U^{238} and Th^{232} was bombarded with electrons close to threshold[114,115]. The study of the character of the mass distribution of the fragments in the fission of nuclei with $Z < 90$ at energies close to the fission threshold began only relatively recently. Fairhall[76], who investigated the fragment mass distribution of bismuth bombarded by deuterons of energy 22 MeV, initiated this study and obtained interesting results. Figure 10 shows the fission fragment mass distribution of a number of nuclei near the fission threshold.*

The presented distributions offer evidence of the existence of two basic laws governing the nuclear fission near threshold. First, the character of the mass distribution of the fragments depends appreciably on the fissioning nucleus: on going from heavy nuclei such as uranium to lighter ones such as gold, a transition is observed from predominantly asymmetrical fission to predominantly symmetrical fission. Another observed singularity is the almost constant position, in the vicinity of the mass numbers A = 132—145, of the right-hand peak on the mass-distribution curve, corresponding to the heavy fragments of predominantly asymmetric fission form, in a wide range of fissioning nuclei. As a consequence of the stable position of the right-hand peak of the mass curve, the left-hand peak of the mass curve, corresponding to the light fragments

*Fission of a nucleus into three fragments of commensurate mass is a much rarer event. According to the results of instrumental measurements, when uranium is bombarded by slow neutrons, there occurs one ternary fission for 10^5 – 10^6 binary fissions. Radiochemical investigations give a ternary-fission yield which is smaller by 3 – 4 orders of magnitude [107a]. With increasing bombarding-particle energy, the probability of fission into three fragments of commensurate mass increases [107b].

*For relatively light nuclei such as bismuth and gold measurable numbers of fissions can be obtained only at excitation energies exceeding the fission barrier by several MeV (owing to the rapid decrease of the fission cross section with decreasing excitation energy).

of the predominantly asymmetrical fission form, shifts towards smaller mass numbers when the mass of the fissioning nucleus decreases.

Fine structure. In the secondary mass distribution of the fission fragments, a noticeable predominance of the yield of products with A = 134 as compared with the smooth curve was obtained when U^{233}, U^{235}, Pu^{239}, and Pu^{241} was bombarded with thermal neutrons[114,115]. The increased yield of fission products with A = 134 can be connected with the predominant yield of fragments which yield products with A = 134 and those complimenting them in the fission process itself, or else can be the result of evaporation of neutrons from the fragments[116]. In the former case we can expect an anomalously high yield of products that are complimentary to A = 134. An increased yield of the mass chain with A = 100 was indeed observed[116,117,118], but only in the case of U^{235} was this chain complementary to A = 134.

When the procedure of measuring the fragment velocities during the time of flight is used to obtain the primary mass distribution, it becomes possible in addition to verify directly the hypothesis of predominant yield of fragments during the fission process itself. The increased yield of the fragment with A = 135 was observed in the primary mass distribution of fission fragments when U^{235} was bombarded with thermal neutrons[119,120]. Although no structure of the fragment yield of any appreciable magnitude was observed in the primary mass distribution of the fission fragments of other nuclei[119,121], an increased yield of fragments with mass numbers 134, 140, 146, and 152 was observed[119,121-123] in the case of fissions with high kinetic fragment energy and with small excitation energy, in the bombardment of U^{233}, U^{235}, and Pu^{239} by thermal neutrons and in the spontaneous fission of Cf^{252}. The predominant yield of these fragments in the primary fission act can be connected with the fact that the total released energy and the fragment excitation energy are larger for even-even nuclei than for odd nuclei in the fission of even-even compound nuclei[121,123,124].

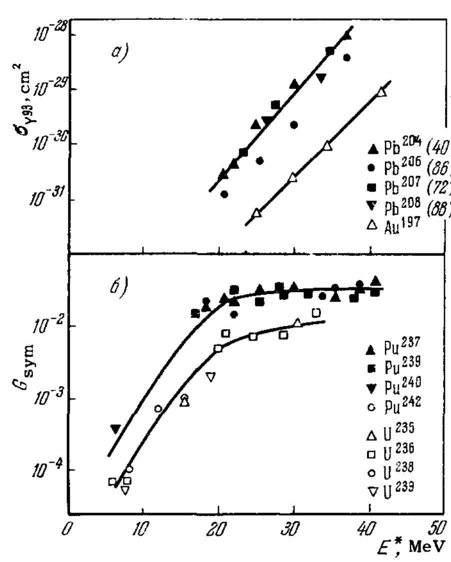

FIG. 11. Dependence of the contribution of the symmetrical fission on the excitation energy of nuclei bombarded with He^4 ions: a) lead and gold isotopes; b) plutonium and uranium isotopes; $G_{sym} = Y_{sym}(\sigma_f/\sigma_{comp})10^{-2}$. (The figure is taken from the paper of Fairhall et al.[77]).

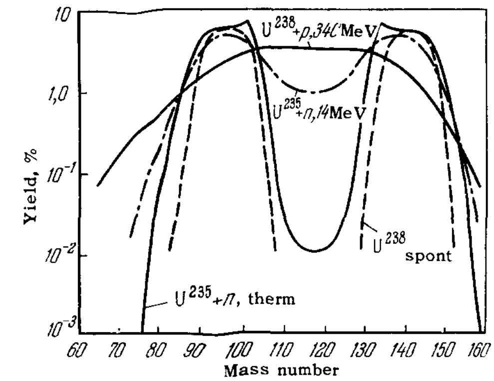

FIG. 12. Mass distribution of fission fragments in spontaneous fission [109] of U^{238}, in the bombardment of U^{235} by thermal neutrons [114] and by 14-MeV neutrons [127], and in the bombardment of U^{238} with 340-MeV protons [73].

5.2. Change of Mass Distribution of Fission Fragments with Increasing Nuclear Excitation Energy

The main features of the change in the mass distribution of fission fragments of heavy nuclei with increasing energy of the bombarding particles are a rapid increase in the contribution of the symmetrical fissions followed by a slow one (Fig. 11b), a decrease in the contribution of the products in the region of the peaks of the two-hump mass distribution, and a certain increase of the contribution of strongly asymmetrical fissions (Fig. 12). Butler et al.[128] have shown that the increased yield of symmetrical fission with increasing energy of the bombarding particles is directly connected with the increase of the excitation energy of the fissioning nuclei. These authors have found, for Th^{232}, U^{238}, and Pu^{239} bombarded with high-energy protons in the interval from 5 to 100 MeV, that the ratio of the yields Y (Ag^{113})/Y (Ba^{139}), of the product of the almost-symmetrical fission to the product of the asymmetrical fission, does not increase monotonically. At each new threshold of the (p, xn) reaction a decrease is observed in the value of this ratio, which may be connected with the cooling of the nucleus after the evaporation of the next neutron prior to fission. At a certain sufficiently high energy of the bombarding particles, a complete filling of the trough of the mass curve takes place in the region of symmetrical fission of the heavy nuclei (see Fig. 12). The fission of heavy nuclei was found to be predominantly symmetrical also when they were bombarded with carbon ions of 100 MeV

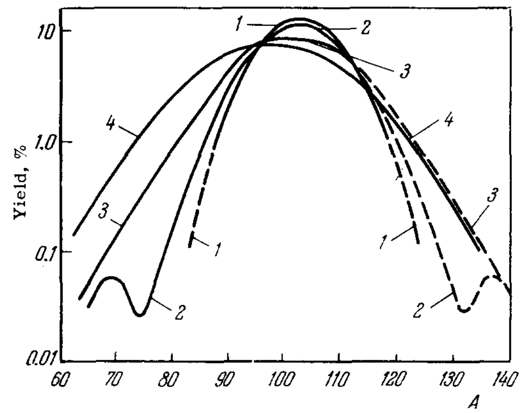

FIG. 13. Fission-fragment mass distribution for bismuth bombarded with 22-MeV deuterons [76] (curve 1) or 36- and 58-MeV protons [75] (curves 2 and 3) and of gold bombarded with 112-MeV C^{12} ions [141] (curve 4).

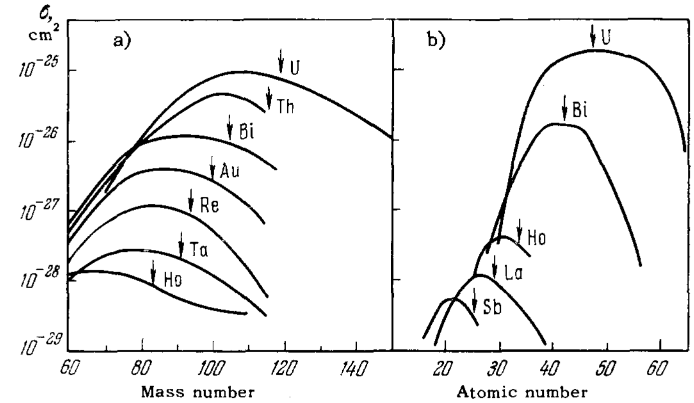

FIG. 14. a) Mass distribution of fission fragments in the bombardment of uranium[140], thorium, bismuth, gold, rhenium, tantalum, and holmium [147] with 450-MeV protons. b) Charge distribution of fission fragments in the bombardment of uranium, bismuth, lanthanum, and antimony with 660-MeV protons and holmium with 460-MeV protons [150,151]. The arrows indicate the value of: a) $A_{targ} + 1/2$; b) $Z_{targ} + 1/2$.

energy[129], 115-MeV gold ions[130], and 150-MeV neon ions[131]. On the other hand, bombardment of heavy nuclei with photons from the bremsstrahlung spectrum did not cause a complete filling of the trough, even in bombardment with photons having the maximum energy 380 MeV[125,126]; this is connected with the appreciable contribution of the photon-induced fissions from the giant-resonance region 14—16 MeV. Once the fission of the heavy nucleus becomes predominantly symmetrical, a further increase of the energy of the bombarding particles leads only to an increase in the fraction of the strongly asymmetrical fissions[132,133] and to a broadening of the mass distribution of the fission fragments.

In the fission of nuclei such as bismuth and gold, which is predominantly symmetrical at all energies, the mass distribution of the fission fragments simply broadens with increasing particle energy[75-77,132,134-142] (Fig. 13).

In the case of the irradiation of radium, which is a nucleus intermediate between uranium and bismuth, and which has a fission-product mass distribution near threshold described by a three-hump curve (see Fig. 10), the contribution of the symmetrical fission increases with increasing energy of the bombarding particles, and the central peak of the mass distribution in this case broadens somewhat[135,137,143,144].

There are few data on the mass distribution of the fission fragments of nuclei lighter than gold in the fission near threshold, owing to their small fission cross section. It is only known that when platinum[145], rhenium[146a], or lutetium[146b] is bombarded with He^4 of energy 40 MeV, the nuclear fission is predominantly symmetrical with a mass-curve width at half the height $W_{1/2}$ equal to 22 m.u., 23 m.u., and 17.5 m.u., respectively. Bombardment of gold and lighter nuclei with high-energy protons up to 660 MeV has shown[147-151] that in this case, too, the nuclear fission is predominantly symmetrical, and the mass distribution of the fission fragments is described by relatively broad single-hump curves (Fig. 14).

Thus, whereas in nuclear fission near threshold the character of the mass distribution of the fragments depends on the target nucleus (see Fig. 10) and a transition from predominantly asymmetrical fission to predominantly symmetrical fission is observed on going from heavy nuclei to lighter ones, when the bombarding particle energies are much higher than threshold the fission of all the nuclei is predominantly symmetrical (see Fig. 14).

At still higher energies, when uranium nuclei are bombarded with protons of several BeV energy, the mass distribution of fragments of predominantly symmetrical fission becomes broader compared with the distribution in the region of proton energies of several hundred MeV[142,152]. In the mass distribution of the products of interaction between protons having energy of several BeV with nuclei of lead[152,153] or tantalum[154], the characteristic peak of the fission products is no longer observed. The latter circumstance is connected both with the further broadening of the mass curves of the fission products with increasing excitation energy of the nuclei, and apparently also with the noticeable contribution made in this proton-energy region by the products of the fragmentation[153] and disintegration of the nuclei.

5.3. Attempts to Explain the Mass Distribution of Nuclear Fission Fragments. The mass distribution of the fission fragments in the liquid-drop model. According to calculations of the deformation of a uniformly charged liquid drop, a symmetrical nuclear shape at saddle point corresponds to the smallest energy deformation and to the smallest fission barrier[23-26]. Attempts were made to introduce refinements in the simple liquid-drop model by taking into account dynamic effects[155], or the compressibility of the drop[156], but it was found that in these cases the symmetrical form of the drop at the saddle point is preferable. Consequently, the symmetrical fission is predominant in the liquid-drop model.

It can be assumed that in the case of sufficiently high excitation energy, the nuclear fission will be similar to the splitting of a charged liquid drop—predominantly symmetrical[133]. With increasing energy of the bombarding particles, the fission of nuclei such as gold or bismuth, as we have seen, remains predominantly symmetrical, but the mass distribution of fission fragments broadens (see Fig. 13). This broadening of the mass distribution of the fission fragments within the framework of the liquid-drop model can be related with the increase in the energy of excitation of the nucleus[133]. At low excitation energy, the nucleus goes through the peak of the potential barrier and has a form that corresponds to the smallest potential deformation energy (in the liquid-drop model—a symmetrical form). With increasing excitation energy, a possibility arises for asymmetrical nuclear deformations which are less favored from the energy point of view, on going through the top of the potential barrier. Since the form of such relatively light nuclei at the saddle point (Fig. 1) is close to the form of the nuclei at the instant of fragment separation, it can be assumed that the mass distribution of the fission fragments is determined by the conditions at the saddle point when the nucleus passes through it. It can be assumed further[133] that the probability that the nucleus will have a symmetrical form or one of the asymmetrical forms on passing through the top of the potential barrier is determined by the statistical competition of these fissions, by the Boltzmann factor:

$$Y_1/Y_2 \sim \exp[-\Delta E/T], \tag{13}$$

where $\Delta E = E_f^{(1)} - E_f^{(2)}$, $E_f^{(1)}$, and $E_f^{(2)}$ are the values of the potential energy of the deformation and the values of fission "barriers" for the first or second configurations of the nucleus, respectively, and T is a certain effective nuclear temperature. Since any asymmetrical nuclear form or critical deformation corresponds in the liquid-drop model to a larger potential energy compared with the symmetrical form, expression (13) explains qualitatively the observed decrease of the fission-fragment yields with increasing ratio of their masses (see Fig. 13). With increasing excitation energy and nuclear temperature, the difference ΔE in the magnitude of the potential energy in critical deformation assumes an ever decreasing role in the relative yield of the two fission products, which leads to the observed broadening of the mass distribution of the fragments.

Nix, Swiatecki[157] and Strutinskiĭ[26] calculated the rigidity of a charged liquid drop against a change in its shape, as characterized by the constant K_m. Starting from the notion of thermodynamic equilibrium at the saddle point and consequently representing the probability of the deviation of the nuclear shape from symmetrical under critical deformation by a Gaussian curve, they obtained an expression for the competition between nuclear fissions* having a given degree of asymmetry $U = m_1/(m_1 + m_2)$:

$$P(U) = \frac{1}{(2\pi T/K_m)^{1/2}} \exp[-(U-1/2)^2/(2T/K_m)]. \tag{14}$$

However, as shown in[142], the growth of strongly asymmetrical fissions with increasing excitation energy of the nucleus is somewhat faster than predicted by expressions such as (13) and (14). This discrepancy is connected with the fact that fission with a given fragment mass ratio can actually occur only when the excitation energy of the nucleus exceeds the corresponding value $E_f^{(i)}$ of the potential energy of the asymmetrically deformed drop under critical deformation, whereas according to (13) and (14) fission with any degree of asymmetry is possible for a given temperature T of the nucleus at the saddle point. It seems that a more accurate expression can be obtained by analyzing more consistently the competition between fissions having different fragment-mass ratios.

As already noted earlier, according to Bohr and Wheeler[21] the fission probability is determined by the number of possible states of the nucleus at critical deformation. When the dependence of the nuclear level density on the excitation energy is $\rho \sim \exp[2(aE)^{1/2}]$, the fission probability is[17]

$$W_f \sim \{[2a^{1/2}(E^*-E_f)^{1/2}-1]\exp[2a^{1/2}(E^*-E_f)^{1/2}]\}+1. \tag{15}$$

If each nucleus passing through the top of the potential barrier, with one degree of shape asymmetry or another, is assigned its own system of possible energy states, depending on the energy of the nuclear excitation in this transition state, on the value of the potential energy of the critical deformation, and, in final analysis, on the height of the potential barrier for this type of deformation $E_f^{(i)}$, then the competition between two fissions with different nuclear shapes, on going through the top of the potential barrier, with corresponding fission barriers $E_f^{(1)}$ and $E_f^{(2)}$, can be represented in the form

$$\frac{Y_1}{Y_2} = \frac{\{[2a^{1/2}(E^*-E_f^{(1)})^{1/2}-1]\exp[2a^{1/2}(E^*-E_f^{(1)})^{1/2}]\}+1}{\{[2a^{1/2}(E^*-E_f^{(2)})^{1/2}-1]\exp[2a^{1/2}(E^*-E_f^{(2)})^{1/2}]\}+1}. \tag{16}$$

If we choose as one of the fission products the symmetrical-fission product, or fission into fragments of equal mass, and we choose as a second product one of the products of fission with successively increasing fragment-mass ratio, then from the experimental determination of the mass distribution of the fission fragments it is possible, with the aid of (16) and knowing the height of the barrier (E_f) for symmetrical fission, to determine the difference ΔE_f of the barriers of the fission of the nucleus into unequal and equal parts.

*Nix and Swiatecki [157] used in their calculations the representation of the nucleus at the saddle point for x < 0.8 in the form of two spheroids in contact.

Table III. Values of ΔE_f, the difference between the fission barrier into fragments with specified mass ratios and symmetrical fission, calculated in accordance with (16) for the case of nuclear fission in bombardment of Au^{197} with 112-MeV particles [141]. The absolute value of the fission barrier of a nucleus with a given fragment-mass ratio is also presented.

A_h/A_l	1.00	1.10	1.20	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00
ΔE_f, MeV	0	0.2	0.5	1.0	1.5	2.2	2.9	3.4	4.1	4.8	5.5
$E_f^{(i)}$, MeV	18.6	18.8	19.1	19.6	20.1	20.8	21.5	22.0	22.7	23.4	24.1

height of the symmetrical-fission barrier into fragments of equal mass is assumed to be E_f = 18.6 MeV, which is the value of the barrier obtained[78] from an analysis of the behavior of the cross section of the fission of the compound nucleus Po^{210}. The level-density constant a was chosen equal to the value a_f obtained for the case of Po^{210} fission. It was proposed that the fission of At^{209} occurs prior to the neutron evaporation* and that the angular momentum of the nucleus does not influence the mass distribution of the fission fragments† .

Figure 15 shows, besides the experimental values of the fragment mass distribution width at half the height, $W_{1/2}$, in the fission of compound nuclei near At^{213}, also the values of $W_{1/2}$ calculated by formulas (13) and (16) for At^{209}, and by formula (14) for Pb^{198}. As seen from Fig. 15, the calculated values of the width of the mass distribution duplicate quite well the experimental values in a wide range of excitation energies of the fissioning nucleus. Figure 15 shows also the experimental dependence of the half-width of the mass distribution $W_{1/2}$ on the nuclear excitation energy at the saddle point, $E^*_{s.p.}$, obtained by Neuzil and Fairhall[136] for the fission of nuclei such as lead near threshold, $W_{1/2} = E^*_{s.p.} + 7$. We see that at low excitation energies, all the dependences are practically the same, and with increasing excitation energy, the linear dependence $W_{1/2} = E^*_{s.p.} + 7$ greatly deviates from both the calculated values (as given by (13), (14), and (16)) and from the experimental values of the width of the mass distribution of the nuclear-fission fragments.

Influence of the nuclear structure. As we have seen before, the character of the fission, predominantly asymmetrical, of heavy nuclei in spontaneous fission and at low nuclear excitation energy differs greatly from that predicted by the liquid-drop model. This is apparently connected with the appearance of an internal structure of the nucleus during the fission process, something not accounted for in the liquid-drop model. Although the influence of the structure of the heavy nucleus on the character of the mass distribution of the fission fragments is now obvious, it is not clear how it appeared and at what stage of the fission.

Vladimirskiĭ[160] indicated a possible instability of the nucleus against asymmetrical deformations, leading to an asymmetrical nuclear shape at the saddle point, owing to the influence of the nucleons with large angular momentum in excess of the filled shell. Johansson[40], using, as already noted earlier, the Nilsson diagram of the single-particle levels to determine the states of the nucleus at the saddle point, found a certain indication of a possible instability of the nucleus at the saddle point to octupole deformations (pear-shaped form).

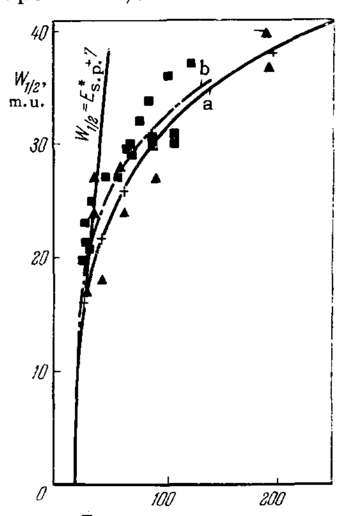

FIG. 15. Calculated and experimental dependences of the width of the mass distribution, at half maximum, of the fission fragments of nuclei close to At^{213}, on the excitation energy. The experimental values of $W_{1/2}$ were taken from [75,76,137,138,139,141,159]; the calculated values: curve a – in accordance with formula (16), curve b – formula (14), crosses – formula (13). The calculated values of $W_{1/2}$ are not corrected for the effect of neutron evaporation. The average excitation energy for the case of nuclear fission in bombardment of Bi^{209} by protons of 660 MeV energy (no compound nucleus is produced) was taken from [142].

*In the case of evaporation of some of the neutrons prior to fission, i.e., fission of the nucleus with a smaller excitation energy, the calculated values of ΔE will be lower than those listed in Table III.

†As shown in [142,158], an increase in the angular momentum of the nucleus with increasing energy of the bombarding particles does not have a noticeable influence on the change of the mass distribution of the fission fragments. A certain dependence can be expected as the result of the fission of the nuclei at earlier stages of the evaporation-fission chain, owing to the increased fissibility of the nuclei with increasing momentum.

Within the framework of the unified nuclear model, a dependence of the mass distribution of the fragments on the spin and parity of the compound nucleus was expected in the fission of heavy nuclei. It was assumed[28,29] that nuclear fissions occurring through the band of rotational states at the saddle point with positive parity (0^+, 2^+, 4^+, etc.) will be more symmetrical (smaller dip in the two-hump mass curve), than nuclear fissions proceeding via the band of states of negative parity (1^-, 3^-, etc.). Fissions through a state of type 1^+, 3^+, or 2^-, 4^-, etc. will lead to mass distributions which are intermediate in character between the aforementioned two fission groups. Thus, for example, in the fission of U^{235} ($I_0 = 7/2^-$) induced by s-neutrons, one should expect in accordance with these concepts that the mass distribution of the fission fragments via the 4^- state will be more symmetrical than in fission in the 3^- state. In recent years a number of experiments were undertaken to verify these concepts, by comparing the mass distributions of the fission fragments of different resonances produced when U^{233}, U^{235}, and Pu^{239} are bombarded with neutrons[161,164]. These measurements, indeed, revealed oscillations of the yields of symmetrical fission of U^{235}, namely an increase up to 22%, a decrease up to 50%, small changes in the yield of the symmetrical fission of U^{233} and Pu^{241}, and quite appreciable changes for Pu^{239}—a decrease of the yield of symmetrical fission in certain resonances by a factor 2—3 compared with fission by thermal neutrons. However, an analysis of the influence of the spin state of the nucleus at the saddle point on the character of the fission symmetry is made difficult by the lack of information on the values of the spins of the resonances in the fission cross section of the indicated nuclei.

However, the main problem of fission theory, the explanation of the predominance of the asymmetrical fission of heavy nuclei and the stable position of the heavy peak of the mass curve in a wide range of fissioning nuclei, can apparently not be resolved within the framework of the concepts that the characteristics of the individual levels have an influence on the asymmetry of the fission. Indeed, the predominantly asymmetrical form of the fission appears also clearly in the fission of heavy nuclei with excitation energy of several dozen MeV in the region of the continuous spectrum of the levels, and the variety of the spin states. Apparently the cause of these singularities of the fission of heavy nuclei lies in the influence of the stable structure of the nucleus during the fission process. The position of the heavy peak of the mass distribution of the fragments near A = 132—145 suggests a possible influence of a substructure[165] containing the magic number of neutrons N = 82, and apparently Z = 50. It is possible that nuclei whose deformation led to such a substructure have a lower fission barrier[166] compared with nuclei of another configuration at the saddle point and are fissioned with a higher probability. Furthermore, as shown by Geĭlikman[167], the path on the surface of the potential energy behind the saddle point, leading to the fragment with N = 82 and Z = 50, is most convenient from the energy point of view.

It has been assumed so far that the fission stage that decides the mass distribution of the fragments is the saddle point. There exists, however, another approach to allowance for the influence of the shell structure in the process of fission of heavy nuclei. According to Ramanna et al.[168] all the nuclei passing through the saddle point during the fission process have a symmetrical shape, and the mass distribution of the fragments is formed between the saddle point and the instant of the separation of the fragments as a result of a probable capture of a nucleon by one of the fragments, when the nucleon oscillates from one edge of the nucleus to the other. To explain the predominant formation of fragments with N = 82 and Z = 50, one introduces formally a high barrier for the absorption of the nucleons by such a magic fragment, which prevents the joining of the nucleons in excess of the filled shell. The transition from the predominantly asymmetrical fission of uranium to the predominantly symmetrical fission of nuclei of bismuth and gold near the fission threshold is, within the framework of this approximation, simply the consequence of the decrease of the deformation, occurring during this stage, from the saddle point to the separation of the nucleons. In nuclei of the bismuth type this stage is so short, that the predominantly symmetrical form of the nucleus at the saddle point has no time to change. According to Fong[169] the stage of deformation of the heavy nucleus from the saddle point to the instant of separation is so long, that a statistical equilibrium can become established during this stage, and the probability of a fission with one asymmetry or another is determined by the level density of the produced fragments[170]. Although a quantitative calculation[171] of the influence of the shell structure of the fragments did not lead to the desired results, namely explanation of the predominance of the asymmetry of fission of heavy nuclei, such a statistical approach, but with introduction of parameters, was used in a number of papers[171,172] to explain the mass distribution of the fission fragments of heavy nuclei. Thus, although there is still no consistent explanation of the behavior of the nuclear substructure during the process of nuclear deformation, nonetheless it seems obvious that it exerts an influence on the predominantly asymmetrical character of the fission of heavy nuclei at low excitation energies.

With increasing excitation energy, as expected, the influence of the shell effect on the formation of a nuclear substructure of 50 protons and 82 neutrons in a heavy fragment becomes weaker, and the contribution of the predominantly asymmetrical fission decreases, and consequently the contribution of the predominantly symmetrical fission increases, during the course of which, as can be assumed, the shells do not come into play. The rapid growth of the yields of the symmetrical-fission products of heavy nuclei with increasing excitation energy reflects in some fashion the rate of vanishing of the shell effects and stops when the influence of the shells during the fission process vanishes completely and the nuclear fission becomes predominantly symmetrical. Further increase in the excitation energy leads only, as in the case of fission of the bismuth-type nucleus, to a broadening of the fragment mass distribution of the predominantly symmetrical fission of heavy nuclei.

On going from heavy nuclei to lighter ones, the fission barrier increases, and the excitation energy necessary for the fission increases, thus leading to a decrease in the influence of the shells on the fission process. Another cause of the change of the character of the mass distribution of the fragments on going from heavy to lighter nuclei may be the different degree of deformation of these nuclei at the saddle point. For heavy nuclei, in which the form of the nucleus at the saddle point does not differ strongly from the initial form, there may appear the influence of the substructure during the deformation process. For lighter nuclei, which experience a stronger change in the form up to the saddle point, one might expect a considerable decrease in the influence of the substructure on the fission process. It is possible that this can explain in part the experimentally established fact that, for an approximately equal excitation energy of the initial nucleus at 20—30 MeV, the fission of heavy uranium* and thorium nuclei is still predominantly asymmetrical[67,134], in radium the contributions of the asymmetrical and symmetrical forms are commensurate[143], and the asymmetrical fission form of nuclei of bismuth amounts to a fraction of 1%[74].

Two types of nuclear fission. We have seen that a rapid growth of the yields of symmetrical-fission products of heavy nuclei is observed with increasing energy of the bombarding particles, especially near threshold (see Fig. 11). The increase in the yields of the symmetrical-fission products with increasing excitation energy is observed also in the fission of nuclei such as lead. On the basis of this similarity in the growth of the symmetrical-fission products yields, Fairhall et al.[77] proposed that symmetrical fission be regarded as an independent type of nuclear fission, which has the same nature for all nuclei. Asymmetrical fission was proposed to be another independent type of fission.

Actually, however, there is a certain difference in the behavior of the symmetrical type of fission of heavy and light nuclei. In the fission of nuclei of the lead type, the rapid growth of the symmetrical-fission product yields reflects the increase of the total fission cross section of these nuclei near threshold (see Fig. 6), whereas in the fission of heavy uranium and plutonium nuclei, the fission cross section in the energy interval under consideration changes little and the rapid increase of the symmetrical-fission yields can be connected, as noted above, with the decreased influence of the shell effects on the nuclear fission process with increasing excitation energy of the heavy nuclei.

Thus, an examination of the available data on the mass distribution of nuclear fission fragments makes it possible to subdivide all fissions in accordance with the character of the mass distribution roughly into two groups. One includes nuclear fission in which the influence of the closed substructures during the fission process comes into play, leading to predominance of asymmetrical fission. An example of such a fission may be the predominantly asymmetrical form of the fission of uranium, radium, and bismuth nuclei (see Fig. 10) at energies close to threshold. The other group includes fission during the course of which the shell structure does not come into play, and the nuclear fission recalls the splitting of a charged liquid drop, where the symmetrical fission is predominant and the mass distribution of the fission fragments broadens with increasing excitation energy. An example of such a fission is the predominantly symmetrical form of the fission of bismuth and gold nuclei at average excitation energy (see Fig. 10), the apparently symmetrical fission of heavy nuclei near threshold and in the region of low excitation energies, and also the fission of all nuclei at high excitation energies at the instant of fission.

6. CHARGE DISTRIBUTION OF FRAGMENTS

Of considerable interest for the understanding of the nature of fission is a study of the charge distribution of the fission fragments. However, there are few data on the charge distribution in the fission of heavy nuclei induced by thermal neutrons, and much fewer data on the fission of nuclei at high excitation energies. This is due in part to the difficulties involved in such measurements. Usually the problem of determining the charge distribution during fission reduces to a determination of the charge distribution of fragments with a given mass number, and to a distribution of the most probable charge of this distribution Z_p and the width of the distribution at half the height. As the result of isobars, a fragment nucleus with a strong neutron excess experiences a number of β^- decays before it reaches the valley of the stable nuclei Z_A. The measured yield of almost each of the product nuclei is the sum of the independent yield of the given nuclide during the fission process and the yields of its predecessors in the isobar series. Only in rare cases, when the predecessor nucleus in the chain is stable or long-lived, is it possible to determine the independent yield of such a protected isobar. Usually it is possi-

*With allowance for the superposition of fissions prior to neutron emission, after the emission of the 1st, 2nd, . . . etc. neutrons.

ble to measure the independent yields of a large number of protected isobars near the stability valley, since the isobars far from this valley have too short lifetimes for chemical separation. In most investigations, use was made until recently of radiochemical or mass-spectrographic methods. Of considerable interest are results obtained in recent times by two physical methods: the method of determining the fragment charge from the x-radiation of its atomic shell[174-177], and results obtained by using a mass spectrograph to separate a fragment of a known mass in combination with a scintillation spectrometer[178] or nuclear emulsion[179] to measure the length of the β-decay chains.

6.1. Charge Distributions of Fragments of Specified Mass

Fission of heavy nuclei with $Z \geq 90$. The independent yields of isobars of a number of mass chains obtained in the fission of uranium nuclei by slow neutrons fit satisfactorily[173] one universal charge-distribution curve $P(Z - Z_p)$, if the dependence of the most probable charge in each mass chain $Z_p(A)$ is chosen under the assumption that the lengths of the β-decay chains of the complementary fragments $(Z_p - Z_A)_l$ $(Z_p - Z_A)_h$ are equal[173]; the indices "l" and "h" pertain to the light and heavy fragments, respectively. Only relatively recently did Wahl et al.[180,181], by bombarding U^{235} with thermal neutrons, measure two independent yields for each of the six mass numbers (91, 94, 95, 139, 142, and 143), and three independent yields for each of four mass numbers (92, 93, 140, 141). The charge distribution is described sufficiently well by a Gaussian curve

$$P(Z) = (c\pi)^{-1/2} \exp[-(Z - Z_p)^2/c] \qquad (17)$$

with mean value c = 0.86 for ten mass chains. Assuming further that for other mass chains, for each of which one independent isobar yield is known, the charge distribution is described by the same curve (17) with c = 0.86*, Wahl et al. found the experimental $Z_p(A)$ dependence for a large number of mass chains (Fig. 16). The experimental $Z_p(A)$ dependence is close to the calculated one under the assumption that the decay chains of the complementary fragments are equal. Figure 16 shows also the data on the average primary charge of the nucleus, obtained by Armbruster et al.[178] for the mass-number intervals 90—102 and 134—146, and by Konecny et al.[179] for the mass numbers 132 and 134, in measurements of the number of β decays of the fission fragments. The mean lengths of the complementary-fragments chains obtained by this method[178] are not equal to one another, thus contradicting the hypothetical prediction that the decay chain

*Strom et al.[182] found, however, a variation in the width of the charge distribution with changing fragment mass number.

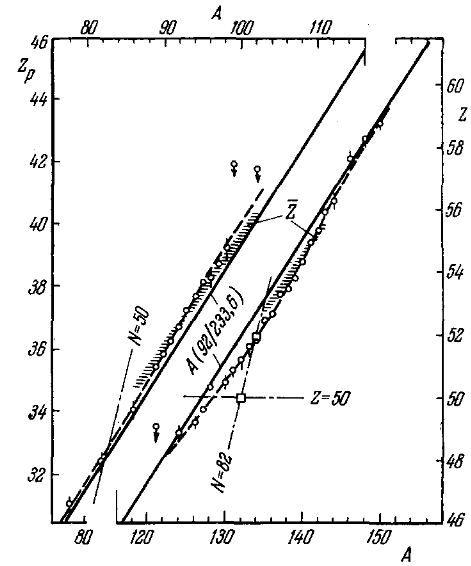

FIG. 16. Empirical values of the most probable charge Z_p and the average charge $\bar{Z}$ (close to the most probable) of the fission products obtained when U^{235} is bombarded with thermal neutrons. (The figure is taken from Wahl's paper [181]; the values of Z_p for A = 121 and 132 are taken from [183] and [179] respectivley). Symbols: ● – values of Z_p determined from two and more independent yields under the assumption that the charges have a Gaussian distribution; o – values of Z_p determined from one value of an independent yield under the assumption of a Gaussian distribution of the charges with c = 0.86 ± 0.15. Band of horizontal dashes – values of the average Z of the products, determined by Armbruster et al. [178] The solid lines denote the average charge of the fission products under the assumption of equal charge density of the fissioning nucleus and of the fission fragments, A × (92/233.6). The dashed lines represent the empirical $Z_p(A)$ dependence.

lengths are equal. The charge distribution of the fission fragments of the nuclei in irradiation of U^{233} and Pu^{239} by thermal neutrons[184] and in the spontaneous fission[180] of Cf^{252} nuclei, determined from two independent yields, is similar to the charge distribution of the fragments in the fission of U^{235} nuclei. The results[176,177] of a determination of the charge distribution of the fragments of spontaneous fission of Cf^{252} by measuring the energy of the K x-rays of the fission fragments were also close to the predictions based on the hypothesis that the complementary-fragment β-decay chains are of equal length.

As seen from Fig. 16, the experimental charge distribution of the fragments in the region of masses with maximum yield differ from the distribution predicted by the hypothesis of the equal charge density of the nucleus and of the fragments; the lighter fragment has in this case a higher charge density, and the heavier a smaller one compared with the charge density of the fissioning nucleus. Whereas in the nuclear fission process an appreciable role was played by the substructure with magic numbers N = 82 and Z = 50 in the heavy fragment, for the fragment with mass 132 the value of the most probable charge can be expected to be 50. According to the results of Konecny et al.[179], for the fragment with mass 132 the most probable (average) value of the charge is indeed close to 50, but this value of Z was obtained for a fragment with a fixed most probable kinetic energy of the fragment. On the other hand, according to the results obtained by a radiochemical method[181,182] (see Fig. 16), the charge density of the fragments with A = 132 differs from the charge density of the substructure with 50 protons and 82 neutrons. Be it as it may, the formation of a magic substructure in the heavy fragment during the course of nuclear fission at low excitation energy apparently plays an important role in the decrease of the charge density of the most probable heavy fragments, and consequently in the increase of the charge density of the complementary most-probable light fragments, and in the deviation of the experimental $Z_p(A)$ dependence for the most probable fragments from the expected $Z_p(A)$ dependence in the case of equal density of the complementary-fragment charges (Fig. 16). For the fragments resulting from the fission of nuclei into equal masses, the strictly symmetrical fission, the prediction of the hypotheses that the β-decay chains are equal and that the complementary-fragment charge densities are equal coincide. Special interest attaches to a study of the charge distribution of fragments of strongly asymmetrical nuclear fission. If the strongly asymmetrical fission of heavy nuclei, just as the symmetrical fission, occurs in those cases when no shells were produced in the heavy fragments, then we can expect the charge distribution of the fragments of strongly-asymmetrical fission to be close to the distribution predicted by the fragment-charge equal-density hypothesis. It seems that such a tendency does exist in the experimental values of Z_p of the fragments of strongly asymmetrical fission of U^{235} (Fig. 16).

With increasing energy of the bombarding particles, the width of the charge distribution of the fission fragments of the heavy nuclei increases somewhat[140,186–188,192]. The available data indicate that the character of the charge distribution $Z_p(A)$ of the fission products of heavy nuclei in the region of medium and high excitation energies is the same as in low-energy fission[187,195], or else is intermediate between the two distributions in accordance with the assumption that the β-decay chains have equal length or that the complementary fragments have equal charge density[189]. If the deviation of the charge distribution $Z_p(A)$ of the fission fragments of heavy nuclei at low excitation energies from the charge distribution predicted by the hypothesis that the complementary-fragment charge density is equal is brought about by the formation of a magic substructure in the heavy nucleus during the fission process, then one can expect the influence of the shell effect to decrease with increasing nuclear excitation energy, and the fragment charge distribution should tend to the distribution predicted by the hypothesis of equal charge density of the complementary fragments. In the fragment mass-number region near A = 140 and of the fragments complementary to them, the charge distribution of the fragments will thus be determined by a superposition of the fission products of the low-excited heavy nuclei after emission of the neutrons, and the fission products of the high-excited nuclei (prior to the evaporation of the neutrons) with different charge distributions. The products of the strongly asymmetrical fission of heavy nuclei bombarded with high-energy particles, which are produced as a result of fission of only high-excited nuclei (see Sec. 5), should have, in accordance with this treatment, a charge distribution corresponding to the hypothesis of equal charge densities of the fissioning nucleus and of the fragments. The experimental results[191] of the study of a charge distribution of light products of strongly asymmetrical fission of uranium bombarded with 170-MeV protons do not contradict such a representation.

By bombarding uranium with protons of energy higher than 1 BeV, Friedlander et al.[152,182] found that the charge distribution of fragments with A = 125–140, or more accurately the dispersion of the charges, is described by a curve with two maxima: the position of one maximum, which corresponds to the neutron-excess fission products, changes little with increasing energy of the bombarding protons in the BeV region, while the second maximum, which corresponds to neutron-deficient fission products, shifts with increasing bombarding-proton energy into the region with a larger neutron deficit. The total yield in this mass region of the fission products of uranium bombarded with high-energy protons can be regarded as a superposition of the fission products of high-excited nuclei (single-hump mass distribution, neutron-deficient fission products) and weakly-excited nuclei (two-hump mass curve, neutron-excess fission products), produced after the cascade stage of the interaction between the fast proton and the nucleus. The aforementioned observed two maxima of the dispersion curve of the uranium fission products are possibly connected with the fission of these two groups of highly-excited and weakly-excited nuclei. The ratio of the areas under these two maxima points to a relatively large contribution, estimated[152,182] at approximately 200 mb, for the fissions of weakly-excited nuclei, produced after the cascade stage of the interaction between protons of energy in the BeV region and the heavy nucleus. It is interesting to note in this connection that in the study of the nuclear fission by the nuclear-emulsion method, following bombardment of uranium with 3-BeV[142] and 9-BeV[193] protons, a considerable number of fissions with relatively low excitation energy was observed, and the bombardment of uranium with protons of 1–2.8 BeV energy, six groups of delayed neutrons were observed[194], just as in the case of fission of weakly-excited uranium nuclei (see Sec. 9 below). The total cross section for the production of the low-energy group of fissioning nuclei is estimated in the latter case at 280 mb. It is also interesting to note that for relatively light uranium fission products ($A \lesssim 80$) and the fission products obtained by bombarding lead with protons in the BeV region, for products produced only at relatively high excitation energy of the fissioning nuclei (single-hump mass curve broadening with increasing excitation energy), the dispersion of the charges is represented by a single-hump curve[152].

Fission of nuclei with $Z < 90$. The data on the charge distribution of the fission products of relatively light nuclei are scanty. As shown in the section dealing with mass distributions, the fission of nuclei such as bismuth and lighter, is reminescent of the splitting of a charged liquid drop. In this case we can expect the charge distribution $Z_p(A)$ of the fission products, as predicted by the hypothesis that the charge densities of the fissioning nucleus and of the fragments are equal. The experimental results obtained by bombarding gold with 40-MeV α particles[196] and bombarding bismuth with 190-MeV deuterons[138] coincide with the predictions of this hypothesis. In the case of fission of gold bombarded with 112-MeV carbon ions, it was found[141] that the charge distribution of the fission products $Z_p(A)$ lies in between the distributions predicted by the hypothesis of the equal charge densities of the nucleus and the fragments, and the hypothesis of the minimum potential energy of the touching fragments.

It is desirable to obtain further information on the charge distribution of the fission fragments of both light and heavy nuclei, in order to compare them and ascertain their similarity or difference, in view of the proposed difference (see Sec. 5) between the character of the fission of these nuclei: the fission is similar to the splitting of a liquid drop in the former case and is influenced by the substructure at low energies in the latter case.

7. ANGULAR DISTRIBUTION OF THE NUCLEAR FISSION FRAGMENTS

In bombardment of U^{235} with 14-MeV neutrons[187] and of Th^{232} with photons having a maximum energy of 16 MeV[198], it was observed that the fission fragments are emitted predominantly at angles 0° and 180° to the beam in the former case, and at 90° in the latter. The connection between the fragment-emission directions and the bombarding-particle direction, as shown in[29,199], is a direct consequence of the law of angular-momentum conservation.

If it is assumed, as was done by Bohr[29], that the fissioning nucleus passing through the saddle point has axial symmetry and that the direction of the symmetry axis, which coincides with the fission direction, is conserved after the nucleus passes through the saddle point, then the direction of the fragment emission is determined by the direction of the symmetry axis of the nucleus at the saddle point, and consequently by the value of K, the projection of the angular momentum of the nucleus I on its symmetry axis. If, furthermore, the nucleus can split at low excitation energies by passing through one of the discrete states at the saddle point[29], then consequently the angular distribution of the fragments is determined completely by the character of this intermediate state.

In bombardment of nuclei by neutrons and charged particles of medium energy, when an appreciable angular momentum is acquired by the nucleus, the continuous spectrum of the possible transition states reveals a certain predominance of states with small values of K, since these states correspond to a lower rotation energy of the nucleus

$$E_{\text{rot}} = \frac{\hbar^2}{2J_{\parallel}} K^2 + \frac{\hbar^2}{2J_{\perp}} (I^2 - K^2), \qquad (18)$$

where $J_{\parallel}$ and $J_{\perp}$ are the moments of inertia of the nucleus at the saddle point with respect to the symmetry axis of the nucleus and an axis perpendicular to it, respectively. If we assume, following Strutinskiĭ[199], that the distribution of the nuclei with respect to the rotation energies at the saddle point is determined by a Boltzmann factor, $W(E_{\text{rot}}) \sim \exp[-E_{\text{rot}}/T]$, where T is the temperature of the nucleus at the saddle point, then the distribution of the nuclei with respect to K will be Gaussian:

$$W(K) \sim \exp[-K^2/2K_0^2],$$

where

$$K_0^2 = \frac{1}{\hbar^2} \frac{J_{\perp} J_{\parallel}}{J_{\perp} - J_{\parallel}} T = \frac{1}{\hbar^2} J_{\text{eff}} T. \qquad (19)$$

At a specified value of I and K, the angular distribution of the fission fragments relative to the particle beam is given by

$$W_{I,K}(\theta) = \frac{2I}{4\pi^2} (I^2 \sin^2\theta - K^2)^{-1/2}. \qquad (20)$$

The angular distribution of the fragments, after integration over all possible values of I and K, has maxima at angles 0° and 180° to the beam of the bombarding particles, and the magnitude of the anisotropy increases with increasing parameter $p = (I_{\max}/2K_0)^2$[200]. At low values of p, the fission anisotropy is

$$W(0^0)/W(90^0) \simeq 1 + (I_{\max}^2/8K_0^2). \qquad (21)$$

In the other limiting case, $p \gg 1$, the angular distribution of the fragments is described by the formula $W(\theta) = 1/\sin\theta$[200]. Qualitatively similar results are obtained by assuming[201] that the distribution of the states with respect to K at the saddle point is linear: $W(K) \sim |K - K_{\max}|$.

Unlike the representation proposed above, where it was assumed that the angular distribution of the fragments is determined by the spatial orientation of the symmetry axes of the nucleus at the saddle point, Ericson and Strutinskiĭ[202] considered the possibility that the angular distribution of the fragments is determined by the distribution of the spins in the fragments. In this case, too, one should expect a predominant emission of the fission fragments at angles 0° and 180° following bombardment with particles.

7.1. Anisotropy at Low and Medium Excitation Energies

Photofission. The observed angular distribution of the fission fragments in bombardment of even-even target nuclei Th^{232}, U^{234}, U^{236}, U^{238}, and Pu^{240} by photons, can be represented[203-209] by a function having the form

$$W(\theta) = a + b\sin^2\theta + c\sin^2 2\theta, \qquad (22)$$

where θ is the angle between the direction of emission of the fragments and the photon beam. In the photon-energy interval 6—20 MeV, the character of the angular distribution of the fragments, determined by the term $b\sin^2\theta$, is evidence of the predominantly dipole absorption of the photons by the nucleus.* However, as was found in[209], the relative contribution of the quadrupole component increases in the case of sub-barrier photofission of U^{238} and Pu^{240}, this offering evidence of a smaller value of the U^{238} and Pu^{240} barrier values in the state 2^+—quadrupole absorption—compared with fission in the state 1^-—dipole absorption (by ~ 0.4—0.5 MeV). With increasing γ-quantum energy, the angular anisotropy decreases. The angular distribution of the photofission fragments of a number of nuclei with odd mass number was found to be isotropic[203].

The revealed singularities of the angular distribution of the fragments in photofission are attributed[203] to the fact that in the case of electric dipole absorption of a photon by an even-even nucleus the lowest possible state of the nucleus at the saddle point is the collective-excitation state 1^- (K = 0). Nuclear fission from this state leads to an angular distribution of the form $\sin^2\theta$, with a maximum at an angle of 90°. With increasing photon energy there appears a possibility of nuclear fission from other states. The superposition of fissions from a number of states with different character of the angular distribution of the fragments leads to an observable decrease in the anisotropy of fission with increasing photon energy. If the target nucleus has an unpaired nucleon, then the possibility of fission from several states is present already near threshold, and this explains the observed isotropy of the fission when a number of nuclei with odd mass number[203] are bombarded with photons. However, Rabotnov et al.[209b] found, in bombardment of Pu^{239} by photons with maximum energy in the interval 5.4—5.9 MeV, a small perpendicular fission anisotropy, which reversed sign with increasing energy and subsequently tended to zero. Such a character of the photofission anisotropy of Pu^{239} nuclei can be explained[209b] by assuming that the band of levels with $K = 1/2^-$ lies lower than the band of levels with $K = 3/2^+$ and the transition state of the Pu^{239} if its ground state has positive parity.

*The measurements of Baz' et al. [205] revealed that at E_γ ~ 6 – 9 MeV the term deciding the angular distribution of the fragments is $c\sin^2 2\theta$, which corresponds to quadrupole absorption of the photons. Later measurements [206,208,209] did not confirm these results.

Fission of nuclei in (n, f), (d, pf), and (α, α'f) reactions. a) Even-even compound nuclei. The effects of the manifestation of the structure of the fission channels in the angular distribution of the fragments were observed in a number of investigations of the angular anisotropy near the fission threshold. Nesterov et al.[210], in irradiation of U^{235} by neutrons of energy 0.08—0.3 MeV, found a perpendicular component in the angular distribution of the fragments. With further increase of the neutron energy, the predominant emission of the fragments was observed at angles 0° and 180°. A considerable anisotropy of fragment emission, $W(0°)/W(90°) \simeq 7$, was found[211] in the U^{238} (α, α'f) reaction at excitation energy 600 keV above the fission barrier of U^{238}. The magnitude of the anisotropy and the character of the angular distribution of the fragments offer evidence that in this region of nuclear excitation energy at the saddle point, the nucleus passes through a transition state with K = 0. When $(E^* - E_f)$ increases from 600 to 1500 keV, the character of the angular distribution of the fragments changes, the anisotropy decreases, thus offering evidence of the opening of one or more bands with $K \neq 0$.

A considerable gap in the spectrum of the energy levels of the Pu^{240} nucleus in the transition state, $2\Delta \simeq 2.6$ MeV (compared with $2\Delta \simeq 1.5$ MeV in the ground state), was observed[212] in a study of the angular distribution of the fragments in the reaction Pu^{239}(d, pf)Pu^{240}. This reaction makes it possible to introduce into the nucleus an excitation energy lower than the binding energy of the neutrons, while simultaneously introducing an appreciable angular momentum. As was found in[212a], $K^2 = 0$ near the barrier and increases jumpwise from ~ 8 to ~ 16 at $E^* - E_f$ = 2.6 MeV, which is connected with the breaking of the bond of the first pair of nucleons and the appearance of quasiparticle states[212a]. Smaller changes in K_0^2 at saddle point excitation energies ~ 0.7 and ~ 1.6 MeV were interpreted* as being due to the contribution of the collective vibrational states of the nucleus at the saddle point.[212a]

b) A-odd compound nuclei. By bombarding Th^{232} with 1.6-MeV neutrons, Henkel and Brolley[213] found that the fission fragments are scattered predominantly

*The noted jumpwise change of K_0^2 with increasing excitation energy of the nucleus can be explained, as shown by Strutinskiĭ [212b], also when the energy gap of the Pu^{240} in the transition state is equal to the energy gap of this nucleus in the ground state.

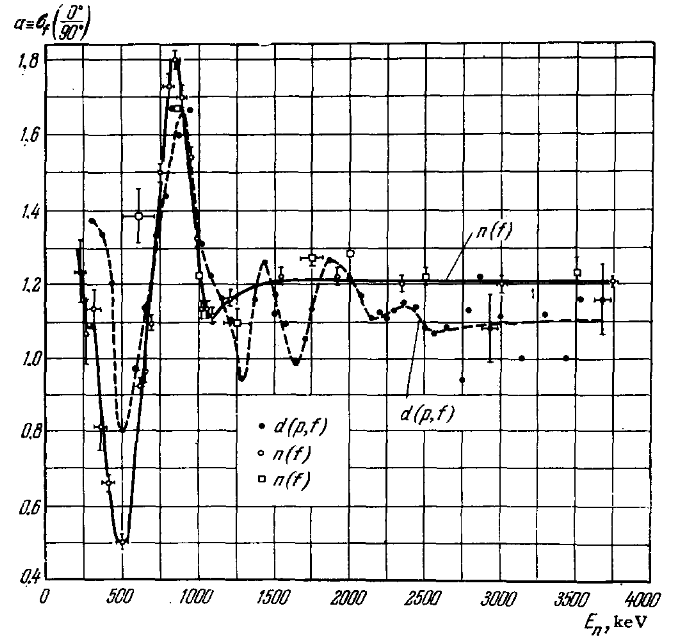

FIG. 17. Angular anisotropy of the fission fragments obtained by bombarding U^{234} with neutrons [215] and with neutrons in the (d, pf) reaction [217]. (The figure is taken from the article by Vandenbosch et al. [217].)

at 90° to the neutron direction. At a somewhat smaller or somewhat larger neutron energy, the perpendicular anisotropy decreases, after which emission of fragments at 0° and 180° to the neutron beam becomes predominant. Later, a predominant perpendicular emission of fragments relative to the neutron beam was observed by bombarding a number of even-even target nuclei with neutrons near the fission threshold[55,214-216]. Lamphere[215] performed a channel analysis of the results of the angular distribution of the fission fragments of nuclei from Th^{232} to Pu^{240} bombarded with neutrons. His conclusion was that the sequence of the level bands at the saddle point with $K = 1/2^+$, $K = 3/2^-$, and $K = 1/2^-$ can explain the observed character and the magnitude of the angular anisotropy for most of the indicated nuclei. In the case of bombardment of Th^{230} and Pu^{238} with neutrons, the observed character of the anisotropy of the fission, as shown by Vorotnikov et al.[216], can be explained better by assuming that the first, lowest band in the sequence of level bands is the band* with $K = 1/2^-$.

Figure 17 shows, besides the results obtained by Lamphere by neutron bombardment of U^{234}, also the values of the fission anisotropy when U^{234} is bombarded with neutrons from the (d, pf) reaction, as obtained by Vandenbosch et al.[217] The dependence of the anisotropy on the excitation energy reveals in this case a much larger structure than in Lamphere's measurements[215c] of the (n, f) reaction. If we ascribe each of the observed maxima or minima of the angular anisotropy to the opening of a new channel, then the data obtained by Vandenbosch et al.[217] indicate that there are in the saddle point of the fissioning U^{235} nucleus approximately eight open channels in the interval of the first 2 MeV of excitation energy, with an average distance ~ 250 keV between them.

c) Dependence of the anisotropy on the bombarding-particle energy. When the energy of the bombarding neutrons is of the order of several MeV, the level density of a heavy nucleus at the saddle point is high, the individual levels no longer influence the angular distribution of the fragments, and in this case, as already noted, the statistical approach to the estimate of the anisotropy of the angular distribution of the fission fragments is justified. In the bombarding-neutron energy interval 2.5—5.5 MeV, the anisotropy of the angular distribution of the fission fragments of heavy nuclei depends little on the neutron energy[214,218-220], but depends on Z^2/A of the target nucleus (see below), and in the case of U^{233}, U^{235}, and Pu^{239} on the spin of the target nucleus.

Thus, it was found that the anisotropy of nuclear fission when U^{233} ($I_0 = 5/2$) bombarded is larger than upon bombardment of Pu^{239} ($I_0 = 1/2$)[214,220], and is still larger than in the two preceding cases in the case of bombardment of U^{235} ($I_0 = 7/2$)[214]. This dependence turns out to be just the opposite of what was expected in[29], since it was assumed that the randomly oriented intrinsic spin of the target nucleus leads to a disorientation of the angular momentum of the compound nucleus $I = L + I_0$, and consequently to a decrease in the anisotropy. A possible cause of the anomalous dependence of the anisotropy on the spin is the dependence of the fission probability Γ_f/Γ_n on the angular momentum of the compound nucleus[228]. A quantitative estimate of the increase in the fission anisotropy with increasing nuclear spin has shown, however, that this can explain only part of the observed effect[221]. Another possible cause of the anomaly is the deviation from Gaussian distribution with respect to K, of the projection of the angular momentum on the symmetry axis of the nucleus at the saddle point in the region of low energies[222]. It is possible, however, that the observed increase in the fission anisotropy is connected not so much with the increase in the spin of the indicated nuclei, as with the decrease of the effective angular momentum of the nucleus at the saddle point with decreasing Z^2/A, which leads to an increase in the fission ansiotropy (see formula (19)). Simmons et al.[219] found for a number of fissioning nuclei that K_0^2, and consequently $J_{eff} \sim K_0^2$, increases with increasing Z^2/A of the nucleus, which agrees with the predictions of the liquid-drop model[24,26]. Leachman and Blumberg[223] compared the fission anisotropy of the com-

*As already noted, Rabotnov et al. [209b], in an analysis of the character of the anisotropy of photofission of Pu^{239} nuclei near threshold, also reached the conclusion that the lowest level band in the transition state, for the fissioning Pu^{239} nucleus, is the band with $K = 1/2^-$.

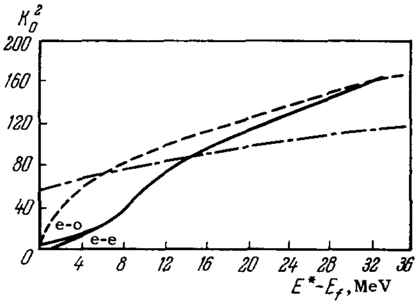

FIG. 18. Dependence of K_0^2 on the excitation energy of nucleus at the saddle point $E^* - E_f$. The solid line denotes the dependence calculated from experiments with neutrons [214,230] and He^4 ions [224] (The symbols e-o and e-e pertain to even-odd and even-even fissioning nuclei.) The dashed dependence was calculated in the Fermi gas model [200]. The dash-dot curve shows the dependence obtained under the assumption that the anisotropy is determined by the spins of the fragments [202] (in this case the ordinate represents $\sigma_1^2 + \sigma_2^2$). (The figure was taken from the paper of Vandenbosch et al. [224])

pound nuclei U^{236} and Pu^{240}, obtained by bombarding the nuclei with low-energy neutrons and with He^4 ions. The difference in the magnitude of the anisotropy of the fission of U^{236} and Pu^{240}, in the case of bombardment with neutrons or He^4 ions, is practically the same, which is also evidence of the dependence of the anisotropy more readily on Z^2/A than on the spin of the nucleus, for in the case of He^4-ion bombardment the target nuclei Th^{232} and U^{236} have no spin.

At a bombarding-neutron energy corresponding to the next reaction (n, xn′f) [214,219,220], the anisotropy of the fission of heavy nuclei increases jumpwise. These characteristic jumps of the anisotropy are attributed to the fact that the nuclear fission is strongly anisotropic [200,201] after emission of a neutron with small excitation energy and with small K_0. The magnitude of

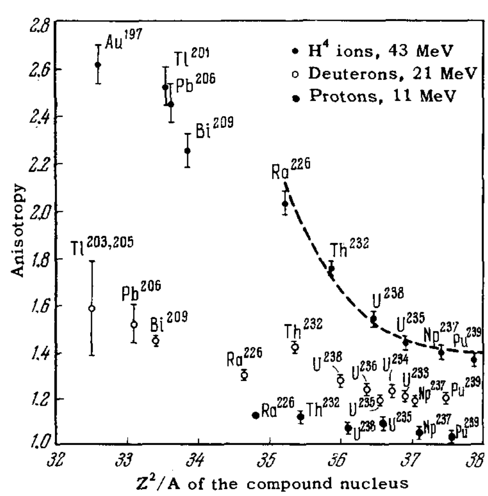

FIG. 19. Dependence of the anisotropy of the angular distribution of fission fragments on Z^2/A of a compound nucleus for a number of nuclei bombarded with protons, deuterons, and α particles [225,226,228].

the jump gradually decreases with increasing neutron energy, owing to the decreased contribution of the fissions after the emission of the neutron. Similar jumps in the anisotropy after neutron emission were observed [223,224] in bombardment of thorium and uranium by He^4 ions.

For nuclei bombarded with protons [225], deuterons [225,226], and He^4 ions [223,224] and heavy ions [227] the fragment angular distribution anisotropy increases with increasing particle energy, owing to the increase of the angular momentum acquired by the nucleus. From the experimental values of the anisotropy, knowing the value of the acquired angular momentum, it is possible to determine the value of K_0^2 at a given excitation energy, and thus obtain the experimental dependence of K_0^2 on the excitation energy. Figure 18 shows this dependence for the case of bombardment of U^{235} by slow neutrons and U^{233} by He^4 ions. The same figure shows the calculated dependences under the assumption that the anisotropy is determined by the state of the nucleus at the saddle point or by the spins of the separating fragments. It is seen that the calculated $K_0^2(E^*)$ dependence obtained under the first assumption agrees better with the experimental dependence. The plots presented show also that at low excitation energy the experimental $K_0^2(E^*)$ dependence lies much lower than the calculated one. This can be attributed to the fact that at excitation energies which are slightly higher than the fission barrier of the heavy nucleus, an appreciable part of the nucleons of the nucleus is paired. Allowance for the pairing effect in the model of the superfluid nucleus [42,212] leads to agreement between the theoretical and experimental $K_0^2(E^*)$ dependences.

Dependence of the angular anisotropy on Z^2/A. It was found that the angular anisotropy of fission increases with decreasing Z^2/A of the fissioning nucleus. Figure 19 shows data on the anisotropy of the fission of a number of nuclei bombarded with protons, deuterons, and He^4 ions. The observed increase in the anisotropy with decreasing Z^2/A of the fissioning nucleus is connected with the accompanying increase of the fraction of fissions after the evaporation of the neutrons, and consequently with the decrease in the nuclear excitation energy at the instant of fission, for nuclei from plutonium to radium [200]. This argument does not hold for an explanation of the anisotropy of fission of nuclei lighter than radium, for these nuclei are fissioned essentially prior to the neutron emission, with a sufficiently high excitation energy. The observed appreciable anisotropy which was nevertheless observed in the fission of nuclei lighter than radium is due to two causes [14]. Relatively light nuclei have high fission barriers, low excitation energy at the saddle point, and a large anisotropy. Another cause may be the more elongated form of these nuclei at the saddle point (see Fig. 1a), $J_\perp - J_\parallel$ is therefore large, and K_0^2 (formula (19)) is small.

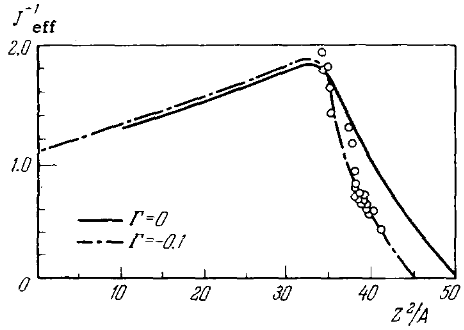

FIG. 20. $J^{-1}_{eff} = (J_\perp - J_\parallel/J_\perp J_\parallel)$, which is the reciprocal of the effective moment of inertia of the nucleus at the saddle point, vs. Z^2/A. The experimental values were calculated from the fission anisotropy in bombardment of nuclei from Au^{197} to Cf^{249} with He^4 ions of 40 MeV energy [231]. The calculated values of J^{-2}_{eff} for nuclei with sharp ($\Gamma = 0$) and diffuse ($\Gamma = -0.1$) boundaries [230].

From the obtained values of K_0^2, knowing the temperature of the nucleus at the saddle point, we can determine J_{eff} (Fig. 20) in accordance with (19). The so obtained values of the effective moment of inertia of the nucleus at the saddle point agree well with the values of J_{eff} in calculations of the deformation of a charged liquid drop, especially in the case of a nucleus with a diffuse boundary[230]. As a result, it is possible to estimate directly from such an analysis the value of $(Z^2/A)_{crit}$, the value at which J^{-1}_{eff} is equal to zero at the saddle point. According to such estimates[231], $(Z^2/A)_{crit}$ is equal to 45.0.

Dependence of the anisotropy on the ratio of the fragment masses. When heavy nuclei are bombarded with photons[204], neutrons[229], and protons[232,233] it was observed that the asymmetrical fission is more anisotropic than the symmetrical fission. With increasing energy of the bombarding particles, the dependence of the anisotropy on the asymmetry of the fission of these nuclei almost vanishes[233,234]. The observed dependence of the anisotropy of the fission of heavy nuclei on the ratio of the mass fragments is explained[200] as being the result of superposition of fissions after the evaporation of the neutrons, which are predominantly asymmetric, with low excitation energy and high anisotropy, and fissions prior to the evaporation of the neutrons, which have high excitation energy and low anisotropy. The vanishing of the dependence of the anisotropy of the fission of the heavy nuclei on the fragment mass ratio with increasing bombarding-particle energy can be attributed to the fact that the contribution of the fissions after the emission of the neutrons, which are predominantly asymmetrical, and have large anisotropy, continue to become smaller with increasing energy.

If only the evaporation of the neutrons prior to fission were to be responsible for the correlation between the anisotropy and asymmetry of fission, then the indicated correlation should not be expected in the case when heavy nuclei are bombarded with neutrons of energy lower than 6—7 MeV and when nuclei of the type of bismuth are bombarded with particles of medium energy, when the fission occurs prior to the neutron evaporation. It was already found that in these two cases there is, so to speak, actually no correlation between the anisotropy and the asymmetry of the fission[217,235–237,239] within the limits of the measurement accuracy.

However, if both the angular distribution and the mass distribution of the fragments are determined during the stage of passage through the top of the potential barrier, then a relation between the anisotropy and the asymmetry of the fission is possible in principle. Thus, in the case of fission of nuclei of the bismuth type, which split in a manner similar to a liquid charged drop in the main symmetrically, one can expect a certain increase in the anisotropy with increasing fragment mass ratio, since an asymmetric configuration of the nucleus at critical deformation, within the framework of the liquid-drop model, corresponds to a larger value of the potential energy compared with the symmetrical configuration. If we take as a consequence of the difference in the potential energies of the asymmetrical and symmetrical deformed nucleus on passing through the top of the potential barrier the values ΔE_f listed in Table III, and assume that the nucleus has at critical deformation the form of two ellipsoids in contact, then it can be shown that the anisotropy calculated in accordance with (21) for fissions with fragment mass ratio 1.3 and 2.0, in the case of bombardment of bismuth with He^4 ions at 42 MeV energy, exceeds the anisotropy of symmetrical fission only by 2 and 6% respectively. This, in particular, explains why Flynn et al.[239] did not find a change in the anisotropy with increasing fragment mass ratio from 1.0 to 1.3 when lead and bismuth were bombarded with 4.2-MeV He^4 ions.* For nuclei such as uranium at low excitation energies, one can expect a certain increase in the anisotropy for symmetrical and highly asymmetrical fission, compared with the most probable fission, if the latter is connected with the manifestation of shell effects already at the saddle point, with a lower fission barrier. The symmetrical and strongly asymmetrical fission of heavy nuclei occurs here in cases when the shell effects do not come into play, and correspond to larger values of fission barriers compared with the most probable fission. In some experimental results obtained so far there is noted only a certain tendency to an increase of the anisotropy for symmetrical and strongly asymmetrical fissions[235–238].

7.2. Angular Distribution of the Fragments in the High-energy Region

When nuclei are bombarded with heavy ions, the fissioning nucleus acquires a large angular momentum

*For the fragment Br^{83}, which corresponds to an asymmetry of fission equal to 1.53, they even found a certain decrease in the anisotropy.

and consequently a large anisotropy is observed in the angular distribution of the fission fragments[93,95,227]. The main laws governing the angular distribution of the fission fragments in this case, namely the increase of the anisotropy with increasing ion energy and with decreasing Z^2/A of the fissioning nucleus, are the same as in bombardment with medium-energy particles. The dependence of the anisotropy on the fragment mass ratio has hardly been investigated, there is only an indication that this dependence is weak[240].

In bombardment of uranium, bismuth, and gold by protons with energies higher than 45 MeV, the angular distribution of the fragments tends to become isotropic[233,241-244]. Earlier, for uranium and thorium bombarded with protons of energy 460—660 MeV, a considerable predominance of the emission of the fission fragments at 90° to the proton beam was observed[245]. In later measurements, these results were not confirmed[241,242]. The angular distribution of the fission fragments of uranium nuclei is close to isotropic, up to bombarding-proton energy 3 BeV[142]. Such a character of the angular distribution of the fission fragments at high bombarding-proton energies is connected apparently with the character of the interaction of the fast proton with the nucleus, and with the emission of cascade nucleons from the nucleus; the result of this is disorientation of the angular moments of the nucleus[142].

8. KINETIC ENERGY OF THE FISSION FRAGMENTS

Dependence of the kinetic energy of the fragments on their mass ratio. If the kinetic energy of the fission fragments were to be determined by their Coulomb interaction at the instant of separation, then for fragments of spherical form, assuming $Z_1/Z_2 = A_1/A_2$, we would have

$$E_k = \frac{Z_1 Z_2 e^2}{r_1 + r_2} = \frac{Z_0^2 e^2}{r_0 A_0^{1/3}} \left\{ \frac{A_h/A_l}{(1 + A_h/A_l)^{5/3}\,[1 + (A_h/A_l)^{1/3}]} \right\}, \quad (23)$$

i.e., the total kinetic energy of the two fission fragments is maximal in symmetrical fission and decreases with increasing fragment mass ratio. It was found,

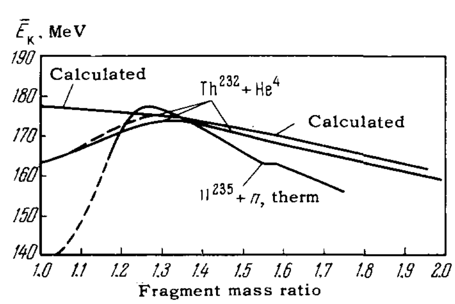

FIG. 21. Average kinetic energy $\bar{E}_k$ of the pair of fission fragments vs. their mass ratio in the case of fission of nuclei by bombarding U^{235} with thermal neutrons [119], Th^{232} with 22-MeV He^4 ions (dashed), and 29.5 MeV He^4 ions [259]. The dependence for the fissioning U^{236} nucleus is also shown as calculated in the liquid-drop model [119].

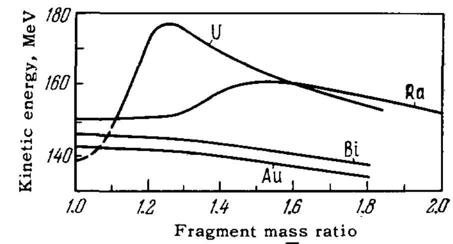

FIG. 22. Average kinetic energy $\bar{E}_k$ of a pair of fission fragments vs. their mass ratio in the case of fission induced by bombarding U^{235} with thermal neutrons [119], Ra^{226} with 14-MeV neutrons [137], and Bi^{209} and Au^{197} with 25.5-MeV He^3 ions [137].

however, in spontaneous fission of heavy nuclei[113,246,247], and in the fission of heavy nuclei induced by thermal neutrons[108,119,248-253] and by medium-energy particles[134,137,144,254-262], that the $\bar{E}_k(A_h/A_l)$ has a minimum in the symmetrical-fission region. In the case of U^{233}, U^{235}, and Pu^{239} bombarded by thermal neutrons, the dip in the kinetic energy in the symmetrical-fission region amounts to about 20—35 MeV* and decreases with decreasing energy of the bombarding particles. Thus, when uranium and thorium are bombarded with 14-MeV neutrons, the dip amounts to 12—15 MeV[254-256], and when they are bombarded with 29-MeV He^4 ions[259-262] the dip is only 6—8 MeV (Fig. 21). A small dip in $\bar{E}_k$ in the symmetrical-fission region is still observed when U^{238} and Th^{232} are bombarded with He^4 ions of energy 42 and 65 MeV[134,260]. When Ra^{226} is bombarded with protons, deuterons, He^3, and He^4 ions of energy from ~10 to ~30 MeV, the dip of $\bar{E}_k$ in the symmetrical-fission region amounts to 6—9 MeV[137,144]. On the other hand, when bismuth and gold is bombarded with 25-MeV He^4 ions and with 42-MeV He^4 ions[137,260], a smooth $\bar{E}_k(A_h/A_l)$ dependence is observed (Fig. 22).

In a number of papers, the $\bar{E}_k(A_h/A_l)$ dependence observed in the fission of heavy nuclei is connected with the influence of the degree of filling of the nuclear shells on the shape of the fragments at the instant of fission[254], with the increased rigidity against deformation of near-magic fragments, and with the decreased rigidity of fragments far from the filled-shell region[169,264,265,287]. To explain the observed increase of the kinetic energy of the fragments of symmetrical (and strongly asymmetrical) fission[260-262] of heavy

*The values of the kinetic energy of the symmetrical-fission fragments of U^{233}, U^{235}, and Pu^{239} bombarded with thermal neutrons, measured with an ionization chamber, semiconductor detectors, and by the time of flight of the fragments, are to a considerable degree indeterminate, owing to the contribution (up to ~50%) of the asymmetrical fissions, which have larger kinetic energies. In measurement of the kinetic energy of symmetrical-fission fragments by the time of flight of the fragments using a radiochemical method [251-253], no uncertainty due to the contribution of the asymmetrical fissions is observed in $\bar{E}_k$, but another difficulty arises, in that the dependence of the fragment range on its kinetic energy is not known definitely.

nuclei with increasing excitation energy, and also a certain decrease of the kinetic energy of the fragments at the maximum (see Fig. 21), it is necessary to assume in this picture[260] that the rigidity of the fragments changes with increasing excitation energy.

In another group of papers[137,256,258,263] the anomalous dip in the kinetic energy of the fragments in the region of symmetrical fission of heavy nuclei is explained from the point of view of the model of two types of fission. The observed $\overline{E}_k(A_h/A_l)$ dependence is explained in this case as a superposition of two independent types of fission, symmetrical and asymmetrical. The symmetrical type of fission of both light and heavy nuclei is connected with the larger distance between the centers of gravity of the fragments compared with the asymmetrical type of fission, and consequently, the lower kinetic energy of the fragments, regardless of the excitation energy of the fissioning nucleus[137]. To explain the increase of the kinetic energy of the fragments of symmetrical fission of heavy nuclei with decreasing nuclear excitation energy, it was proposed in another treatment of the model of two types of fission[263] that the symmetrical type of fission of both light and heavy nuclei is a fast process, in which the additional excitation energy goes over into degrees of freedom that are connected with the motion of the centers of gravity of the nuclei. In none of these treatments of the properties of the two types of fission, however, it is possible to explain the simultaneously observed slight increase of the kinetic energy of the fragments of symmetrical and strongly asymmetrical fissions of heavy nuclei with increasing excitation energy of the nucleus, and the independence of the kinetic energy of the symmetrical-fission fragments of nuclei such as gold and bismuth of the excitation energy (see the next section).

It is possible, however, to present the following picture[142]. We have seen in Sec. 5 that fission of nuclei such as gold and bismuth recalls, in the character of the mass distribution of the fragments, the splitting of a charged liquid drop, and if this is so, then, in accordance with expression (23) the dependence of the average kinetic energy of the fragment pair on their mass ratio $\overline{E}_k(A_h/A_l)$ should be smooth, as is indeed observed (see Fig. 22). Symmetrical fission of heavy nuclei can be regarded (as already proposed in Sec. 5) as a fission during which the influence of the shells is completely or partially weakened. At low excitation energies this weakening can be due to large deformations of the nucleus during the fission process, possibly even before or at the saddle point. Fission from such strongly deformed states leads to an anomalous decrease of the kinetic energy of the fragments of symmetrical fission (and apparently also the strongly asymmetrical fission). With increasing excitation energy of the nucleus, the symmetrical fission can proceed from a less deformed state of the nucleus, the symmetrical fission can proceed from a

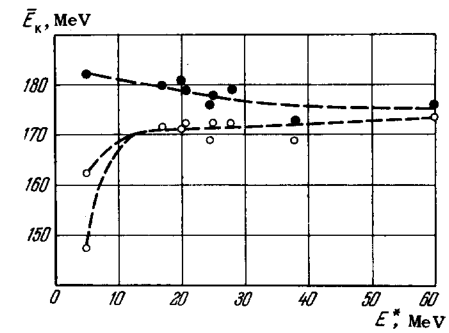

FIG. 23. Average kinetic energy $\overline{E}_k$ of a pair of symmetrical-fission fragments (○) and of fission with maximum kinetic energy (●) vs. the excitation energy of the compound nucleus following bombardment of Pu^{239} with thermal neutrons [119,249], U^{233} with He^4 of energy 22.1, 25.7, and 29.5 MeV [259], of U^{238} with He^4 ions of energy 29.4 and 42 MeV [260], and of U^{238} with 65-MeV He^4 ions [134].

less deformed state of the nucleus, in which the shells are broken as a result of the increased excitation energy. Thus, the growth of the excitation energy of the heavy nucleus leads both to an increase in the yields of the symmetrical-fission products, and to an increase of their kinetic energy (see Figs. 11, 21, and 23). The predominantly asymmetrical form of fission of heavy nuclei (see Sec. 5) is apparently due to the influence of the closed shells of 82 neutrons and 50 protons in the heavy fragment. Nuclear fission during which the influence of shell effects becomes manifest proceeds from less deformed states with increased fragment kinetic energy. With increasing excitation energy of the fissioning nuclei, the influence of the shell effects decreases, and the kinetic energy of the fragments in the mass region 132 decreases, approaching the value predicted by the liquid-drop model (Figs. 21 and 23). At sufficiently high heavy-nucleus excitation energy, when the influence of the shell effects is completely annihilated, the dependence of $\overline{E}_k(A_h/A_l)$ can, in accordance with such a representation, be described by a smooth curve. It is interesting to note that, in analogy with the connection between the decrease of the dip in the symmetrical-fission region on the mass curve and the kinetic energy in the fission of heavy nuclei with increasing particle energy (Figs. 12 and 21), on going from heavier to lighter nuclei the decrease of the gap in the region of symmetrical fission on the mass curve is accompanied by a decrease in the dip of the kinetic energy of the symmetrical-fission fragments (see Figs. 10 and 22). In the case of gold bombardment, both the yield and the kinetic energy of the fragments have maxima in the case of fission into fragments of equal mass.

Dependence of the average kinetic energy of the fission fragments on the excitation energy. Since, as we have seen, the average kinetic energy of a pair of fragments of fission of a heavy nucleus in the region of low and medium excitation energies depends to a strong degree on the fragment mass ratio, one can expect in principle, in this region of excitation energies, a certain change in the average kinetic energy of the fragments, due to the change in the character of the mass distribution of the fission fragments of heavy nuclei. It was found[266] in the case of spontaneous fission of Pu^{240} and fission of Pu^{239} bombarded with thermal neutrons, that the average kinetic energy of the fragments does not change, within the limits of errors.

In the region of resonances one can expect an increase (decrease) of the symmetrical-fission yields for any resonance level or group of levels to lead to a decrease (increase) of the average kinetic energy of the fission fragments, owing to the anomalously low kinetic energy of the symmetrical-fission fragments. Small variations in the average kinetic energy of fragments were observed for U^{235} bombarded with neutrons of energy from 0.025 to 1 eV[267], but these variations of $\overline{E}_k$ cannot be directly related with the changes in the yields of symmetrical fission. Vandenbosch et al.[217] did not find, within the limits of 1%, a change in $\overline{E}_k$ for different levels at the saddle point in the study of the channel structure of the compound nucleus U^{235} with the aid of the (d, pf) reaction. A certain change of $\overline{E}_k$ at a still higher neutron energy, 500—700 keV, was observed by Blumkina et al.[268] in bombarded U^{233} and U^{235}, and was ascribed to opening of fission p-channels.

In the region of medium excitation energies, the slight observable change, namely a decrease in the kinetic energy of the fragments of U^{235} fission by neutrons, agrees qualitatively and quantitatively[269] with the expected change due to the decreased contribution

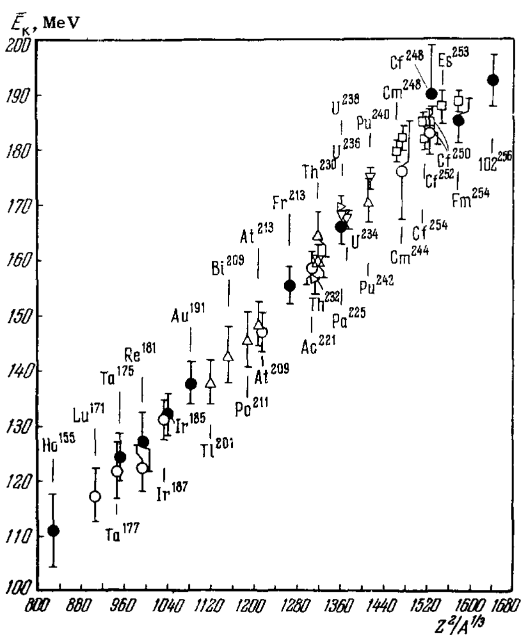

FIG. 24. Dependence of the average kinetic energy $\overline{E}_k$ of the fission fragments on $Z^2/A^{1/3}$ of the fissioning nucleus: [113,119,121,137,260,273-276]. □ – spont.; ▽ – n, therm.; △ – He^4; ○ – C^{12}; ● – O^{16}; ▷ – γ.

of the asymmetrical fissions with maximum kinetic energy and due to the decrease of the value of the maximum kinetic energy itself for asymmetrical fission, with increasing excitation energy. For U^{233} and U^{235} bombarded with neutrons of energy up to 20 MeV[269] the average kinetic energy of the fission fragments remains essentially unchanged. A similar result was obtained for U^{238} and Th^{232} bombarded with neutrons of energy up to 90 MeV[270,271], with deuterons and protons of high energy[272], and also in the bombardment of lighter nuclei Au^{197} and Bi^{208} by alpha particles[273] and heavy ions[274]. This independence of $\overline{E}_k$ on the energy of the bombarding particle offers evidence that the kinetic energy of the fragments is indeed due essentially to the Coulomb interaction of the separated fragments. Figure 24 shows the average kinetic energy of the fragments of a number of spontaneously fissioning nuclei and of nuclei fissioning by bombardment with particles and photons, as a function of $Z^2/A^{1/3}$. The choice of the parameter $Z^2/A^{1/3}$ is governed by the fact that in the fission of a nucleus into two equal fragments of spherical form, the kinetic energy of the fragments, which is equal to the energy of the Coulomb interaction, is

$$\overline{E}_k = \frac{Z_1 Z_2 e^2}{r_1 + r_2} = \text{const} \cdot \frac{Z_0^2}{A_0^{1/3}}. \tag{24}$$

Terrell[277], systematizing the experimental values of $\overline{E}_k$ of the fission fragments of heavy nuclei from thorium to fermium, found that the linear relation $\overline{E}_k = 0.121\, Z^2/A^{1/3}$ describes sufficiently well the experimental data. However, for the data shown in Fig. 24, which cover a wider region of fissioning nuclei, the dependence best describing the experimental values can be represented by

$$\overline{E}_k = 17.5 + 0.1092 Z^2/A^{1/3}. \tag{25}$$

Let us see why the values of the average kinetic energy of the fission fragments of relatively light nuclei, whose fission is predominantly symmetrical, with a "normal" dependence of the kinetic energy of the fragments from their mass ratio, fit on a single straight line (see Fig. 24) together with the values of $\overline{E}_k$ of fission fragments of heavy nuclei, which fission predominantly asymmetrically at low energies, with an anomalous $\overline{E}_k(A_h/A_l)$ dependence, and with a dip of the kinetic energy of the fragments in the region of symmetrical fission. If the fission of the heavy nuclei were to proceed in a manner similar to the fission of relatively light nuclei, i.e., predominantly symmetrically, with "normal" $\overline{E}_k(A_h/A_l)$ dependence, as is apparently the case for the fission of heavy nuclei in the region of high excitation energy at the instant of fission, then a common $\overline{E}_k(Z^2/A^{1/3})$ dependence for these two groups of fissioning nuclei would be understandable. In the case of fission of weakly-excited heavy nuclei, the average value of the kinetic energy of the fragments, determined essentially by the kinetic energy of the most probable fragments, is close, as we have seen earlier, to the value of $\overline{E}_k$ of the fission fragments of the strongly excited heavy nuclei, which apparently can explain the observed common $\overline{E}_k(Z^2/A^{1/3})$ dependence for all the fissioning nuclei.

If we represent the nucleus at the instant of separation in the form of two identical collinear uniformly-charged ellipsoids in contact, then in order for their electrostatic-interaction energy to satisfy (25) it is necessary to assume that the ratio of the semiaxes of the ellipsoid C/A has changed from 1.92 (light nuclei) to 2.25 (heavy nuclei) in the investigated interval (see Fig. 24) of the fissioning nuclei. The ratio of the semiaxes of the ellipsoids was determined with the aid of the calculated values of the energy of electrostatic interaction of two charged ellipsoids in contact[24]. For heavier fissioning nuclei, the "experimental values" of C/A obtained in this manner are close to the calculated values of C/A, which satisfy the condition of minimum potential energy for two ellipsoids in contact, and exceeds slightly, by ~15%, the latter in the case of light fissioning nuclei. In a real case, the fissioning nucleus at the instant prior to separation is apparently represented by two ellipsoids connected by a neck. In this case, the condition of the minimum potential energy of the nucleus at the instant of separation of the fragments corresponds to a lower fragment deformation and to a smaller value of the energy contained in the deformation, which is subsequently transformed into excitation energy; this is in better agreement with the available data on the excitation energy of fragments[119].

9. NEUTRONS, γ QUANTA, AND CHARGED PARTICLES EMITTED IN THE FISSION OF NUCLEI

The energy released in the fission of a nucleus is in the form of kinetic energy of the fission fragments and in the prompt neutrons and γ quanta emitted from the fragments. Since the average kinetic energy of the fragments remains practically unchanged with increasing excitation energy of the nucleus, the additional energy of excitation, introduced into the nucleus, goes essentially to evaporation of the additional neutrons. At sufficiently high excitation energy, charged particles are emitted together with the neutrons during the nuclear fission. In some rare cases the charged particles, in the main alpha particles, are emitted in spontaneous fission of nuclei and in nuclear fission produced by low-energy particles. The mechanism of the occurrence of these charged particles apparently differs from the evaporation mechanism.

9.1. Neutron Emission

Since the minimum of the potential energy at the instant prior to the separation of the fragments corresponds in the liquid-drop model to a fragment shape different from spherical[24-26], and the minimum of the potential energy of the fragments in the case of infinite separation corresponds to their spherical form, this

Table IV. Average number of neutrons $\bar{\nu}$ emitted in thermal-neutron fission of nuclei

Target nucleus	$\bar{\nu}$	Reference	Target nucleus	$\bar{\nu}$	Reference
Th^{229}	2.18±0.08	49	Pu^{239}	2.892±0.011 2.871±0.014	49 50
U^{232}	3.04±0.05	49			
U^{233}	2.497±0.008 2.494±0.009	49 50	Pu^{241}	3.00±0.04 2.969±0.023	49 50
U^{235}	2.426±0.006 2.430±0.008	49 50			

difference in the deformation energy of the fragments is transformed into internal energy of fragment excitation. The fragments of fission of a heavy nucleus have a large neutron excess. This excess is decreased partially by evaporation of neutrons from the fragment as the result of the fragment excitation energy.

Dependence of the neutron yield on the excitation energy. Table IV lists the experimental values, averaged over all the universal data, of the number of fission neutrons $\bar{\nu}$ for the bombardment of a number of nuclei by thermal neutrons.

With increasing nuclear excitation energy, the number of emitted neutrons increases. If the excitation energy introduced additionally into the nucleus were to be completely transformed into fragment excitation energy, then a linear dependence would be observed between the number of prompt neutrons $\bar{\nu}$ and the nuclear excitation energy. Complete transformation of the excitation energy of the nucleus into excitation energy of the fragments is possible if exchange of energy between the internal degrees of freedom and the collective degrees of freedom of the nucleus, similar to the motion of viscous liquid[167], occurs during the process of the deformation point from the saddle point to the instant of separation. However, a deviation from the linear $\bar{\nu}(E_n)$ dependence was observed recently[268,278,279] (Fig. 25). It was found in neutron-The results of such calculations for the case of nuclear fission produced by bombardment of Au^{197} with C^{12} ions of energy 112 MeV[141] are listed in Table III. The

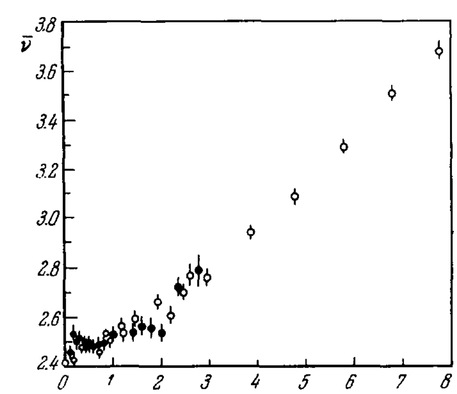

FIG. 25. Dependence of the number of prompt fission neutrons $\bar{\nu}$ on the energy of the bombarding neutrons in bombardment of U^{235} [268,279].

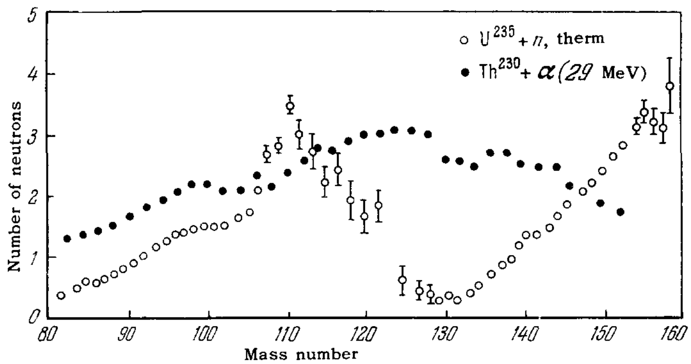

FIG. 26. Dependence of $\bar{\nu}$ on the fragment mass for U^{235} bombarded with thermal neutrons [285] and for Th^{230} bombarded with 29-MeV He^4 ions [259b].

bombarded U^{235} and Pu^{239} nuclei[278,279] that in the neutron-energy interval from thermal to ~2 MeV the number of neutrons increases with excitation energy more slowly, $d\bar{\nu}/dE = 0.08-0.11$ MeV^{-1}, than when the neutron energy exceeds 3 MeV, where $d\bar{\nu}/dE = 0.16-0.18$ MeV^{-1}. The difference in the values of $\bar{\nu}$ for spontaneous fission of U^{238}[280] and for fission by 7-MeV photons[281] corresponds to a slope ~0.10 neutron/MeV, and in the case of Th^{232} bombarded with protons the number of prompt neutrons even increases with decreasing neutron energy from 1.6 to 1.4 MeV[49,281]. Further more complete investigations are needed to establish the nature of this variation of $d\bar{\nu}/dE$.

Dependence of the number of prompt neutrons on the fragment mass. Measurement of $\bar{\nu}$ as a function of the fragment mass in the case of spontaneous fission of Cf^{252} and fission of U^{233}, U^{235}, and Pu^{239} by thermal neutrons[246,282-285] that this dependence has a sawtooth form (Fig. 26). With increasing masses of the light and heavy fragments, the number of neutrons increases in such a way that it is minimal for the lightest fragment in the light group of fragments and maximal for the heaviest fragment in these two groups.

The region of symmetrical fission is apparently a transition region for these two branches $\bar{\nu}(A)$[285]. A similar $\bar{\nu}(A)$ dependence was obtained also from a comparison of the primary and secondary mass distributions of the fission fragments[116,286].

The light fragment emits on the average a few more neutrons than the heavy fragment[283-285,296,298], by 10–30% in the case of U^{236} fission and by 16% in spontaneous fission of Cf^{252}. In investigations of the $\bar{\nu}(A_h/A_l)$ dependence made by Apalin et al.[285] it was found that the largest number of neutrons is emitted in symmetrical fission of the nuclei U^{234}, U^{236}, and Pu^{240}. The difference in the fragment excitation energy in symmetrical and asymmetrical fission of these nuclei by thermal neutrons is approximately 20 MeV[285], which is almost equal to the dip of the kinetic energy of the symmetrical-fission fragments of these nuclei.

A qualitative explanation of these experimental data is based on the assumption[254,282,286,298b] that the form of the fragments at the instant prior to the separation depends on the closeness of the fragment to the magic number of neutrons and protons in it. Fragments with a magic number of nucleon have a larger surface tension and their shape is close to spherical. To the contrary, fragments with shells that are far from filled have a much lower surface tension and consequently a more elongated form. The fragment excitation energy, which is proportional to the deformation of the fragments prior to separation, is the smallest for fragments close to the filled shells with N = 82, Z = 50, with A = 132. Calculations[265,287] have led to a sufficiently good agreement with the experimental $\bar{\nu}(A)$ dependence in the case of U^{235} fission induced by thermal neutrons and in the case of spontaneous fission of Cf^{252}.

Unfortunately, there are no data on the $\bar{\nu}(A)$ dependence in the fission of lighter nuclei, such as gold, bismuth, and in the case of fission of heavy nuclei at high excitation energy, when the nuclear fission occurs, as proposed in Sec. 5, in a manner similar to the fission of a charged liquid drop, and we can therefore expect a smooth increase in the number of neutrons $\bar{\nu}$ with increasing fragment mass number A. In a very recent paper[259b], where the dependence of $\bar{\nu}(A)$ was obtained for Th^{230} and U^{233} bombarded with He^4 of energy 26 and 29 MeV by subtracting from the mass distribution of the fragments prior to the neutron emission obtained during the time of flight of the fragments[259a], and the mass distribution of the fragments after the neutron emission, obtained with the aid of semiconductor detectors. The average number $\bar{\nu}$ of neutrons per fragment increased almost smoothly with increasing fragment mass (see Fig. 26). It must be noted, however, that when one subtracts from this primary fragment mass distribution[259a] the secondary mass distribution obtained by the radiochemical method, the $\bar{\nu}(A)$ dependence reveals a structure, with a drop of $\bar{\nu}$ at A ≃ 132. Such a $\bar{\nu}(A)$ dependence can be attributed to a superposition of the sawtooth $\bar{\nu}(A)$ dependence observed for nuclei fissioning after the neu-

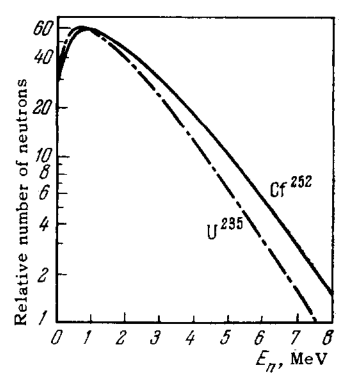

FIG. 27. Energy distribution of the prompt neutrons (in 1-MeV intervals) from spontaneous Cf^{252} fission [289] and thermal-neutron fission of U^{235} [288].

tron emission, and a $\bar{\nu}(A)$ dependence that approaches the liquid-drop dependence, with increasing excitation energy of a nucleus that fissions prior to the neutron emission.

Energy spectrum of prompt neutrons. Figure 27 shows the energy spectra, in the laboratory frame, of the prompt neutrons of spontaneous fission of Cf^{252} and of the fission of U^{235} bombarded with thermal neutrons. The spectra of neutrons of energy from several eV to ~14 MeV, with a most probable energy 0.72 MeV and with an average energy of approximately 2 MeV, have a Maxwellian character. The energy spectra of the neutrons in fission of other nuclei[290-293] are similar to those shown in Fig. 27. The average energy of the fission neutrons can be represented in the form[287]

$$\bar{E}_n = \bar{E}_{nf} + E_{n,\,\text{c.m.s.}} \simeq 0{,}75 + 0{,}65\sqrt{\bar{\nu}+1}, \qquad (26)$$

where $\bar{E}_{nf}$ is the energy of a neutron having the same velocity as the fission fragment, equal to about 0.75 MeV for a wide range of fissioning nuclei, $E_{n,\,c.m.s.}$ is the average neutron energy in the system of the moving fragment, and $\bar{\nu}$ is the average number of neutrons per fission.

The energy spectrum of the neutrons measured in the laboratory frame is a complicated superposition of a number of spectra of the neutrons emitted by fragments of different masses and different excitation-energy distributions, at different angles to the direction of fragment motion, etc. If it is assumed that the prompt neutrons are evaporated isotropically in the moving-fragment frame with a Maxwellian energy distribution

$$W_n(E_n) \sim E_n^{1/2} e^{-E_n/T}, \qquad (27)$$

then in the laboratory frame, owing to the superposition of the translational fragment velocity, the energy spectrum of the neutrons, as shown by Watt[294], will be of the form

$$W_n(E_n) \sim e^{-E_n/T}\,\mathrm{sh}\,(2\sqrt{E_n E_{nf}}/T). \qquad (28)$$

The experimental energy spectra of the prompt neutrons of spontaneous fission[289] of Cf^{252}, and from the fission of U^{233}, U^{235}, and Pu^{239} by thermal neutrons,[288,290] are described by expression (28) with suitably chosen parameters E_{nf} and T at values E_{nf} < 0.75 MeV (E_{nf}—energy of the neutron having the same velocity as the fragment (see (26)). By combining four Watt spectra it is possible to obtain agreement with the experimental energy spectra of the neutrons at values of E_{nf} close to experimental[27]. Terrell[277] calculated the energy spectra of neutrons in the laboratory system with allowance for the distribution of the fragments with respect to the excitation energies, under the assumption that in the moving-fragment frame the neutron spectrum corresponds to evaporation, $W_n(E_n) \sim E_n e^{-E_n/T}$. The obtained total spectrum of the neutrons in the laboratory system was found[277] to be close to the experimentally observed Maxwellian distribution.

Measurements were made recently of the energy spectra of the prompt neutrons emitted by fragments of fixed mass, obtained in spontaneous fission[283] of Cf^{252} and in the fission of thermal-neutron-bombarded U^{233} [284].

In both cases it was found that the average neutron energy and the c.m.s. fragment energy are close to each other for the complementary light and heavy fragments with maximum for the fragments of symmetrical fission. This indicates that the temperatures of the complementary fragments are approximately equal, although, as we have seen earlier, the number of emitted neutrons, and consequently the fragment excitation energy, depends strongly on the mass of the fragment. A possible explanation of such a dependence of $\bar{E}_n$ and $\bar{\nu}$ on the mass of the fragment lies in the assumption[283] that the fragments have significantly different specific heats, by a factor ~4, for example for fragments with masses 120 and 132 and much less for near-magic fragments, owing to their small level density.

Angular correlations of neutrons and fragments. If the fission neutrons are emitted by moving fragments, then an anisotropy of the relative direction of the fragment motion should be observed in the angular distribution of the neutrons. Thus, in the case of nuclear fission in bombardment of U^{235} by thermal neutrons, $W_n(0°) : W_n(90°) : W_n(180°) = 9 : 1 : 4$[297]. Most neutrons are emitted from completely accelerated fragments within a time shorter than 4×10^{-14} sec[295]. As shown by measurements of the energy and number of neutrons as a function of the angle between the neutron emission and the fragment emission, the experimental values agree with the calculated ones under the assumption that approximately 10—15% of the prompt neutrons are emitted not from moving fragments, but at a certain earlier stage of the separation of the fragments in the case of spontaneous fission[283] of Cf^{252} and thermal-neutron fission of U^{235}[296-298a].

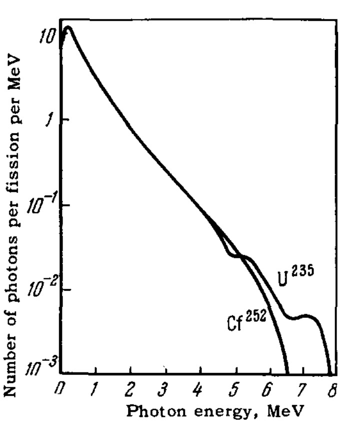

FIG. 28. Energy spectrum of prompt γ quanta of spontaneous fission of Cf^{235} [303] and thermal-neutron fission of U^{215} [302].

9.2. Prompt Gamma Quanta

In view of the fact that the time of emission of prompt γ quanta is smaller than or of the order of 10^{-9} sec[175,299,300], i.e., much larger than the time for neutron emission ($\lesssim 4 \times 10^{-14}$ sec)[295], we can expect the emission of γ quanta from fission fragments to occur after the emission of the prompt fission neutrons, and consequently, the yield of the γ quanta and their energy spectrum should depend little on the initial energy of excitation of the nucleus. Indeed, it was found[301] that within the limits of experimental error the average energy of the γ quanta does not change when U^{235} is bombarded with thermal neutrons and deuterons of energy 2.8 and 14 MeV.

Energy spectrum. Figure 28 shows the γ-quantum energy spectrum in the case of bombardment of U^{235} with thermal neutrons and in the case of spontaneous fission of Cf^{252}. The spectra of other fissioning nuclei are similar. We see that the spectrum of the γ quanta is cut off abruptly near 7 MeV, i.e., near the binding energy of the neutron in the fragment. The average gamma-quantum energy is about 1 MeV, and since 8—10 quanta are emitted during fission, the total energy carried away by the γ quanta is about 8—9 MeV per fission[302-304]. In the low-energy region of the spectrum, 100—500 keV, individual lines have been observed[174,175] against the background of the continuous spectrum, and may be connected with K and L radiation of the fragment atomic shell.

The average energy carried away by the gamma quanta (per fission), calculated under the assumption that the gamma quanta are emitted by the fragments after evaporation of the last energetically-possible neutron, is 4—6 MeV[277,306-308], 1.5—2 times smaller than the experimental value 8—9 MeV. However, if a correction δ is introduced in the dependence of the fragment level density on the fragment excitation energy, allowing for the even-odd differences of the fragments, then the calculated value increases to 7.66 MeV.[307]

Dependence of yield and energy of the gamma quanta on the fragment mass. Milton and Fraser did not observe a strong dependence of the gamma-quantum energy on the fragment-mass ratio in a study of the spontaneous fission[246] of Cf^{252}. In the case of thermal-neutron fission of U^{235} it was noted, however, that the yield of the gamma quanta[305,309] and their energy[305,310] increase somewhat in the case of a fragment-mass ratio of 1.2 in the former case and for fragments with the magic N = 82 and Z = 50 in the latter. In recent experiments with a better mass resolution, these quantities were measured for symmetrical fission of U^{236}[311] and it was found that in symmetrical fission more gamma quanta are produced, and the energy carried away by them is larger than in asymmetrical fission, although the average energy of one gamma quantum is higher in the region of the shell fragments. It is interesting that the dependence of the yield of the prompt gamma quanta on the mass number of the fragment, as found by two different methods in the spontaneous fission[300] of Cf^{252} and in the thermal-neutron fission of U^{235}[311], has a sawtooth form similar to that for prompt neutrons.

Anisotropy. Important information on the fission of the nucleus at the instant of the fragment separation was obtained by investigating the angular distribution of the gamma quanta relative to the fragment emission direction. It turned out that in the fission of U^{233}, U^{235}, and Pu^{239} by thermal neutrons[312-316] and in the spontaneous fission[317] of Cf^{252} the angular distribution of the gamma quanta shows a predominant emission of the gamma quanta in the direction of the fragment emission. This anisotropy of the gamma-quantum emission, amounting to 12—15%, can be connected with the angular momentum acquired by the fragments as a result of their noncollinear separation[318]. The angular momentum of the fragments, as estimated from the values of the anisotropy, is about $7\hbar$[315]. It is interesting to note that approximately the same values of the fragment angular momentum were obtained from an analysis of the yields of the isomers in nuclear fission[319]. The acquisition of an appreciable angular momentum by the fragments at the instant following the separation can explain also other features of the gamma-quantum emission from the fragments, besides the anisotropy, such as the high multiplicity of the gamma quanta and the small average energy of the gamma quanta[300]. It is possible that the relatively high value of the angular momentum of the fragment leads to competition between the gamma radiation and the neutron emission, which can explain the aforementioned difference between the calculated and experimental values of the energy carried away by the gamma radiation of the fragment[307,320]. In light of the foregoing, the sawtooth dependence of the gamma quantum yield on the fragment mass is a manifestation of the dependence of the initial spin of the fragment on its mass[300]. The more rigid fragments close to the magic numbers have a low excitation energy, a small spin, and a higher gamma-quantum energy compared with the less rigid fragments, which have a higher excitation energy and acquire a large angular momentum during the instant of separation, thus explaining the high multiplicity of the emission of the gamma quanta by these fragments and the low energy of the gamma quantum.

9.3. Emission of Charged Particles

Long-range charged particles. In the fission of heavy nuclei by slow neutrons*[321-326] and in the spon-

*The review of N. A. Perfilov et al. [321] contains a list of papers published up to 1960 and devoted to nuclear fission with emission of long-range charged particles.

taneous fission of nuclei[327-332], a long-range alpha particle in a few rare cases, approximately in one out of 500 nuclear fissions produced by thermal-neutron bombardment of U^{235}. The probability of such a complicated fission increases with increasing Z^2/A of the fissioning nucleus. In still rarer cases[324,331,333-336], fission takes place with emission of other light charged long-range particles, from hydrogen nuclei up to beryllium nuclei.

The most thoroughly investigated cases are those of nuclear fission with emission of a long-range alpha particle. In the case of thermal-neutron fission of U^{235} the energy distribution of the alpha particles has a maximum near 15—17 MeV[321] and the maximum alpha-particle energy reaches 29 MeV. The angular distribution of the long-range alpha particles is not isotropic; predominant emission is observed at an angle ~80° to the direction of motion of the light fragment[321]. This character of the energy spectrum and angular distribution of the alpha particles can be attributed to Coulomb interaction of the alpha particles with the fission fragments at the instant of separation, with allowance for the initial momentum of the alpha particles in the nucleus, if the alpha particle is emitted from the neck of the nucleus at the instant of fragment separation[337,338] or from the heavy fragment at a time not exceeding 10^{-19} sec following the separation[339].

The mass distribution of the fragments, in the case of ordinary binary fission of U^{235} is the same as in fission with emission of a long-range alpha particle[340]: in both cases they have a two-hump form. A detailed comparison of these two distributions leads to the conclusion that the alpha-particle and prompt-neutron yields have a similar dependence on the fragment mass (sawtooth dependence) in the case of thermal-neutron fission of U^{235}[341]. Such a $P_\alpha(A)$ dependence is evidence of an increase in the alpha-particle emission probability with increasing fragment deformation[341]: the alpha-particle emission probability is minimal for emission from fragments of mass ~132, containing 82 neutrons and 50 protons, the shape of which is close to spherical. The influence of the structure of the fragment-nucleus on the alpha-particle emission probability, and in final analysis the influence of the nuclear deformation, are demonstrated also by the recent results of studies of the angular dependence of the alpha-particle emission[342]. They found, in the case of spontaneous fission of Cf^{252}, that the most probable angle between the alpha-particle emission and that of the light fragment depends on the fragment mass ratio and increases with increasing fission-fragment mass ratio: for fissions close to symmetrical, the point of emission of the alpha particle is close to the heavy fragment, the influence of the Coulomb forces of the heavy fragment is strong, and the alpha particle is deflected in the direction of the light fragment. With increasing fragment mass ratio, the point of emission of the alpha particle and the point of separation of the fragment, if the alpha particle is emitted from the point of separation, shifts, in accordance with the results, towards the lighter nucleus.

The distributions of the fragment kinetic energies of the double fission and of the fission with alpha-particle emission are also similar[340,343-345]. In both cases is an anomalous dip observed in the kinetic energy of the fragments of the symmetrical fission of U^{235} by thermal neutrons[340]. The average fragment kinetic energy[340,343-345] and the average number of prompt neutrons[346] are smaller in the case of fission with emission of a long-range alpha particle than the corresponding values in ordinary fission into two fragments.

The frequency of occurrence of fission with alpha-particle emission was measured by bombarding U^{233}, U^{235}, and Pu^{239}[347,348] by resonant neutrons. Only in a few measurements[348] was a certain variation observed in the probability of fission with emission of an alpha particle from resonance to resonance. When the excitation energy of the fissioning nucleus is appreciably increased, a certain change is observed in the relative frequency of appearance of fission with emission of an alpha particle. Thus the decrease in the probability of such a complicated fission is revealed already by a comparison of the spontaneous fission of nuclei with fission of nuclei by thermal neutrons[324]. Bombardment of uranium by neutrons of energy 2.5—3.0 MeV[349,350] and 14 MeV[349] produces 500, 780, and 1300 ordinary binary fissions, respectively, for each fission with alpha-particle emission. This decrease can be attributed qualitatively to a decrease in the probability of formation of alpha substructures in the region of the neck of the nucleus with increasing excitation energy[338,349,352]. However, Drapchinskiĭ et al.[351] observed no changes in the probability of fission with alpha-particle emission in the fission of U^{235} and U^{238} by 2- and 14-MeV neutrons. The reason for the discrepancy between the results is still unclear. It was found[352,353] that with further increase of the energy of the bombarding particles the probability of fission with alpha-particle emission increases.

The angular distribution of the long-range alpha particles with respect to the bombarding particle beam was found to be isotropic[353] in the case of bombardment of U^{238} by 17.5-MeV protons. At the same time, measurements by Ramanna et al.[350,354] of uranium bombarded with 3- and 14-MeV neutrons showed a predominant alpha-particle emission at c.m.s. angles 0° and 180° relative to the neutron beam. To explain an anisotropy of this type, the authors of[354] proposed that the long-range alpha particles are evaporated from the neck of the deformed nucleus at the instant prior to the scission. Obviously, further research is necessary on the fission of nuclei with emission of a long-range charged particle, in order to refine the available experimental data and to obtain new ones, and in order to determine the mechanism of emission of such particles.

Evaporation of charged particles. At sufficiently high excitation energies of the fissioning nuclei, charged particles, protons, deuterons, alpha particles, etc. can be evaporated besides the neutrons. The possibility of evaporation of charged particles (and neutrons) before and after the fission and from the fragments is determined by the ratio of the fission width Γ_f to the evaporation width Γ_{evap}, Γ_f/Γ_{evap}, data on which are quite scanty at high excitation energy.

It was found in[132,142,151] (see also Fig. 14b) that at a given bombarding-proton energy the number of charged particles emitted in nuclear fission increases with decreasing Z^2/A of the fissioning nucleus. If the charged particles were to be emitted by the nucleus prior to the fission, this would lead to an additional decrease of the fission probability, owing to the decrease of the fissility parameter Z^2/A. The observed increase of the number of charged particles emitted in fission with decreasing Z^2/A of the fissioning nucleus can be easily explained by assuming that the charged particles, or at least some of them, are emitted after fission of the nucleus, from the fragments. In this case the increase in the number of charged particles during fission with decreasing Z^2/A of the nucleus can be connected with the simultaneously observed increase of the average excitation energy of the fissioning nuclei[132,142], and consequently of the fission fragments. The change in the mass distribution of the fission fragment in a wide range of fissioning nuclei with increase in the energy of the bombarding particles is also evidence (see Sec. 5.2) that the excitation energy increases during the instant of fission, and hence that the excitation energy of the fission fragments increases.

9.4. Beta Decay of Fission Products and Delayed Neutrons

The kinetic energy of the fission fragment, the emission energy of the prompt neutrons and gamma quanta constitute the so-called prompt part of the energy released in fission. The neutron-excess fission products of heavy nuclei are transformed after the emission of the prompt neutrons and gamma quanta, via a number of β^- transitions, into stable isobars. In a number of rare cases, when the β^- decay of the isobar results in a nuclide with excitation energy higher than the neutron binding energy, delayed neutrons are emitted. The β^--decay energy of the fission products is ~8 MeV per fission, the energy of the antineutrino is ~11 MeV, and the energy of the γ radiation* is ~6 MeV. The sum of these energies of the processes accompanying the β decays is the delayed part of the energy released during fission. The γ radiation of the fission products, together with the neutrons, is the main component of the penetrating radiation of a nuclear reactor, and information concerning this radiation is essential for the reactor-shield design. A detailed analysis of the β^--decays and of the emission of delayed gamma quanta from the fission products can be found in Griffin's paper[356].

*During the time between the instant of emission of the prompt neutrons, $< 10^{-9}$ sec, and that of the emission of the γ radiation after the β decays, $\geq 10^{-3}$ sec, there are emitted γ quanta connected with transitions from the isomer states of the fission-product nuclei [355].

As already indicated, delayed neutrons are emitted in those rare β^- decay cases when the produced nuclide has an excitation energy higher than the neutron binding energy. The half-life of a nucleus emitting delayed neutrons is exactly equal to the half-life of the ancestor nucleus experiencing the β^- decay. By now, six groups of delayed-neutron emitters* have been observed in the fission of heavy nuclei, with approximate half-lifes 55, 22, 6.0, 2, 0.5, and 0.2 sec. The small values of the half-life are connected with the fact that the conditions for the emission of a delayed neutron are realized for the terms with large neutron excess of the β^- decay chain with short lifetime. The short lifetimes of the ancestors of the delayed neutrons make it difficult to separate them chemically. The following ancestors of delayed neutrons[359] have been identified chemically to date: Br^{87} for the first group, Br^{88} and I^{137} for the second, Br^{89} and I^{138} for the third, and I^{139} and possibly also Br^{90} for the fourth. Predicted ancestors of delayed neutrons of the fifth and sixth groups may be bromine and ion isotopes having a still larger neutron excess, and possibly other contributors[358,360].

When U^{233}, U^{235}, or Pu^{239} is fissioned by thermal neutrons, by fission-spectrum neutrons[361], and by 2.4- and 3.3-MeV neutrons[362], the yields of the delayed neutrons depend little on the bombarding-neutron energy. However, further increase of the energy of the bombarding neutrons, to 14 MeV, nearly doubles the delayed-neutron yields[362-364]. The change of the delayed-neutron yield YP_n with increasing excitation energy of the fissioning nucleus is determined by the change in the yield Y of the nuclei emitting the delayed neutrons, if the probability P_n, for delayed-neutron emission by the given nuclide does not depend on the conditions for its production, as is indeed expected. Since the delayed-neutron-emitting nuclei lie in the region of the peaks of the two-hump mass distribution of the heavy-nucleus fission fragments, and since the fragment yields change little with increasing energy in the region of the peaks, and only decrease slightly, a similar energy dependence could be expected for the yield of the delayed neutrons, provided the given group of delayed neutrons were to come from a single progenitor. The "experimental value" of the probability

*Keepin [357] systemized the data on delayed neutrons in the fission of nuclei from Th^{232} to Cf^{252}, obtained up to 1956. Later data can be found in the review article of Amiel [358].

P_n can change is several unknown emitters with nearly equal lifetimes, whose relative contribution varies with increasing excitation energy of the nucleus, contribute to the given group of delayed neutrons.*

In spite of the relatively small yield (less than ~1% of the yield of prompt neutrons), the delayed neutrons play a decisive role in reactor control, namely, owing to the presence of delayed neutrons, any random deviation and increase of the number of neutrons in the active zone does not lead to a progressive uncontrolled neutron multiplication. This fundamental role played by the delayed neutrons in the control of the rate of the fission chain reaction was predicted by Zel'dovich and Khariton back in 1940[3].

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*According to preliminary results by Hermann et al. [365], the delayed-neutron yields measured by them for the fission of U^{238} and Th^{232} by 14-MeV neutrons are lower by a factor 2–3 than the values measured in earlier investigations [362-364] at the same neutron energy, and agree well with the calculated values. See also the discussion in [19], v. 2, p. 221, concerning this discrepancy.

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