Measurements of the duration of nuclear reactions induced by heavy ions

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A review is presented of experiments that determine the duration of nuclear reactions by means of new methods based on measurement of the spectra of the positrons and electrons produced in heavy-ion collisions and also on observing the angular distribution, the angular correlation, and the spectrum of the nuclear interaction products. The modern development of the crystal blocking method, applied to heavy-ion reactions, is described. For nuclear reactions that take place through the formation of a compound nucleus the measured durations are presented systematically. On the basis of a statistical description of the process, the temperature of the compound nucleus is found systematically as a function of the excitation energy. Experimental determinations of the lifetime of dinuclear systems are reviewed.

INTRODUCTION

In the majority of cases, the duration of nuclear reactions is in the range $\tau = 10^{-22}$–10^{-14} sec. Experimental measurement of the duration is needed to elucidate the mechanism of the nuclear reaction and to construct a quantitative theory. In a number of cases, the determination of the duration of the process has more information value than a measurement of its probability.

From the methodological point of view, the measurement of ultrashort time intervals $\tau < 10^{-10}$ sec is a complicated task, for the solution of which numerous methods have been proposed, both direct and indirect. They are listed in Fig. 1 together with an indication of the time interval for which the one or other method is intended. Figure 1 was prepared on the basis of literature data found in the review of Refs. 1–4. The methodological problems of measuring the reaction duration increase as the measured time interval gets shorter. Therefore, not all of the proposed methods have been sufficiently developed in practice. The direct methods that have been applied practically in the range $\tau < 10^{-14}$ sec include the crystal blocking method (see the following section), the method that uses the characteristic x-ray emission of the K vacancies of the compound atom,[5–9] the method that uses the interference of the bremsstrahlung[10–13] emitted as the particles approach each other and then separate, the nuclear-particle interference method,[14–16] which is close to the proximity-scattering method,[17–18] and the method of the interference structure in the spectrum of δ electrons accompanying the nuclear reaction.[19–22] In the majority of the listed cases, the duration of the nuclear reaction is determined by comparison with a time scale set by an atomic process. The methods of Refs. 5–22 are among those that have been used in practice to determine reaction durations; the results obtained by means of them are included in the systematics of the compound-nucleus lifetimes (see Sec. 4). However, the application of these methods to the study of reactions induced by heavy ions has not yet given informative results, and therefore they are not described in detail.

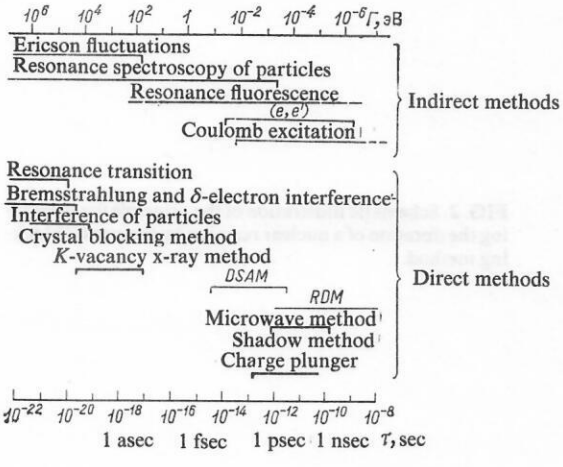

FIG. 1. Range of applicability of different methods for measuring ultrashort durations of nuclear processes.

In this review, we shall not consider methods applied to the interval of comparatively long lifetimes, such as the charge-plunger method[23]; nor shall we consider the indirect methods that have been described in detail, for example, the Ericson-fluctuations method,[24] or methods that have not as yet found practical application, for example, the resonance-transition method.[25] We also do not consider fundamental theoretical approaches to the description of the duration as an observable in quantum mechanics. Theoretical results can be found in the original studies of Refs. 26–31 and in the recent theoretical review of Ref. 32.

In the present review, we describe in detail the results of the use of the crystal blocking method, applied to nuclear reactions with heavy ions (see Secs. 1–3), the estimates of the duration of heavy-ion reactions in the interval 10^{-21}–10^{-19} sec on the basis of measurements of the spectra, angular distributions, and angular correlations of the particles, and also the results of new experiments to determine the lifetimes of dinuclear systems (see Sec. 4). Hardly any of the results given here have been discussed in other reviews on the description of the duration of nuclear reactions.

1. BLOCKING EFFECT IN A HEAVY-ION BEAM

The passage of charged particles through single crystals along the crystallographic axes or planes is accompanied by a whole gamut of phenomena having a common cause—the establishment of a periodic trajectory of the motion of a particle under the influence of the ordered potential of a sequence of atoms.[33] One of the main ones is the blocking ef-

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fect,[34] which consists of a decrease in the yield of product particles of nuclear reactions along the crystallographic directions. The structure of the blocking pattern in the spatial distribution of particles emerging from a single crystal target reflects the geometrical symmetry of the crystal. The intensity of the blocking effect shows the degree of perfection of the single crystal, or rather, the contribution of the particles emitted by atoms not displaced from the lattice sites. The angular width and shape of the blocking dips are determined by the details of the potential through which the charged particle interacts with the elementary rows and planes of the lattice.

The effect in the case of heavy-ion interactions with single crystals has been investigated at the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research since 1970. The first experiments were completed by observation of the effect in a heavy-ion beam and an estimation of the duration of a fission reaction. These results were included in the review of Ref. 35. In the present paper, we describe the development of investigations during recent years (1980–1985). The aim of the work was to measure the duration of heavy-ion nuclear reactions in the range 10^{18}–10^{-16} sec, to obtain information about the details of the interaction of heavy particles with crystals, and to determine the damage done by the ions to single crystals. This group of questions is fairly large, but it is dictated by the requirement that the results must not be ambiguous. The main importance is given to the measurement of nuclear reaction durations.

The principle of the crystal blocking method is illustrated in Fig. 2. When a single-crystal target is used, the angular distribution of the reaction products exhibits blocking dips of two identical crystallographic axes making different angles θ with the beam. The relative yield of the particles at the minimum, χ, for each of the axes is determined by the normal component of the displacement of the emitting nucleus: $v_\perp \tau = v\tau \sin \theta$. Therefore, measurement of the difference $\Delta\chi = \chi_2 - \chi_1$ for axes making angles θ_2 and θ_1 with the beam makes it possible to find $v\tau$, i.e., for known velocity v of the emitting nucleus to determine the reaction duration τ.

The measurable interval of $v\tau$ is from 5.10^{-10} to $5\cdot10^{-8}$ cm, corresponding to a time interval from 10^{-16} to 10^{-14} sec for reactions with neutrons and protons and from 10^{-18} to 10^{-16} sec for heavy-ion reactions. These limits are determined by the amplitude of the thermal vibrations of the atoms in the case of small displacements and by the disappearance of the blocking effect itself at very large displacements.

Actually, the yield at the blocking dip is determined not only by the displacement of the nuclei during the time of the reaction. The observed value χ_{exp} contains several components, including some due to the initial imperfection of the crystal and dechanneling on thermal vibrations of the atoms, χ_0, and to radiation damage, χ_{rad}:

$$1-\chi_{exp}=\prod_{i=0}^{n}(1-\chi_i). \qquad (1)$$

In the experiment it is therefore important, on the one hand, to study the influence of the different factors on the yield χ and, on the other, to measure the time component of the yield χ_τ by a difference method. In the scheme shown in Fig. 2, this is foreseen; the yield χ_1 is, in its essence, a reference quantity, including the contribution of all factors fully except χ_τ, which is reduced because of the motion of the recoil nucleus at a small angle to the crystallographic axis. In such an arrangement of the experiment, the observation of even a small $\Delta\chi$ can with fair confidence be attributed to the influence of the reaction duration.

An example of a spatial pattern of the blocking effect, i.e., a photograph of a glass track detector of fission fragments emitted by a UO_2 single crystal, is shown in Fig. 3. At a high density of the fragment tracks, the surface of the glass becomes mat, and the blocking distribution can be observed visually. Under the influence of the irradiation with heavy ions, the single-crystal structure gradually deteriorates, the blocking picture becomes less clear, and the yield at the minimum χ for all directions increases. Thus, when one is making quantitative measurements of reaction durations it is necessary to investigate the damage done by the various

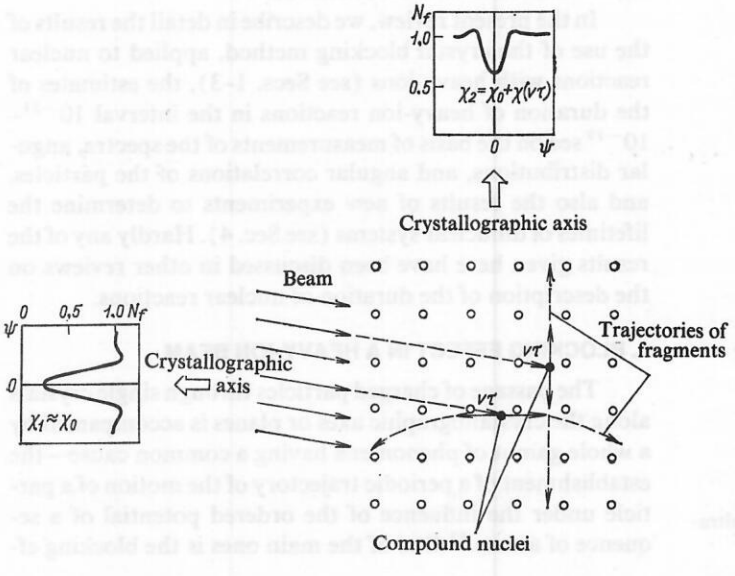

FIG. 2. Schematic illustration of the principle for measuring the duration of a nuclear reaction by the crystal blocking method.

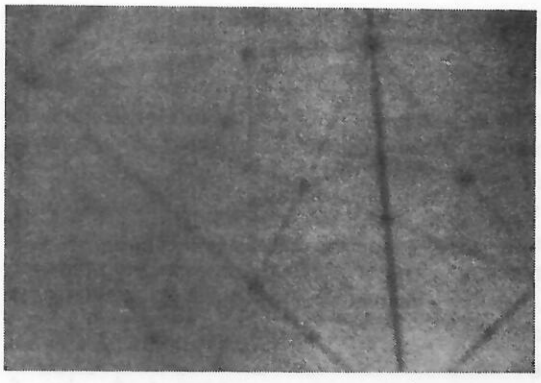

FIG. 3. Photograph of the blocking pattern obtained by a glass track detector of fission fragments.

heavy ions and to establish systematic laws for the determination of this damage.

The damage done by the nuclear particles to the single crystals is caused by the knocking of atoms from the sites of the crystal lattice. At low particle energies, the main process is the collision of neutral atoms; at very high energies, the main source of ejected atoms is associated with inelastic nuclear and hadron interactions, while in the region of intermediate ion energies 0.5–10 MeV/nucleon, which are considered here, elastic nuclear scattering of particles makes the main contribution.[1)] One must therefore expect a correlation between the damage done by an ion and the cross section of nuclear scattering on an atom of the single crystal. It is also impossible to rule out a dependence of the radiation stability of the single crystal on the details of the band spectrum of any particular single crystal. Experimental investigation of the damage done by heavy ions to single crystals of metals and semiconductors has established that as a result of the appearance of displaced atoms the crystal lattice becomes imperfect and, in addition, mechanical stresses arise in it and the lattice constant is increased somewhat.[36] At a sufficiently high intensity of heavy ions interacting with a semiconductor, one can observe the formation of cracks in the region of the highest gradient of the particle flux, hitting of the surface of the type of radiation etching, and even the formation of a crater at the point of incidence of the ion beam. In the case of a comparatively low particle flux, about 10^{12} $\text{sec}^{-1}\cdot\text{cm}^{-2}$ and less, damage to the surface is not observed. There is a gradual accumulation of defects in the irradiated volume of the single crystal, and under certain conditions a smoothing of the microscopic irregularities of the surface is possible. Further, it has been established that at room temperature some of the defects recombine in the process of irradiation, and an increase in the temperature of the single crystal leads to an effective thermal annealing of the defects, which raises the admissible dose of the particles by 100 and more times.[37] If the direction of the beam coincides with a crystallographic axis or plane, the damage done by the ions is reduced by several times as a result of the decrease in the probability of nuclear scattering of the channeled particles.

The accumulation of defects in an irradiated single crystal was studied in experiments on the observation of the blocking effect in nuclear reactions and the scattering of the ions ^{14}N, ^{16}O, $^{20,22}Ne$, ^{31}P, and ^{40}Ar with energy 0.6–8 MeV nucleon by GaP, Ge, W, UO_2 single crystals.[38] The yield χ at the blocking dip serves as a quantitative measure of the degree of damage of the single crystal under the influence of the particle dose I. By a simple processing in accordance with the method of Ref. 39 the function $\chi(I)$ can be transformed into the dependence of the mean concentration $n_D(I)$ of point defects on the dose for the surface region (of micron thickness) of the irradiated single crystal. The experiments were made at a relatively low beam intensity ($\approx 10^{10}$ sec^{-1}), this precluding heating of the single crystal and also damage to its surface. The beam diameter was 1 mm. The beam was directed onto the single crystal in a direction that did not coincide with a crystallographic distinguished direction. As an example, Fig. 4 gives the results of investigation of the damage done by heavy ions to a Ge single crystal. It can be seen that the yield at the minimum, which is equal to χ_0 for the unirradiated single crystal, increases with increasing dose, the defect concentration $n_D(I)$ also increasing. To characterize quantitatively the destructive capacity of the ions, we introduce the harmful dose $I_{0.2}$. This corresponds to an increase in the yield at the minimum due to the radiation damage to $\chi_{rad} = 0.2$, where χ_{rad} is determined from the condition $1-\chi_{rad} = (1-\chi_{exp})(1-\chi_0)^{-1}$.

The ion dose $I_{0.2}$ must be inversely proportional to the product of the nuclear scattering cross section and the mean recoil energy, i.e., to the parameter $\varkappa = Z_1^2 Z_2^2 A_1 A_2^{-1} E^{-1}$ in the simplest approximation. Therefore, the product $\varkappa I_{0.2}$ can be regarded as invariant with respect to a change in Z, A, and E of the interacting atoms. Figure 5 shows the dependence of $\varkappa I_{0.2}$ on the mean depth $\langle d \rangle$ of the yield of particles from the single crystal, measured in units of the total range R of the particles. It can be seen that $\varkappa I_{0.2}$ decreases regularly with increasing $\langle d \rangle$ in accordance with the usual laws for the deterioration of the blocking effect due to dechanneling in the case of passage through a layer of a damaged single crystal. In addition, a dependence of the radiation stability on the details of the structure of the single crystal appears. The appreciable difference between the harmful doses for the GaP and Ge single crystals, which have similar properties,

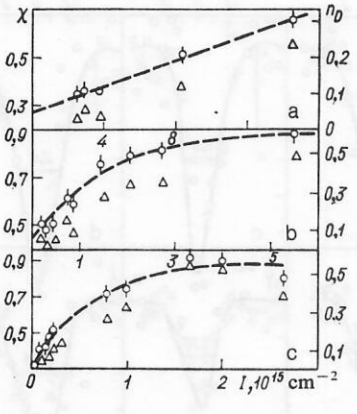

FIG. 4. Dependence of χ (open circles) and n_D (open triangles) measured[38] for the ⟨111⟩ Ge crystallographic axis on the dose I: a) 104-MeV ^{20}Ne ions; b) 12-MeV ^{20}Ne ions; c) 24-MeV ^{40}Ar ions.

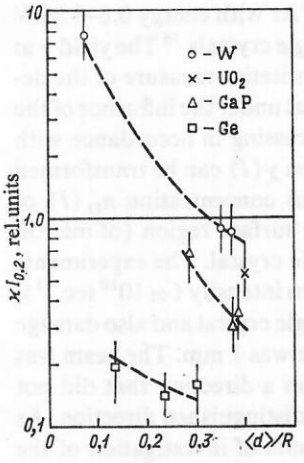

FIG. 5. Systematics[38] of the harmful dose of heavy ions interacting with single crystals.

can be explained by the behavior of the concentration of free charge carriers in the irradiation process. Therefore, a change in the state of the electron subsystem of the crystal also influences the interaction of the charged particles with the lattice. In general, the degree of influence of a particle dose on different properties of the single crystal is different. For example, a GaP single crystal that is irradiated changes color, the degree of its blackening reaching saturation at a relatively small dose, at which the crystal lattice still remains basically undamaged. Experiments to observe the blocking effect give information specifically about the degree of perfection of the lattice and not about its macroscopic characteristics in general. Figure 5 can be regarded as a systematic representation of the heavy-ion dose that causes appreciable damage to the lattice of single crystals.

The shape and angular width of the blocking dips are determined by the potential with which the particle interacts with an atomic row or plane. Experiments with proton and α-particle beams have accumulated material sufficient to determine the shape of the atomic potentials. A property of heavy ions is that when one is describing the interaction of a heavy particle with a lattice atom it is not possible to ignore the recoil phenomenon, which decreases the scattering angle of the particle in the laboratory system. Therefore, with increase in the ratio A_1/A_2 of the particle mass to the lattice-atom mass the effective atomic potential decreases in proportion to $(1+A_1/A_2)^{-2}$, and the critical angle in proportion to $(1+A_1/A_2)^{-1}$. This is how it must be in the case when the particle is scattered by each atom separately, as by an unbound atom. But if the interaction of the particle with the lattice as a whole, as in the Mössbauer effect, is important, then the dependence of the critical angle on A_1/A_2 must be weakened or disappear altogether. Therefore, by studying the dependence of the angular half-width $\psi_{1/2}$ of the blocking dips on A_1/A_2, one can establish the fraction of interactions of Mössbauer type when particles pass through a single crystal.

As an example, Fig. 6 shows the shape of the axis and plane blocking dips observed[40] for the interaction of ^{14}N nuclei with a GaP single crystal, and also ^{20}Ne, ^{40}Ar, and Ge with a Ge single crystal. Figure 7 gives the dependence of $\psi_{1/2}$ on the ion dose, the particle energy, and the factor $1+A_1/A_2$. The appearance of the dependence of $\psi_{1/2}$ on A_1/A_2 makes it necessary to take into account the change in $\psi_{1/2}$ with the energy E of the ions and their atomic number Z_1. Therefore, in Fig. 7c the quantities $\psi_{1/2}$ are given as their ratio to ψ_c, which is equal to

$$\psi_c = \frac{a}{E^{1/3}}\sqrt{\frac{Z_1 Z_2}{d}}, \qquad (2)$$

where a is a normalizing constant, and d is the interatomic spacing in the series. The points in Fig. 7c exhibit a good correspondence of the results for the GaP and Ge single crystals; one observes a decrease in the angular half-width with increasing mass number of the particle. However, this dependence was less strong than expected in the simple approximation $\psi_{1/2}\sim(1+A_1/A_2)^{-1}$. Therefore, some of the interactions occur in the form of binary scattering and some in the form of a collective interaction of Mössbauer type. The establishment of this fact, and also the dependence of the destructive capacity of the ion on the state of the electron subsystem of the crystal (see above), show that one should

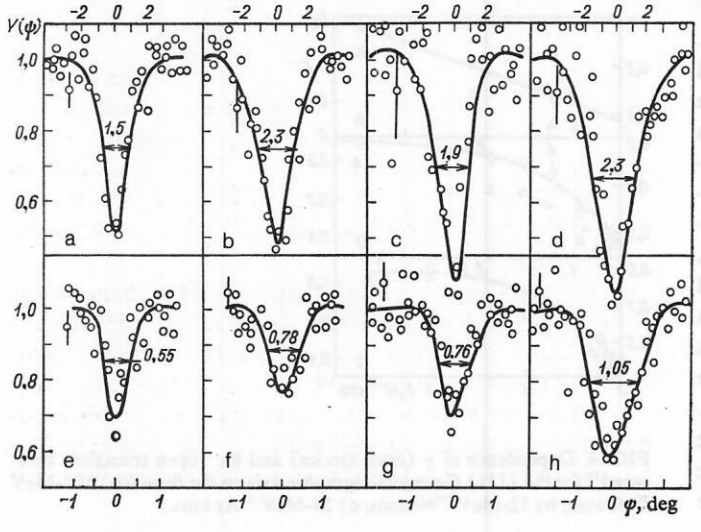

FIG. 6. Profiles of axis ⟨111⟩ (a–d) and plane (110) (e–h) blocking dips[40] obtained in the observation of: a) ^{14}N ions scattered by a GaP single crystal at angle 125° to the beam; b) ^{20}Ne ions, Ge single crystal, 130°; c) ^{40}Ar ions, Ge single crystal, 71°; d) Ge recoil nuclei, Ge single crystal, 68°; e) ^{14}N ions, GaP single crystal, 115°; f) ^{20}Ne ions, Ge single crystal, 119°; g) ^{40}Ar ions, Ge single crystal, 73°; h) Ge recoil nuclei, Ge single crystal, 74°.

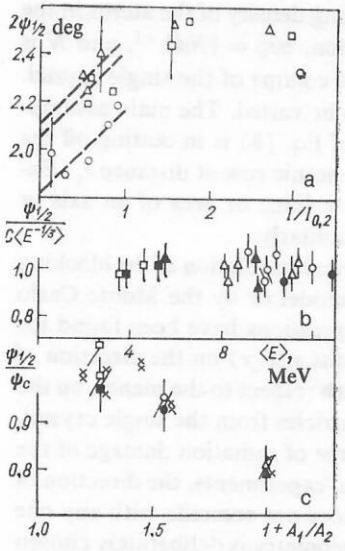

FIG. 7. Dependence of the angular half-width $\psi_{1/2}$ of the blocking dips on the dose of the ions (a) and on the energy (b) and mass number (c) of the particles.[40] For axis minima the points relate to interaction with a Ge single crystal of the following nuclei: ^{20}Ne (open squares), ^{40}Ar (open circles), and Ge (open triangles). The corresponding minima for planes are represented by the black symbols, while the crosses give the results for a GaP single crystal.

not ignore the electronic bonds between the atoms when considering the interaction of charged particles with atoms in a crystal.

An important feature of the motion of a heavy ion in a solid medium is its partial charge exchange; this must lead to an additional spread of the transverse energy for a particle moving along a distinguished crystallographic direction. This feature also requires experimental investigation, although it has already been established[41,42] that there is a resonance charge exchange of heavy ions at a frequency corresponding to the period of traversing the interatomic distance in the crystallographic axis.

2. DURATION OF FISSION REACTIONS

Formation of fragments as a process that develops in time

In the laboratory system, a fissioning nucleus moves with a definite velocity, and therefore the time delay is transformed into a displacement S along the normal to the atomic row in the crystal. The value of S determines the intensity of the blocking effect and, therefore, can be measured. Study of the dynamics of the development of the process in time shows that the displacement S contains several components:

$$S = S_1 + S_2 + S_\tau + S_{sp} \qquad (3)$$

The formation of the displacements S_i is illustrated in Fig. 8a; each of them arises at a definite stage, the sequence of which is numbered in Fig. 8a from 1 to 5. The quantity $S_\tau = v_\perp \tau$ has the main physical significance; it arises because of the lifetime of the composite system from the moment at which the interacting nuclei touch to the separation of the fragments. The other components have a subsidiary significance, but it is necessary to analyze their contribution to the total displacement. The displacement S_1 arises already before the colliding nuclei touch because of the effect of the Coulomb field. For a head-on collision in the nonrelativistic case,

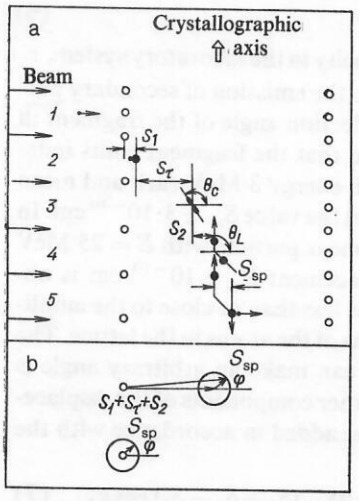

FIG. 8. Scheme of formation of additional displacements (a) (the numbers 1–5 identify the successive phases in the development of the process in time) and addition of the vectors S_{sp} and $S_1 + S_2 + S_\tau$ (b).

$$S_1 = R\frac{A_1 \sin\theta_L}{A_1+A_2} \times\left[1-\sqrt{1-\frac{B}{E}}+\frac{B}{E}\ln\frac{2\sqrt{R_\infty}}{\sqrt{R}\left(1+\sqrt{1-\frac{B}{E}}\right)}\right], \qquad (4)$$

where R is the sum of the radii of the nuclei, B is the barrier of the nuclear reaction, R_∞ is a screening parameter, equal in order of magnitude to 10^{-9}–10^{-8} cm, and θ_L is the angle between the directions of the crystallographic axis and the beam. Calculation in accordance with Eq. (4) shows that $S_1 \approx 10^{-12}$ cm, i.e., this is much less than the displacement that can be observed by means of the blocking effect.

The displacement S_2 occurs as a result of the motion of the center of mass of the fissioning system during the time of acceleration of the fragments in the Coulomb field and can be calculated in accordance with the formula

$$S_2 = \frac{R_0}{2}\sin(\theta_c-\theta_L)\left[1+\ln\frac{2\sqrt{R_\infty}}{\sqrt{R_0}}\right], \qquad (5)$$

where R_0 is the distance between the centers of charge of the fission fragments at the scission point, and θ_c and θ_L are their angles of emission in the center-of-mass system and in the laboratory system relative to the beam. The displacement S_2 is of the same order as S_1. For example, for the ^{238}U(^{22}Ne, f) reaction their sum is $S_1 + S_2 \approx 3\cdot 10^{-12}$ cm, i.e., it is negligibly small.

The displacement S_{sp} arises because of the change in the direction of motion of a fragment as a result of recoil following the emission of secondary particles. If a fragment begins to move along a crystallographic axis only after the emission of a secondary particle, this means that before this it acquired an additional displacement S_{sp} from the axis. The magnitude of S_{sp} can be estimated in accordance with the formula

$$S_{sp} = v_2^L \tau_2 \sin \bar{\theta}, \quad (6)$$

where v_2^L is the fragment velocity in the laboratory system, τ_2 is the lifetime with respect to the emission of secondary particles, and $\bar{\theta}$ is the mean deflection angle of the fragment in this process. If it is assumed that the fragment emits independently five neutrons with energy 3 MeV each and mean time $\tau_2 \approx 10^{-17}$ sec, we obtain the value $S_{sp} \approx 3 \cdot 10^{-10}$ cm. In the case of the emission of one α particle with $E = 25$ MeV and $\tau_2 \approx 10^{-18}$ sec, a displacement $S_{sp} \approx 10^{-10}$ cm is obtained, i.e., the value of S_{sp} is less than or close to the amplitude of the thermal vibrations of the atoms in the lattice. The direction of the vector $\mathbf{S}_{sp}$ can make an arbitrary angle φ with the vector sum of the other components of the displacement, and therefore they are added in accordance with the formula

$$S^2 = (S_1 + S_2 + S_\tau)^2 + S_{sp}^2 + 2S_{sp}(S_1 + S_2 + S_\tau)\cos\varphi. \quad (7)$$

Figure 8b shows the addition of these vectors in two cases: when the direction of the beam is perpendicular to a crystallographic axis ($S_1 + S_2 + S_\tau > S_{sp}$), and when the beam is directed along the axis ($S_1 + S_2 + S_\tau \approx 0$). It can be seen that in the latter case S_{sp} is the main component of the displacement, although it is small, being comparable with the amplitude of the thermal vibrations of the atoms. We note an important restriction on the use of the formulas given here. The estimate of S_{sp} in accordance with (6) is valid only under the condition $v_2^L \tau_2 \leqslant d$. For very large values of $v_2^L \tau_2$, corresponding, for example, to the emission of a final neutron by a product with low residual excitation energy ($\tau_2 \sim 10^{-16}$–10^{-15} sec), one could formally obtain values $S_{sp} \sim 10^{-8}$ cm. In this case, however, Eq. (6) ceases to be valid, since the fission fragment will have already succeeded in avoiding several tens of atoms along the axis and will be deflected by their field. In other words, the blocking dip is formed before the secondary particle will have been emitted. At the same time, deflection of the fragment through a small angle $\bar{\theta} \approx 0.5°$ has an effect on the blocking dip not greater than the angular resolution of the experiment if it is about 0.5°. Thus, the emission of secondary particles in the initial section of the fragment trajectory ($v_2^L \tau_2 \leqslant d$) can be taken into account by a calculation in accordance with Eqs. (6) and (7), while the effect of the particles emitted later ($v_2^L \tau_2 > d$) consists of a certain spreading of the angles in addition to the angular resolution of the experiment.

Relation for the transition from the measured quantities to the reaction duration

For the determination of nuclear reaction durations by means of the crystal blocking method, the choice of the correct relations for the transition from the measured parameters of the blocking dip to the displacement $v_\perp \tau$ is important. In Ref. 43 a formula is given that relates the observed yield χ at the minimum to the mean displacement:

$$\chi = \frac{2D(v_\perp \tau)^2}{r_0^2}\left[1 - \left(1 + \frac{r_c}{v_\perp \tau} + \frac{r_c^2}{2v_\perp^2 \tau^2}\right) e^{-\frac{r_c}{v_\perp \tau}}\right] + e^{-\frac{r_c}{v_\perp \tau}}, \quad (8)$$

where r_0 is related to the packing density of the atoms in the given crystallographic direction, $\pi r_0^2 = (Nd)^{-1}$, and N is the number of atoms per unit volume of the single crystal. The parameters D and r_c can be varied. The main assumption made in the derivation of Eq. (8) is in cutting off the action of the potential of the atomic row at distance r_c. Expressions for calculating the volume or area of an axis or plane blocking are obtained similarly.

Calculations with numerical simulation of the blocking dip in a statistical diffusion model or by the Monte Carlo method have been made. Expressions have been found for the dependence of the functions $\chi(v_\perp \tau)$ on the direction of motion of the recoil nuclei with respect to the planes, on the depth of emergence of the particles from the single crystal, and possibly also on the degree of radiation damage of the crystal. In the majority of real experiments, the direction of motion of the recoil nuclei does not coincide with any one crystallographic plane; this geometry is deliberately chosen to avoid channeling of the beam. In addition, under the conditions of an experiment there is averaging over the thickness of a layer of the order of several thousand angstroms and more and over an interval of the harmful dose of the beam from zero to the value corresponding to a small or moderate damage of the single-crystal structure. For these real conditions, the dependences of the function $\chi(v_\perp \tau)$ on the listed parameters are effectively averaged, and the resulting function $\chi(v_\perp \tau)$ does not differ that strongly from the calculation in the simple model in accordance with Eq. (8). Figure 9 gives the results of theoretical calculations[37,44,45] of the functions $\chi(v_\perp \tau)$ for the directions ⟨110⟩ Ge and ⟨111⟩ UO_2. They are compared with calculated results in accordance with Eq. (8) for the parameter choice $D = 2.5$, $r_c = (4$–$6)a_{TF}$, where a_{TF} is the parameter of the Thomas–Fermi screening. It can be seen that the analytic formula gives results intermediate between the different variants of the numerical simulation. This circumstance, in conjunction with the convenience of using an analytic expression, justifies the use of Eq. (8) as a transition relation. In the cases when nothing is said especially, we shall assume that the displacement S contains only the main component S_τ.

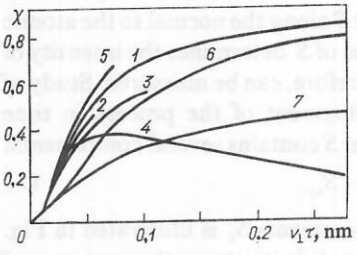

FIG. 9. Transition relations calculated for the interaction of fragments with the axis ⟨111⟩ UO_2 (curves 1–4) and of 4-MeV protons with the axis ⟨110⟩ Ge (curves 5–7) by numerical simulation in Ref. 44 (curves 2 and 3), Ref. 45 (curve 5), and Ref. 37 (curve 7), and also by calculation in accordance with Eq. (8) for the parameter choice $r_c = 5a_{TF}$ (curves 1 and 4) and $r_c = 4.5a_{TF}$ (curve 6). Curve 4 shows the difference $\Delta\chi(v\tau) = \chi_{91°} - \chi_{161°}$. The direction of motion of the recoil nucleus is close to the plane (110) (Ref. 44), to the axis ⟨112⟩ (Ref. 37), and is not fixed (Ref. 45).

Duration of the fission reaction of tungsten and tantalum induced by heavy ions

Several experiments have been made to determine the duration of the fission reactions of the tantalum and tungsten nuclei initiated by the heavy ions ^{12}C, ^{16}O, ^{22}Ne, and ^{31}P.[46–50] A typical experiment will be described for the example of the $^{16}O + W$ reaction.[50] A thick single-crystal target of metallic tungsten (of natural isotope composition) was irradiated in the U-300 cyclotron at Dubna with a beam of 136-MeV ^{16}O ions. The beam was restricted by a collimator and had diameter 1 mm; the beam energy was lowered by aluminum absorbers. The plane of the single crystal coincided with the crystallographic plane (110). The two axes $\langle 111\rangle$ and $\langle 11\bar{1}\rangle$ made angles 93 and 164° with the ion beam, which was directed at an angle of about 5° to the $(1\bar{1}0)$ plane.

Fission fragments were detected by glass track detectors. Examination of the glasses made it possible to determine the profile of the blocking dips and find their basic parameters $\psi_{1/2}$ and χ. Figure 10 gives the results of the measurements as functions of the ion dose. In Fig. 11, the yield χ at the minimum (164°) and the difference $\Delta\chi = \chi(93°) - \chi(164°)$ are plotted as functions of the ion energy. The crosses and black circles show the results of the theoretical description (in two variants); this description is briefly characterized in the next section. It can be seen that the difference $\Delta\chi$ is not equal to zero and decreases rather regularly with increasing particle energy. This behavior corresponds to the influence of the lifetime τ of the fissioning nucleus on χ_τ, since τ must decrease with increasing excitation energy of the nucleus in accordance with the statistical model. In the case of fragment emission at angle 164° to the beam, the yield at the minimum $\chi(164°)$ is obviously little changed by the lifetime of the system, i.e., χ_τ in this case is a small fraction of the observed value. This is clear from examination of the dependence of $\chi(164°)$ on the ion energy—instead of the decrease associated with decrease of τ one observes a rather weak increase of $\chi(164°)$ with increasing E_L. It is evident that the value of $\chi(164°)$ is determined mainly by methodological factors, in particular by dechanneling of the fragments in a layer of finite thickness. From the results of Fig. 11, it is easy to find the mean duration of the fission reaction: $\bar{\tau} \approx 10^{-17}$ sec.

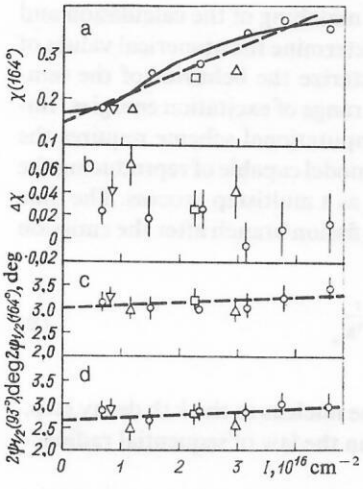

FIG. 10. Dependences measured[50] for the $^{16}O + W$ reaction of $\chi_{exp}(164°)$, $\Delta\chi$, and the angular widths $\psi_{1/2}$ of axis $\langle 111\rangle$ blocking dips on the dose; the open circles are for ion energy 131 MeV, the open squares for energy 114 MeV, the inverted open triangles for 104 MeV, and the open triangles for 95 MeV.

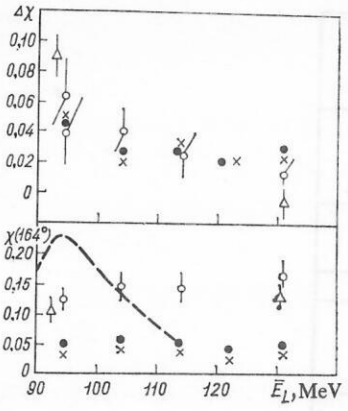

FIG. 11. Yield at the minimum (after subtraction of χ_{rad}) and the difference $\Delta\chi$ as functions of the ^{16}O ion energy. The open circles are from Ref. 50, the open triangles from Ref. 46, and the broken curve from Ref. 48.

A more accurate analysis requires allowance for the multistep process of decay of the compound nucleus, i.e., study of several branches of fission after neutron emission. Such an analysis is made in the next section. It is here important to note that the experiment directly yields a difference $\Delta\chi$ that, although small in absolute magnitude, can be related with a good degree of certainty to the influence of the reaction duration ($\bar{\tau} \approx 10^{-17}$ sec) on the blocking dip. This result does not completely correspond to the conclusions of Refs. 48 and 49, which reported the observation of a fairly large contribution (about 20%) of a long-lived fission component with $\tau \gtrsim 10^{-16}$ sec. The long-lived component was obtained in Refs. 48 and 49 on the basis of observation of a difference of the yields χ for the fission fragments and for elastically scattered ions and from the decrease in χ with increasing excitation energy of the fissioning nucleus. In our experiments, we were unable to confirm the decrease of $\chi_{164°}(E_L)$ for either the $^{16}O + W$ or the $^{22}Ne + W$ reaction.[51] The difference between χ for the fragments and the elastically scattered ions may be explained by the influence of factors not associated with the lifetime of the compound nucleus. A long-lived fission branch has been found[51] only for the $^{12}C + ^{238}U$ reaction, and its contribution of about 5% of the fission cross sections corresponds to fission events after reactions with incomplete momentum transfer.

Duration of fission reactions of uranium nuclei induced by ^{3}He and ^{4}He ions

In Ref. 52, measurements were made for fission reactions of ^{238}U nuclei induced by ^{12}C, ^{18}O, and ^{22}Ne ions; however, it was subsequently shown that an appreciable contribution to the measured $\Delta\chi$ values could be made by branches of fission after reactions of inelastic interaction of the colliding nuclei. Therefore, experiments in beams of $^{3,4}He$ ions were made; in reactions with these particles at energy < 10

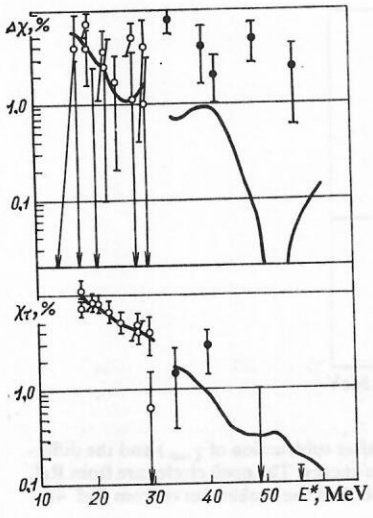

FIG. 12. Comparison of the results of measurement of $\Delta\chi$ and $\chi_\tau(147°)$ with the calculation: the open circles are for the reaction $^4He + ^{238}U$, and the black circles for $^3He + ^{238}U$.[54]

MeV/nucleon the contribution of fission after processes with incomplete momentum transfer is lower than in heavy-ion reactions. The $^{3,4}He + ^{238}U$ reactions were studied,[53,54] and also $^4He + ^{235,238}U$ (Ref. 55) and $^2H + ^{235}U$ (Ref. 56).

The experiments are described for the example of the $^{3,4}He + ^{238}U$ reactions.[54] The target was a UO_2 single crystal, and blocking dips were observed for the pair of crystallographic axes ⟨110⟩ and ⟨101⟩, which were oriented at angles 88 and 147° to the beam. The irradiation was done with beams of the U-200 cyclotron of the Laboratory of Nuclear Reactions at Dubna in the range of energies 23–35 MeV of the ^4He ions and 25–47 MeV of the ^3He ions.

The main results are given in Fig. 12 in the form of the dependences of $\Delta\chi$ and χ_τ (147°) on the excitation energy E^* of the compound nucleus. To understand the measured values, a calculation in accordance with the statistical model was made. The compound-nucleus lifetime was calculated using the temperature of the nucleus in accordance with the Fermi-gas model with parameters chosen in accordance with the experimental[57,58] values of τ for the $^1n + ^{235,238}U$ reactions. The contribution of the branches of fission after emission of different numbers of neutrons was calculated on the basis of empirical material from the fission probability of plutonium isotopes (Fig. 13). Then the measured quantities $\chi_\tau(147°)$ and $\Delta\chi$ were calculated. The transition relation (8) was used. Allowance was made for the change in the anisotropy of the angular distribution of the fission fragments with increasing number of emitted neutrons. In accordance with the data of Fig. 12, it can be seen that the time component $\chi_\tau(147°)$ is well described by the calculation, whereas a discrepancy that increases with increasing E^* is observed for $\Delta\chi$. This means that the compound-nucleus lifetime decreases with the excitation energy less strongly than in the Fermi-gas calculation. Such a conclusion does not contradict the results obtained in reactions on a W single crystal.

In Refs. 55 and 56, the measured values of χ for the $^{235,238}U(^4He,f)$ and $^{235}U(^2H,f)$ reactions were analyzed

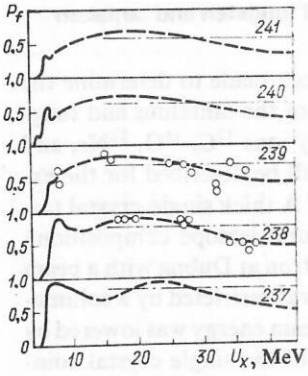

FIG. 13. Fission probability of plutonium isotopes. The broken curve is the interpolation from the experimental results; the remaining values represent literature data compiled in Ref. 54.

with a view to extracting the values of τ for specific nuclides formed in an excited state during cascade emission of neutrons. In Table I we give as an example the values of τ obtained[55] for the ^{240}Pu nucleus. The results were found to differ not strongly from the direct measurements of τ for the $^{235,238}U(n,f)$ reactions[57,58] in the region of excitation energy a few mega-electron-volts above the neutron binding energy B_n.

3. SYSTEMATICS OF THE NUCLEAR TEMPERATURE

Description of the fission reaction duration

In the statistical approach, the lifetime of an excited nucleus is determined by the ratio of the level densities in the initial and final states of the decay. The level density depends on the excitation energy, the mass number, and the angular momentum of the nucleus, $\rho(E^*, A, l)$, and is related to the nuclear temperature $T(E^*, A, l)$. To describe the fission reaction duration, the dependence $T(E^*)$ can be parametrized, and the condition of matching of the calculation and experiment can be used to determine the numerical values of the parameters that characterize the behavior of the temperature in the investigated range of excitation energies. Implementation of such a computational scheme requires the creation of a mathematical model capable of reproducing the decay of an excited nucleus as a multistep process. The time distribution of events of the fission branch after the emission of x neutrons has the form

$$N_x(t) = \frac{N_0}{\tau_x} \sum_{k=0}^{x} C_{xk} e^{-\frac{t}{\tau_k}}, \qquad (9)$$

where τ_k is the lifetime of the nucleus in the k th decay step, and C_{xk} are the coefficients in the law of sequential radioactive decay.

The total yield at the blocking dip can be represented as a sum of the contributions of the fission branches, $\chi = \sum_{x=0}^{m} \chi_{xn} = \sum_{x=0}^{m} P_x \chi_{xf}(A_x)$, and the partial yield χ_x can be calculated[59] in accordance with the formula

TABLE I. Dependence of the lifetime of the ^{240}Pu nucleus on the mean excitation energy as obtained in the ^{4}He + ^{238}U reaction.[55]

E_L, MeV	E^*, MeV	τ, 10^{-16} sec
24,7	6,0	$5{,}2^{+8{,}3}_{-2{,}6}$
25,2	6,2	$8{,}9^{+8{,}0}_{-4{,}0}$
26,5	6,8	$5{,}3^{+4{,}8}_{-1{,}8}$
27,2	7,2	$3{,}4^{+1{,}7}_{-1{,}1}$
28,1	7,8	$2{,}7^{+1{,}5}_{-0{,}9}$
28,8	8,5	$1{,}6^{+0{,}8}_{-1{,}6}$
29,6	9,2	$<1{,}1$

$$\chi_x = \frac{1}{(v_\perp \tau_x)} \sum_{k=0}^{x} C_{xk} \times \left\{ \frac{2D\,(v_\perp \tau_k)^3}{r_0^2} \left[1 - \left(1 + \frac{r_c}{v_\perp \tau_k} + \frac{r_c^2}{2v_\perp^2 \tau_k^2} \right) e^{-\frac{r_c}{v_\perp \tau_k}} \right] + v_\perp \tau_k e^{-\frac{r_c}{v_\perp \tau_k}} \right\}. \quad (10)$$

Equation (10) is obtained using (8) as the transition relation. A shortcoming of Eq. (10) is that it does not take into account the distribution of the residual excitation energy U_x after the emission of x neutrons; the spectrum U_x is replaced by a mean value. In Ref. 53, formulas are given that take into account the spectral distribution dW/dU_x of the excitation energy of the residual nucleus and the dependence of the fission probability P_f on U_x:

$$\chi_{xn} = \left(\sum_{x=0}^{m} P_{xnf} \right)^{-1} \int_0^{E^* - \Sigma_x} f(U_x)\, \chi(U_x)\, \frac{dW}{dU_x} P_f(U_x)\, dU_x; \quad (11)$$

$$P_{xnf} = \int_0^{E^* - \Sigma_x} P_f(U_x)\, \frac{dW}{dU_x}\, dU_x. \quad (12)$$

Here, $\Sigma_x = \sum_{i=1}^{x} B_{ni}$ is the sum of the binding energies of the x neutrons, P_x is the probability of the branch x normalized by the total fission cross section, P_{xnf} is the absolute probability of the fission branch after emission of x neutrons, f is a function that takes into account the dependence of the angular anisotropy A on U_x, and $\chi(U_x)$ is calculated in accordance with Eq. (8). The distribution dW/dU_x is calculated in accordance with the formula[60]

$$\frac{dW}{dU_x} = \frac{(E^* - \Sigma_x - U_x)^{2x-1} \left(1 - \sum_{i=0}^{x-1} P_{in} \right)}{I\left(\frac{E^* - \Sigma_x}{T},\ 2x \right) T^{2x} (2x-1)! \prod_{i=0}^{x-1} \left(1 + \frac{\Gamma_f}{\Gamma_n} \right)_i} \times e^{-\frac{E^* - \Sigma_x - U_x}{T}}, \quad (13)$$

where $I(z, m)$ is the incomplete gamma function, and T is a mean temperature that characterizes the branch x. Equation (10) is simpler and is more convenient to use in the case when the dispersion of the distribution dW/dU_x is much smaller than the energy $\overline{U}_x - B_n$; when they are comparable, it is better to use Eq. (11).

A numerical calculation for the ^{3,4}He + ^{238}U reactions was made[54] in accordance with Eq. (11), and the results are given in Fig. 12. The nuclear temperature in accordance with the Fermi-gas model was used, and a satisfactory description of the experimental values of $\Delta\chi$ and χ_τ in the region of compound–nucleus excitation energies 18–30 MeV was obtained. For the ^{16}O + W reaction, the problem of describing the duration in a wide range of excitation energies on the basis of the choice of a temperature of the nucleus was solved.[50] Both variants, Eqs. (10) and (11), were used in order to test the error of the calculation. For the description of the results, the fission probabilities were taken on the basis of known empirical material. The spin distribution of the fission cross section $\sigma_l P_f(l)$ in this reaction is rather narrow with a maximum at l levels rather close to the maximal l_m. Therefore, there is a possibility of replacing physical quantities that depend on l by values averaged over the spin distribution, the resulting error being small. The mean values of the rotation energy and the fission probability for an ensemble of fissioning nuclei were calculated:

$$\langle E_{\text{rot}} \rangle = \frac{\hbar^2}{2J} \sigma_f^{-1} \sum_{l=0}^{l_m} l(l+1)\, \sigma_l P_f(l); \quad (14)$$

$$\langle P_f \rangle = \sigma_f^{-1} \sum_{l=0}^{l_m} \sigma_l P_f^2(l), \quad (15)$$

where J was assumed to be equal to the moment of inertia of a rigid sphere, and $\sigma_l \sim 2l + 1$. The probability of events for which the nucleus emits x neutrons and then fissions is $G_{xf} = P_x \langle P_f \rangle$, where P_x is the distribution of the number of neutrons emitted before fission. From the probability G_{xf}, one can readily find the absolute fission probability P_{xf} for branch x, since

$$G_{xf} = P_{xf} \prod_{k=0}^{x-1} (1 - P_{kf}).$$

As usual, it was assumed in the calculation that the lifetime of the excited nucleus is $\tau = \hbar \Gamma_T^{-1}$, where the total width is given by $\Gamma_T = \Gamma_n (1 - P_f)^{-1}$. The neutron width Γ_n was calculated in accordance with the formula of the statistical model, and the level density $\rho(E^* - \langle E_{\text{rot}} \rangle - \Delta)$ was parametrized on the basis of a choice of the temperature in the form $T = C_t (U/A)^m$, where U is the thermal excitation energy. To describe the results, the quantity P_x and the parameters C_t and m were varied. The agreement achieved between the calculation and experiment is shown in Fig. 11; the black circles and the crosses correspond to the two variants represented by Eqs. (10) and (11), respectively. It can be seen that the difference between them is small, and in both

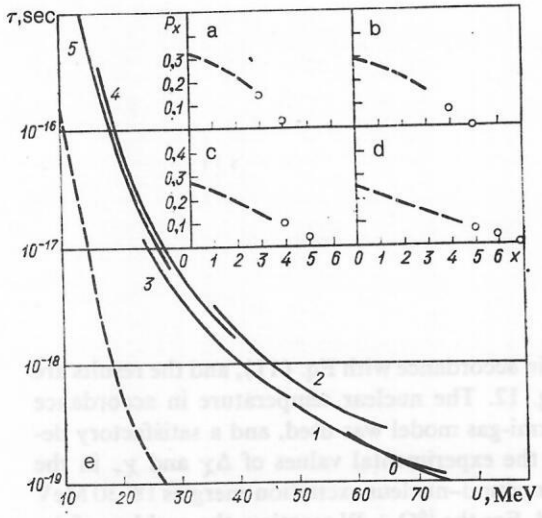

FIG. 14. Results of a calculation that characterize the decay of the ^{200}Pb nucleus formed in the $^{16}O + ^{184}W$ reaction: distribution of the number $P_x(x)$ of neutrons emitted before fission at energy 95 MeV (a), 104 MeV (b), 114 MeV (c), and 131 MeV (d); e) dependence of the lifetime τ on the mean thermal excitation energy U after the emission of x neutrons. The numbers x are given in the figure.[50] The broken curve is calculated using the Fermi-gas model.

cases a reasonable description of the experimental dependences $\Delta\chi(E_L)$ and $\chi_\tau(E_L)$ is achieved. The difference of χ_τ and $\chi(164°)$ in absolute magnitude is due to the methodological component of the yield χ, which was not taken into account in the calculation.

The satisfactory reproduction of the results of the experiment by the calculation was achieved by choosing the parameters of the nuclear temperature function in the form $T = 1.94(U/A)^{1.3}$ and also by taking definite values of P_x. Figure 14 shows the calculated dependence of the lifetime of the nuclei on the thermal excitation energy for decay of the compound nucleus ^{200}Pb; the distributions obtained for P_x for four values of the energy are also given. The functions $P_x(x)$ were found to be consistent with the results of the experimental determination for neighboring nuclei given in the literature. The lifetime of the nuclei decreases rather sharply with increasing excitation energy, although not so strongly as when the Fermi-gas model is used for the nuclear temperature.

Description of the spectra of neutrons emitted by excited nuclei

The neutron spectra can give information about the dependence of the nuclear temperature on the excitation energy. However, the acquisition of reliable information requires the selection of reactions in which the contribution of the nonequilibrium neutron-emission mechanisms is small compared with the neutron yield from decay of the compound nucleus. The equilibrium component of the spectrum is separated on the basis of kinematic verification of the emission of neutrons by a source moving with the velocity of the compound nucleus, and also on the basis of an analysis of the shape of the spectrum. For this, it is necessary to use an adequate mathematical model; in particular, it is necessary to take into account correctly the cascade component of the observed neutron spectra. In Ref. 61, recursion relations are obtained for the spectrum $n_{x+1}(\varepsilon)$ of the neutrons of the $(x+1)$th generation and for the distribution W_{x+1} of the nuclei with respect to the excitation energy U_{x+1} after emission of the $(x+1)$th neutron with allowance for the reduction in the energy due to the emission of photons in each step of the cascade:

$$n_1(\varepsilon) = C_1(E^*)\, N_1^n(\varepsilon,\ E^*) + \int_{B_{n1}+\varepsilon}^{E^*} C_1(U_\gamma)\, W^\gamma(U_\gamma)\, N_1(\varepsilon,\ U_\gamma)\, dU_\gamma; \tag{16}$$

$$W_1(U_1) = C_1(E^*)\, N_1^n(E^* - B_{n1} - U_1,\ E^*) + \int_{B_{n1}+U_1}^{E^*} C_1(U_\gamma)\, W^\gamma(U_\gamma)\, N_1^n(U_\gamma - B_{n1} - U_1,\ U_\gamma)\, dU_\gamma; \tag{17}$$

$$n_{x+1}(\varepsilon) = \int_{B_{nx+1}+\varepsilon}^{E^*-\Sigma_x} \Big[C_{x+1}(U_x)\, N_{x+1}^n(\varepsilon,\ U_x) + \int_{B_{nx+1}+\varepsilon}^{U_x} C_{x+1}(U_\gamma)\, W^\gamma(U_\gamma)\, N_{x+1}^n(\varepsilon,\ U_\gamma)\, dU_\gamma \Big] \times W_x(U_x)\, dU_x; \tag{18}$$

$$W_{x+1}(U_{x+1}) = \int_{B_{nx+1}+U_{x+1}}^{E^*-\Sigma_x} \Big[C_{x+1}(U_x)\, N_{x+1}^n(U_x - B_{nx+1} - U_{x+1},\ U_x) + \int_{B_{nx+1}+U_{x+1}}^{U_x} C_{x+1}(U_\gamma)\, W^\gamma(U_\gamma)\, N_{x+1}^n(U_\gamma - B_{nx+1} - U_{x+1},\ U_\gamma)\, dU_\gamma \Big] \times W_x(U_x)\, dU_x, \tag{19}$$

where B_{nx} is the binding energy of the xth neutron, and $W^\gamma(U_\gamma)$ is the distribution of the excitation energy after the emission of the photons in each step of the neutron cascade. The function $W^\gamma(U_\gamma)$ can be calculated in accordance with relations that are in principle analogous to (19) for the γ cascade. The normalizing function C and the shape of the spectrum $N^n(\varepsilon, E^*)$ of the neutrons emitted by a nucleus with fixed excitation energy E^* are calculated in accordance with the formulas

$$C_{x+1}(U_x,\ A-x) = \frac{[1-P_f(U_x)]\,\Gamma_n(U_x)}{\Gamma_n(U_x)+\Gamma_\gamma(U_x)} \Big[\int_0^{U_x - B_{nx+1}} N_{x+1}^n(\varepsilon,\ U_x)\, d\varepsilon \Big]^{-1}; \tag{20}$$

$$N^n(\varepsilon,\ E^*) = \begin{cases} \rho_A^{-1}(E^* - \Delta_A)\, \varepsilon \rho_{A-1}(E^* - B_n - \varepsilon - \Delta_{A-1}) \\ \text{for } 0 \leqslant \varepsilon \leqslant E^* - B_n - \Delta_{A-1}; \\ \rho_A^{-1}(E^* - \Delta_A)\, \varepsilon \rho_{\text{col}}(A-1) \\ \text{for } E^* - B_n - \Delta_{A-1} < \varepsilon \leqslant E^* - B_n, \end{cases} \tag{21}$$

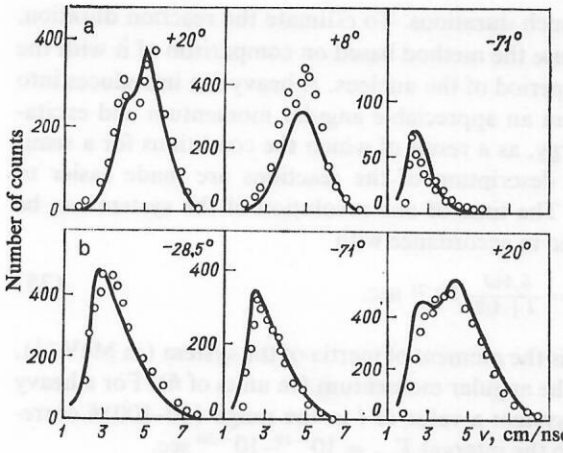

FIG. 15. Comparison of measured[62] velocity spectra (points) with the calculation (curves)[61] for the ^{86}Kr(1.02 GeV) + ^{166}Er interaction as a function of the direction of emission of neutrons for quasielastic reactions ($E^* \leqslant 112$ MeV) (a) and for deep inelastic collisions ($342 \leqslant E^* \leqslant 472$ MeV) (b).

where Δ is the pairing energy, and ρ_{col} is the mean density of the collective states of the nucleus in the region $E^* \leqslant \Delta$.

Besides the formulas given here, Ref. 61 contains an analysis of the values of the temperature obtained from analysis of the neutron spectra. In particular, the possibility of describing the velocity spectra of the neutrons emitted by the products of the inelastic interaction ^{86}Kr(1.02 GeV) + ^{166}Er (Ref. 62) is investigated. In this reaction, the observation of coincidences of neutrons with a pair of fragments makes it possible to separate in an almost pure form the spectra of the neutrons emitted by each fragment separately. If the deep inelastic products are observed, one can detect neutrons emitted by nuclei excited to energies 200–300 MeV. Figure 15 shows the description achieved for the spectral and angular distributions of the neutrons. It is interesting to note that satisfactory agreement between the calculation and experiment is obtained under the assumption that the neutrons are emitted by fragments that have been completely accelerated in the Coulomb field. The time of acceleration of the fragments to 95% of the maximal velocity in the center-of-mass system is estimated at $0.8 \cdot 10^{-20}$ sec for the deep inelastic case. Therefore, most of the neutrons are emitted within an interval $\tau > 10^{-20}$ sec after the collision. This estimate of τ is of interest, since it relates to nuclei excited to an energy of more than 200 MeV.

Analysis of neutron spectra obtained in many studies made it possible to construct[61] the systematics of half the mean neutron energy or the nuclear temperature (Fig. 16). It can be seen that despite the great variety of the experimental results included in the analysis the spread of points is moderate, and through them a semiempirical dependence of the form $T = 2.22(U/A)^{1/3}$ can be drawn. This function $T(U)$ is in satisfactory agreement with the function obtained earlier from the description of the duration of the fission reactions ^{16}O + W (Ref. 50) and $^{1}n + ^{235,238}$U (Ref. 63). Thus, it is possible to eliminate the appreciable discrepancy between the values of T obtained by analyzing the reaction duration and from the neutron spectra.

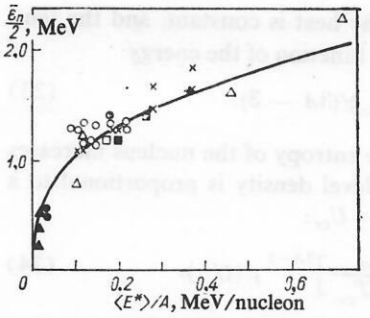

FIG. 16. Systematics[61] of half the mean neutron kinetic energy, $\bar{\varepsilon}_n/2 = T$, as a function of the specific thermal excitation energy per nucleus. Literature in Ref. 61.

Asymptotic behavior of the nuclear temperature at high excitation energies

The exact form of the thermodynamic equation of state of a nucleus is *a priori* unknown. One uses analogy with a gas of noninteracting Fermi particles, $U \sim T^2$, on the ground that the nucleon spin is $\frac{1}{2}$. For a degenerate Bose gas, $U \sim T^{5/2}$; α particles, pairs of nucleons, and excitation phonons can be regarded as bosons. In addition, it is known that the thermodynamic equation of state depends essentially on the nature and the strength of the interaction between the particles within the system. For example, a crystal consisting of molecules in the form of a long one-dimensional chain is characterized by $U \sim T^2$; but for the same substance the isomer shape of the molecules in the form of two-dimensional planar formations leads to $U \sim T^3$, while for three-dimensional molecules we obtain $U \sim T^4$. It is clear that the details of the structure of the intranuclear interaction of the nucleons can lead to a significant change of the thermodynamic characteristics of a nucleus compared with the simplest model of a degenerate gas of noninteracting Fermi particles.

The asymptotic behavior of the temperature and the other thermodynamic functions can be obtained by considering the specific heat of the nucleus:

$$c = A^{-1}\,\partial U/\partial T, \tag{22}$$

for which there is[64] the classical limit $c_{lim} = 3$ nuclear units $= 3$ MeV/(MeV·nucleon) $= 5.97$ cal/(g·deg), which is equal to the specific heat of simple solids at a temperature that is not low. To this limit for a condensed system there corresponds the physical situation in which the number of excited degrees of freedom is equal to the total number and does not increase with increasing energy. For a nucleus, one can also establish a certain energy U_{cr}, at which the specific heat reaches the critical value $c = c_{lim}$. We shall assume that the quark structure of the nucleon does not change the spectrum of excited nuclear states; then the total number of degrees of freedom of the nucleus is $3A - 3$ and $c_{lim} \approx 3$ nuclear units. If the relationship between the temperature and the energy, $T = 2.22(U/A)^{1/3}$, obtained above is used, the condition $c = c_{lim}$ leads to the values $U_{cr} = 670$ MeV and $T_{cr} = 3.33$ MeV for the ^{200}Pb nucleus (for example). In the

region $U > U_{cr}$, the specific heat is constant, and the temperature becomes a linear function of the energy:

$$T = T_{cr} + (U - U_{cr})/(3A - 3). \quad (23)$$

In the region $U > U_{cr}$, the entropy of the nucleus increases logarithmically, and the level density is proportional to a power-law function of $U - U_{cr}$:

$$\rho(U) = \left[1 + \frac{U - U_{cr}}{(3A-3)T_{cr}}\right]^{3A-3} \rho(U_{cr}). \quad (24)$$

The resulting value $U_{cr} = 670$ MeV is appreciably less than the total binding energy of the nucleus, which is equal to 1580 MeV, i.e., the limiting value of the specific heat is reached at a temperature corresponding to a bound state. This result is analogous to the well-known one for condensed media. Therefore, the basic properties of nuclear matter such as the incompressibility and the saturation of the nuclear forces, which lead to the picture of a nucleus as a drop of condensed matter, are augmented by the nature of the behavior of the thermodynamic parameters. In the case of the nuclear temperature, taken in accordance with the Fermi-gas model, $T = 3.16(U/A)^{1/2}$, such estimates lead to $U_{cr} = 4500$ MeV for ^{200}Pb. Thus, the Fermi-gas model describes the nucleus as a system like an electron gas in a metal, for which U_{cr} could be achieved only at a temperature corresponding to an unbound state. It is not clear whether such a model is close to the real properties of nuclear matter.

The values of the level density and nuclear temperature in the region of high energy U must be changed by the restrictions associated with the finite number of single-particle levels in the potential well of the average field. These changes become appreciable at values of the temperature approaching the nucleon binding energy. We note, however, that at a high energy of the bombarding particles (high energy per nucleon) the most probable process becomes the emission of particles through fast and pre-equilibrium processes. To such a reaction mechanism there correspond other temperature parameters in the statistical description. The estimate of the temperature made here refers to a highly excited compound nucleus, and it may be helpful for analyzing the equilibrium (slow) component in the spectra of the particles emitted under the influence of nuclei of intermediate and high energy. Recently, processes have been observed[65] with complete momentum transfer (of compound-nucleus type) in the interaction of ^{12}C nuclei (60 MeV/nucleon) with Au and U.

4. DISTRIBUTION OF REACTION PRODUCTS. THE REACTION DURATION

Estimate of reaction duration based on the angular distribution of the products

To determine the duration of nuclear reactions in the region $\tau < 10^{-18}$ sec, it is difficult to use the crystal blocking method, and therefore it is necessary to use other methods. Under certain conditions, the decay of the compound nucleus may have a duration in the range 10^{-20}–10^{-19} sec; inelastic reactions that take place through a stage involving the formation of a dinuclear system can also be characterized by such durations. To estimate the reaction duration, one can use the method based on comparison of it with the rotation period of the nucleus. A heavy ion introduces into the system an appreciable angular momentum and excitation energy, as a result of which the conditions for a semiclassical description of the reactions are made easier to achieve. The time of one revolution of the system can be calculated in accordance with

$$T_{rot} = \frac{4.14J}{l + 1/2}\, 10^{-21} \text{ sec}, \quad (25)$$

where J is the moment of inertia of the system (in MeV^{-1}), and l is the angular momentum (in units of $\hbar$). For a heavy nuclear system a value of l in the range (10–100)$\hbar$ corresponds to the interval $T_{rot} = 10^{-19}$–10^{-20} sec.

If the lifetime of the nuclear system is greater than the rotation period, then the angular distribution of its decay products is symmetric with respect to 90° in the center-of-mass system; but if $\tau < T_{rot}$, a forward–backward asymmetry must necessarily appear in the emission of the reaction products. Applied to the fission of nuclei induced by heavy ions, the possibility of estimating the duration by comparison with the rotation period of the fissioning system was proposed in Ref. 66. Recently, such a method was used[67] to obtain the fission reaction time $\tau \approx 10^{-20}$ sec in the ^{208}Pb + ^{58}Fe system at energy of the ^{208}Pb ions equal to 5.9 MeV/nucleon. This reaction revealed a forward–backward asymmetry of the fragment emission with the heavy fragment directed mainly forward and the light fragment backward. It was found from this that the fission takes place after rotation of the system through an angle of about 120°. Recently, however, there have appeared[68] some rough estimates of the fission duration by comparison of it with the imprecisely determined time of establishment of statistical equilibrium with respect to the angular degrees of freedom. This treatment is based on the inaccurate assumption that an angular distribution of the form $\sin^{-1}\theta$ corresponds to fission of a nonequilibrium system. As is well known,[69] the $\sin^{-1}\theta$ distribution arises when two conditions are satisfied: 1) the fission takes place in the plane strictly perpendicular to the angular momentum of the system; 2) before the fission, the system makes several revolutions, so that the fragments are distributed uniformly in the plane. The second condition means that one cannot speak of observation of prompt fission on the basis of an angular distribution that approximates the form $\sin^{-1}\theta$. Prompt (direct) fission could lead to an angular distribution of the fragments with maxima that has the type known for quasielastic direct reactions induced by heavy ions. However, such an angular distribution for the fission fragments has not been observed (according to the literature).

In the ^{50}Ti(250 MeV) + ^{208}Pb reaction, the angular distributions of fragments with $Z = 47$ and 54 have been measured[70]; no difference of the forward–backward asymmetry for emission of the light and heavy fragments was found. In Fig. 17, these angular distributions are compared with those obtained[71] for the ^{22}Ne(125 MeV) + ^{238}U reaction. The compound nuclei in these reactions are similar as regards the atomic number, $Z = 104$ and 102, and as regards

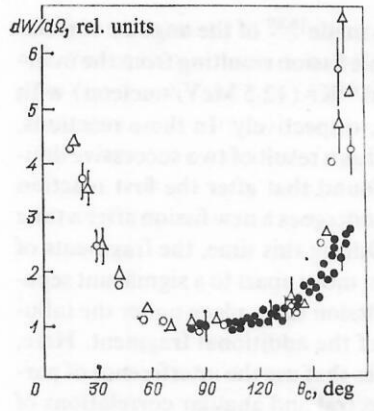

FIG. 17. Angular distributions of symmetric fragments measured in the reactions $^{50}Ti + {}^{208}Pb$ (Ref. 70) and $^{22}Ne + {}^{238}U$ (Ref. 71). The open circles and open triangles are, respectively, for the products with $Z = 47$ and 54 in the first reaction, and the black circles represent the fission fragments in the second reaction.

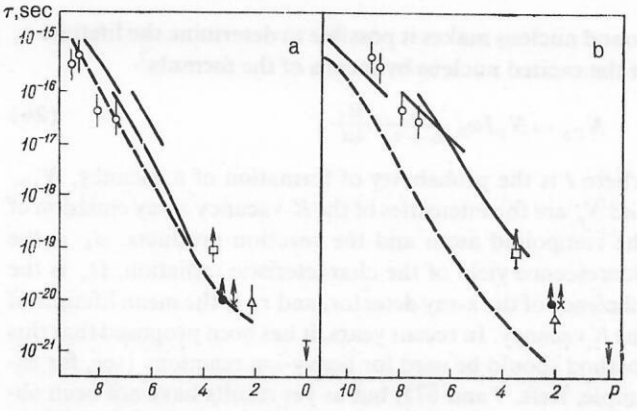

FIG. 18. Systematics[71] of measured values of τ as a function of the parameter P for temperature chosen in accordance with the systematics of Fig. 16 (a) and in accordance with the Fermi-gas model (b). The continuous curves represent the results of the measurements of Refs. 44, 50, and 54; the points are as follows: open circles for Refs. 6–8 and 37, open squares for Ref. 70, crosses for Refs. 61 and 62, black circles for Ref. 73, open triangles for Ref. 67, and ↓ for Ref. 21; the broken curves are the results of calculation.

the angular momentum, $\bar{l} = (20\text{–}25)\hbar$, while the excitation energy in the first reaction is significantly less than in the second: 32 and 60 MeV, respectively. This difference partly explains the observed difference of the anisotropy. Therefore, it can be assumed that the form of the angular distribution does not give clear indications of a significant difference between the reaction mechanisms in the $^{22}Ne + {}^{238}U$ and $^{50}Ti + {}^{208}Pb$ reactions. Using Eq. (25) and taking into account the symmetry of the angular distribution about 90°, one can estimate the reaction duration at $\tau > 10^{-19}$ sec.

Estimates have recently been made[72] of τ on the basis of the angular distribution of the products of interaction reactions of the ions ^{238}U (6 MeV/nucleon) with nuclei from ^{48}Ti to ^{89}Y; values from 10 to $3 \cdot 10^{-21}$ sec, respectively, were obtained. For lighter targets, a lower bound is given for τ; for example, $\tau > 1.5 \cdot 10^{-20}$ sec for the fission reaction $^{238}U + {}^{27}Al$.

In an investigation of the $^{3}He(90\ MeV) + Ag$ reaction, the emission of light nuclei with $Z = 3$–9 was observed,[73] the angular distribution of the products having a maximum in the backward hemisphere in the region of $\theta = 180°$ The dependence of the cross section for the production of products on Z makes it possible to identify them as decay products of a compound nucleus,[73] and the angular distribution makes it possible to estimate the decay time of the nucleus: $\tau > 10^{-20}$ sec.

The estimates of the reaction duration in the range $\tau \sim 10^{-21}$–10^{-19} sec make it possible to construct the systematics of τ in its dependence on the parameter that characterizes the decay of the compound nucleus in the statistical approach. The aim is to compare the values obtained by different methods and to discover reactions that could have a nonstatistical mechanism. The systematics is represented in Fig. 18 and includes the results of measurements by means of the crystal blocking method[37,44,50,54] and by means of the K-vacancy x-ray method,[6–8] and also estimates of the duration from the angular distribution of the products measured in Refs. 67, 70, and 72 and from the spectrum of neutrons[61] emitted by products of deep inelastic reactions in the $^{86}Kr(1.02\ GeV) + {}^{166}Er$ system.[62] The systematizing parameter is a quantity that has a statistical significance: $P = -\ln \sum_i \exp(-B_i/T)$, where B_i is the activation energy of the compound-nucleus decay channel. The quantities B_i were assumed to be equal to B_f, $\bar{B}_n$, $\bar{B}_p + 0.6V_c$ for the main decay channels—fission and the emission of neutrons and protons. The quantities B_n and B_p were averaged over the parity of the neutron number and proton number in order to take into account the dependence of the level density on the pairing energy. The proton Coulomb barrier V_c was taken with a factor 0.6 in view of its high penetrability. Figure 18 also gives the shortest time τ for $P = 0$, corresponding to the collision time of heavy nuclei.[21] The nuclear temperatures were calculated in two ways: in accordance with the systematics of Ref. 61, $T = 2.22(U/A)^{1/3}$ (Fig. 18a), and in accordance with the Fermi-gas model, $T = 3.16(U/A)^{1/2}$ (Fig. 18b). It can be seen from the data of Fig. 18 that the existing results of measurements and the limits based on the experimental data fit the general dependence $\tau(P)$ well. Thus, decay of a compound nucleus is confirmed for the majority of the reactions included in the systematics. In addition, it can be seen that if the temperature from the systematics of Ref. 61 is used, the statistical calculation gives values close to the measured values in a wide range of temperature and, accordingly, the parameter P. But in the Fermi-gas model the values of τ are almost two orders of magnitude smaller than the measured values at excitations $U > 20$ MeV.

The systematics given in Fig. 18 contains points obtained by using the characteristic K-vacancy x-ray emission of the compound nucleus,[5–9] and it is therefore worth saying a few words about the x-ray method. The compound-nucleus decay time is compared with the period of population of a K vacancy of the compound nucleus formed by absorption of the incident particle. In practice, the method can be used for inelastic proton scattering. To identify the process, coincidences of scattered protons with x rays are observed. The measured intensity of the K-vacancy x-ray line of the com-

pound nucleus makes it possible to determine the lifetime τ_c of the excited nucleus by means of the formula[7]

$$N_{CN} = N_p I \omega_k \frac{\tau_c}{\tau_c + \tau_k} \frac{\Omega_x}{4\pi}, \quad (26)$$

where I is the probability of formation of a vacancy, N_{CN} and N_p are the intensities of the K-vacancy x-ray emission of the compound atom and the reaction products, ω_k is the fluorescence yield of the characteristic radiation, Ω_x is the efficiency of the x-ray detector, and τ_k is the mean lifetime of the K vacancy. In recent years, it has been proposed that this method should be used for heavy-ion reactions (see, for example, Refs. 7 and 67), but as yet results have not been obtained. This is probably explained by the rather high background in the x-ray range of γ rays emitted when the products of the interaction of complex nuclei decay.

Generally speaking, the systematics of the decay time of excited nuclei should include data on light nuclei. However, the lifetime of isolated resonances, which are usually observed in light nuclei because of the low level density, is determined not by statistical factors but by the matrix element of the main transition to the level of the final nucleus. Therefore, these data are not included in Fig. 18. Experimental results of such type are available in the literature, and they were obtained mainly by the crystal blocking method,[74–78] and also by measurement of the excitation functions and of the ratio of the yields of nuclear reactions.[79,80] There is also the method of resonance absorption of particles and γ rays,[81,82] in which the width of the resonance is determined from the reaction yield for known energy resolution of the beam.

Experiments to determine the lifetime of dinuclear systems

In recent years, a few attempts have been made to determine the lifetime of dinuclear systems (quasimolecules). In particular, the angular distribution of the products has been used.[83,84] For the reactions ^{197}Au(^{22}Ne, ^{24}Na) (Ref. 83) and Ag(^{40}Ar, O) (Ref. 84), an angular distribution with a maximum in the backward hemisphere at angles near 180° has been found. This means that the reaction duration is comparable with the rotation period of the system, from which we can estimate $\tau > 8 \cdot 10^{-21}$ sec and $\tau > 3 \cdot 10^{-21}$ sec for the first and second reaction, respectively. The observation of a maximum in the backward hemisphere for $^{16}O + {}^{28}Si$ elastic scattering,[85,86] which corresponds to $\tau > 2 \cdot 10^{-21}$ sec, also belongs in this category.

Well known are the observations of an oscillating structure of the angular distribution and the excitation function in the case of the interaction of two light nuclei (see, for example, Refs. 87 and 88), which have been interpreted as quasimolecular states of a compound system. The general form of the angular distributions (excluding oscillations) is fairly symmetric about 90°, and therefore the lifetime of the quasimolecule can be estimated at $\tau > 5 \cdot 10^{-21}$ sec, which does not contradict the determination of τ from the width of the quasimolecular resonances[88]: $\Gamma < 100$ keV, $\tau = \hbar/\Gamma > 6 \cdot 10^{-21}$ sec.

The angular correlation between the reaction products of heavy nuclei has also been used to estimate reaction durations. A measurement was made[18,89] of the angular correlation of the fragments of triple fission resulting from the interaction of the ions ^{129}Xe and ^{84}Kr (12.5 MeV/nucleon) with the nuclei ^{122}Sn and ^{166}Er, respectively. In these reactions, three fragments are formed as a result of two successive double-fission events. It was found that after the first reaction stage the heavy fragment undergoes a new fission after a time interval $\tau \approx 3 \cdot 10^{-21}$ sec. During this time, the fragments of the first fission event cannot move apart to a significant separation, so that the second fission takes place under the influence of the external field of the additional fragment. Here, we shall not consider studies that use the interference of particles,[14,15] in which the spectral and angular correlations of the products are also measured. However, in recent years this method has been developed, primarily to estimate the size of the region of interaction of relativistic particles with nuclei.

There have recently appeared several studies in which attempts were made to determine the lifetime of the heaviest double nuclear system. The accelerator at Darmstadt was used[90] in a program of research into quantum electrodynamics under conditions of superstrong fields using accelerated ions of the heavy elements Pb and U. This succeeded in detecting the production of positrons in heavy-atom collisions; detailed studies were made of the spectra of the δ electrons, γ rays, and the pair conversion of γ rays that accompany the interaction of nuclei such as U + Cm. The main aim of the investigation is to prove the spontaneous production of positrons in the supercritical field of the quasiatom with total atomic number $Z_1 + Z_2$ formed by the close encounter of two heavy atoms with Z_1 and Z_2. The description of the structure and the dynamics of the formation of supercritical atomic systems does not correspond to the main theme of the present review. Therefore, studies of the atomic collisions of very heavy ions are considered here only to the extent that they permit determination of the duration of a nuclear interaction.

If as a result of nuclear forces two heavy atoms of U + Cm type are kept together for a time greater than the free-encounter time, the intensity of the spontaneous production of positrons increases, and their spectrum acquires a line structure, reflecting the levels of the compound atom. The energy width of the lines in the positron spectrum is determined by the lifetime of the system, i.e., by the duration of the nuclear interaction. Figure 19 shows the spectrum of positrons produced in $^{238}U + {}^{246}Cm$ collisions at ion energy 5.8 MeV/nucleon. There is a clear line at $E_{e^+} \approx 330$ keV, which has a small width. It is concluded in Ref. 90 that in collisions of the U and Cm nuclei in a certain range of impact parameters a double system (quasimolecule) is formed with a lifetime that can be determined in accordance with the formula $\tau = \hbar/\Gamma \approx 10^{-19}$ sec. In a series of experiments, some tests were made, including measurements of the excitation function for the line component of the spectrum, the dependence of the line intensity on the emission angle of the products of the nuclear interaction, the angular correlation, and the Doppler broadening of the positron line. These tests gave a result that satisfied the interpretations on the basis of the formation of a nuclear quasimolecule. However, the line

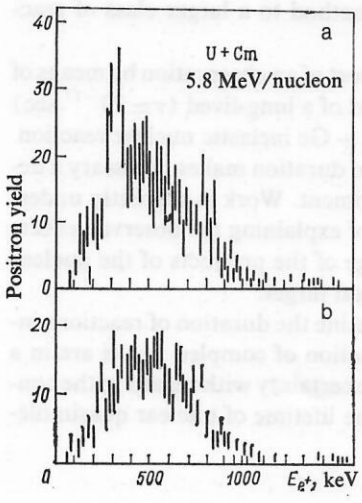

FIG. 19. Positron spectrum in the $^{238}U + ^{246}Cm$ reaction[90] obtained in coincidence with a product of inelastic interaction emitted in the interval of scattering angles $27.5 \leqslant \theta \leqslant 40°$ (a) and $\theta < 27.5°$ (b).

$E_{e^+} \approx 330$ keV has also been recently observed[91] in the Th + Ta reaction, and this does not correspond to the expected dependence of the energy of the positrons and their yield on the charge $Z_1 + Z_2$ of the compound atom. It is also interesting to note that the positron line spectrum corresponding to quasimolecule formation is observed only in a rather narrow range of energies of the incident particles in the case of observation of the products of a moderately inelastic interaction of the colliding nuclei. A raising of the energy of the ions and detection of coincidences of positrons with the fragments gives a continuous positron spectrum, this corresponding to a lifetime of the nuclear system close to the collision time $\tau \lesssim 10^{-21}$ sec.[21] In the theoretical description of the results, calculations of the interaction potential of heavy nuclei have been made, and minima of the potential (pockets) corresponding to the configuration of two touching nuclei have been found.[90]

A search for interference structure in the spectrum of δ electrons accompanying the collision of heavy ions is reported in Refs. 22 and 90. This is one further example of the use of an "atomic clock" to determine the duration of a nuclear process. The amplitude of the δ-electron wave function contains two components corresponding to the emission of the electrons as the ions approach each other and then as they separate. If there is a phase shift associated with a lifetime τ of a nuclear system, the coherent addition of the amplitudes gives a periodic oscillation in the shape of the electron spectrum over an energy interval that is related to the delay time τ. For the I + Pb reaction at energy 500 MeV of the ions, an interference structure of the spectrum was not found,[22] and therefore the time of the nuclear interaction does not exceed the collision time. However, in the I + Au system in the case of the detection of coincidences of δ electrons with the products of inelastic nuclear interaction, structure corresponding to a system lifetime of about 10^{-20} sec was observed.[90]

In principle, the δ-electron spectrometry method is similar to the method based on bremsstrahlung interference.[10–13] In this case, the interference structure is also associated with the emission of bremsstrahlung photons as the interacting nuclei approach each other and then separate. Bremsstrahlung interference has been successfully observed for $^{12}C(p, p)$ elastic scattering near resonances of the excitation function for $E_p < 2$ MeV, and their lifetime has been estimated at around $2 \cdot 10^{-20}$ sec. To observe coincidences of bremsstrahlung photons with an "elastically scattered" proton an interference structure is observed in the γ spectrum in the region of photon energies corresponding to the resonance energy of the coincident protons. We have put the words "elastically scattered" in quotation marks because the emission of bremsstrahlung photons means by definition that the process is inelastic—"elastic" means the absence of residual excitation energy of the target nucleus. It is not impossible that in the future the bremsstrahlung method will also be used for heavy-ion reactions. Attempts to measure the spectrum of γ rays accompanying the interaction of very heavy atoms were reported in Ref. 90, but in general this spectrum contains all forms of γ rays produced in the collisions, and this makes it difficult to observe bremsstrahlung interference.

The lifetime of a quasimolecule consisting of two light nuclei, $^{16}O + ^{12}C$, was determined in the experiment of Ref. 92 by the crystal blocking method. As already mentioned, characteristic structures explained by the formation and decay of a quasimolecule have been established, and a lower limit $\tau > 5 \cdot 10^{-21}$ sec for the lifetime has been obtained. By the crystal blocking method one can give a direct experimental estimate of τ. A thin diamond single crystal was irradiated with 120-MeV ^{16}O ions. At angle 16° to the ion beam a $\langle 110 \rangle$ blocking minimum was observed, and its variation on the transition from elastically scattered ions to inelastic interaction products was determined. For nuclei with $Z = 6$–9, a time delay of the emission up to $3 \cdot 10^{-18}$ sec was found. The lower limit for the sensitivity of the crystal blocking method was reduced in this case to values $\tau \approx 5 \cdot 10^{-19}$ sec on account of the high velocity of the center of mass in the given reaction. Despite the successful measurement of the reaction duration τ, the lifetime of the $^{16}O + ^{12}C$ quasimolecule could not be established because the observed delay time relates primarily to the secondary process of decay of an excited product formed in the first stage of the reaction. In the given case, the displacement of the point of emission of the particle from the crystallographic axis due to the secondary decay, S_{sp} (see Sec. 2), is substantial because of the participation in the reaction of light nuclei whose mass number is comparable with the mass of the secondary particles, for example, ^{16}O and ^{4}He. Thus, the experiment of Ref. 92, which was of undoubted methodological interest, did not cast any light on the question of the lifetime of the $^{16}O + ^{12}C$ nuclear quasimolecule.

According to the adopted ideas, deep inelastic reactions of complex nuclei take place through a stage in which a dinuclear system is formed. The reaction products have a broad spectrum of values of Z, A, and the kinetic energy. Their angular distribution, which is usually structureless, covers a wide range of angles. When these products are detected, it is

rather difficult to separate a definite exit channel of the reaction. Despite the absence of determination of the quantum numbers of the system, the authors of Ref. 93 succeeded in observing fluctuations in the cross section of deep inelastic reactions in the $^{28}Si + {}^{64}Ni$ system for ion energies in the range 120–127 MeV. Correlation analysis of the excitation functions made it possible to determine the coherence interval and to estimate the reaction time at $\tau = (1\text{–}4) \times 10^{-21}$ sec for products with different Z. This example is interesting not only from the point of view of obtaining a definite result; it is also important to note the observation of fluctuations of the cross section (of Ericson type) for reactions not associated with a compound nucleus and in the absence of exact determination of the final product. This means an extension of the possibilities of the method to a larger class of reactions.

In Ref. 94 there is a report of an observation by means of the crystal blocking method of a long-lived ($\tau \approx 10^{-17}$ sec) dinuclear system in a $^{20}Ne + Ge$ inelastic nuclear reaction. The unusually long reaction duration makes necessary a detailed analysis of the experiment. Work is currently underway to test the possibility of explaining the observed effects by the details of the passage of the products of the nuclear reactions in the single-crystal target.

Thus, studies to determine the duration of reactions involving the inelastic interaction of complex nuclei are in a stage of progress. Complete certainty with regard to the conditions of formation and the lifetime of nuclear quasimole-

TABLE II. Experiments to detect long-lived dinuclear systems.

Reaction	Energy, MeV/nucleon	Result of measurements	Duration, sec	Interpretation	Reference
$^{238}U + {}^{238}U$, ^{246}Cm	5,8—6,2	Spectrum of positrons in coincidence with a product of inelastic interaction	$\approx 10^{-19}$	Nuclear quasimolecule	[90]
$^{127}I + {}^{197}Au$	—	Spectrum of δ electrons accompanying an inelastic nuclear interaction	$\approx 10^{-20}$	The same	[90]
$^{208}Pb + {}^{58}Fe$	5,9	Angular distribution of fragments	$\approx 10^{-20}$	Decay of compound nucleus or double system	[67]
$^{22}Ne + {}^{197}Au$	5,5	Angular distribution of products with $Z = 9$ and 11	$> 8 \cdot 10^{-21}$	Decay of double system	[83]
^{218}Ra	$E^* = 1 \div 3$ MeV	Scheme of excited levels	10^{-12}—10^{-9}	Excited levels of α-cluster branch	[95]
$^{20}Ne + Ge$	5,1	Blocking effect for targetlike product	$\approx 10^{-17}$	Nuclear quasimolecule	[94]
$^{40}Ar + Ag$	8,4	Angular distribution of nuclei with $Z = 3$–9	$\geqslant 3 \cdot 10^{-21}$	Decay of double system	[84]
$^{28}Si + {}^{28}Si$	4,3	Resonances of the excitation function	$> 6 \cdot 10^{-21}$	Nuclear quasimolecule	[88]
$^{16}O + {}^{28}Si$	2,0—3,5	Angular distribution of elastic scattering	$\geqslant 2 \cdot 10^{-21}$	Coherent superposition of amplitudes	[85]
$^{16}O + {}^{12}C$	7,5	Blocking effect for inelastic products with $Z = 6$–9	$\approx 10^{-18}$	Decay time of excited products	[92]
$^{28}Si + {}^{64}Ni$	4,4	Fluctuations of cross section	$(1\text{—}4) \cdot 10^{-21}$	Decay of a double system	[93]

cules has not yet been achieved, and it is therefore worth presenting a list of experiments in which information has been obtained (Table II). Besides the investigations already mentioned, the observation[95] of an α-cluster branch of excitations in ^{218}Ra is interesting. It is found that the quasimolecule, consisting of an α particle and a ^{214}Rn nucleus, has a lifetime in the interval 10^{-12}–10^{-9} sec and decays by a transition to levels of the compound nucleus ^{218}Ra. In this case, the nuclear quasimolecules are related to another physical phenomenon—cluster decay of heavy nuclei from the ground state.[96–101] In recent years, this effect has been established for several α-radioactive nuclei heavier than lead, which in a certain fraction of cases emit ^{14}C and ^{24}Ne nuclei. Therefore, even the ground state of heavy nuclei contains an admixture of the wave function of a quasimolecular system. Of course, this admixture is small, and the probability of such a decay branch is accordingly low; however, in principle it exists and has been observed experimentally.

The question of the formation and decay of short-lived dinuclear systems produced by the interaction of complex nuclei is intimately related to various features of these reactions. The present paper does not have the aim of giving a detailed description of the features of inelastic nuclear interactions. On this subject, there has recently been published a detailed review of the data,[102] in which estimates are also given of the duration of deep inelastic reactions found on the basis of the angular and energy distributions of the products.

CONCLUSIONS

The review of the studies made in recent years demonstrates the successful development of new methods for measuring the duration of nuclear reactions as well as an extension of the region of applicability of the methods already known. Accompanying the progress in the methods there is a development of the ideas about nuclear processes. New and previously undiscussed features have been revealed. Among them, we may mention the results that demonstrate that the decay time of the compound nucleus at a high excitation energy is significantly above the theoretical values. In addition, the attempts to determine experimentally the lifetimes of dinuclear systems (quasimolecules) warrant attention. And generally speaking the broad spectrum of reactions with heavy ions presents a large field for investigating the duration of nuclear processes. This problem will remain topical in the future too.

[1)]We have in mind scattering by nuclei that does not lead to their excitation, including Rutherford scattering.

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