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FISSION TIME-SCALE IN EXPERIMENTS AND IN MULTIPLE INITIATION MODEL

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Rate of fission for highly-excited nuclei is affected by the viscose character of the system motion in deformation coordinates as was reported for very heavy nuclei with $Z_C > 90$. The long time-scale of fission can be described in a model of "fission by diffusion" that includes an assumption of the overdamped diabatic motion. The fission-to-spallation ratio at intermediate proton energy could be influenced by the viscosity, as well. Within a novel approach of the present work, the cross examination of the fission probability, time-scales, and pre-fission neutron multiplicities is resulted in the consistent interpretation of a whole set of the observables. Earlier, different aspects could be reproduced in partial simulations without careful coordination.

INTRODUCTION

At present, the long time-scale fission is firmly established with the crystal-blocking [1–4] and atomic-clock [5] methods for heavy and super-heavy nuclear systems. The parameters of mentioned experiments are reduced in the table.

Great volume of results on the integral fission probability was deduced from the measured excitation functions of fission at moderate $Z_C < 90$ and of fusion–evaporation cross sections at $Z_C \geqslant 90$ in reactions with heavy ions. Additionally, a bulk of information is available on the pre-fission neutron multiplicity. Over recent decades, the coexistence of very high fission probability with long time-scale of fission for heavy nuclei was typically interpreted assuming that fission is driven by a multi-step neutron evaporation process. Residual excitation of the nucleus is decreasing in a course of the neutron-emission cascade, and the fission time is delayed due to that. The neutron-clock approach was founded in [6–8] and supported by many other groups. In [9], the idea of "fusion by diffusion" was introduced as an extension of the fission time description [10] in a model of the overdamped motion. The starting point of calculations [11–17] was linked to the neutron-clock approach similar in idea to [6–8] with variation of theoretical details of used equations and parameters. Full list of references would be too heavy for quotation here, but relevant bibliography is contained in reports [13].

Quantitatively, the time scale of fission was deduced attracting the statistical width of neutron emission and the multiplicity of pre-fission neutrons, sometimes neglecting [6] the longest time of a final step of the cascade — the step of successful fission. The time scale could be extended to 10^{-19} s [8, 10] and is explained in terms of fission retardation by friction forces in the viscose liquid flow. The Kramers theory involving the transient time for fission activation was applied in [18], unlike the simplified Kramers factor used as early as in 1970th [19]. The overdamped a diabatic motion takes, obviously, place in fission, but a quantitative accuracy of the existing theoretical models seems questionable.

Indeed, let us reduce the citation from one of the basic publications by Natowitz *et al.* [8]: "The decrease of P_f at higher energies is contrary to the normal statistical model expectations. It is this hindrance of the fission process which has been attributed to a dynamic effect." Similar remarks are contained also in [16]. The statistical model is thus unsatisfactory, but it is still used by the same authors for quantitative simulation of the neutron-fission competition. Somewhat inconsistent scheme does not allow one to trust the simulations [11–17] and similar variants as the final and accurate solution of theory. Even neglecting the logical defects, in quantitative simulations, the existing models could not yet resolve discontinuities in comparison to the experiments.

At moderate fissility parameter $Z^2/A \approx 34$–36, the theory may reproduce both fission probability and time-scale of the cascade process. However, for super-heavy systems, it would be impossible to do, because the fission time-scale is still long that should be combined with the picobarn scale for the cross

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Experiments for fission time-scale measurement

Target	Projectile	Z_C	E^*, MeV	Lifetime result	Reference
Crystals Si, Ni, Ge	^{208}Pb, ^{238}U	120–124 92–106	Up to 80 10–150	$>10^{-18}$ s (10%); 10^{-17}–10^{-18} s	[1, 2]
Crystal W	^{32}S, ^{48}Ti, ^{58}Ni, ^{74}Ge	90, 96, 102, 106	Definite values at 50 to 100	$(0.7$–$3) \times 10^{-18}$ s	[3, 4]
^{238}U	^{238}U	Inelastic, $Z \approx 92$	∼105 MeV	$\geqslant 4 \times 10^{-18}$ s (52%)	[5]

section of the evaporation-residue survival. In partial approach, very low cross sections for super-heavy element formation could be reproduced by theory [20], but not the long time-scale of "prompt" fission.

Recently, it was shown in [21] that fission probability for relatively light nuclei, as is deduced from the fission-to-spallation ratio, disagrees with the predicted energy dependence. In fission of light targets [8] by heavy ions, the decrease of P_f at high energy was also found, and some similarity with the results of [21] could be evident. That is despite very different characteristics of the ensembles of fissile nuclei in reaction with ions [8] and past spallation [21]. The nucleon composition, the excitation energy, and angular momentum distributions are very different.

A similarity could originate from the common nature of the fission process as a collective deformation of the massive system to scission. There exists, obviously, a factor retarding the fission rate by friction forces. This follows directly from the experimental results independent of the conventional analysis within the neutron-clock approach [6–8] with attraction of the complicated theories [9–19]. Such calculations exploit, among other components, the standard statistical widths for the compound nucleus (c.n.) decay and the viscosity parameters. However, they are yet imperfect containing the logical defects and inconsistencies listed below:

1. According to statistical model, the multichance pre-fission emission of neutrons should be suppressed at high fissility parameter $Z^2/A > 38$. But long time-scale of fission is manifested in this range, same as for the moderate Z^2/A nuclei. Therefore, long time is not due to the pre-fission processes reducing the excitation energy, E^*.

2. Very low cross section for super-heavy elements, $Z_C \geqslant 105$, contradicts the long time-scale of fission, despite the fact that both are measured for similar reactions.

3. Intense manifestation of fission delay with $\tau > 10^{-18}$ s for $Z_C = 120$ and 124 nuclei (unlike $Z_C = 114$) in French experiments [1] may mean very high fission barrier at $Z_C \geqslant 120$ and promises high cross sections for evaporation residue. That is not yet confirmed either by theory or by experiments.

Thus, developed earlier neutron-clock scheme driving fission is unable to reproduce in a consistent manner the time-scale experiments, the cross sections, and neutron multiplicities, all together, and in a wide range of Z_C from 70 to 124.

FISSION OF THE SPALLATION RESIDUE

Below, we formulate a new approach that should be, in general, appropriate for understanding of the listed above inconsistencies in a satisfactory manner. In experiments [22–24], the fission-to-spallation ratios were determined and it was possible to deduce fission probability for relatively light nuclei with $Z \approx 70$. Now, we try to demonstrate that standard statistical approach fails to reproduce for the measured excitation functions. Then, the revealed deviations will support a new fission scheme that follows from the time-scale analysis, as is explained below.

Traditionally, the "intermediate" energy of protons is defined as corresponding to the range of $100 < E_p < 1000$ MeV, where the mechanisms of pre- and non-equilibrium emission of nucleons are switched on and become competitive to the statistical evaporation mechanism. One may assume that at 150 MeV, the equilibrium and non-equilibrium mechanisms make comparable contributions in the abundance. For simplicity, we will join pre- and non-equilibrium processes under common term of the fast reaction mechanism. At intermediate energy, the slow (evaporation) stage of the excited residue decay proceeds past the fast stage including the intranuclear cascade and the pre-equilibrium emission. In the series of experiments carried out [22–24] at Dubna synchrocyclotron, the yields of spallation and fission products have been systematically measured in reactions of protons with the Hf, Ta, W, and Re targets at $E_p = 100$–650 MeV.

In experiments, Z and A numbers of the detected products are reached after ending of both stages of the reaction. As measured, mass distributions show that a mean number of emitted nucleons does not exceed 8 to 15 particles at $E_p = 100$ to 200 MeV, respectively. During the fast stage, neutrons and protons are emerged with almost equal probability without specific selectivity, unlike the statistical evaporation of mostly neutrons. Before evaporation, the residual product remains near the β-stability line if the β-stable nucleus is used as a target.

Experimental mass distributions allow to estimate Z, A, and E^* for intermediate residual products, and then the statistical calculations might be productive for the fission probability prediction. Certainly, this approach looks schematic, but in restricted range of the proton energies from 100 to 300 MeV, an accuracy of predictions must be acceptable. As a typical example, the measured [24] fission-to-spallation ratio is shown in Fig. 1 for the reactions of protons with the $^{\rm nat}$Hf and ^{179}Hf targets.

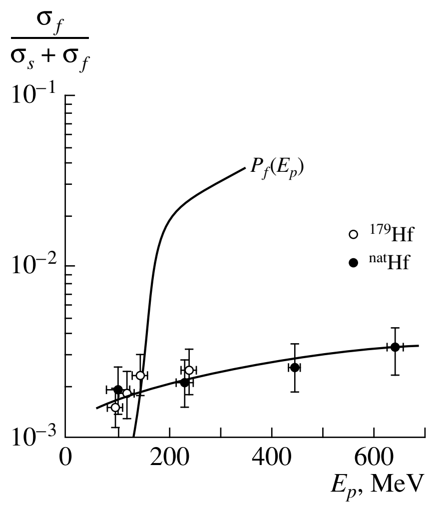

Fig. 1. The calculated integral fission probability $P_f(E_p)$ in comparison to the measured fission-to-spallation ratio shown by points and accompanied with the guide line [24].

Shown excitation function just defines a behavior of the integral fission probability in these reactions. For comparison, the theoretical calculations are carried out for the ^{174}Yb nucleus which should be formed as a spallation residue in interaction of protons with Hf and Ta targets at energies $E_p \leqslant 200$ MeV. In statistical model, the probability depends on (E^* and is expressed as a ratio of decay widths: $w_f(E^*) = \Gamma_f(E^*)/\Gamma_t(E^*)$, where Γ_t is a total width containing all partial widths of the opened decay channels with emission of neutrons, protons, gammas, etc.: $\Gamma_t = \Gamma_f + \Gamma_n + \Gamma_p + \Gamma_\gamma + \ldots$ The applied scheme was adjusted earlier for simulation of the fission data in [21, 25, 26].

At moderate E^* values, main contribution corresponds to the neutron emission, and $w_f \approx \Gamma_f/(\Gamma_n + \Gamma_f)$. In numerical calculations, the level density $\rho(E^*)$ function was taken by the Gilbert–Cameron formula [27], and the Moretto equation [28] was used for Γ_n calculations. Fission width was obtained in the Bohr–Wheeler approach multiplied by Kramers factor taken in the simple approximation [19]:

$$\Gamma_f(E^*) = \frac{\left(\sqrt{1+\eta^2}-\eta\right)}{2\pi\rho_c(E^*)} \times \times \int\limits_0^{E^*-B_f} \rho_f(E^*-B_f-\varepsilon)d\varepsilon. \tag{1}$$

The Kramers factor includes a nuclear-matter viscosity η parameter, and its numerical value, being constant, does not influence the energy dependence of Γ_f, only defines the absolute scale. For better approximation to the absolute Γ_f values, we took a moderate value $\eta = 5$ in our calculations, according to [25]. The level density parameters were taken as in [25]: $a_n = a_c = A/10$ and $a_f = 1.1a_n$. The calculated fission probability $w_f(E^*)$ is a differential function, thus for the comparison to experiments one has to account for the multi-chance fission probability after emission of neutrons. The corresponding sum was finally integrated over whole range of possible E^* values at definite proton energyE_p. The spectral weight function $S(E^*, E_p)$ was in account, and the integral fission probability function $P_f(E_p)$ could be obtained after integration. The result of calculations is compared in Fig. 1 with the experimental values. The choice of spectral function and other details are contained in [21].

For the present discussion, it would be essential to see that calculated $P_f(E_p)$ probability, being a steep function, cannot fit the experimental points. Such discrepancy is steady under variation of the parameters within a reasonable range. Similar behavior was deduced earlier in [23] from more complicated calculations using the standard code verified for simulation of the spallation yields. Again, strongly growing fission probability versus energy resulted despite a different method of calculations. One might be sure that more or less flat $P_f(E_p)$ function revealed in experiments [22–24] contradicts the statistical calculations. What is the reason for that?

From Eq. (1) it follows that the Γ_f/Γ_n ratio should grow up exponentially with the nuclear temperature T increase when fission barrier B_f is much higher than the neutron binding energy B_n. The ratio is

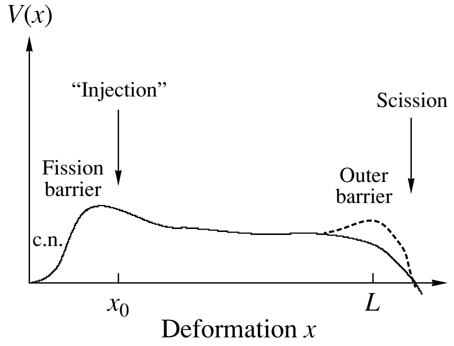

Fig. 2. Model lay-out of the potential energy extremes versus the generalized deformation parameter for a fissile system. The figure is taken from [3].

approximated by $\exp[-(B_f - B_n)/T]$ due to the exponent in a level density $\rho(E^*)$ function. In our case, the spallation residue ^{174}Yb and the neighbor nuclei should be really characterized, according to [29], by high fission barrier $B_f \approx 20$–25 MeV which is much higher than $B_n \approx 7$ MeV.

Thus, the calculation just reflects a natural trend, as far as the statistical approach is chosen for simulations. The observed contradiction to experimental results means that the general scheme of the mechanism should be revisited. The same conclusion follows from the long time-scale of fission for heavy systems. Both relatively light and heavy fissile nuclei create the difficulties for data fit. Possibly, the statistical model is still worthy for the medium-mass nuclei, but we are interested to resolve the logical contradictions in the wide range of Z^2/A.

LONG TIME-SCALE OF DEFORMATION

The viscose character of the nuclear-matter collective motion was realized since many years ago. The simplified account of the viscosity in a form of the Kramers factor, as in Eq. (1), does not allow extension of the deformation time up to 10^{-18} s. In more developed models, several groups [9–17] have obtained a factor that modifies the time scale from 10^{-20} to 10^{-19} s, and not longer. However, the experimental results insist on the essentially longer time [3, 4]. The magnitude of time is typically near 10^{-18} s for fission of $Z_C = 90$, 96, 102, and 106 nuclei formed in irradiation of W crystal by S, Ti, Ni, and Ge ions, respectively. The time scale does not demonstrate a trend of strong dependence on the c.n. excitation.

Let us assume that the potential gradient creates relatively weak driving force in collective coordinates, and the type of motion is explicitly defined by very high viscosity. This approximation corresponds to the known diabatic overdamped motion. The elongation is accumulated due to the diffusion in collective coordinates, and the potential force does not dominate on the way from the "injection"' point to the scission. In Fig. 2, the process scheme is illustrated for heavy systems. The injection point corresponds to the figure of touching projectile and target nuclei, both massive. "Elongation" replaces in Figs. 2 and 3 the generalized collective coordinate.

Diffusion mechanism is essentially linked to random fluctuations when the thermal energy is transformed into the kinetic energy of a collective mode. Each random push supplies only a little step in collective coordinates due to both possible dissipation of the collective velocity and its reorientation by the following pushes. Slow development of the process in time could be expected. However, a system may progress in any direction and finally reach different exit channels of the reaction.

There is a chance to reach a compound nucleus minimum located at zero deformation. In excited super-heavy systems, the minimum should be narrow and not very deep. Thus, it is reached by diffusion with low probability just due to the restricted phase volume of the specific deformation range near zero. A motion against the potential force additionally suppresses the probability. When the system appears by lucky chance at small deformation, it would continue the diffusion out of the fission barrier. The stabilization of a system near zero deformation by neutron evaporation may happen with extremely low probability. Finally, the evaporation residue formation will be characterized by a product of two low-probability factors, and the cross section for super-heavy element synthesis at a level of picobarns becomes understandable. Such a scheme does not, in principle, contradict the known mechanism of "fusion-by-diffusion" [9].

What can be concluded from the same scheme of Fig. 2 for the fission process? Due to the diffusion, a system may drift to the scission point. After a projectile capture, the united system is formed and it cannot return back to the entrance channel, because the ion kinetic energy is already absorbed. The only sink remains open to scission via the fission valley. Naturally, the fission probability turns out to be almost 100%.

In this discussion, we stress mostly the diffusion mechanism and almost ignore the potential landscape properties. Some directions in the collective coordinates are forbidden by strong growth of the potential energy. The elementary push in such a direction is immediately reflected and its kinetic energy could pump some vibration mode, but it is damped fast with the transfer of energy back to the thermal energy due to high viscosity. The only direction is opened to provide real step in collective coordinates — the fission valley characterized by relatively weak potential gradient. But, even in this case, the motion to scission is essentially random because each consequent push may shift the system to opposite or useless direction, not to the scission. Finally, scission deformation can be accumulated due to the random statistics of elementary pushes. Each of them shifts a system to the "right", or "wrong" direction and the asymmetry arises only after many events. Thus, we propose the following title for the model described here: "multiple-initiation model". Some details are given below in the corresponding section.

Let us return to the fate of the long-lived fissile system. On the way to scission, it is still excited and can evaporate neutrons with the temperature decrease. The neutrons do not supply an additional contribution to the evaporation residue yield because the binary system is driven to split into two fragments. The pre-scission neutron evaporation can stop even before that, if the excitation energy remains only in a form of the deformation energy. The post-scission neutron multiplicity M_n of about 2—3 may be explained as a manifestation of the deformation energy at scission point.

In experiments, the post-scission values do not exceed much that, being of $M_n \approx 4$—5, and the conclusion follows that fission evolution time should be as long as is required for almost complete cooling of the deformed system. Remaining excitation is enough to add only 1 or 2 neutrons. Thus, long time-scale, near 10^{-18} s, is confirmed also by relatively low multiplicity of the post-scission neutrons in addition to direct estimates of fission time in blocking experiments. Fission probability could be reproduced due to variation of the fission barrier as is already commented, and now it is possible to conclude that different manifestations in fission can be explained all together without internal contradictions within this new approach to fission mechanism.

One could ask, whether the scheme is really new, or it is practically similar to the known neutron-clock scenario [6]? In the logics of [6], the fission is delayed because of decreased excitation energy in multi-step neutron evaporation cascade. The probability and lifetime for each individual step of the fission-neutron competition are supposed to be obtained within the standard statistical-model calculations. In general, nothing very new was proposed in [6], as compared to previous works, for instance [30, 31], because in [6] there is developed in more detail the known cascade scheme of the c.n. decay. The quantitative analysis showed [25, 32] that the cascade scheme is capable to describe fission properties only at moderate fissility parameter. Within the range of $Z^2/A \approx 34$—36, the width ratio Γ_f/Γ_n, being comparable to unity, provides an extended chain of multi-chance fission. Delayed fission due to the decreased E^* may take place in this case, but not for lighter, or heavier systems.

Long way in deformation coordinates should be passed by the system before it reaches the scission shape starting from the initial configuration. The corresponding time parameter τ_d serves as an inherent characteristic for fission evolution, not the statistical model time $\hbar/\Gamma_f$. Fission is not retarded in time due to the neutron emission with E^* decrease. Oppositely, the neutrons have time for evaporation because of the deformation-time τ_d parameter. It inherently defines both the fission evolution time and the pre-scission neutron multiplicity. The causal consequence of the processes is reversed now, as compared to the statistical approach. This formal argument is enough to cancel the idea on similarity of the novel scheme and of the neutron-clock interpretation [6]. Other, developed theories [9—17] did not yet include the discussion of the reversed causal order in the fission—evaporation competition.

The internal contents of the novel approach should also be very different from the previously discussed in literature, some arguments and results are discussed in the following section. The diffusion time may influence the integral fission probability for light nuclei, not only provides long time-scale for heavy nucleus fission. Some points remain still unclear, for instance, possible existence of an additional potential barrier near the scission point. It is shown in Fig. 2 for illustration. Clearly, if exists, it should retard fission because diffusion against potential force is manifested in the suppressed fission rate. Thinkable reasons for appearance of a barrier at scission point were discussed earlier in [3, 33, 34]. For simplicity, we skip here those arguments because the experimental results can be explained in the diffusion model without additional barrier.

MULTIPLE INITIATION MODEL

For relatively light fissile nuclei with $Z^2/A \sim 32$, fission barrier is as high as $B_f \approx 22$ MeV [29], and the corresponding saddle point is located near the scission deformation. Thus, long path corresponds to the motion from initial configuration to the saddle (scission) elongation. Let us estimate the time scale of fission for light nuclei in semi-quantitative scheme that might be valuable despite simplifications. It was explained above that fission probability for light nuclei should demonstrate in statistical model the exponential growth with nuclear temperature and this is not confirmed in experiments. But what is expected in the novel approach?

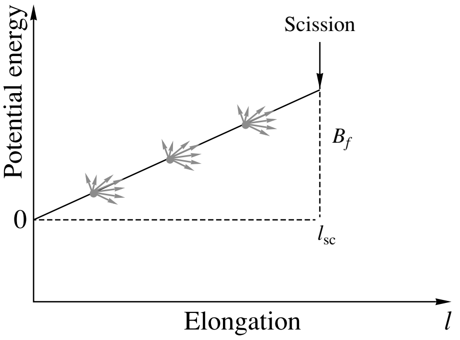

Fig. 3. Multi-step initiation of the collective motion.

Within the dissipative inertial process, the deformation time τ_d should depend on the path length in collective coordinates. According to theories [14], the friction parameters are changing slowly at temperature $T > 0.5$ MeV, and nothing else must strongly influence the fission rate for some definite nucleus. Then, fission excitation function should appear as a relatively flat function. One may assume that fission probability is still defined by the process rate linked to the characteristic time $\sim\tau_d^{-1}$. This assumption looks natural, even despite another physical content of τ_d , as compared to the τ_f parameter in traditional models. In excited nucleus, the thermal energy can be transferred to the collective mode in a quantity proportional to the temperature T via mechanism of random fluctuations, like in Brown motion. Correspondingly, the collective velocity should be proportional to the square root of temperature $v_d \sim \sim T^{1/2}$, the deformation time τ_d is defined by v_d^{-1} and fission probability by τ_d^{-1}. Collecting all together, one obtains:

$$W_f \sim \tau_d^{-1} \sim \left[(v_d)^{-1}\right]^{-1} \sim T^{1/2}. \qquad (2)$$

From qualitative estimates according to Eq. (2), it is clear that fission probability should be a flat function of the excitation energy, unlike the statistical exponential growth. This is one argument more to the favor of the novel approach, because the flat dependence is revealed in experiments [22–24], and in particular, is shown in Fig. 1. The system evolution to scission is accompanied by the neutron emission, but it cannot modify the inherent fission time, either to prevent fission until a sum of deformation and thermal energy is suppressed below the fission barrier. A total time $\sum\tau_n$ of the neutron cascade reducing E^* down to B_f value should be compared to the dynamical deformation time τ_d, and this ratio will define the probability of successful fission:

$$W_f = \frac{\sum\tau_n}{\tau_d}. \qquad (3)$$

For some definite nucleus, the nominator would not be strongly dependent on the initial excitation energy, because $\sum\tau_n$ is defined mainly by the last step of the cascade. Then, the probability W_f is proportional to τ_d^{-1}, as is assumed in Eq. (2).

The statistical-model calculations are applied for the simulation of fission properties in many publications. But recent experiments bring the evidence that this model is unable to reproduce the fission timescale for very heavy systems, and must be strongly modified for simulation of the fission probability in the case of medium-mass nuclei. For medium $Z^2/A \approx \approx 34$–36, the time parameters of both neutron cascade $\sum\tau_n$ and fission–deformation path τ_d are comparable in magnitude. Therefore, a scheme of competition between both processes in the statistical-model style could be applied. However, at much higher and much lower Z^2/A values, the traditional scheme, obviously, fails.

Let us specify the model for quantitative estimates of the characteristic time τ_d. The scission deformation is reached due to the multi-step pumping of the collective mode by random thermal fluctuations. The scheme is illustrated in Fig. 3. For collective motion, the simplifying assumptions are introduced here, as follows: the effective mass to be a half of the composite system mass $M_C/2$, the potential energy to be a linear function scaled at the scission elongation: $U(l_{\rm sc}) = B_f = 22$ MeV, and the temperature to be a constant. The quantitative estimates are carried out taking $T = 1.5$ MeV, and the corresponding mean-energy step in the collective mode to be $3T/2$.

The direction to successful scission is supposed to be a vector in three-dimensional space. In forward hemisphere, the collective velocity should be projected to the corresponding axis, and the longitudinal velocity is averaged over the polar angle θ from 0 to $\pi/2$ and φ from 0 to 2π. The random direction of fluctuations is accounted by this procedure. A mean energy deposited into the collective-deformation growth is then deduced to be $T/2 = 0.75$ MeV which defines a potential-energy step to scission past a single fluctuation. In kinetic approximation, it is possible to estimate the time of collective velocity deceleration by the growing potential:

$$t = -\frac{v_0}{a} = \frac{1}{2}\left(T \cdot M_C\right)^{1/2}\left(\frac{dU}{dl}\right)^{-1}, \qquad (4)$$

where dU/dl is the gradient of potential energy, a is the corresponding deceleration value, and v_0 is initial velocity due to the thermal fluctuation push. The velocity v should degrade to zero within time of about 1.5×10^{-21} s, according to Eq. (4), and the potential energy is increased by a step of 0.75 MeV over this time. Clearly, 30 successful steps are needed to reach a fission barrier when it is as high as of about 22 MeV.

The velocity vector orientation in backward hemisphere is contra-productive for the wanted processing to scission because it reduces the potential energy and the deformation magnitude. In general, the thermal fluctuations provide equal probability for vector orientation to forward or backward hemispheres. Random oscillations regularly happen remaining the elongation near the initial coordinate. Only 50% of all elementary pushes shift the deformation to right direction, while 50% of them return the system back. Due to statistics, the asymmetry between the numbers of "right" and "wrong" fluctuations may arise, and it is proportional to the square root $N^{1/2}$ of a total number of attempts. Excessive 30 fluctuations to right direction may appear past 900 elementary pushes, in total. As estimated above, the collective velocity is decelerated by potential force to zero within time-scale of 1.5×10^{-21} s. 900 elementary pushes may happen during the time interval comparable with 1 as $= 10^{-18}$ s, and this is in good accordance with the typical fission time measured by crystal blocking method for different targets and projectiles [1–4].

In excited nuclei, the collective motion is coupled with thermal energy due to the high viscosity of nuclear matter. The elementary pushes are systematically produced by thermal fluctuations. The rate of pushes should correspond to the characteristic time of about 10^{-21} s, according to [14, 15], but the accurate value of this time is unknown. In the present estimates the periodicity time of about 1.5×10^{-21} s is assumed. Similar time interval characterizes the deceleration of the collective velocity by the potential force, as is shown above. In reality, the periodicity time of pushes can be shorter, or longer. If longer, then the fission time should be extended to a value $>10^{-18}$ s, and this is still in agreement with the blocking experiments, but deviates from theoretical estimates of [9–19].

Another scenario corresponds to the case when the viscosity is so high that the elementary pushes happen very often with the periodicity time shorter than 10^{-21} s. So short time is not enough for the kinetic energy transformation into the potential deformation energy because each next push breaks the previous one and destroys the directed motion. Then, the required number of total events for accumulation of the barrier potential energy should increase reversely proportional to an efficiency of the potential energy pumping. The concluded fission time remains practically stable near 10^{-18} s, because increased rate of perturbations is accompanied by the decreased efficiency of energy transfer to the barrier energy. The time range of about 10^{-18} s seems trustable for qualitative comparison to experiments.

Similar logic should be valid for very heavy systems, as well, even if the fission barrier is almost completely diminished. There is no need to pump the potential energy for climbing to the barrier top, but instead, the elongation coordinate should be accumulated past many events of the kinetic energy initiation by thermal fluctuations. Same as above, each next push may destroy the directed motion due to the previous one, and the significant deformation is reached only past many single fluctuations via the diffusion mechanism.

SUMMARY

Finally, within the model of multi-step initiation of the collective motion, the fission time is estimated on the scale of 10^{-18} s, in accordance with known experimental results. This model includes an exchange between the thermal energy and collective modes due to intense friction (viscosity) in nuclear matter. Time of deformation by diffusion plays the role of a key parameter for treatment of the fission process, in general. Deformation defines the full time-scale of fission for heavy systems, and it may influence the integral fission probability for relatively light nuclei. In the fission-neutron competition, the causal order is now reversed because the long deformation time is responsible for a multiplicity of the pre-scission neutrons. Earlier, it was on the contrary supposed that fission delay is caused by neutron emission due to the excitation decrease.

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REFERENCES

1. M. Morjean, D. Jacquet, J. L. Charvet, *et al.*, Phys. Rev. Lett. **101**, 072701 (2008).
2. F. Goldenbaum, M. Morjean, J. Galin, *et al.*, Phys. Rev. Lett. **82**, 5012 (1999).
3. J. U. Andersen, J. Chevallier, J. Forster, S. A. Karamian, *et al.*, Phys. Rev. C **78**, 064609 (2008).
4. J. U. Andersen, J. Chevallier, J. S. Forster, S. A. Karamian, *et al.*, Phys. Rev. Lett. **99**, 162502 (2007).
5. J. D. Molitoris, W. E. Meyerhof, Ch. Stoller, *et al.*, Phys. Rev. Lett. **70**, 537 (1993).
6. D. Hilscher and H. Rossner, Ann. Phys. (Paris) **17**, 471 (1992).
7. P. Paul and M. Thoennessen, Ann. Rev. Nucl. Part. Sci. **44**, 65 (1994).
8. J. B. Natowitz, M. Gonin, M. Gui, *et al.*, Phys. Lett. B **247**, 242 (1990).
9. W. J. Swiatecki, K. Siwek-Wilczyńska, and J. Wilczyński, Phys. Rev. C **71**, 014602 (2005).

10. K. Siwek-Wilczyńska, J. Wilczyński, R. H. Siemssen, and H. W. Wilschut, Phys. Rev. C **51**, 2054 (1995).
11. V. Zagrebaev and W. Greiner, J. Phys. G **31**, 825 (2005).
12. V. A. Rubchenya, A. V. Kuznetsov, W. H. Trzaska, *et al.*, Phys. Rev. C **58**, 1587 (1998).
13. I. I. Gontchar, Fiz. Elem. Chastits At. Yadra **26**, 932 (1995); P. Fröbrich, Nucl. Phys. A **545**, 87c (1992).
14. H. Hofmann and D. Kiderlen, Phys. Rev. C **56**, 1025 (1997).
15. H. Feldmeier, Rep. Prog. Phys. **50**, 915 (1987).
16. D. J. Hinde, D. Hilscher, H. Rossner, *et al.*, Phys. Rev. C **45**, 1229 (1992).
17. V. V. Sargsyan, Yu. V. Palchikov, Z. Kanokov, *et al.*, Phys. Rev. C **76**, 064604 (2007).
18. J. Benlliure, P. Armbruster, M. Bernas, *et al.*, Nucl. Phys. A **700**, 469 (2002).
19. K. T. R. Davies, R. A. Managan, J. R. Nix, and A. J. Sierk, Phys. Rev. C **16**, 1890 (1977); J. Blocki, Y. Boneh, J. R. Nix, *et al.*, Ann. Phys. (N.Y.) **113**, 330 (1978).
20. V. Zagrebaev and W. Greiner, Phys. Rev. C **78**, 034610 (2008).
21. S. A. Karamian, Yad. Fiz. **72**, 982 (2009).
22. S. A. Karamian, J. Adam, D. V. Filossofov, *et al.*, Nucl. Instrum. Methods A **489**, 448 (2002).
23. S. A. Karamian, J. Adam, P. Chaloun, *et al.*, Nucl. Instrum. Methods A **527**, 609 (2004).
24. S. A. Karamian, C. A. Ur, J. Adam, *et al.*, Nucl. Instrum. Methods A **600**, 488 (2009).
25. S. A. Karamian, J. S. Forster, J. U. Andersen, *et al.*, Eur. Phys. J. A **17**, 49 (2003).
26. S. A. Karamian, A. B. Yakushev, Yad. Fiz. **70**, 227 (2007).
27. A. Gilbert and A. G. W. Cameron, Can. J. Phys. **43**, 1446 (1965).
28. L. G. Moretto, Nucl. Phys. A **180**, 337 (1972).
29. A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
30. J. S. Forster, I. V. Mitchell, J. U. Andersen, *et al.*, Nucl. Phys. A **464**, 497 (1987).
31. V. N. Bugrov, V. V. Kamanin, S. A. Karamian, Yad. Fiz. **33**, 611 (1981).
32. V. N. Bugrov, S. A. Karamian, Yad. Fiz. **40**, 857 (1984).
33. S. A. Karamian, in *Book of Abstracts, International Conference "Nucleus 2007"*, Ed. by A. K. Vlasnikov (Nauka, St. Petersburg, 2007), p. 140.
34. S. A. Karamian, in *Proceedings of the International Symposium EXON 2009, Sochi, Sept. 2009*, Ed. by Y. E. Penionzhkevich and S. M. Lukyanov (AIP Press, Melville, New York, 2010), p. 402.

ШКАЛА ВРЕМЕНИ ДЕЛЕНИЯ СОГЛАСНО ЭКСПЕРИМЕНТАМ И В МОДЕЛИ МНОГОКРАТНОГО СТАРТА

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Известно, что деление очень тяжелых ядер с $Z_C > 90$ при высокой энергии возбуждения определяется вязким характером движения ядерной жидкости в координатах параметров деформации. Шкала времени деления оказывается длительной, если процесс описывается в модели "деления посредством диффузии" в диабатическом пределе заторможенного движения. Отношение вероятностей деления и скалывания в реакциях с протонами промежуточной энергии также подвержено влиянию вязкости. В новом подходе настоящей работы перекрестный анализ временнóй шкалы и вероятности деления, а также множественности преддделительных нейтронов приводит к выводу о возможности непротиворечивого описания всего набора наблюдаемых величин. Ранее различные аспекты описывались фрагментарно, без должного согласования.