E7-2016-21

V. V. Volkov [1], E. A. Cherepanov [1, 2, *], Sh. A. Kalandarov [1, 3]

INTERPRETATION OF THE MECHANISM OF SPONTANEOUS FISSION OF HEAVY NUCLEI IN THE FRAMEWORK OF DINUCLEAR SYSTEM CONCEPTION

Submitted to "Particles and Nuclei, Letters"

[1] Joint Institute for Nuclear Research, Dubna
[2] State University "Dubna", Dubna, Russia
[3] Institute of Nuclear Physics, Tashkent
[*] E-mail: cher@jinr.ru

Волков В. В., Черепанов Е. А., Каландаров Ш. А. E7-2016-21

Интерпретация механизма спонтанного деления тяжелых ядер
в рамках концепции двойной ядерной системы

Предлагается новый подход к интерпретации процесса спонтанного деления тяжелых ядер, который опирается на данные, полученные в ядерно-физических исследованиях с тяжелыми ионами. Спонтанное деление включает в себя три последовательно протекающие стадии: кластеризацию валентных нуклонов тяжелого ядра в легкое ядро-кластер, в результате чего возникает двойная ядерная система; эволюцию двойной ядерной системы, протекающую путем передачи нуклонов от тяжелого к легкому ядру, и распад двойной системы из равновесной конфигурации на два ядра-осколка.

Работа выполнена в Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2016

Volkov V. V., Cherepanov E. A., Kalandarov Sh. A. E7-2016-21

Interpretation of the Mechanism of Spontaneous Fission
of Heavy Nuclei in the Framework of Dinuclear System Conception

A new approach to the interpretation of the process of spontaneous fission of heavy nuclei is suggested. It is based on nuclear physics data which are obtained in heavy ion collisions. The process of spontaneous fission consists of three sequential stages: clusterization of the valent nucleons of a heavy nucleus into a light nucleus-cluster, which leads to the formation of a dinuclear system; evolution of the dinuclear system which proceeds by nucleon transfer from the heavy to light nucleus; and decay of the dinuclear system from the equilibrium configuration into two fragments.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2016

INTRODUCTION

The assumption about a possibility of spontaneous fission of ^{238}U nuclei was first made by N. Bohr and J. Wheeler in their classical paper clarifying the mechanism of fission of uranium nuclei [1]. The description of low-energy fission of uranium was based on the liquid-drop model of the nucleus. In the framework of this model, spontaneous fission of ^{238}U nuclei was impossible due to the lack of energy needed to overcome the fission barrier. However, the authors in [1] used quantum mechanics to interpret this nuclear process. The decay of ^{238}U nucleus into two fragment nuclei proceeded at the expense of quantum mechanical penetration of one of the nuclei through the fission barrier. The required kinetic energy was drawn from the energy of zero fluctuations of the quantum system consisting of two nuclei ($hw \sim 0.8$ MeV). The calculation of the penetrability of the fission barrier was done using the method proposed by G. Gamow for the description of α decay [2]. According to the calculations in [1], the ^{238}U half-life was to be $\sim 10^{22}$ years. Such a value of half-life held out little hope for the experimental observation of spontaneous fission of ^{238}U.

However, K. A. Petrzhak and G. N. Flerov managed to observe experimentally the decay of ^{238}U nuclei into two nuclear fragments in 1940. After thorough experiments which excluded the influence of cosmic rays, it was reliably proved that they observed spontaneous fission of ^{238}U nuclei [3]. But the half-life turned out to be 6 orders of magnitude smaller than predicted by the theory. The rapid development of nuclear physics in the post-war years, first and foremost, the experiments on the synthesis of transuranium elements, resulted in a discovery of tens of new spontaneously fissioning nuclei. Their half-lives varied in quite a wide range: from 10^{18} years up to seconds and milliseconds. The most complete information about the spontaneous fission of isotopes of elements from thorium to meitnerium can be found in a review by N. Holden and D. Hoffman published in 2000 [4].

1. THE PRESENT-DAY CONCEPT OF THE MECHANISM OF SPONTANEOUS FISSION

The mechanism of spontaneous fission is briefly described in the chapter “Spontaneous Fission” in the book [5]: “Spontaneous fission, i.e., the disintegration of the nucleus in two heavy fragments without exterior supply of energy,

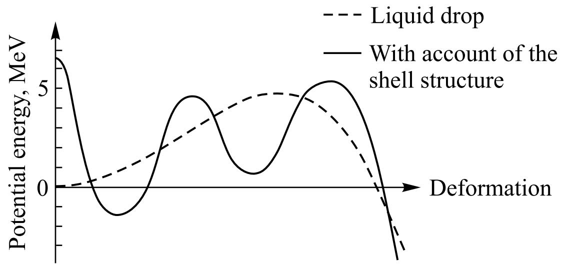

Fig. 1. A schematic representation of the fission barriers for the actinides

occurs via a quantum mechanical tunneling through the fission barrier, so the penetration of this barrier is the dominant factor in determining the probability for spontaneous fission.

The ground state spontaneous fission half-life $T_{1/2}$(SF) can be expressed as $T_{1/2}(\mathrm{SF}) = \ln 2/(f_0 P_0)$, where $f_0 = w_0/2\pi$ is the frequency of oscillations in the fission mode for the ground state in the first well, and P_0 is the barrier penetrability for the ground state. For a vibrational frequency corresponding to $hw_0 = 1$ MeV, one obtains a number of barrier assaults $f_0 = 2.5 \cdot 10^{20}$ per second. The barrier penetrability P_0 is usually calculated along the effective fission trajectory from the ground state to the exit of the barrier along a one-dimensional path of least action (WKB approximation)."

Figure 1 shows fission barriers for the actinide nuclei [5]. The way from the ground state up to the point of exit from the fission barrier is calculated for the one-dimensional trajectory in accordance with the classical principle of least action. It is assumed that a spontaneously fissioning nucleus in the ground state has a zero energy level ~ 0.5 MeV, which ensures the frequency of oscillations in the fission mode of $\sim 10^{20}$ oscillations per second, leading to a spontaneous fission of the original heavy nucleus.

Because the penetration through the fission barrier is a dominant factor in the spontaneous fission, it is useful to briefly examine this phenomenon. The passage of a microparticle through the potential barrier is a quantum mechanical process taking place due to its corpuscular-wave dualism. If we address such classical processes as α decay and cluster radioactivity, we shall see that both the α particle and the cluster nucleus make oscillating motions inside a "potential pocket" which localizes their motion in a particular area of space. The wave properties of an α particle and a cluster nucleus, their mass, and the size of the "potential pocket" determine the frequency of zero oscillations of these particles.

During a spontaneous fission, there is no spatial "potential pocket" where the fissioning nucleus could make zero oscillations. It can only change its shape. If a zero quantum level is achieved at the first minimum of potential energy (see Fig. 1), it will produce only pulsating vibrations of shape of the heavy nucleus, which will hardly lead to its spontaneous fission. This situation does not change in the case when the potential energy of a spontaneously fissioning nucleus is represented as a function of its deformation along the large axis.

Nuclear physics research using heavy ions, in our opinion, allows one to analyze the mechanism of spontaneous fission of heavy nuclei in a brand new way.

2. NEW INFORMATION ABOUT THE PROPERTIES OF NUCLEI AND NUCLEAR PROCESSES OBTAINED IN HEAVY ION INVESTIGATIONS

Nuclear physics research using heavy ions resulted in a discovery of two new objects of nuclear micro-world and a principally novel evolutionary nuclear process. In 1960, E. Almqvist, D. A. Bromley and J. A. Kuchner [6] observed the formation of nuclear molecules in a collision of two ^{12}C nuclei. Such a nuclear molecule is composed of two nuclei being in close contact with each other, yet preserving for a long time, at a nuclear scale, their own individuality.

The discovery of deeply inelastic transfer reactions (DITR) [7, 8] indicated that the collision of two nuclei with an energy higher than the Coulomb barrier is accompanied by a complete dissipation of the collisional kinetic energy that transforms into internal excitation of the colliding nuclei as well as by the formation of a nuclear complex — a dinuclear system (DNS). Both nuclei in the DNS intensively interact with each other and exchange weakly bound nucleons of the upper shells while preserving their individuality due to the tightly bound nucleons of the lower shells. Contrary to nuclear molecules, the DNS is unstable. Its evolution progresses fairly quickly at the expense of nucleon transfer from one nucleus to another. The evolution of the DNS is governed by its potential energy which is dependent on the system's charge and mass asymmetry. If the nucleons are passed from the light to heavy nucleus, such an evolution culminates in the emergence of a compound nucleus. However, the nucleon transfer in the opposite direction results in the DNS shape symmetrization. This shape proves to be unstable for a massive DNS which breaks up into two nuclear fragments during a quasi-fission process.

The fission of a heavy nucleus is an evolutionary process where the fissioning nucleus is to pass through an array of intermediate states. A classical analogue of this process will be a liquid drop of a smoothly varying shape that may break up into two smaller droplets. The interpretation and description of the heavy-nucleus fission in the framework of the liquid-drop nuclear model [1] have stayed in nuclear physics for a long time.

The DNS, together with DITR, has revealed a real evolutionary nuclear process which leads to deep restructuring of the nucleus or a system of two nuclei formed after their collision. Nuclei are composed of neutrons and protons, and the most natural way for their deep restructuring is to donate and accept nucleons. But the nucleon transfer is possible only in the presence of another nucleus contacting with the given nucleus. Therefore, we arrive at the following remarkable conclusion: an essential prerequisite for a deep restructuring of the nucleus or a complex of two nuclei is the formation of a dinuclear system.

During the fusion of nuclei into a compound nucleus or a quasi-fission process, the formation of a DNS is obvious: when a collision of two nuclei occurs, the kinetic energy of collision transforms into internal nuclear excitation, and the colliding nuclei become bound together into a dinuclear system by the nucleus–nucleus potential. However, with the spontaneous fission we have to deal with a heavy nucleus in the ground state. How does the formation of a DNS occur in that case? The answer is suggested by the cluster radioactivity. Analysis of this nuclear process in paper [9] indicated that nuclei heavier than ^{208}Pb have the ability to spontaneously condense valence nucleons — the nucleons which are found in the states of super-closed proton and neutron shells of the ^{208}Pb nucleus playing the role of the cores — into nuclei of light elements, the clusters. Formation of an asymmetric nuclear molecule takes place when all the valence nucleons have been condensed to a cluster, as it happens in the light isotopes of radium and actinides. We assume that the ability of heavy nuclei to condense valence nucleons to nuclear clusters is inherent to all nuclei heavier than ^{208}Pb.

3. THE MECHANISMS OF SPONTANEOUS FISSION OF HEAVY NUCLEI IN THE FRAMEWORK OF THE DINUCLEAR SYSTEM CONCEPTION

In the framework of the proposed approach, spontaneous fission of heavy nuclei takes place in the space of the DNS charge and mass asymmetry. It includes three consecutive stages: formation of the DNS, its evolution up to the equilibrium configuration and decay into two nuclear fragments. Further, we shall consider such stages in more detail.

Based on the concept of the mechanism of cluster radioactivity expounded in our previous article [9], we formulate the following statement: spontaneous condensation of valence nucleons of a heavy nucleus to a light cluster nucleus is peculiar not only to light isotopes of radium and actinides but also to isotopes of all elements heavier than lead. However, for heavy isotopes of uranium and transuranium elements it is impossible for all valence neutrons to be condensed to a cluster. This would be energetically unfavourable as it would lead to the formation of light super neutron-excess nuclei with a very low binding energy of neutrons. As a consequence, part of the neutrons will be found in covalent states; i.e., they will envelop in their motion both the cluster nucleus and the associated heavy nucleus.

Covalent nucleons play an important role in the process of spontaneous fission of heavy nuclei. They encompass in their motion both nuclei of the molecule, intensify their interaction, and enhance the transfer of kinetic energy of the relative motion of the nuclei into the nuclear excitation energy. As a result, the nuclear molecule with covalent nucleons transforms into a dinuclear system. The nuclei formed in the DNS are not engaged in the relative motion and only exchange nucleons. Due to the DNS formation, the binding energies of the nucleons in both nuclei get closer together as the mass number of the clusters increases (see Fig. 4 in [9]). It should be emphasized that the formation of the DNS is the final stage in the clusterization of the valence nucleons of a heavy nucleus.

The main property exhibited by the DNS is its capability for evolution taking place via nucleon transfer from one nucleus to another. The tendency of evolution is determined by the potential energy of the system which is dependent on its charge and mass asymmetry. Figures 2–5 show the DNS potential energies formed from such nuclei as ^{238}U, ^{242}Pu, ^{246}Cm, and ^{250}Cf.

The arrows point to the initial configurations of the DNS which are formed during the condensation of the valence nucleons of these nuclei into a light cluster nucleus. From the data presented in Figs. 2–5 it is obvious that in all of the DNS the evolution will proceed towards the potential energy minimum. This is the second stage of spontaneous fission of heavy nuclei.

At the potential energy minimum, the DNS consists of two nuclei which are close in their charge and mass. The Coulomb forces acting between them reach a maximum value causing deformation of the nucleus and decay of the DNS into two fragment nuclei. This corresponds to the third stage of spontaneous fission of heavy nuclei.

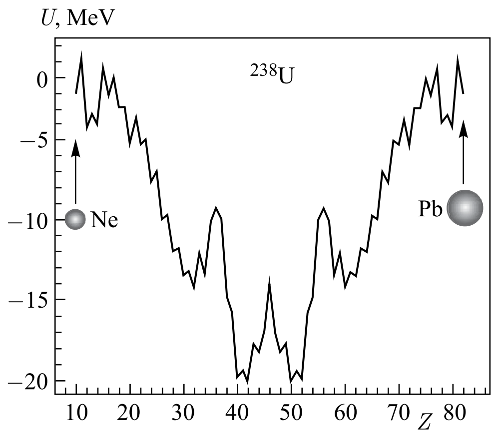

Fig. 2. The potential energy of the DNS formed at the spontaneous fission of the ^{238}U nucleus

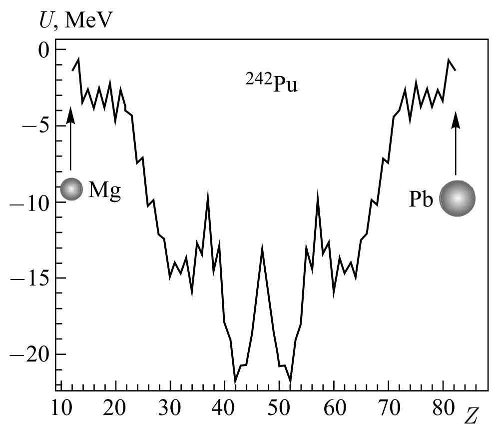

Fig. 3. The same for the ^{242}Pu nucleus

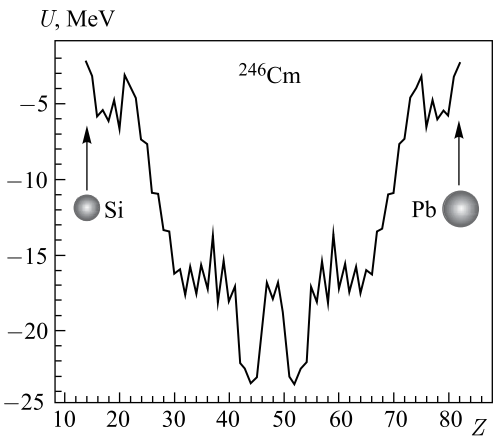

Fig. 4. The same for the ^{246}Cm nucleus

In the proposed interpretation of the spontaneous fission, the half-life $T_{1/2}$ (SF) depends not on the quantum-mechanical penetration through the fission barrier but on the time of full clusterization of the valence nucleons of the heavy nucleus to the light nucleus in a dinuclear system. This is a very complex nuclear process where a considerable number of valence nucleons of the heavy nucleus make quantum transitions into light nucleus cluster states that are radically different in their characteristics. The valence neutrons and protons are paired, possess a large shell angular momentum and localize their motion in the surface area of the heavy nucleus. In the light cluster nuclei, nucleons under the same name are not paired, have a small angular momentum and concentrate their motion in a far lesser area of space.

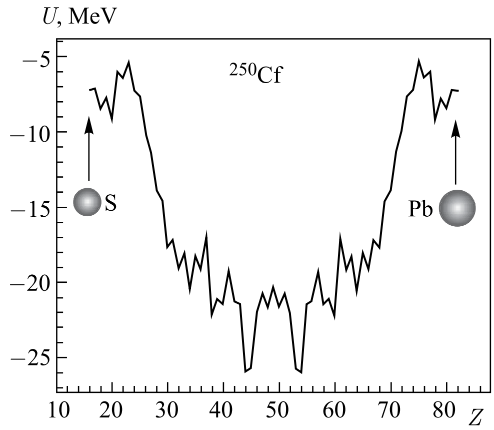

Fig. 5. The same for the ^{250}Cf nucleus

Experimental values of the spectroscopic factors ($W_{\rm exp}$)

Cluster	$W_{\rm exp}$/(**)	Cluster	$W_{\rm exp}$/(**)
^{14}C	$2.0 \cdot 10^{-10}$/(*)	^{28}Mg	$2.0 \cdot 10^{-22}$/(^{234}U)
^{24}Ne	$7.1 \cdot 10^{-19}$/(^{232}U)	^{28}Mg	$6.1 \cdot 10^{-22}$/(^{236}Pu)
^{24}Ne	$7.8 \cdot 10^{-18}$/(^{234}U)	^{28}Mg	$4.6 \cdot 10^{-21}$/(^{238}Pu)
		^{32}Si	$2.1 \cdot 10^{-24}$/(^{238}Pu)

*Average values for ^{222}Ra, ^{224}Ra and ^{226}Ra.
**Parent nucleus.

The quantitative analysis of this complex nuclear process is an exceptionally challenging task. Useful data on the time of full clusterization of the valence nucleons of heavy nuclei can be obtained from the experimental data for the spectroscopic factors of nuclear molecules.

The respective experimental values taken from review [10] (see also references therein) are shown in table. We can see that these values point to a lengthy duration of clusterization of the valence nucleons of heavy nuclei, as expected.

4. THE POTENTIAL ENERGY OF A DNS

The potential energy of a DNS is calculated as follows:

$$U(R, Z, A) = B_1 + B_2 + V(R, Z, A, \beta_1, \beta_2) - B_{12}, \tag{1}$$

where B_1 and B_2 are the mass excesses of the fragments in their ground states; Z and A are the charge and mass numbers of one of the nuclei in the DNS; β_1 and

β_2 are their quadrupole deformation parameters which are taken from [11] for even–even nuclei. For the quadrupole deformation parameter of an odd nucleus we choose the maximal value from the deformation parameters of the neighboring even–even nuclei. The experimental values of B_1 and B_2 are used, if available in [12]. Otherwise, we use the values from [13]. Here, B_{12} is the mass excess of the initial nuclei. The nucleus–nucleus potential

$$V(R, Z, A, \beta_1, \beta_2) = V_C(R, Z, A, \beta_1, \beta_2) + V_N(R, Z, A, \beta_1, \beta_2) \qquad (2)$$

in Eq. (1) is the sum of the Coulomb potential V_C and the nuclear potential V_N. For calculation of the Coulomb potential we applied the well-known Wongs formula from [14]. For the nuclear part of the nucleus–nucleus potential, we use the double-folding formalism [15]

$$V_N \int \rho_1(r_1)\rho_2(R - r_2)F(r_1 - r_2)\, dr_1\, dr_2, \qquad (3)$$

where

$$F(r_1 - r_2) = C_0 \left[F_{\rm in}\frac{\rho_0(r_1)}{\rho_{00}} + F_{\rm ex}\left(1 - \frac{\rho_0(r_1)}{\rho_{00}}\right)\right]\delta(r_1 - r_2)$$

is the Skyrme-type density-depending effective nucleon–nucleon interaction, which is known from the theory of finite Fermi systems [16], and

$$\rho_0(r) = \rho_1(r) + \rho_2(R - r), \quad F_{\rm in,ex} = f_{\rm in,ex} + f^2_{\rm in,ex}\frac{(N_1 - Z_1)(N_2 - Z_2)}{(N_1 + Z_1)(N_2 + Z_2)},$$

where $\rho_1(r_1)$, $\rho_2(r_2)$ and $N_2(Z_2 = A_2 - N_2)$ are, respectively, the nucleon densities of the light and heavy nuclei of the DNS and the neutron (charge) number of the heavy nucleus of the DNS. Our calculations are performed with the following set of parameters: $C_0 = 300$ MeV $\cdot$ fm^3, $f_{\rm in} = 0.09$, $f_{\rm ex} = -2.59$, $f'_{\rm in} = 0.42$, $f'_{\rm ex} = 0.54$ and $\rho_{00} = 0.17$ fm^{-3} [16]. The densities of the nuclei are taken in the two-parameter symmetrized Woods–Saxon form. The radius parameter r_0 in nuclear densities is taken as 1.2 fm for all nuclei, except for the α particle for which we take 1.02 fm. The diffuseness parameter is parametrized here as

$$a_0 = 0.54 + (0.011 \cdot Z)^2(A - 2Z)/A$$

in order to take effectively into account the deformation and isospin effects on the nuclear densities during the fission process.

Due to the sum of the repulsive Coulomb and attractive nuclear forces in Eq. (2), the nucleus–nucleus potential has a "pocket" with a minimum situated for the pole–pole orientation at the touching distance between the nuclei

$$R = R_m \approx R_1\left(1 + \sqrt{\frac{5}{(4\pi)\beta_1}}\right) + R_2\left(1 + \sqrt{\frac{5}{(4\pi)\beta_2}}\right) + 0.5 \text{ fm},$$

where $R_i = r_0 A_i^{1/3}$ are the radii of the interacting nuclei. The DNS is localized in the minimum of this pocket. The position of the Coulomb barrier in V approximately corresponds to

$$R = R_b \approx R_m + 2\ \text{fm}$$

in the DNS under consideration. Then the depth of the potential pocket is

$$d_{\text{pot}} = V(R_b, Z_1, A_1, \beta_1, \beta_2) - V(R_m, Z_1, A_1, \beta_1, \beta_2).$$

The depth of the potential pocket depends on the charge asymmetry of the DNS. For the asymmetric DNS, the potential pocket is deeper than for a more symmetric configuration. For spontaneous fission the excitation energy of DNS is $E^*(\text{DNS}) = -U(R, Z, A)$.

5. THE INTERPRETATION OF SOME PROPERTIES OF SPONTANEOUS FISSION

The growth of the atomic number Z and mass number A of transuranium elements is accompanied by a drastic decrease in the spontaneous fission half-life $T_{1/2}$(SF). In our opinion, this is due to the following factors. With the growth of Z of the heavy nucleus, the binding energy of the valence nucleons, especially of protons, diminishes.

This assists and accelerates the formation of the DNS through clusterization of the valence nucleons. Further, with rising Z and A of the heavy nucleus, the cluster charge and mass increase as well, which is attended by a growth in the binding energy of the nucleons in the cluster.

With the light and medium nuclei, this growth is especially notable. As a result, the nucleon transfer from the associated heavy nucleus to the cluster nucleus does not stop with ^{208}Pb, which is the case with cluster radioactivity, and continues. One can see from Fig. 6 that with growing Z and A of the heavy nucleus the excitation energy of the DNS is augmented, which is the major factor affecting the rates of its evolution and decay. It is also clear from the figure that the depth of the nucleus–nucleus potential decreases with a growth in the mass of the light fragment of the DNS, which leads to enhanced probability of the spontaneous fission in this configuration.

At one time considerable interest was aroused in the characteristics of the spontaneous fission of ^{257}Fm, ^{258}Fm, ^{259}Fm, ^{260}Md nuclei. In the mass distributions of the spontaneous fission fragments of these nuclei, only one maximum was observed, which coincided with half of the fissioning nucleus mass. The kinetic energy of the fragments corresponded to a decay under the action of the Coulomb forces of a system of two non-deformed nuclei being in contact with

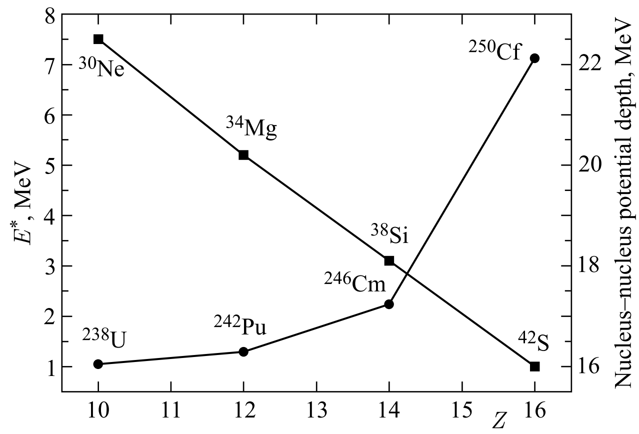

Fig. 6. The energy release E^*(DNS) during the clusterization of nuclei is marked by dots, and the nucleus–nucleus potential depth, by squares

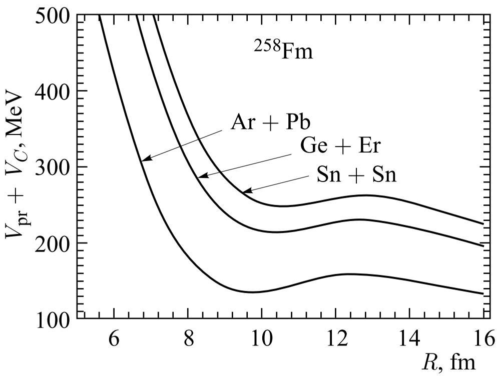

Fig. 7. The nucleus–nucleus potential for the DNS formed from the ^{258}Fm nucleus during its evolution towards the equilibrium configuration

their surfaces. From our point of view, the presence of only one maximum in the mass distribution of the spontaneous fission fragments is due to the fact that the potential energy minimum of the DNS for these nuclei coincides with its symmetric configuration.

The changes in the nucleus–nucleus potential for the evolving DNS formed from the ^{258}Fm nucleus were also observed. As is visible from Fig. 7, the potential pocket holding the DNS nuclei in contact becomes very shallow upon reaching the equilibrium configuration, thus opening a way for the DNS to decay into two identical fragment nuclei. The closed proton shell in these nuclei plays a certain role as well.

A possibility for the spontaneous fission of the ^{232}Th nucleus was considered. However, the experimental endeavors to register spontaneous fission of ^{232}Th did not meet with success for quite a long time. And only in 1995 it was observed for the first time with a half-life of $1.2 \cdot 10^{21}$ y [17].

Figure 8 displays the potential energy of the DNS which can be formed from the ^{232}Th nucleus. The condensation of the valence nucleons of this nucleus to the light cluster nucleus is accompanied by the formation of a neutron-excess oxygen isotope. As can be seen from Fig. 8, the initial configuration of the DNS (the associated ^{208}Pb heavy nucleus) is in the local minimum of the DNS potential energy, and its evolution towards the primary minimum of the DNS potential energy turns out to be impossible. Nevertheless, the cluster nucleus can quantum-mechanically penetrate through the potential energy local maximum at the expense of the energy released at nucleon condensation, and then spontaneous fission of the ^{232}Th nucleus will take place. In this case, the half-life will be very large.

Let us now consider the spontaneous fission of a light isotope of uranium, ^{232}U. In [18] its half-life was calculated to be $5 \cdot 10^{10}$ y. But all attempts at experimental observation of its spontaneous fission were not successful. The lower limit $T_{1/2}$(SF) amounted to $6.8 \cdot 10^{15}$ y. A peculiarity of the ^{232}U nucleus is that condensation of all the valence nucleons leads to the formation of an asymmetric nuclear molecule $^{208}\text{Pb} + {}^{24}\text{Ne}$ where further transfer of neutrons is prohibited for the energetic reasons and the proton transfer is hampered by the ^{24}Ne nucleus “neutron atmosphere” without overlapping of the wave functions of the ^{208}Pb nucleus protons and cluster nucleus protons. This is a classical nuclear molecule that decays via ^{24}Ne nucleus emission due to the ^{24}Ne nucleus quantum

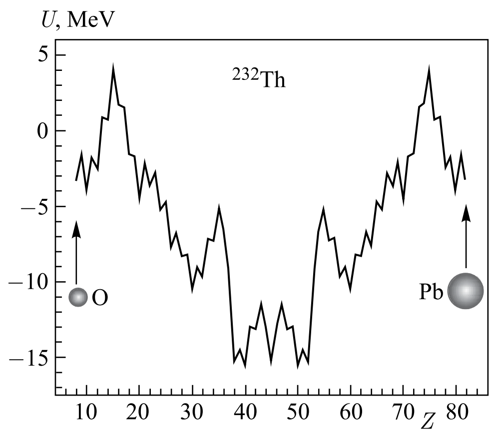

Fig. 8. The potential energy of the DNS formed at the spontaneous fission of the ^{232}Th nucleus

mechanical penetration through the potential barrier. Cluster radioactivity (^{24}Ne emission) with a half-life of $3.4 \cdot 10^{13}$ y was indeed observed for the ^{232}U nuclei.

Quite an intriguing peculiarity is found in the spontaneous fission of californium isotopes. The spontaneous fission channel is the major channel for the radioactive decay of the ^{254}Cf and ^{256}Cf heavy isotopes. It is also the main channel of radioactive decay for such neutron-deficient californium isotopes as ^{237}Cf and ^{238}Cf. However, if the half-lives for the heavy isotopes are measured in days and minutes, for the light isotopes they reduce to seconds and even milliseconds.

We have attempted to gain an insight into this peculiarity of spontaneous fission for the above californium isotopes in the framework of the developed approach. In the ^{252}Cf and ^{254}Cf nuclei, sulfur isotopes with a great excess of neutrons are formed as starting clusters. Further transfer of neutrons from the ^{208}Pb nucleus makes no sense energetically, and the proton transfer is hindered by the "neutron atmosphere" surrounding the cluster nuclei. In the ^{237}Cf and ^{238}Cf nuclei, on the contrary, starting clusters are represented by such neutron-deficient sulfur isotopes as ^{29}S and ^{30}S. The transfer of both neutrons and protons from the ^{208}Pb nucleus into these cluster nuclei proves to be energetically beneficial. As a result, the evolution of the DNS towards the equilibrium configuration proceeds in these nuclei more rapidly.

In study [19], an attempt was made to observe the spontaneous fission of the ^{208}Pb nucleus. A lower limit on its half-life was obtained to be $T_{1/2} \geqslant 2 \cdot 10^{19}$ y. From our point of view, the spontaneous fission is in principle impossible for the ^{208}Pb nucleus: this nucleus has no valence nucleons from which a light cluster nucleus could be formed. This implies that even the first stage of spontaneous fission cannot be realized here.

CONCLUSIONS

A possibility for a new approach to the interpretation of the mechanism of spontaneous fission of heavy nuclei is considered. It is based on the information about nuclear interactions obtained in nuclear physics research using heavy ions. Of key importance here is the discovery of dinuclear systems and their evolution via the nucleon transfer from nucleus to nucleus and governed potential energy of the system. According to the new approach, the process of spontaneous fission of heavy nuclei includes three consecutive stages. At the first stage, the valence nucleons of the heavy nucleus are condensed into the light cluster nucleus, which leads to the formation of a dinuclear system. At the second stage, the evolution of the dinuclear system takes place proceeding by way of nucleon transfer from the heavy nucleus to the cluster nucleus. Such an evolution is governed by the potential energy of the system, which is a function of its charge and mass asymmetry. It ends when the DNS reaches the potential energy minimum. In this state the DNS is unstable and falls into two fragment nuclei close in mass under the action of the Coulomb forces. This is the third stage of the spontaneous fission process.

A qualitative interpretation of some properties of spontaneous fission of heavy nuclei is made in the framework of the developed approach. Along with this, the authors hope that it provides a more realistic picture of the mechanism of spontaneous fission of heavy nuclei as our approach relies on the experimental data on nuclear interactions.

REFERENCES

1. *Bohr N., Wheeler J. A.* The Mechanism of Nuclear Fission // Phys. Rev. 1939. V. 56. P. 426.
2. *Gamov G.* Quantum Theory of the Atomic Nucleus // Z. Phys. 1928. V. 51. P. 204.
3. *Petrazhak K. A., Flerov G. N.* Spontaneous Fission of Uranium // JETP. 1940. V. 10, P. 1013.
4. *Holden N. E., Hoffman D. C.* Spontaneous Fission Half-Lives for Ground-State Nuclides // Pure Appl. Chem. 2000. V. 72, No. 8. P. 1525–1652.
5. *Wagemans C.* Spontaneous Fission // The Nuclear Fission Process / Ed. C. Wagemans. Boca Raton, Ann Arbor, Boston, London: CRC Press, 1991. P. 35–43.
6. *Almqvist E., Bromley D. A., Kuchner J. A.* A New Interpretation of Cluster Radioactivity Mechanism // Phys. Rev. Lett. 1960. V. 4. P. 515.
7. *Volkov V. V.* Deep Inelastic Transfer Reactions — the New Type of Reactions between Complex Nuclei // Phys. Rep. 1978. V. 44. P. 93–157.
8. *Schroder W. V., Huizenga J. R.* Treatise on Heavy-Ion Science / Ed. D. A. Bromley. N.Y., London, 1984. V. 2. P. 115–734.
9. *Volkov V. V., Cherepanov E. A.* Formation of Nuclear Molecules in Cluster Radioactivity. On Interpretation of the Cluster Radioactivity Mechanism // Part. Nucl., Lett. 2013. V. 10, No. 3(180). P. 347–353.
10. *Zamyatnin Yu. S. et al.* Cluster Radioactivity: Achievements and Perspectives // Phys. Part. Nucl. 1990. V. 21. P. 537.
11. *Raman S., Nestor C. W., Tikkanen P.* Transition Probability from the Ground to the First Excited 2^+ State of Even–Even Nuclides // At. Data Nucl. Data Tables. 2001. V. 78. P. 1.
12. *Audi G., Wapstra A. M., Thibault C.* The Ame2003 Atomic Mass Evaluation: II. Tables, Graphs and References // Nucl. Phys. A. 2003. V. 729. P. 337.
13. *Möller P. et al.* Nuclear Ground-State Masses and Deformations // At. Data Nucl. Data Tables. 1995. V. 59. P. 185.
14. *Wong C. Y.* Interaction Barrier in Charged-Particle Nuclear Reactions // Phys. Rev. Lett. 1973. V. 31. P. 12.
15. *Adamian G. G. et al.* Potential Energy of Dinuclear System // Intern. J. Mod. Phys. E. 1996. V. 5. P. 191.

16. *Migdal A. B.* Theory of Finite Fermi System and Properties of Atomic Nuclei. Nauka, 1983.
17. *Bonetti R. et al.* First Observation of Spontaneous Fission and Search for Cluster Decay of ^{232}Th // Phys. Rev. C. 1995. V. 51. P. 2530.
18. *Randrup J. et al.* Spontaneous Fission Half-Lives for Even Nuclei with $Z \geqslant 92$ // Phys. Rev. C. 1976. V. 13. P. 229.
19. *Zakharova V. P., Zenkevich V. S., Funstein V. B.* On the Period of Spontaneous Fission of Lead // Phys. At. Nucl. 1995. V. 58. P. 709.

Received on March 28, 2016.

Редактор *Е. И. Кравченко*

Подписано в печать 27.04.2016.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 1,06. Уч.-изд. л. 1,5. Тираж 215 экз. Заказ № 58805.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/