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CENTRIFUGAL FRAGMENTATION OF A DINUCLEAR SYSTEM IN THE PROCESS OF ITS EVOLUTION TO THE COMPOUND NUCLEUS

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Центробежная фрагментация двойной ядерной системы в процессе
ее эволюции к составному ядру

Рассматривается физическое содержание центробежной фрагментации — специфического ядерного процесса, который реализуется в процессе эволюции двойной ядерной системы к составному ядру при больших угловых моментах столкновений и на стадии большой массовой асимметрии системы. Концепция двойной ядерной системы, которая описывает процесс образования составного ядра в реакциях с тяжелыми ионами, предсказывает возможность центробежной фрагментации. Приводятся экспериментальные данные, которые можно рассматривать как доказательство реализации этого ядерного процесса. Обсуждается возможная схема модели центробежной фрагментации.

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Centrifugal Fragmentation of a Dinuclear System in the Process
of Its Evolution to the Compound Nucleus

The physical content of centrifugal fragmentation is discussed. It is a specific nuclear process which is realized in the evolution of a dinuclear system into a compound nucleus at large angular momenta and large mass asymmetry of the system. The dinuclear system concept which describes the process of the compound nucleus formation in heavy ion reactions predicts the possibility of centrifugal fragmentation. Experimental data giving evidence of the realization of this nuclear process are given. A possible scheme of the centrifugal fragmentation model is discussed.

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

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INTRODUCTION

The analysis of the transactinoid and superheavy element synthesis shows that the dinuclear system concept (DNSC) today provides the most realistic picture of the process of complete fusion of nuclei and the mechanism of the compound nucleus formation [1]. According to the DNSC, at the capture stage after full dissipation of the collision kinetic energy a dinuclear system (DNS) is formed. The DNS evolves in time by means of nucleon transfer from a light nucleus to a heavy one. The DNS nuclei retain their individuality during the DNS evolution. This important peculiarity of the DNS evolution is the consequence of shell structure of nuclei. The synthesis of transactinoid and superheavy elements occurs at a bombarding energy close to the Coulomb barrier, thus the angular momenta are not large but the inertia momenta of the DNS are large and centrifugal forces do not play an essential role in these reactions.

The situation is changed radically when medium mass target nuclei are used in the reaction and the bombarding energy is several dozens MeV higher than the Coulomb barrier. A lot of angular momenta contribute into the reaction, and the role of centrifugal forces sharply grows, especially for the strong mass asymmetry of the DNS. Under these conditions a new nuclear process is possible, namely, the centrifugal fragmentation which means the decay of the DNS into two asymmetric fragments under the influence of strong centrifugal forces. The possibility of centrifugal fragmentation of the DNS was discussed in [2, 3]. However the success of the DNSC from which the centrifugal fragmentation is one of the logical consequences makes us turn again to the discussion of this interesting nuclear process.

1. THE SCHEME OF CENTRIFUGAL FRAGMENTATION

The essence of the phenomenon of centrifugal fragmentation is as follows. In collisions of nuclei at large angular momenta, which are however smaller than the critical one ($l_{\mathrm{i}} < l_{\mathrm{cr}}$), in the process of evolution of a DNS into a compound nucleus the «potential pocket» disappears as a result of an increase in centrifugal forces. The «potential pocket» binds two nuclei in one DNS. As a consequence, the DNS evolution proceeds in a regime characteristic of deep inelastic transfer reactions (DITR). The system evolves into the compound nucleus and at the same time decays into two fragments in all intermediate configurations. In the process of evolution to the compound nucleus the DNS mass and charge asymmetry grows and, consequently, the nuclear component of the nucleus–nucleus potential decreases. On the contrary, the centrifugal force component increases as a result of the conservation of the system's angular momentum and a decrease in the momentum inertia of the DNS. The centrifugal forces start to dominate in the interaction of DNS nuclei.

It is interesting to compare the interaction between DNS nuclei in the quasifission and centrifugal fragmentation processes. In the symmetrization of a massive DNS the Coulomb repulsion between DNS nuclei begins to dominate over nuclear attraction, and the DNS decays in the quasifission channel. In a strongly asymmetric DNS having the large angular momentum the centrifugal forces begin to dominate and the DNS decays into two asymmetric fragments as a result of the centrifugal fragmentation.

In order to occur, the centrifugal fragmentation requires special conditions. First of all it is the large angular momentum of collision of nuclei which can be obtained if the collision energy essentially exceed (dozens of MeV) the Coulomb barrier. However, in collisions between massive heavy ions such as Kr or Xe with heavy nuclei it is possible to obtain the large angular momentum, but the potential energy of the DNS leads it to the symmetric form and finally to quasifission. The situation with the most light ions (B, C, N, O) is not quite clear. From scarce experiment data it is possible to make a conclusion that most suitable heavy ions for the observation of the centrifugal fragmentation are argon ions or ions close to argon.

2. EXPERIMENTAL INDICATION OF THE CENTRIFUGAL FRAGMENTATION EFFECT

It is necessary to note that the phenomenon of centrifugal fragmentation in fact has not been considered in literature and no experiment on its study made. It is evidently connected with the fact that this nuclear process is only possible in the framework of the DNSC. In all other models of complete fusion of nuclei the centrifugal fragmentation is not possible. That is why we will present here fragmentary experimental data which can be considered as an indication of this interesting nuclear process.

2.1. The Dependence of $l_{\rm cr}$ on Mass Asymmetry of Colliding Nuclei. It is well known that the critical angular momentum $l_{\rm cr}$ divides the angular momentum scale in two parts. When $l < l_{\rm cr}$, complete fusion of two nuclei and the formation of the compound nucleus is possible. When $l > l_{\rm cr}$, deep inelastic transfer reactions are realized [4, 5]. At a fixed summed mass of colliding nuclei and the excitation energy of corresponding compound nucleus, the value of $l_{\rm cr}$ depends on the mass (charge) asymmetry of colliding nuclei. In Fig. 1 experimental points and the solid curve show how $l_{\rm cr}$ is changed in the reactions which yield the same compound nucleus ^{170}Yb with the excitation energy 107 MeV if different bombarding ions, from ^{10}B to ^{40}Ar, are used. For ^{40}Ar $l_{\rm cr}$ = 100 $\hbar$, for ^{11}B it drops down to 40 $\hbar$.

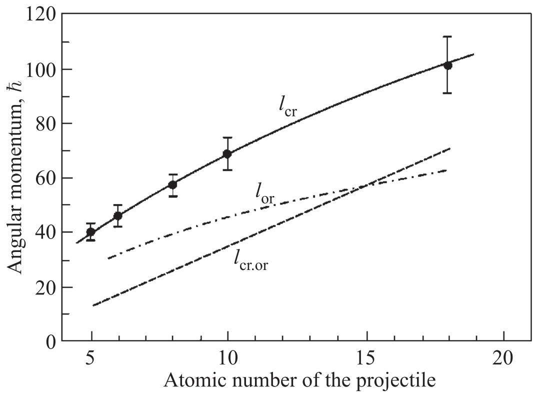

Fig. 1. Critical angular and orbital momenta of the DNS. The points and the solid curve are experimental data for $l_{\rm cr}$ which were obtained for the compound nucleus ^{170}Yb with the excitation energy 107 MeV but for different combinations of the projectile and target nucleus [6, 7]. The dashed line is the calculated values of the critical orbital angular momentum $l_{\rm cr.or}$. The dash-dotted line shows the change in the orbital angular momentum of the DNS which is formed in the reaction ^{130}Tb + ^{40}Ar with $l_{\rm i}$ = 0.9 $l_{\rm cr}$ in the process of DNS evolution to the compound nucleus

In collisions of nuclei with the angular momentum $l_{\rm i} < l_{\rm cr}$, there are full dissipation of the kinetic energy and partial conversion of the angular momentum $l_{\rm i}$ into the spins of colliding nuclei. The nuclei stick together and the formed DNS rotates as an integration. It is possible to calculate spins of the DNS nuclei and the orbital angular momentum. In Fig. 1 the dashed line indicates critical orbital angular momenta $l_{\rm cr.or}$ which correspond to the critical angular momenta $l_{\rm cr}$. Calculations were made for two touching spherical nuclei [2]. The dash-dotted line shows a change in the orbital angular momentum of the DNS which is formed in the reaction ^{40}Ar + ^{130}Tb at the collision angular momentum $l_{\rm i}$ = 0.9 $l_{\rm cr}$. In this case the capture of the bombarding ion by the target nucleus is realized and the DNS evaluates into the compound nucleus by means of nucleon transfer from ^{40}Ar to ^{130}Tb. From Fig. 1 one can see that when the nucleus ^{40}Ar transforms into the P nucleus by means of nucleon transfer the orbital angular momentum of the DNS becomes equal to $l_{\rm cr.or}$ and in the process of further evolution exceeds it. It means that in the DNS nucleus–nucleus potential the «potential pocket» disappears and the centrifugal fragmentation channel opens for the DNS decay into two fragments. Thus, in the framework of the DNSC the centrifugal fragmentation naturally arises as a consequence of the predomination of centrifugal forces over nuclear attraction at the large angular momentum and strong mass (charge) asymmetry in the process of the DNS evolution to the compound nucleus.

2.2. The Centrifugal Fragmentation and Deep Inelastic Transfer Reactions. It is well known that the yield of DITR products monotonously drops when the atomic number Z and mass number A of the product move away from Z and A of the initial nuclei. It can be seen from large experimental bulk of the data [4, 8]. The theoretical analysis of DITR supports this tendency. However, one should note that experimentalists did not study the yield of the lightest products of DITR. Such attempts were made in works [9, 10]. In the reactions $^{\rm nat}$Ag + ^{40}Ar (285 MeV) and ^{197}Au + ^{40}Ar (290 MeV) the yield of light DITR products including helium isotopes ^{3}He, ^{4}He and ^{6}He was measured. The differential cross section for the yield of isotopes was measured for the emission angle 40° (LSC). For the $^{\rm nat}$Ag target this angle corresponds to the negative angle of emission. The results are shown in Fig. 2. The cross sections are plotted as a function of the number of protons and neutrons in the isotope. A typical of the DITR picture

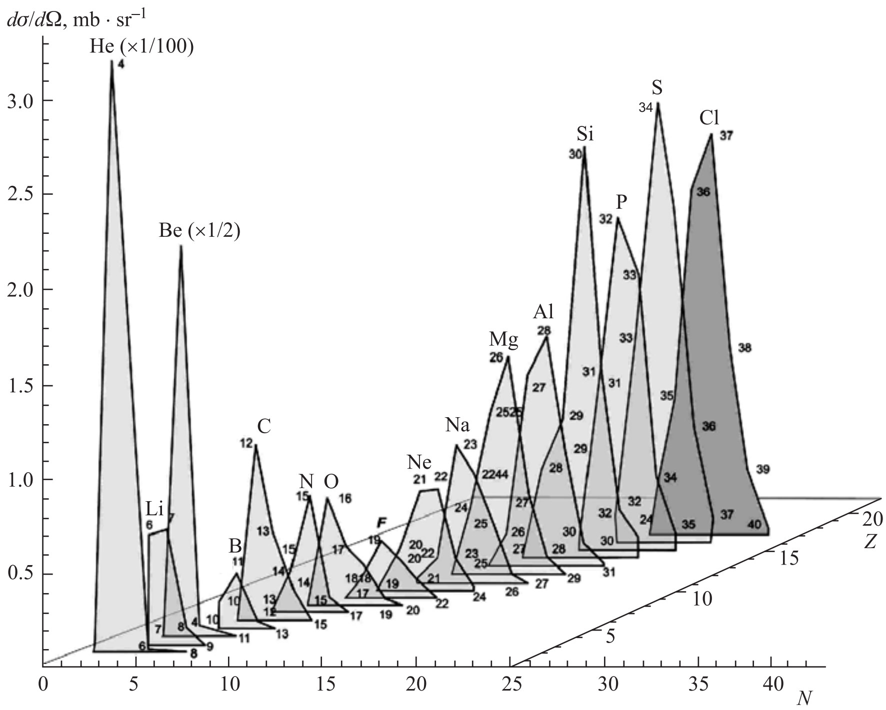

Fig. 2. Differential cross sections of isotopes of elements with $2 \leqslant Z \leqslant 17$ which are the products of the deep inelastic transfer reaction $^{\rm nat}$Ag + ^{40}Ar (285 MeV)

is observed up to fluorine isotopes: the formation cross section of the isotopes with the maximum yield decreases at moving away from the initial nucleus ^{40}Ar. However, after fluorine the tendency changes to the opposite: the cross sections increase with a decrease in Z and A of the isotope and the influence of closed nuclear shells strongly manifests itself. The isotopes with closed proton and neutron shells have the largest cross sections. In the case of ^{4}He the production cross section is especially large. It is hundred times bigger than those of other isotopes, although the DNS configuration with ^{4}He as a light nucleus is the most removed one from the initial DNS.

Fig. 3 shows the Q_{gg}-systematics for the production cross sections of isotopes of the lightest elements from nitrogen to helium. The secondary nuclear processes,

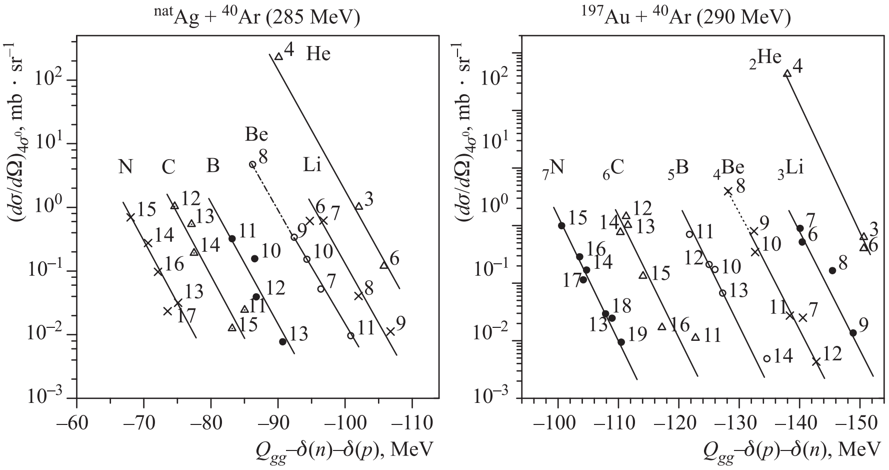

Fig. 3. Q_{gg}-systematics of differential cross sections of isotopes of elements with $2 \leqslant Z \leqslant 7$

such as the evaporation of neutrons and protons, cannot distort the yield of such light nuclei. From Fig. 3 it is seen, that helium isotopes obey to the same Q_{gg}-systematics as the isotopes of other light elements. This may be considered as an indication of the common mechanism of their production.

From our point of view, such a specific picture of the isotope yield in the reactions $^{\rm nat}$Ag + ^{40}Ar (285 MeV) may be explained as the superposition of two nuclear processes: the DITR and CF (centrifugal fragmentation). The former gives the main contribution into the production of isotopes of more heavy elements, up to fluorine. Isotopes of more light elements are the result of CF. The shapes of the energy spectra of isotopes in the two groups are nearly the same. It points to the similarity of the mechanisms of the DNS decay in DITR and in CF.

2.3. «Strange» Behavior of the γ-Quantum Multiplicity Registered in Coincidence with the DITR Products. A typical dependence of the γ-quantum multiplicity M_γ on the atomic number Z of the light DITR product is shown in Fig. 4. The measurements were made for the reaction $^{\rm nat}$Ag + ^{22}Ne (175 Mev) [11]. The increase in M_γ with decreasing the Z value of light DITR products reflects the properties of these reactions. The transfer of nucleons from ^{22}Ne to $^{\rm nat}$Ag (it is this process that leads to a decrease in the Z value of DITR light products)

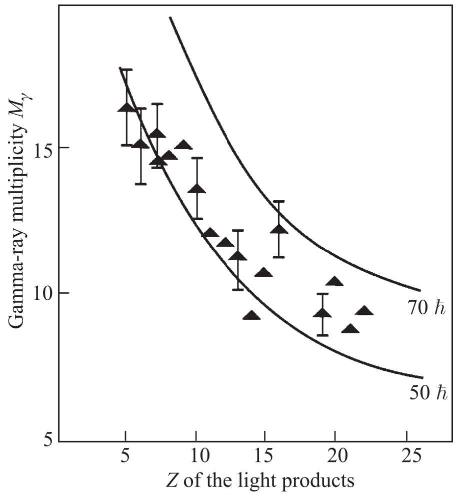

Fig. 4. The multiplicity of γ-quanta M_γ as a function of the atomic number Z of the light product of the deep inelastic transfer reactions $^{\rm nat}$Ag + ^{20}Ne (175 MeV). The angle of registration is 90°. Solid lines are theoretical calculations for the DNS with the critical angular momenta 50 $\hbar$ and 70 $\hbar$

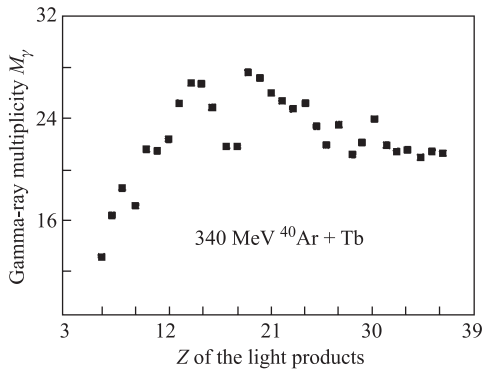

Fig. 5. The dependence of M_γ on the atomic number Z of light products of the deep inelastic transfer reactions ^{159}Tb + ^{40}Ar (340 MeV)

increases the conversion of the angular momentum l in spins of the DNS heavy nucleus. The de-excitation of the DNS heavy nucleus produces the main contribution into M_γ. The solid curves representing theory describe this situation. However, in the reactions ^{159}Tb + ^{48}Ar (340 MeV) [12] one can see quite a different picture (Fig. 5). In the case of the light nuclei, M_γ drops with decreasing the Z value of the light product. Such a tendency contradicts theoretical predictions. (Authors do not show the corresponding curve representing theory.) The contradiction can be removed if one supposes that the main contribution into the production of the lightest nuclei comes from CF, in which smaller than $l_{\rm cr}$ angular momenta are realized.

2.4. Quasi-Emission of α Particles. The very high yield of α particles requires special consideration. The reason of this effect is the unique strength of the ^{4}He nucleus. The binding energy of the ^{4}He nucleus is 28 MeV, whereas in the neighboring nuclei ^{3}He and ^{3}H it is the level of about 8 MeV. It means that there is a very deep minimum in the nucleus–nucleus potential for the DNS configuration with the ^{4}He nucleus. This configuration is very stable in respect to changes in its Z and A values and can exist for a very long time. The DNS evolution as if stops by the α-cluster configuration of the DNS and this configuration plays the role of a nuclear storage ring. For the α-cluster configuration of the DNS there is only one way of changing, it is the decay with emitting an α particle. It is very probable that energy and angular distributions of these α particles will be very similar to those of α particles evaporated from the compound nucleus. Thus, this process may be given the name of α-particle quasi-emission [13].

The α-particle quasi-emission manifests itself by the excess of the α-particle yield from an excited compound nucleus. Indeed, the increase in the yield of the evaporated α particles as compared with the theoretical calculation is observed in experiments. In work [14] devoted to the study of the reaction ^{197}Au + ^{40}Ar (340 MeV), the calculations in the framework of a statistical model yielded only one α particle per 250 events of fission of the compound nucleus ^{237}Bk, the fission barrier of which is equal to 2 MeV. In the experiment the number of registered α particles was by two orders larger: one α particle per three events of fission. In the reaction ^{232}Th + ^{40}Ar (240 MeV) the experimental cross section of the evaporated α particles was 70 mb [15]. Theoretical calculations in the framework of the statistical model produced a hundred times smaller value [16].

3. ABOUT THEORETICAL MODEL OF CENTRIFUGAL FRAGMENTATION

The purpose of the author, who is an experimentalist, was not the creation of a theoretical model of CF. In this section he only suggests some ideas which may be useful in the creation of such a model.

The key purpose of the CF model is the description of mass and charge distributions of CF products. Within the model it should be possible to calculate those Z and A values of the DNS light nucleus starting from which the «potential pocket» in the nucleus–nucleus potential disappears at the given angular momenta $l_{\rm i}$ and the DNS can decay in the CF. Denoting these values of Z and A of the light DNS as critical ones $Z_{\rm cr}$ and $A_{\rm cr}$, we must solve the equation:

$$(Z_{\rm cr}\, A_{\rm cr}) = f(l_{\rm i}). \tag{1}$$

All DNS having Z and A values less than $Z_{\rm cr}$ and $A_{\rm cr}$ ones can decay in the CF channel. As a result, there arises competition between different DNS in decaying into CF. Thus, a criterion is necessary which could determine the probability of the CF decay for different DNS.

3.1. Possible Elements of a CF Model

a) Potential energy of a DNS. CF is realized in the process of the DNS evolution into the compound nucleus. As in the complete fusion process, this evolution is directed by the potential energy of the DNS which includes masses of the DNS nuclei, the Coulomb, nuclear and centrifugal potentials:

$$V(R) = M_1 + M_2 + V_C\,(R) + V_N + V_{\rm rot}(R), \tag{2}$$

where R is the distance between DNS nuclei. In the first variant of the model it is possible to introduce some simplifications. It is possible to ignore the deformation of DNS nuclei and to use the configuration of two touching spheres. Since the main contribution in CF comes from light nuclei, it is not reasonable to use the proximity potential which describes nuclear interaction between two massive nuclei [17]. In our opinion, for V_N it is possible to use the double folding potential [18], energy density potential [19] and Woods–Saxon optical potential [20].

It is well known that the evolution of a DNS to the compound nucleus runs along many trajectories in Z and A space of their nuclei. As the first step it is possible to use «the main trajectory» which goes along the bottom of the potential valley of the DNS.

b) The disappearance of the DNS potential pocket. In the collision of nuclei with a kinetic energy substantially higher than the Coulomb barrier many values of the angular momentum $l_{\rm i}$ contribute into the complete fusion of nuclei. For each value of $l_{\rm i}$ there exists its own set of DNS which can undergo CF. The number of such DNS grows with the value of $l_{\rm i}$

One of postulates of the CF model can be formulated like this: all DNS with A and Z less than $Z_{\rm cr}$ and $A_{\rm cr}$ decay by means of centrifugal fragmentation.

c) The competition between different channels of centrifugal fragmentation. After the disappearing of the «potential pocket» the DNS acquires a state which is typical of DITR. The DNS takes part in two processes simultaneously: it evaluates by nucleon transfer from a light to heavy nucleus into a compound nucleus and decays into two fragments from all intermediate configurations. The cross section of the DITR products is described by the Q_{gg}-systematics. This indicates that the DNS decay obeys statistical regularities. Although in DITR full statistical equilibrium is not achieved, nevertheless there appear conditions which are close to the statistical equilibrium.

Figure 3 shows that the yield of CF products also obeys the Q_{gg}-systematics. It opens up possibilities of using a statistical approach to the analysis of the competition between different DNS in the CF.

The second postulate of the CF model can be formulated as follows. The probability of the DNS decay in the CF channel is proportional to the phase volume corresponding to a given DNS. The phase volume to a great extent is determined by the excitation energy of the DNS heavy nucleus conjugate to the light nucleus:

$$E^{*}(Z_{\rm hev}\,A_{\rm hev}) = E_0 + Q_{\rm gg} - E_c - E_{\rm rot}, \tag{3}$$

where E_0 is the heavy ion initial kinetic energy, Q_{gg} is the energy which is needed for the transformation of initial nuclei into the DNS ones, E_c and $E_{\rm rot}$ are the Coulomb and centrifugal energies of the DNS which decays in the CF channel. The calculation of the competition between different DNS in CF is made for each value of the angular momentum $l_{\rm i}$ in the interval $l_{\rm i} + \Delta l$, since in dependence on $l_{\rm i}$ a different number of DNS take part in the competition. The summing of DNS decays at different intervals of the angular momentum allows one to determine the relative contribution of different DNS into CF.

CONCLUSION

The DNSC allows us to make a conclusion on the realization in reactions with heavy ions of a specific nuclear process – centrifugal fragmentation which is a decay of a DNS, evolving into a compound nucleus, in two asymmetric fragments. The centrifugal fragmentation occurs at a collision energy which is substantially higher than the Coulomb barrier. The cause of a DNS decay is the domination of centrifugal forces over the nuclear attraction at high angular momenta and strong mass (charge) asymmetry in the DNS. There are experimental data which testify to the realization of centrifugal fragmentation, however, a systematic study of this nuclear process has not yet been made. In CF the shell structure of light nuclei is strongly manifested. It is manifested especially strongly by the very high yield of α particles, and the phenomenon deserves a special name – the α-particle quasi-emission. The α-particle quasi-emission and quasi-fission are two nuclear processes, which are realized at the capture of a projectile by the target nucleus but are not accompanied with the compound nucleus formation.

CF is only possible in the framework of the DNSC, and it cannot occur in the framework of other models of complete fusion of nuclei.

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