ANALYSIS OF NUCLEAR REACTIONS USED FOR THE SYNTHESIS OF HEAVY AND SUPERHEAVY ELEMENTS IN THE FRAMEWORK OF THE DINUCLEAR SYSTEM CONCEPT

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Dedicated to Adam Sobiczewski in honour of his 70th birthday

Reactions used for the synthesis of heavy and superheavy elements are analyzed within the framework of the dinuclear system concept. The important role of quasi- fission and the inner fusion potential barrier is emphasized. The results of calculation of the production cross sections for heavy and superheavy elements synthesized in cold and hot fusion reactions are given in comparison with experimental data. The minimum value of compound nucleus excitation energy is calculated for elements from 104 to 114, produced in cold fusion reactions. This article is a short survey of some results obtained by a group of physicists, using the dinuclear system concept.

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1. Introduction

There are two main theoretical aspects to the problem of the synthesis of superheavy elements (SHE). One is the properties of the superheavy nuclei, *i.e.* the "magic" numbers Z and N, what is the mode and half-life of the radioactive decay [1]. The other is nuclear reactions used for the synthesis of SHE: their type, the expected production cross sections, the optimal value of the excitation energy of the compound nucleus. This article discusses the latter aspect.

SHE can only be produced in the complete fusion of two massive nuclei, and we must have an idea about the mechanism of compound nucleus formation in these reactions. However, there are two serious difficulties encountered in solving this problem.

One is that a process of complete fusion is of a closed nature. Fusing nuclei do not send any signals that would allow one to understand the mechanism of compound nucleus formation. Experimentalists detect the decay products of a compound nucleus, but it is well known that the compound nucleus "forgets" the history of its formation. The other difficulty lies in the fact that the transformation of two multinucleon nuclear systems into a new one is very difficult to analyze theoretically.

How do theoreticians act in such a situation? They create theoretical models, simplifying reality. A theoretical model can be considered to be a certain theoretical image of a real nuclear process. There being various ways to make simplifications, several theoretical pictures are now available of the same nuclear process. The fusion of nuclei has been studied for more than forty years. Various approaches have been proposed to describe the complete fusion of nuclei, which reflects the progress made in the experimental study of this fundamental nuclear process.

2. First models of the complete fusion of nuclei

In the first models of the complete fusion of nuclei the compound nucleus formation mechanism was not considered. In early experiments, rather light heavy ions of ^{12}C, ^{14}N, ^{16}O and ^{20}Ne were used. In reactions with these ions, the capture of a projectile by a target nucleus inevitably leads to the formation of a compound nucleus. The compound nucleus production cross section $\sigma_{\rm CN}$ was equal to the capture cross section $\sigma_{\rm c}$

$$\sigma_{\rm CN} = \sigma_{\rm c}\,. \tag{1}$$

Theoreticians made efforts to create models for calculating the capture cross section. Created were the optical model [2], the critical distance model [3], the surface friction model [4]. All those models considered the critical angular momentum $l_{\rm cr}$ to be the most important characteristic of the complete fusion process. The compound nucleus production cross section $\sigma_{\rm CN}$ was defined by the well-known relation:

$$\sigma_{\rm CN} = \pi\lambda\!\!\!^{-2} \sum_{l=0}^{l_{\rm cr}} (2l+1)T(l), \tag{2}$$

where $T(l)$ is the penetration factor for the entrance potential barrier.

This approach was used successfully for calculating the production cross sections of transfermium elements ($Z > 100$), which were synthesized in reactions with not very massive heavy ions. The production cross section $\sigma_{\rm ER}$ is defined by two factors: $\sigma_{\rm CN}$ and $W_{\rm sur}$, where $W_{\rm sur}$ is the survival probability for the compound nucleus when de-excited.

$$\sigma_{\text{ER}} = \sigma_{\text{CN}} * W_{\text{sur}}\,, \tag{3}$$

σ_{CN} was estimated by ratio (2); W_{sur} was calculated on the basis of a statistical model.

However, this approach is in conflict with experimental data on the synthesis of heavier elements. Fig. 1 shows experimental data and calculated results obtained in the framework of the traditional theoretical approach for the production cross sections of elements 104, 108 and 110. These elements were synthesized in cold fusion reactions, in which ^{208}Pb is used as the target nucleus and ions of ^{50}Ti, ^{58}Fe and ^{64}Ni as a projectile [5]. The calculations were made in [6]. One can see large discrepancy between experimental data and calculations for elements 108 and 110. This discrepancy is due to the fact that there occurs a quasi-fission process — the dinuclear system formed on the capture stage decays into two nearly equal fragments without producing a compound nucleus.

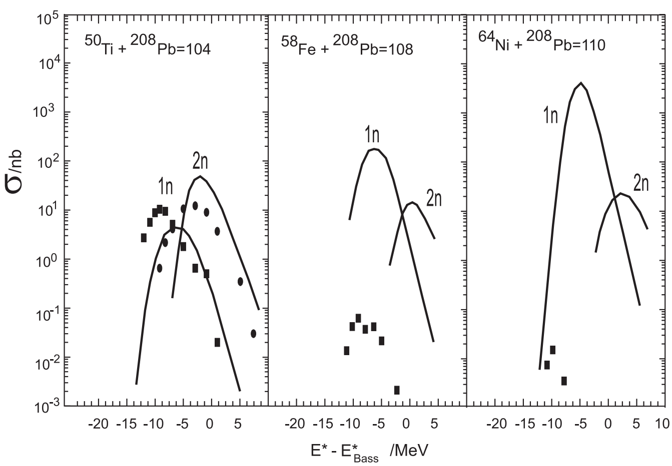

Fig. 1. The production cross sections of elements 104, 108 and 110 synthesized in cold fusion reactions (HI,1n, 2n); points are experimental data [5], the curves — results of calculations [6].

That quasi-fission is likely to occur in reactions between massive nuclei was predicted by Swiatecki in 1972 [7]. However, the term *quasi-fission* was only introduced by him in 1980 [8]. Figure 2, taken from [7], shows how two nuclear liquid drops brought in contact evolve depending on the parameter Z^2/A and the initial asymmetry. The initial nuclear system is seen to evolve to a symmetric form, if the value of Z^2/A is large and the mass asymmetry is small. When in the symmetric form, the heavy nuclear system is unstable and decays into two nearly equal fragments.

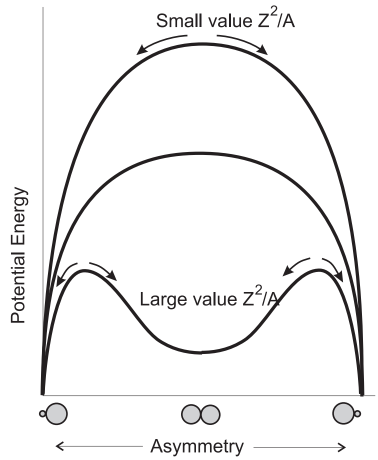

Fig. 2. The potential energy of two touching nuclear liquid drops in dependence of the parameter Z^2/A and mass asymmetry [7].

In reactions used for the synthesis of SHE, the reaction channel associated with quasi-fission is predominant. To estimate competition between the complete fusion and quasi-fission channels and to calculate the compound nucleus production cross section $\sigma_{\rm CN}$, we must have an idea of how a compound nucleus is formed in the complete fusion of two massive nuclei.

3. The macroscopic dynamic model

Swiatecki's macroscopic dynamic model (MDM) [8] was the first to describe the whole history of the complete fusion of two nuclei from the moment their surfaces come in contact to the moment a compound nucleus is formed.

This model simplifies reality, first, by substituting colliding nuclei, which are composed of nucleons and have shell structure, with drops of a hypothetical viscose nuclear liquid and, second, by considering the fusion of two nuclei to be a purely dynamic process governed by the classical equations of motion.

The complete fusion of two nuclei is the dynamic evolution of a nuclear system in deformation space. It is characterized by the following three parameters: the center-to-center distance between the nuclei, the system mass asymmetry and the neck form. Nuclear viscosity plays a very important role.

The MDM revealed such important aspects of the fusion of two massive nuclei as quasi-fission, the extra push and the extra-extra push. It turned out that for two massive nuclei to fuse into a mononucleus, a surplus of kinetic energy above the Coulomb barrier is needed — the extra push. For a compound nucleus to form from the mononucleus, the extra-extra push is needed. The MDM considers the fusion of nuclei and the formation of a compound nucleus to be different stages of nuclear processes.

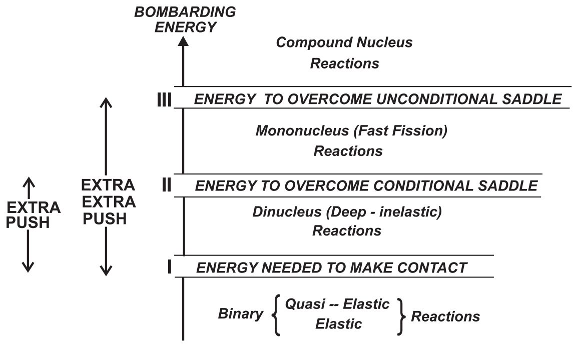

Fig. 3. The systematic of nuclear processes which are realized in the collision of two massive nuclei [8].

Figure 3, taken from [8], shows different nuclear processes that are likely to occur in the head-on collision of two massive nuclei. The type of process is defined ultimately by the initial kinetic energy E_{i} in respect to the Coulomb barrier B_{c}, the extra push E_{x} and the extra-extra push E_{xx}. The MDM is a strictly deterministic model; competition between complete fusion and quasi-fission channels is excluded. The MDM was very popular among experimenters. The terms *quasi-fission*, *the extra push* and *the extra-extra push* became an integral part of the physics language.

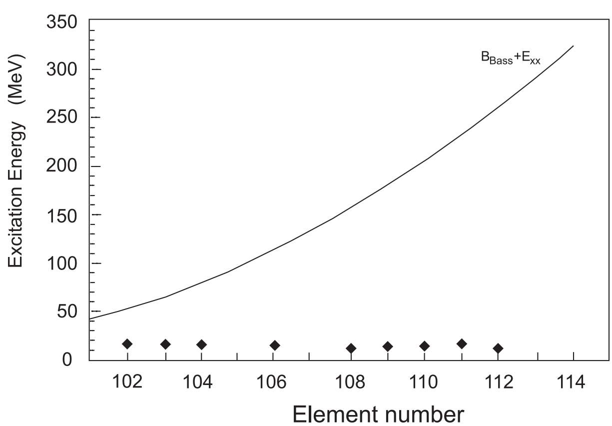

Fig. 4. The excitation energy of compound nuclei of 102 − 112 elements synthesized in cold fusion reactions (HI,1n); diamonds are experimental data [9], the line is the result of calculations with using the MDM [10].

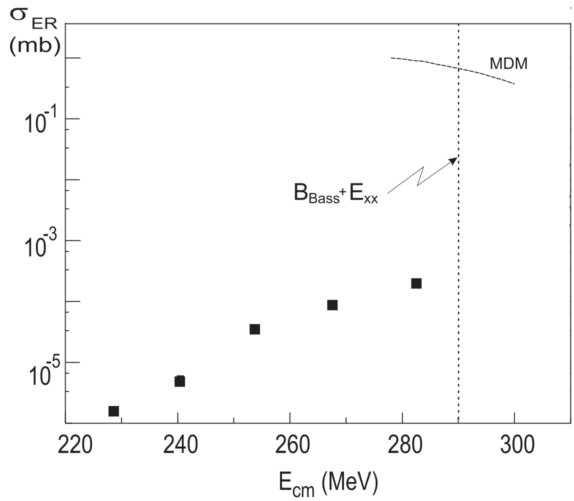

Fig. 5. The evaporation residue cross sections in the reactions ^{110}Pd $+^{110}$Pd; squares are the experimental data, the curve is the result of calculation with using the MDM [11b].

However, the MDM had difficulty describing reactions used for the synthesis of SHE. Figure 4 shows the excitation energy of the compound nuclei with the charge numbers Z from 102 to 112, which were synthesized in cold fusion reactions. Experimental data are shown with diamonds [9]; the line shows the result of calculations in the framework of the MDM [10]. The calculated data show extra-extra pushes to be of enormous values in these reactions. The Fig. 5 gives the evaporation residue cross section $\sigma_{\rm ER}$(E) for the reaction ^{110}Pd+^{110}Pd. Experimental data are shown by squares; the curve represents the results of calculations with the use of the MDM. The difference between experiment and calculations reflects the influence of the quasi-fission channel, which dominates in this reactions. However, the MDM doesn't consider the complete fusion and quasi-fission channels to be competing channels. From our point of view, the difficulty which the MDM encountered is due to the fact that it simplifies reality too radically.

4. The dinuclear system concept for the complete fusion of two massive nuclei

The dinuclear system concept (DNS-concept) was proposed at Dubna [11]. The DNS-concept is not a traditional theoretical model. The DNS-concept gives a qualitative picture, a scenario of the complete fusion process much as the compound nucleus concept qualitatively describes the properties of excited compound nuclei. The DNS-concept is based on the statement: "The complete fusion of nuclei and deep inelastic transfer reactions (DITRs) are similar nuclear processes". Indeed, in both processes, the full dissipation of collision kinetic energy occurs and the same conservative and dissipative forces act. On the collision angular momentum scale, there is a section where both processes can be realized. What does the statement that the complete fusion process and DITRs are similar processes provide? In contrast to the complete fusion process, DITRs are open reactions. Studying the mass, charge, energy and angular distributions of DITR products makes it possible to build up a realistic picture of nuclear interaction on full dissipation of collision kinetic energy when the relative velocity of nuclei drops to zero. It is this unique information about the interaction between two nuclei in a dinuclear system formed in deep inelastic collision that is used to reveal the mechanism of compound nucleus formation.

The DNS-concept proposes the following scenario of the complete fusion of nuclei and quasi-fission.

- At the capture stage, after the full dissipation of the collision kinetic energy, a dinuclear system (DNS) is formed.

- The DNS evolves in time by means of nucleon transfer from one nucleus to the other. There are two ways for the system to evolve: one leads to the complete fusion of nuclei, the other to the symmetric form of the system. The former results in a compound nucleus being formed. The latter leads to the decay of the DNS into two nearly equal fragments, which means quasi-fission has occurred.

- The DNS nuclei retain their individuality as the DNS evolves. This important peculiarity of the DNS evolution is the consequence of the shell structure of nuclei. Fig. 6 shows the principal distinction between the views of the MDM and the DNS-concept on the complete fusion process. According to the MDM, fused nuclei lose their individuality very quickly due to a neck being formed. The DNS-concept supposes that fused nuclei retain their individuality until the complete fusion process ends.

As is known from DITRs [12,13], the DNS evolution is determined by the potential energy of the system as a function of its charge (mass) asymmetry and spin. The DNS potential energy is calculated according to the equation:

$$V(Z,J) = B_1 + B_2 + V(R^*,J) - [B_{\mathrm{cn}} + V_{\mathrm{rot}}(J)]\,, \tag{4}$$

where Z is the atomic number of one of the DNS nuclei; J is the spin of the DNS, which is determined by the angular momentum of collision

L; B_1, B_2 and $B_{\rm cn}$ are the binding energies of the DNS nuclei and the compound nucleus; $V(R,J)$ is the nucleus–nucleus potential, which includes the nuclear, Coulomb, and centrifugal potentials:

$$V(R,J) = V_{\rm n}(R) + V_{\rm Coul}(R) + V_{\rm rot}(R,l). \tag{5}$$

R is the distance between the centers of the nuclei; $R = R^*$ when the DNS is at the bottom of the pocket of the potential $V(R)$. The DNS was represented as two slightly overlapping spheres. $V_{\rm n}(R)$ was calculated by the double folding method [14]. $V_{\rm rot}(R,J)$ was calculated for the rigid-body momentum of inertia of the DNS. Isotopic composition for the DNS nuclei was chosen in such a way as for the system to have a N/Z equilibrium. The deformation of the DNS nuclei was not taken into account. The DNS potential energy was normalized to the potential energy of the compound nucleus, which was taken as zero.

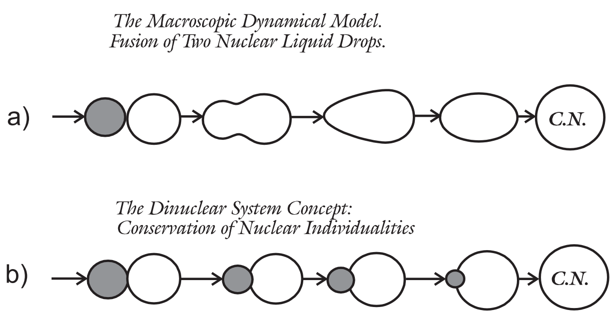

Fig. 6. The schematic illustration of the process of the compound nucleus formation in the complete fusion of two massive nuclei according to: (a) the macroscopic dynamical model [8], (b) the dinuclear system concept [11] (the figure from [11b]).

5. Peculiarities of the complete fusion of massive nuclei that were revealed by the DNS-concept

The DNS-concept reveals two important peculiarities in the complete fusion of massive nuclei:

- the existence of a potential barrier on the way to complete fusion and
- competition between the complete fusion and quasi-fission channels in the initial DNS formed at the capture stage.

Figure 7 shows the potential energy of the DNS formed in four reactions with different initial charge and mass asymmetry, but the compound nucleus is the same — ^{246}Fm. The injection points of the reactions are indicated.

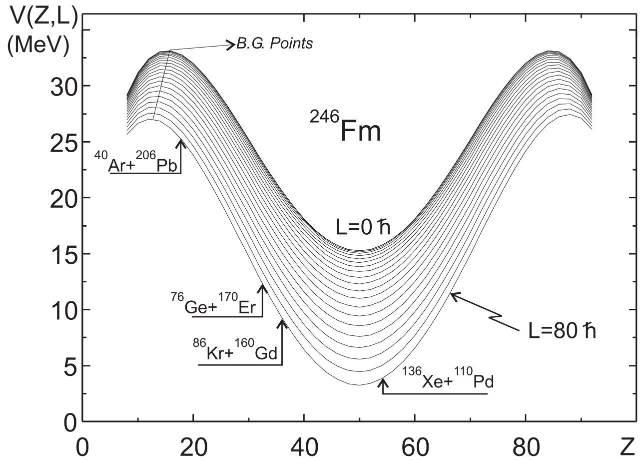

Fig. 7. The potential energy of the DNS which is formed in four reactions with the same compound nucleus ^{246}Fm; Z is the atomic number of one of the DNS nuclei [16].

To form a compound nucleus, an evolving DNS must overcome a potential barrier — the inner fusion barrier $B^*_{\rm fus}$. The height of $B^*_{\rm fus}$ depends on the charge asymmetry of the reaction. For the reaction with ^{40}Ar ions, $B^*_{\rm fus}$ is equal to a few MeV; for the reaction with ^{136}Xe, it is equal to about 20 MeV. The energy to overcome the inner fusion barrier is taken from the excitation energy of the DNS. The asterisk symbolizes this peculiarity. The value of $B^*_{\rm fus}$ determines the energy threshold for the fusion of two massive nuclei. The DNS initial excitation energy $E^{\rm x}_{\rm i}$ must be higher than $B^*_{\rm fus}$.

That there is competition between complete fusion and quasi-fission channels is due to the fact that the DNS evolution is of a statistical nature. On full dissipation of the collision kinetic energy, the relative velocity of two nuclei drops to zero and the DNS evolves by transferring nucleons from one nucleus to the other. As is known from DITRs, this process is governed by statistical laws [12,13]. Fig. 8 illustrates two ways for the DNS to evolve. In the case of quasi-fission, the DNS must overcome the quasi-fission barrier $B_{\rm qf}$ in the nucleus–nucleus potential $V(R,J)$.

The MDM and the DNS-concept can be seen to differ fundamentally in describing the nature of the evolution of a nuclear system to a compound nucleus. The MDM considers this process to be a dynamic evolution, whereas the DNS-concept takes it to be a statistical evolution.

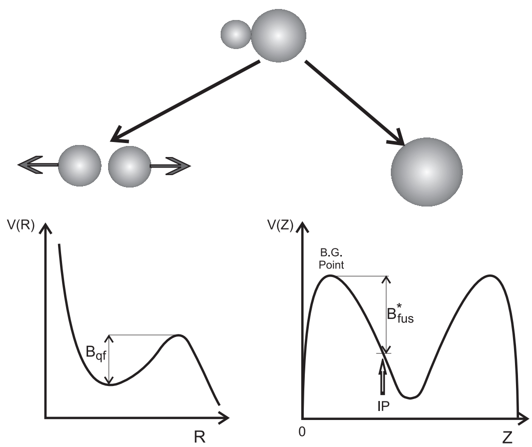

Fig. 8. Two ways of evolution of a massive DNS. The nucleus–nucleus potential (left) and potential energy of DNS (right) are indicated [11b].

6. Production cross section of superheavy elements

According to the DNS-concept, the production cross section of heavy and superheavy elements is determined by the expression:

$$\sigma_{\mathrm{ER}} = \sigma_{\mathrm{c}} \cdot P_{\mathrm{cn}} \cdot W_{\mathrm{sur}} \,, \tag{6}$$

where σ_{c} is the capture cross section; P_{cn} is the probability of a compound nucleus being formed in competition with quasi-fission; W_{sur} is the survival probability for the compound nucleus when de-excited. The values of σ_{c} and W_{sur} can be calculated using existing theoretical models. To calculate the factor P_{cn}, no theoretical models were available.

The DNS-concept allowed creating models that take account of competition between complete fusion and quasi-fission channels in symmetric and asymmetric nuclear reactions.

6.1. Symmetric reactions

A DNS can be at thermal (partial) equilibrium for several units of 10^{-22}s. The initial DNS is in a quasi-equilibrium state because it lies at the minimum of the DNS potential energy. This allows one to use a statistical approach for calculating competition between complete fusion and quasi-fission. The probability that the evolution of the initial DNS will end by complete fusion or by decay through the quasi-fission channel is proportional to the DNS level density at the tops of the fusion barrier $B^*_{\rm fus}$ and the quasi-fission barrier $B_{\rm qf}$:

$$P_{\rm cn} = \frac{\rho_{B^*_{\rm fus}}}{\rho_{B^*_{\rm fus}} + \rho_{B^*_{\rm qf}}}\,. \tag{7}$$

The DNS level density ρ is described according to the formula proposed in [15]. Fig. 9 shows $\sigma_{\rm ER}(E)$ for the reaction ^{110}Pd+^{110}Pd calculated by this model.

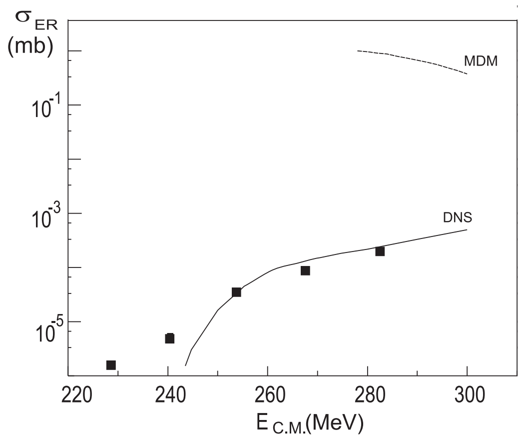

Fig. 9. The evaporation residue cross section in the reaction ^{110}Pd $+^{110}$Pd calculated by using the DNS-concept (solid line) and the MDM (dashed line) [11b].

6.2. Asymmetric reactions

To calculate the factor $P_{\rm cn}$ in asymmetric nuclear reactions, two DNS-concept-based models were created. One employs the Monte-Carlo method, and the other uses the Kramers approach for solving the Fokker-Planck equation.

The Monte-Carlo-using model [16], simplifying the DNS evolution process, assumes that from any configuration, the DNS is likely to pass only to the configuration neighboring in Z and A. This means that one proton and one or two neutrons are transferred from one nucleus to the other. Cluster transfer is excluded. The probability of nucleon transfer is proportional to the DNS level densities in the neighboring configuration. The level density is determined by the DNS excitation energy. It is calculated according to the formula proposed in [15]. The DNS evolution proceeds along the large number of trajectories in the Z and A space of the DNS nuclei. The model substitutes all these trajectories with one trajectory that goes along the potential energy valley. Using the Monte-Carlo method, the DNS evolution process is calculated for different angular momenta of collision L. It is assumed that on getting over the top of the fusion barrier $B^*_{\rm fus}$, the DNS goes irreversibly into the complete fusion channel. The DNS that has reached the symmetric form goes irreversibly into the quasi-fission channel. Fig. 10 shows the result of calculation of the values of $P_{\rm cn}$ for four reactions in which the same compound nucleus ^{246}Fm is produced. The calculated results for $P_{\rm cn}$ permitted reproducing the experimental values of $\sigma_{\rm ER}$ for these reactions [17].

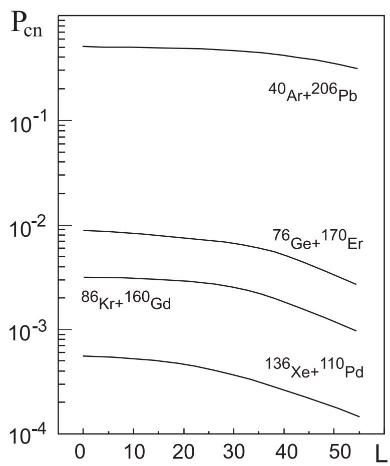

Fig. 10. The probability of complete fusion $P_{\rm cn}$ for reactions: ^{40}Ar+^{206}Pb, ^{76}Ge+^{170}Er, ^{86}Kr+^{160}Gd and ^{136}Xe +^{110}Pd calculated in the framework of the model using the Monte-Carlo method [16].

The Kramers approach-using model considers competition between complete fusion and quasi-fission to be competition between two ways of evolution for a viscose DNS [18]. One way is changing the mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$. A_1 and A_2 are the masses of the DNS nuclei. The other way is changing the distance between the centres of the nuclei — R. To describe the DNS evolution, the stationary solution to the Fokker-Planck equation is used in the form suggested by Kramers [19]. The parameter of the model is the DNS viscosity. The value of $P_{\rm cn}$ is defined by the stationary flow of probability through the fusion barrier $B^*_{\rm fus}$ and the quasi-fission barrier $B_{\rm qf}$. The model was tested with nuclear reactions in which the factor $P_{\rm cn}$ could be calculated using experimental data for the evaporation residue cross section.

7. Analysis of cold fusion reactions used for the synthesis of transfermium elements

The fission of excited nuclei of transfermium elements is the main factor that decreases their production cross sections as their atomic number Z increases. The use of ^{208}Pb target strongly decreases the excitation energy of the compound nucleus formed and increases the production cross section of the element to be produced. This approach, proposed by Yu.Ts. Oganessian [20], was named *cold fusion*. In cold fusion, a compound nucleus is produced with excitation energy of 12–15 MeV and the reaction channel with emission of only one neutron (HI, $1n$) may be used for the synthesis of a new transfermium element. All the new transfermium elements with atomic number Z from 107 up to 112 were synthesized in cold fusion reactions [21]. However, an attempt to synthesize element 113 failed.

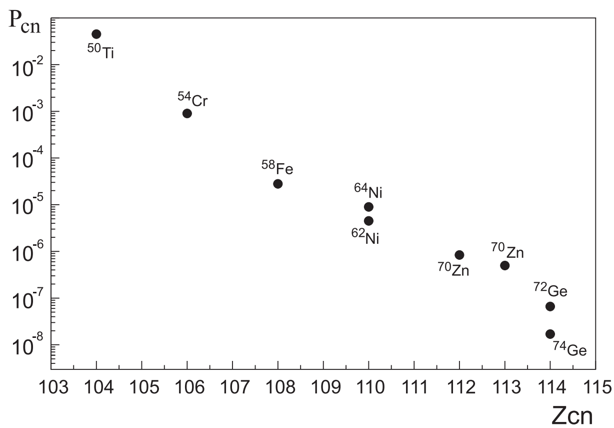

Fig. 11. The probability of complete fusion $P_{\rm cn}$ in cold fusion reactions calculated in the framework of the model using the Kramers type stationary solution to the Fokker-Planck equation [18].

The DNS-concept allows one to understand why that attempt was unsuccessful. Fig. 11 shows the values $P_{\rm cn}$ for the cold synthesis of a transfermium elements. Those values are calculated by model [18]. Quasi-fission is seen to strongly make the probability of compound nucleus formation to decrease as the atomic number increases. $P_{\rm cn}$ is $\sim 5\times10^{-2}$ for element 104, but it drops to the value $\sim 10^{-6}$ for element 112. Those calculations show quasi-fission to be the main factor responsible for a decreased production cross section in cold fusion reactions.

The use of the optical model to calculate the capture cross section and the statistical model to calculate the survival of the compound nucleus when de-excited (the factor $W_{\rm sur}$) made it possible to satisfactory reproduce ex-

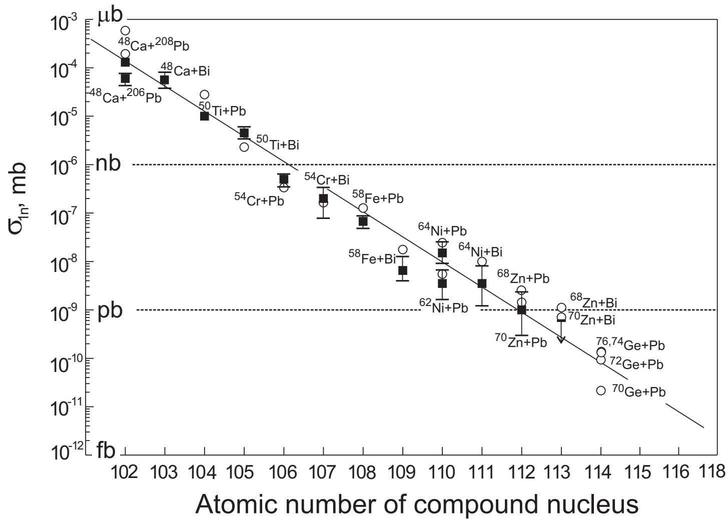

Fig. 12. Experimental data (black squares) and theoretical calculations (open circles) for the synthesis of elements from 102 to 114 in cold fusion reactions (HI, $1n$) [27].

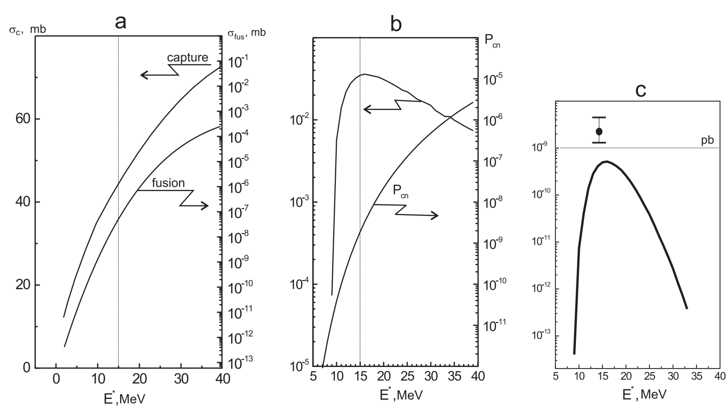

Fig. 13. The analysis of the reaction ^{208}Pb+^{86}Kr in the framework of the DNS-concept [23]: a — the capture and fusion cross sections; b — the energy dependence of the factor $P_{\rm cn}$ and the ratio of $\Gamma_{\rm n}/\Gamma_{\rm f}$; c — the energy dependence of the production cross section of element 118; the point is experimental data obtained in [24].

perimental data on the production cross sections of transfermium elements in cold fusion reactions (Fig. 12).

The DNS-concept permits estimating the real value of the production cross section of element 118 in the reaction ^{208}Pb+^{86}Kr. According to the model proposed by Smolanczuk [22], it should be more than five hundreds of picobarns. Fig. 13 shows the result of an analysis of that reaction in the framework of the DNS-concept [23]. The factor $P_{\rm cn}$ for excitation energy of 15 MeV is equal to 10^{-9}, and the maximum value of the production cross section is equal to 0.5 pb. It means that for that amount of bombardment carried out in experiments at Berkeley [24], the probability of the synthesis of element 118 was very small.

8. Analysis of the synthesis of superheavy elements 114 and 116 in reactions with ^{48}Ca ions

At FLNR JINR, in order to synthesize superheavy elements, neutron-rich actinide isotopes (^{244}Pu and ^{248}Cm), and ^{48}Ca were used as the target and bombarding ions, respectively [25,26]. Fig. 14 demonstrates calculations of the production cross section of element 114 in the reaction $^{244}\mathrm{Pu} + ^{48}\mathrm{Ca}$ [27]. The upper curve is the capture cross section, the curve next to it represents the compound nucleus production cross section. The lower curves reflect competition between fission and emission of a different number of neutrons during the de-excitation of the compound nucleus. The experimental value of the production cross section of $^{288}114$ (the $4n$ channel) is equal to $0.5^{+0.6}_{-0.3}$ pb [25]. Calculations [27] were made while the experiment was still in progress.

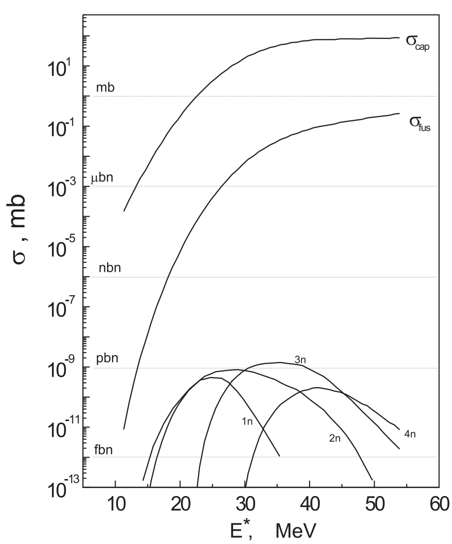

Fig. 14. The analysis of the reaction $^{244}\mathrm{Pu} + ^{48}\mathrm{Ca}$ in the framework of the DNS-concept: $\sigma_{\rm c}$ — the capture cross section, $\sigma_{\rm fus}$ — the fusion cross section, curves with indices $1n, 2n, 3n, 4n$ are the production cross section of different isotopes of element 114 [27].

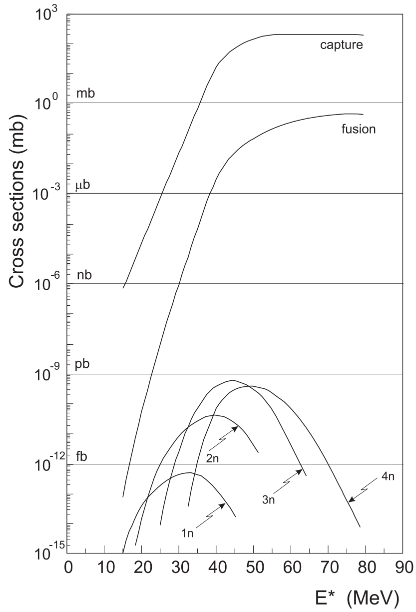

Fig. 15. The same calculations as in the Fig. 14 but for the synthesis of element 116 in the reaction ^{248}Cm +^{48}Ca [28].

Figure 15 shows some calculations for the reaction ^{248}Cm+^{48}Ca, used for the synthesis of element 116 [28]. The experimental value of the production cross section of ^{292}116 (the $4n$ channel) is equal to $0.5^{+0.8}_{-0.3}$ pb [26]. The difference between the $\sigma_{\rm c}$ and $\sigma_{\rm fus}$ curves reflects the influence of quasi-fission in both reactions. The factor $P_{\rm cn}$ is equal to $\sim 10^{-3}$. In cold fusion reactions, the value $P_{\rm cn}$ is equal to 10^{-7} for the synthesis of element 114 and 10^{-8} for the synthesis of element 116. In reactions with ^{48}Ca ions, the excitation energy of the compound nucleus is higher than in cold fusion reactions, but the smaller value of the factor $W_{\rm sur}$ is compensated by the more advantage value of the factor $P_{\rm cn}$.

9. The minimum of the excitation energy of compound nuclei in the synthesis of transfermium and superheavy elements

According to the DNS-concept, the minimum of compound nucleus excitation energy, $E^*_{\rm min}$, is determined by the height of the inner fusion barrier (Fig. 16). It means that $E^*_{\rm min}$ is determined by the shape of the potential energy curve. When formed, a compound nucleus acquires most of its minimum excitation energy as the DNS descends from the top of the barrier $B^*_{\rm fus}$. However, the fate of the DNS itself is decided when the system is

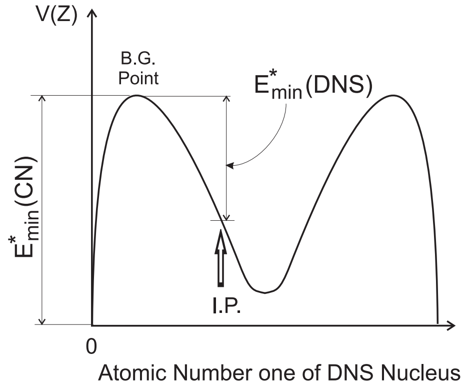

Fig. 16. The minimum of the excitation energy of the DNS necessary for complete fusion of two massive nuclei and the minimum value of the compound nucleus excitation energy according to the DNS-concept [11c].

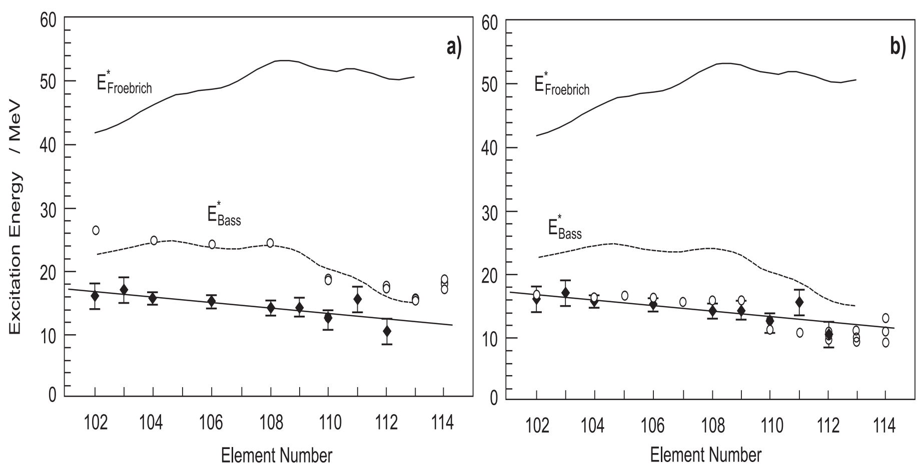

Fig. 17. The minimal excitation energy of the compound nuclei of 102−114 elements in cold fusion reactions (HI,1n); black points are experimental data, open circles are the calculated data according to the DNS-concept: (a) the deformation of the heavy nucleus of the DNS are taken into account, (b) the deformations of the heavy and light nuclei of the DNS is taken into account [11c].

approaching the top of the barrier $B^*_{\rm fus}$. At this evolution stage, the DNS excitation energy is the lowest and the DNS is cold. This peculiarity of the DNS evolution in the synthesis of transfermium and superheavy elements requires some modification of calculation of its potential energy. Instead of the liquid-drop masses, the real tabulated masses were used for the DNS nuclei. The heavy nucleus of the DNS was assumed to have ground state deformation. The large axis of the heavy nucleus was directed in such a way as for the system to have minimum potential energy. The calculated results for $E^*_{\rm min}$ for nuclei of elements from 102 to 114 produced in cold fusion reactions are shown in Fig. 17(a). One can see that the calculated values of $E^*_{\rm min}$ are close to experimental data. However, the calculated data turned out to be about 5 MeV higher than experimental data. This discrepancy disappears on the assumption that the light nucleus of the DNS is deformed (see Fig. 17(b)). In Fig. 17(b), its deformation corresponds to the excited state 2^+. So the DNS-concept makes it possible to estimate the minimum excitation energy of the compound nucleus in the synthesis of SHE and, consequently, the optimal value of bombarding energy.

10. Conclusions

1. Analysis of nuclear reactions used for the synthesis of superheavy elements is possible if we have a realistic picture of the mechanism of compound nucleus formation in the complete fusion of two massive nuclei.

2. The DNS-concept, based on experimental information about deep inelastic collisions of nuclei, permits one to create theoretical models that are capable of describing all the important aspects of the synthesis of heavy and superheavy elements.

3. The DNS-concept revealed a fusion barrier of a new type – $B^*_{\rm fus}$ and statistical competition between the complete fusion and quasi-fission channels in the DNS formed at the capture stage.

4. The DNS-concept makes it possible to calculate the production cross section of heavy and superheavy elements in cold and hot fusion reactions.

5. The DNS-concept permits estimating the minimum value of the excitation energy of the compound nucleus in cold fusion reactions.

6. One can say that at present the DNS-concept gives the most realistic picture of the mechanism of compound nucleus formation.

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