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ANALYSIS OF REACTIONS OF SUPERHEAVY ELEMENT SYNTHESIS WITHIN THE FRAMEWORK OF THE DINUCLEAR SYSTEM CONCEPT

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1. Introduction

In the present talk we would like to discuss some results of the analysis of the reactions which are used for the synthesis of heavy and superheavy elements (SHE) within the framework of the dinuclear system concept (DNS-concept).

On the basis of the DNS concept three topics are considered.

1. The minimum value of the compound nucleus excitation energy of heavy and SHE which can be obtained in the complete fusion reactions.
2. The role of quasi-fission in the reaction of SHE synthesis, the probability of compound nucleus formation in the conditions of strong competition with quasi-fission.
3. The perspective of using the symmetric reactions for the production of SHE with a low excitation energy of the compound nucleus.

2. Dinuclear system concept

2.1. The main features of the DNS-concept

The description of the DNS-concept and comparison of it with existing theoretical models of complete fusion are given in [1]. The main idea of the DNS-concept is the assumption that complete fusion reactions and deep inelastic transfer reactions are similar nuclear processes. This assumption gives us a possibility to use the unique information on the interaction of two nuclei in the deep inelastic collision, which was obtained in the study of deep inelastic transfer reactions. According to the DNS-concept the scenario of the complete fusion process is as follows.

- At the capture stage, after full dissipation of the collision kinetic energy the dinuclear system (DNS) is formed.
- The complete fusion process is the DNS evolution which proceeds via a nucleon transfer, shell by shell, from one nucleus to another.

- The DNS nuclei retain their individuality throughout their way to the compound nucleus. This peculiarity of the DNS evolution is the consequence of the shell structure of the nuclei.

Fig. 1 illustrates the compound nucleus formation process within the framework of the DNS-concept in the comparison with the interpretation of this process by the popular macroscopic dynamical model (MDM) of Swiatecki [2]. In the MDM the fused nuclei very quickly lose their individuality as the result of the neck formation. In the DNS-concept the fused nuclei retain their individuality until the end of the complete fusion process.

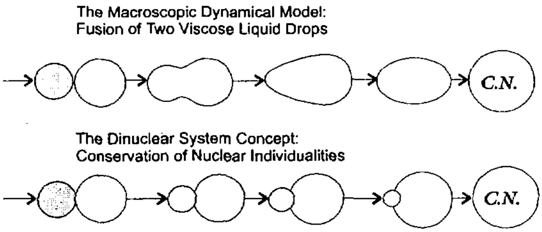

Fig. 1. Illustration of the compound nucleus formation process within the framework of the MDM and DNS-concept.

2.2. Peculiarities of complete fusion of massive nuclei

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

- the appearance of a specific inner fusion barrier - B^*_{fus} and
- the competition between the complete fusion and quasi-fission channels in the dinuclear system.

The DNS evolution is determined by the potential energy of the system as a function of charge (mass) asymmetry and the angular momentum of collision. The DNS potential energy is calculated according to the ratio:

$$V(Z,J) = B_1 + B_2 + V(R^*,J) - [B_{cn} + V_{rot}(J)], \qquad (1)$$

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

$$V(R,J) = V_{Coul}(R) + V_n(R) + V_{rot}(R,J). \qquad (2)$$

R is the distance between the centres of the nuclei, R^* is the R value for which the DNS is situated in the bottom of the pocket of the potential V(R). The DNS was taken in the form of two slightly overlapping spheres. The $V_n(R)$ was calculated by the double folding method [3]. $V_{rot}(R,J)$ was calculated for the rigid-body momentum of inertia of the DNS. The isotopic composition of the DNS nuclei was chosen from the conditions of the N/Z equilibrium in the system. The deformations of the DNS nuclei were not taken into account. The DNS potential energy was normalized to the potential energy of the compound nucleus which was taken as zero.

Fig. 2 shows the potential energy of the DNS which is formed in four reactions with different charge and mass asymmetry but the same compound nucleus - ^{246}Fm. The injection points of the reactions are indicated. To form the compound nucleus the evolving DNS must overcome the potential barrier - inner fusion barrier B^{*}_{fus}. The height of B^{*}_{fus} depends on charge asymmetry of the reaction. For the reaction with ^{40}Ar ions B^{*}_{fus} is equal to a few MeV, for the reaction with ^{136}Xe ions it is equal to about 20 MeV. The energy for overcoming the inner fusion barrier B^{*}_{fus} is taken from the excitation energy of the DNS.

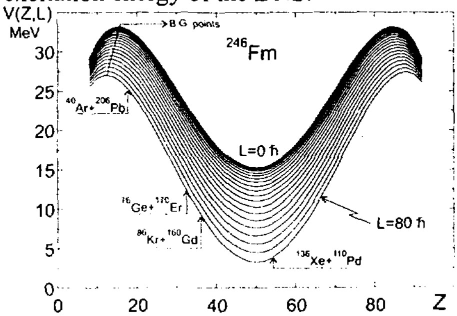

Fig. 2. Potential energy of the DNS which is formed in four reactions with the same compound nucleus ^{246}Fm. Z is the atomic number of one of the DNS nuclei.

There are two ways of evolution for the massive asymmetric DNS (Fig. 3). One of them brings the DNS to the compound nucleus.

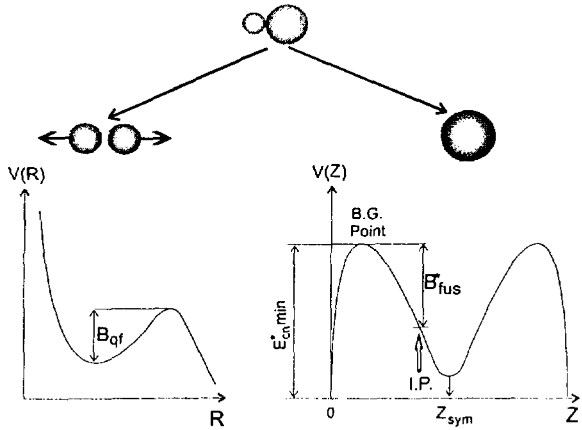

Fig. 3. Two ways of evolution of a massive asymmetric DNS. The nucleus-nucleus potential (left) and potential energy of DNS (right) are indicated.

This way requires the overcoming of the inner fusion barrier B^{*}_{fus}. The other way leads to the symmetric form of the DNS. In the symmetric DNS the Coulomb repulsion between nuclei has a maximum value and the massive DNS decays in two fragments. It means that quasi-fission takes place. In quasi-fission the DNS overcomes the quasi-fission barrier - B_{qf}. The statistical nature of the DNS evolution gives rise to the competition between the complete fusion channel and the quasi-fission channel.

3. Analysis of reactions of heavy and superheavy element synthesis

3.1. The minimum of the excitation energy of compound nuclei

The popular models of complete fusion, i. e. the macroscopic dynamical model of Swiatecki [2] and the surface friction model of Fröbrich [4], predict too high excitation energy of the compound nuclei of heavy and SHE which are produced in the complete fusion reactions. This can be seen in Fig. 4 taken from [5]. In the MDM the very high extra-extra push leads to the excitation energy of the 114 element's nucleus to nearly 300 MeV. According to the surface friction model [4] the excitation energy of compound nuclei near element 114 is equal to about 50 MeV. However, the experimental excitation energy of heavy compound nuclei in the cold fusion reactions turns out to be on the level of 13-16 MeV.

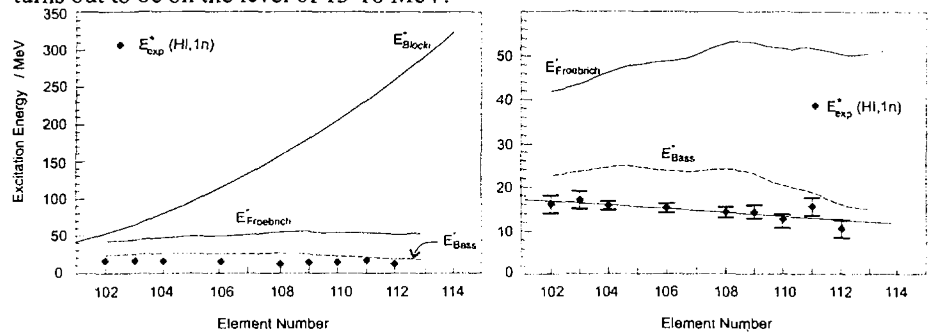

Fig. 4. *The minimal excitation energy of the compound nuclei of the 102-112 elements which have been synthesized in cold fusion reactions (HI,1n).* ♦ *- the experimental data, the solid lines present the results of calculations within the framework of the MDM and the surface friction model, the dashed line indicates the compound nucleus excitation energy in the collision when kinetic energy is equal to the Bass barrier [5].*

According to the DNS-concept the minimum of the compound nucleus excitation energy, E^*_{min}, is determined by the height of the fusion barrier B^*_{fus} relative to the compound nucleus (Fig. 5).

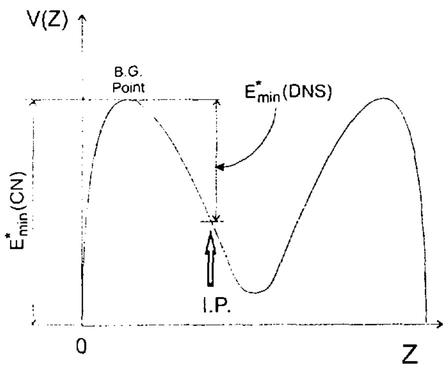

Fig. 5. *The minimum of the excitation energy of the DNS necessary for complete fusion; and minimum excitation energy of the compound nucleus according to the DNS-concept.*

It means that E^*_{min} is determined by the shape of the potential energy curve. The main part of the minimum excitation energy of the compound nucleus which has to be formed is received during the DNS descent from the top of B^*_{fus}. However, the fate of the DNS itself is determined at the approaching of the system to the top of the barrier. 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 SHE requires some modification of the potential energy calculation. Instead of the liquid-drop masses the real masses taken from the table were used for the DNS nuclei. The deformation of the heavy nucleus of the DNS was taken into account. The deformation was taken for the ground state of the heavy nucleus. The orientation of the large axis of the heavy nucleus corresponds to the minimum of the system's potential energy. The results of the calculations of E^*_{min} for the nuclei of elements from 102 to 114 produced in cold fusion are shown in Fig. 6a.

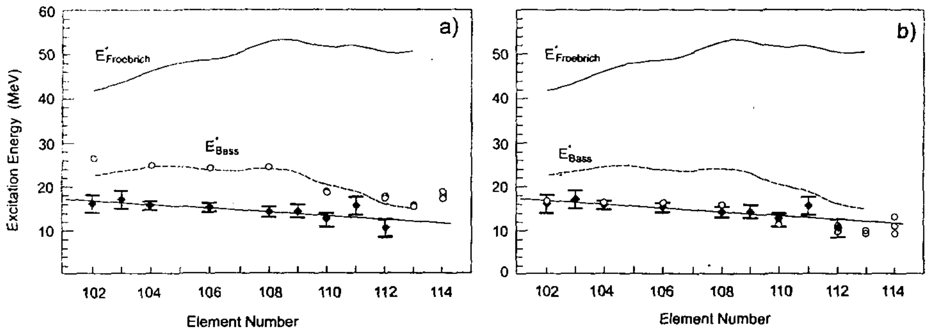

Fig. 6. The minimal excitation energy of the compound nuclei of 102-114 elements in cold fusion reactions (HI,1n). ♦ - the experimental data, o - the calculated data according to the DNS-concept: a) the deformation of the heavy nucleus of the DNS is taken into account, b) the deformation of the heavy and light nuclei of the DNS is taken into account.

One can see that the calculated values of E^*_{min} are close to the experimental data. However, the calculated data turned out to be about 5 MeV higher than the experimental data. This difference disappears if one takes into account the possible deformation of the light nucleus of the DNS (see Fig. 6b). We put in the deformation which corresponds to the deformation of the light nucleus in the excited state 2^+. So the DNS-concept gives a possibility to estimate the minimum excitation energy of the compound nucleus in the synthesis of SHE and optimal value of the bombarding energy.

3.2. The role of quasi-fission in the reactions of SHE synthesis

According to the DNS-concept the production cross section of heavy and SHE is determined by the following expression:

$$\sigma_{ER} = \sigma_c \cdot P_{cn} \cdot W_{sur}, \qquad (3)$$

where σ_c is the capture cross section, P_{cn} is the probability of the compound nucleus formation in the competition with quasi-fission, W_{sur} is the survival probability of the compound nucleus during its deexcitation. The values of σ_c and W_{sur} may be calculated using existing theoretical models. But there is no theoretical model for the calculation of P_{cn}. We suggest two models for the estimation of P_{cn}. The first one employs the Monte-Carlo method. The second one is based on the Kramers approach to the solution of the Fokker-Planck equation.

In the first model some simplifications of the DNS evolution process have been introduced. From any configuration the DNS may pass to the neighboring in Z and A configurations only. This means that one proton and one or two neutrons are transferred from one nucleus to another. The cluster transfer is excluded. The probability of the nucleon transfer is proportional to the DNS level densities in the neighboring configurations. The level density is determined by the DNS excitation energy. It is calculated according to the ratio proposed by Nörenberg [6].

The DNS evolution proceeds along the large number of trajectories in the Z and A space of the DNS nuclei. In the model all these trajectories are substituted by one trajectory which goes along the potential energy valley. The calculation of the DNS evolution process is carried out using the Monte-Carlo method for different angular momenta L. It is assumed that the DNS which crossed the top of B^*_{fus} goes irreversibly into the complete fusion channel. The DNS which has reached the symmetric form goes irreversibly into the quasi-fission channel. The model was tested in the calculation of the production cross section of ^{244}Fm in four reactions with different charge and mass asymmetries but the same compound nucleus ^{246}Fm. These reactions are ^{206}Pb+^{40}Ar, ^{170}Er+^{76}Ge, ^{160}Gd+^{86}Kr and ^{110}Pd+^{136}Xe (Fig. 2). The experimental data were obtained at the GSI by Gäggeler et al. [7].

In the second model the competition between complete fusion and quasi-fission is considered as the competition between two ways of evolution in the viscous DNS. One way is the change of the system's mass asymmetry $\eta=(A_1-A_2)/(A_1+A_2)$. A_1 and A_2 are the masses of the DNS nuclei. The second way is the change of the distance between the centers of the nuclei - R. The stationary solution to the Fokker-Planck equation is used in the form suggested by Kramers for the description of the DNS evolution. The parameter of the model is the DNS viscosity. The stationary flow of the probability through the inner barrier B^*_{fus} and quasi-fission barrier B_{qf} defines the value of P_{cn}. The model was tested for the nuclear reactions in which P_{cn} could be calculated using experimental data for the evaporation residue cross section.

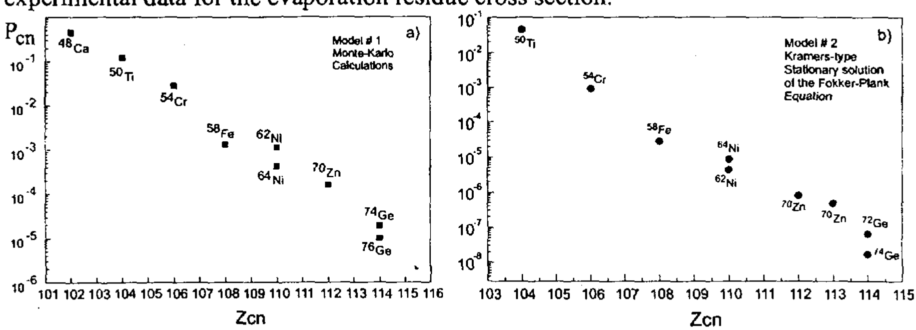

Fig. 7. The probability of complete fusion P_{cn} in the cold fusion reactions (HI,1n): a) the Monte-Carlo calculations are used, b) the Kramers type stationary solution to the Fokker-Planck equation is used.

Both models were used for the calculation of P_{cn} in the reactions of cold synthesis of elements from 104 to 114. The results of calculation are presented in Fig. 7. One can see that quasi-fission decreases strongly the probability of the compound nucleus formation with increasing the atomic number of the element. In the first model quasi-fission from intermediate configuration of the DNS is not taken into account, and the slope of the P_{cn} data is more gradual.

Traditionally fission of an excited compound nucleus is considered to be the principal hazard for the synthesis of SHE. The DNS-concept reveals a new serious hazard - quasi-fission.

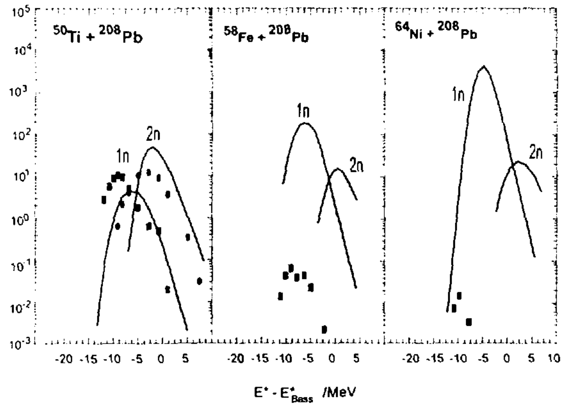

Fig. 8. The production cross section of elements 104, 108, 110 in cold fusion reactions (HI,1n). ■ - the experimental data obtained at the GSI, the lines are results of calculations within the framework of the statistical model [8].

Figure 8 demonstrates the results of calculation of the production cross sections of elements 104, 108 and 110 in the reactions of cold fusion. The calculations were made by B.Pustylnik within the framework of a statistical model [8]. For element 104 one can see a good agreement between the results of calculation and the experimental data. Large discrepancy is observed, however, for elements 108 and 110. The cause of this discrepancy is the quasi-fission. Quasi-fission is the main factor of a decrease in the production cross section of very heavy nuclei with increasing their atomic number.

3.3. Perspectives of using symmetric nuclear reactions for the SHE synthesis

Symmetric nuclear reactions between two massive nuclei are considered to be one of possible ways for the synthesis of SHE. Due to the large negative values of Q the compound nucleus in these reactions should have a very low excitation energy on the level of several MeV.

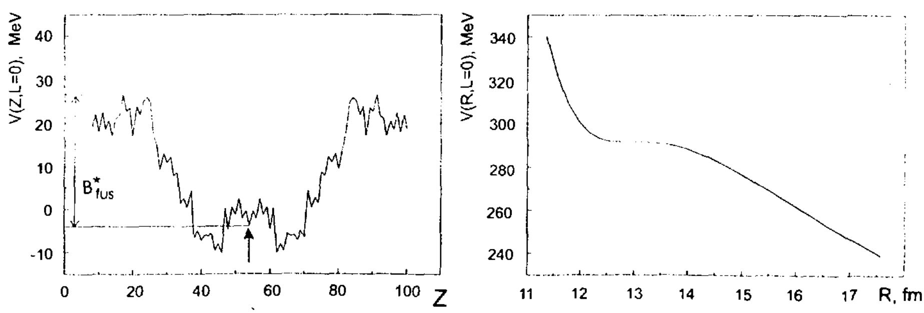

Fig. 9. The DNS potential energy (left) and nucleus-nucleus potential (right) in the reaction ^{136}Xe + $^{136}Xe \rightarrow {}^{272}108$.

We considered the fusion of two ^{136}Xe nuclei into the nucleus $^{272}108$ within the framework of the DNS-concept. Figure 9 shows the potential energy of the DNS which is formed in this reaction in a head-on collision.

One can see that the inner fusion barrier B^*_{fus} has a value of about 30 MeV. To overcome the fusion barrier the DNS must have an excitation energy of no less than 30 MeV. The compound nucleus will have nearly the same excitation energy. With increasing Z of the compound nucleus, B^*_{fus} increases also. This means that it is not possible to produce a cold nucleus of SHE in symmetric nuclear reactions.

The symmetric massive DNS has a vanishingly low quasi-fission barrier. The high fusion barrier and low quasi-fission barrier make the quasi-fission channel to dominate strongly over the complete fusion channel. The P_{cn} value in the reaction $^{136}Xe+^{136}Xe$ is equal to a few units of 10^{-9}. Thus the DNS-concept indicates that symmetric nuclear reactions have no perspective in the synthesis of SHE.

4. Summary

1. The DNS-concept gives a possibility to obtain realistic minimal values of the compound nucleus excitation energy in the reactions of SHE synthesis.
2. The DNS-concept reveals an important role of quasi-fission in the reactions of SHE synthesis. In the cold fusion reactions quasi-fission is the main factor in decreasing the production cross section with increasing the atomic number of the element.
3. The DNS-concept indicates that symmetric reactions between massive nuclei are not perspective in the synthesis of SHE.
4. At present the DNS-concept is the most realistic approach to the analysis of the nuclear reactions used for the synthesis of SHE.

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Анализ реакций синтеза сверхтяжелых элементов в рамках концепции двойной ядерной системы

Для анализа реакций синтеза тяжелых и сверхтяжелых элементов использована концепция двойной ядерной системы для процесса полного слияния ядер. Рассчитана минимальная энергия возбуждения составного ядра элементов с Z от 104 до 114, получаемых в реакциях холодного слияния. Обсуждается роль квазиделения в реакциях синтеза сверхтяжелых элементов. Описываются две модели конкуренции полного слияния и квазиделения. Рассматриваются перспективы использования симметричных реакций между массивными ядрами для синтеза сверхтяжелых элементов, и указаны главные особенности концепции двойной ядерной системы.

Работа выполнена в Лаборатории ядерных реакций им.Г.Н.Флерова и в Лаборатории теоретической физики им.Н.Н.Боголюбова ОИЯИ.

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Analysis of Reactions of Superheavy Element Synthesis within the Framework of the Dinuclear System Concept

The dinuclear system concept employed for a description of the complete fusion process is used for the analysis of reactions of heavy and superheavy elements synthesis. The minimum value of the compound nucleus excitation energy of elements from 104 to 114, which are formed in the cold fusion reaction is calculated. The role of quasi-fission in the reactions of superheavy element synthesis is discussed and two models of the competition between complete fusion and quasi-fission are described. The perspective of using the symmetrical reactions between massive nuclei for the synthesis of superheavy elements is considered. The main features of the dinuclear system concept are indicated.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions and at the Bogoliubov Laboratory of Theoretical Physics, JINR.

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