DYNAMICS OF HEAVY NUCLEI FUSION WITHIN CONCEPT OF DINUCLEAR SYSTEM

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Main aspects of dynamic model and methods for calculation of dinuclear system evolution for description of heavy nuclei fusion are presented. Analysis of nuclear-nuclear potentials during fusion $U^{235}+n, U^{238}+n, Pu^{239}+n$ end $Pu^{241}+n$ are presented within the frames of concept of dinuclear system. For description of fusion dynamics "proximity" potential was chosen as the most realistic. Initial conditions of DNS formation were determined, the most probable combination Z_1 end Z_2 with fixed A_1+A_2 and probabilities for formation of all probable pairs Z_1+Z_2 for all combinations over A_0, and potential energy, Coulomb energy and latent bond are also calculated.

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1. INTRODUCTION

A series of works [4 - 7] were devoted to investigation of nuclear reactions dynamics within the concept of dinuclear system [1 - 3]. The DNS approach is successfully applied for description of fission - quasi-fusion processes with synthesis of super-heavy elements. DNS approach is based on information about interaction of nuclei in deep non-elastic collisions and evolution of the generated DNS occurs at the cost of nucleon transfer from fragment to fragment. This process depends on mass and charge asymmetry of DNS, excitation energy, fragment deformation etc. In the presented work main approaches are discussed in order to describe heavy nuclei fusion within DNS concept and methods for calculation of its evolution are presented. Nuclear interaction potentials for spherical DNS fragments, reactions $U^{235}+n(Z_0=92), U^{238}+n(Z_0=92), Pu^{239}+n(Z_0=94)$ end $Pu^{241}+n(Z_0=94)$ are analyzed.

2. MAIN FORMALISM OF THE APPROACH TO DISCRIPTION OF DNS EVOLUTION WITH NUCLEI FUSION

DNS is an unsteady system continually changing at the cost of nucleon transfer from nucleus to nucleus. DNS concept regarding heavy nuclei may interpreted as follows:

1. After excitation a nucleus with neutron in A position (Fig.1) DNS is generated consisting of two fragments with collective and individual single-particle energy levels. Initial conditions of generation are determined from the fact that the nuclear potential is equal to zero and from the law of normal nuclear density conservation.

2. In the course of time under action of nuclear-nuclear potential the distance between DNS fragments changes and as a consequence the number of individual and collective single-particle energy levels changes.

3. In the course of DNS evolution in coordinate R - the distance between centers of the fragments from the point of formation - A, there is partial dissipation of kinetic energy to the point of break - B. In the case of spherical fragments this process stops when $R_0=R_1+R_2$, where R_1 and R_2 - radii of DNS nuclei.

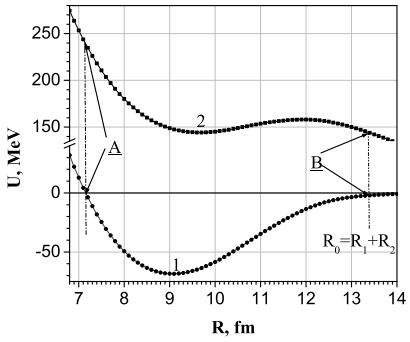

Fig.1. *Dependence of nuclear potential (curve-1) and nuclear-nuclear potential (Coulomb+nuclear)(curve-2) on the distance between DNS fragments*

4. In this process exchange of nucleons occurs between DNS fragments towards decrease of the potential energy of the system, mainly at collective single-particle energy levels up to the moment of break. This process is defined by potential energy of DNS [2, 3], that is, $U_{CN}=V_{CN}+B_1+B_2-B_{CN}$, where B_1, B_2, B_{CN} - bound energies of DNS fragments and compound nucleus, V_{CN} - nuclear-nuclear potential of DNS. This process takes place during DNS existence. Therefore, DNS evolution takes place not only

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in R coordinate but also in A and Z, numbers of nucleons and protons in DNS fragments. The number of protons in DNS may be determined from the condition of the minimum potential energy with fixed $A_1 + A_2 = A_0$ and R, where A_1, A_2, A_0 - the number of nucleons in DNS fragments and in compound nucleus, respectively. This basic process may characterize DNS evolution to the moment of cessation of collective energy levels. At this time mass and energy distribution with nuclei fission is formed.

To describe DNS evolution one may apply Schredinger unstationary equation for two bodies $\imath\hbar\frac{\partial}{\partial t}\Psi(q,t) = -\frac{\hbar^2}{2\mu(q,t)}\Delta\Psi(q,t)+U(q,t)\Psi(q,t)$, where q - generalized coordinates, t - duration of DNS existence, $\mu(q,t)$ - reduced mass of the fragments, $U(q,t)$ - potential energy of the system, $\Psi(q,t)$ - wave-function describing the system at arbitrary moment t_i. As a rule, generalized coordinates are variables describing the system evolution most completely. In our case we will use the number of nucleons in DNS nuclei as the generalized coordinates; then laplacian $\Delta = \partial^2/\partial A^2$. Therefore, in the first approximation the wave-function, potential energy and reduced mass of the fragments depend only on A and t. This implies that for description of DNS evolution it is necessary to apply the Schredinger equation to all the possible pairs of input channels being generated in A_i and Z_i coordinates. The number of equations below is defined by the probable combinations $A_1 + A_2 = A_0$ and $Z_1 + Z_2 = Z_0$, where Z_1, Z_2 and Z_0 - the number of protons in DNS fragments and in the compound nucleus, respectively:

$$i\hbar\frac{\partial}{\partial t}\Psi_i(A,t)k_1 = -\frac{\hbar^2}{2\mu_i(A,t)}\frac{\partial^2}{\partial A^2}\Psi_i(A,q)k_2 + \\ +U_i(A,t)\Psi_i(A,t), \quad (1)$$

where k_1 and k_2 - parameters of the rate fixing. DNS evolution occurs on multiple trajectories in A and Z space, and as at the point of DNS formation there are multiple input channels it is necessary to take into account overlapping the trajectories from all the channels of DNS formation; therefore the limiting number of equations (1) should be $(A_0/2)(Z_0/2)$. In quasi-classic approximation the system of equations follows from (1) (k_1, k_2 - unsuspected parameters):

$$\left.\begin{aligned}\frac{\partial}{\partial t}S_i(A,t) + \frac{1}{2\mu_i}(\frac{\partial}{\partial A}S_i(A_i,t))^2 + U_i(t) = 0\\ \frac{\partial}{\partial t}P_i(A,t) + \frac{1}{\mu_i}\frac{\partial}{\partial A}(P_i(A,t)\frac{\partial}{\partial A}S_i(A,t)) = 0\end{aligned}\right\}$$

where $P_i(A,t)$ - density of probability. First equation is the classic Hamilton-Jacobi equation for action $S_i(A,t)$; it defines the rate of nucleon transfer in coordinate A. The second equation is the continuity equation and defines change in distribution of density of probability in mass numbers A in the course of time t at classic velocity $\nu_i = \frac{1}{\mu_i}\frac{\partial}{\partial A}S_i(A,t)$. Approximated solution with initial conditions $P_i(A, t=0) = f_i(A)$, where $f_i(A)$ - probability of distribution in DNS over input channels for each pair of fragments will be: $P_i(A,t) = \frac{f_i(A)}{A}(A - \sqrt{2}\sum_0^{A_0}\frac{1}{\mu_i}\int_0^{t_i}\sqrt{U_i(t)}dt)$, where t_i - duration of existence of each pair in DNS configuration.

3. NUCLEAR-NUCLEAR POTENTIAL OF DNS FRAGMENTS

The main part in description of the fusion process plays the choice of nuclear-nuclear potential. Nuclear-nuclear potential includes Coulomb, centrifugal and nuclear potentials: $V_{CN} = V_C + V_{rot} + V_N$. Coulomb potential with partial overlapping spaces for all the probable pairs of DNS fragments was calculated on the formula [3] for $R \le R_1 + R_2$:

$$V_C = \frac{Z_1 Z_2 e^2}{2(R_1+R_2)}[3 - (\frac{R}{R_1+R_2})^2], \quad (2)$$

where Z_1 and Z_2 - the numbers of protons DNS, R_1 and R_2 - radii of the fragments, R - the distance between the fragments. More precise value for Coulomb potential may be obtained numerically with account of the realistic Fermi density distribution. Comparison of numerical and analytic representations showed [8] that it is possible to apply the relationship (2). For calculation of centifugal potential the relationship for solid moment of inertia for a nuclear system is used: $V_{rot} = \hbar^2 l(l+1)/(2R^2\mu)$, where l - orbital angular moment, μ - reduced mass of the nuclear system.

For calculation of nuclear potential for all the possible pairs of DNS fragments Saxon-Voods phenomenological optical potential (OPSV), symmetrized "folding-1" potential, "folding-2" potential and "proximity" potential were used.

Phenomenological OPSV was widely used to describe interaction of heavy ions with nuclei [9, 11, 12]; OPSV may be used in the form [13]:

$$V_N^{OPSV} = V_0\{1 + exp[\frac{R - r_0(A_1^{1/3} + A_2^{1/3})}{d}]\}^{-1},$$

where $V_0 = 70\,MeV, r_0 = 1.2\,fm$, and $d = (0.95 - 0.00039)Z_1Z_2 fm$ - parameters of the optical potential. For reactions $U^{235} + n, Pu^{239} + n, U^{238} + n$ and $Pu^{241} + n$ OPSV potentials were calculated for all the probable pairs of DNS fragments. From the calculations one may conclude that OPSV does not describe dependence $V_N(R)$ at short distance R between DNS fragments and gives incorrect dependence of the radial friction coefficient on the distance between the DNS fragments.

Symmetrized "folding-1" potential [11, 13] is calculated on the formula:

$$V_N^{fold(1)} = \frac{1}{2}[V_{12}(R) + V_{21}(R)] = \\ = \frac{1}{2}[\int V_1(R - R')\rho_2(R')d^3R' + \\ + \int V_2(R - R')\rho_1(R')d^3R'].$$

"Folding-2" potential is determined by summation nucleon-nucleon interactions between both

nuclei of all the nucleons depending on the distance between them [10, 11, 12]; this potential may be written in the form:

$$V_N^{fold(2)} = \int \rho_1^{(0)}(R-R_1) f_{eff}[\rho]\rho_2^{(0)} \cdot \cdot(R-R_2)d^3R.$$

"Proximity" potential was obtained in assumption that interaction energy of two closely located surfaces may be written as: $U = \int_S e(D)dR$, where S - surfaces themselves, D - distance between the surface elements, $e(D)$ - interaction energy per the surface unit between the two planes. According to [14, 15] nuclear-nuclear potential between DNS fragments is calculated:

$$V_N^{prox} = 4\pi\gamma\overline{R}b\Phi(\xi), \qquad (3)$$

where $\gamma = 0.951[1-1.17826((N-Z)/A)^2](MeV\cdot fm)$, $\overline{R} = C_1C_2/(C_1+C_2)$, $b = 1$, $\xi = s/b = s$, $s = R-(C_1+C_2)$, $C_i = R(1-b^2/R^2+...)$, $R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{1/3}, i = 1, 2$.

$$\Phi(\xi) = \begin{cases} -1.7817 + 0.927\xi + 0.143\xi^2 - 0.09\xi^3, \xi < 0 \\ -1.7817 + 0.927\xi 0.01696\xi^2 - 0.005148\xi^3, \\ 0 < \xi < 1.9475 \\ -4.41exp(-\xi/0.7176), \xi > 1.9473 \end{cases}$$

From the analyses of nuclear potentials for reactions proximity potential was chosen (Fig.1.) because at the distances between DNS fragments smaller than R_{cr} nuclear potential reverses its sign that may be explained as increasing nuclear density above the normal ($0.17fm^{-3}$). From the equality of proximity potential to zero an approximated expression were found for the critical distance, that is, the distance between the centers of the fragments at the moment of DNS formation from all the probable DNS pairs for $U^{235}+n, Pu^{239}+n, U^{238}+n$ and $Pu^{241}+n$ having the following form:

$$R_{cr}(fm) = 1.29(A_1^{1/3} + A_2^{1/3}) - 4.99, \qquad (4)$$

where $A_1 + A_2 = A_0$ - the number of protons in compound nuclei. This expression is used for determination the initial conditions for DNS formation.

4. PARAMETERS OF DNS FORMATION

Potential energy of DNS at the point of formation ($R = R_{cr}$) is equal to: $U_{CN} = V_{CN} + B_1 + B_2 - B_{CN}$, where $V_{CN} = V_C$, as both nuclear and centrifugal potential are equal to zero. Putting $A_1 + A_2 = A_0$ for above reactions for all the probable combinations $Z_1 + Z_2 = Z_0$, we calculated potential energy of DNS, Coulomb energy and latent bond energy ($B_1 + B_2 - B_{CN}$). In the Fig.2 initial DNS characteristics are presented for reaction $U^{235} + n$ at the point of DNS formation with all the probable combinations $A_1 + A_2 = A_0$ and for the most probable relationships $Z_1 + Z_2 = Z_0$ (these values were found from the calculated values of normalized probability with DNS formation from compound nucleus). Along the horizontal axe the number of nucleons in the first fragment is plotted. Similar results were obtained for the rest three reactions. We discussed the probability of DNS formation as a fluctuation from the compound nucleus with fixed values $A_1 + A_2 = A_0$, where A_1 - ranges from 1 to $A_0 - 1$. Using this approach we determined the probability of DNS formation with fixed values $A_1 + A_2 = A_0$ for all the probable pairs with $Z_1 + Z_2 = Z_0$. Thus, this approach is based on energy dependence of the probability of DNS formation and initial (compound nucleus) and end (DNS) conditions of the state are known then [16]:

$$P = exp(-\frac{\Delta E}{T}), \qquad (5)$$

where - $T = (E^*/a)^{1/2}$ - DNS temperature, $E^* = B(n) + E_n[A_0/(A_0-1)]$ - excitation energy ($B(n)$ - energy of neutron binding in the nucleus A_0, E_n - neutron energy), $a = A_0/12\,MeV^{-1}$ - level density, ΔE - difference between potential energy of the compound nucleus and generated DNS.

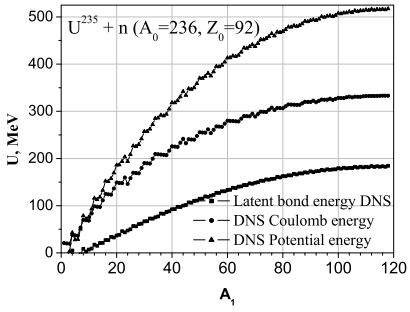

Fig.2. *Initial DNS characteristics for reactions $U^{235}+n$, ($A_0 = 236, Z_0 = 92$)*

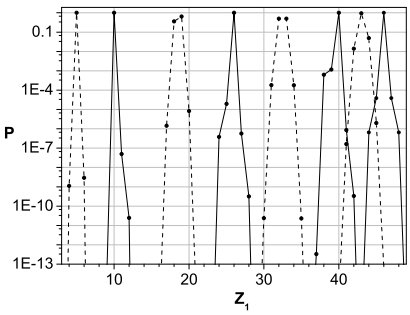

Fig.3. *Dependence of the probability of DNS fragment formation on the proton number in the first nucleus with fixed values of $A_1 + A_2$. From left to right, for nucleon number: 9+227, 20+216, 39+197, 58+178, 77+159, 98+138, 109+127, 118+118*

Fluctuation theory is successfully used for description of nucleus break into fragments [17] and formation of mass and charge distributions, and also for other characteristics being observed with fusion

[18]. In the Fig.3 dependence of the probability of DNS formation on the number of protons in the light fragment for several fixed values $A_1 + A_2$, reaction $U^{235} + n$ is presented. The most probable DNS formation with calculated numbers of nucleons and protons is showed in the Fig.4.

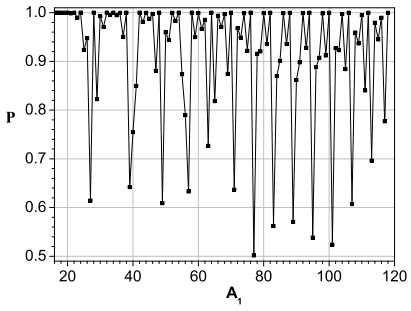

Fig.4. *Dependence of the most probable values in Z_1 in DNS fragments on the nucleon number in the first nucleus for reaction $U^{235} + n$*

5. DNS ENERGY DISSIPATION

For description of the relative motion the DNS fragments of spherical nuclei we will use Newton equation including friction and accounting only radial motion, in the form:

$$\frac{d}{dt}(\mu_i(R) \cdot \dot{R}(t)) + K_R(R) \cdot \dot{R}(t) = F_i(R), \qquad (6)$$

where R - distance between the centers of the DNS fragments, $\mu_i = m_i m_{A_0-i}/(m_i + m_{A_0-i})$ - reduced mass which is determined over all the probable pairs of the fragments DNS accounting the mass conservation law, $K_R(R) = K_R^0(\nabla V_N(R))^2$ - radial friction force acting with changing the distance between the DNS nuclei. Initial conditions for this equation are defined by the relationships (4) and (5), and velocity of relative movement of DNS at the point of formation is equal to zero. $F_i(R) = -\partial U_i(R)/\partial R$ - derivative of nuclear-nuclear potential, K_R - coefficient of radial friction. he solution of this equation will give the dependence R on t for solving Schredinger equation. One should keep in mind that in the case of calculation the initial conditions of DNS formation, the probability of formation depends on the excitation energy, that is, on neutron energy.

6. CONCLUSIONS

An approach is proposed for description of heavy nuclei fusion based on DNS concept which will allow description not only fusion dynamics (equations: $1-6$) but dynamics of fission - quasifusion of nuclei with synthesis of super-heavy elements. Further, to the proposed dynamic model the following processes will be included:

1. Identification of nucleon emission from DNS. This will change mainly DNS evolution in A and Z coordinates. DNS single-particle energy levels both collective and individual will be calculated. Because of the fact that the distance between DNS fragments changes under action of nuclear-nuclear potential, heights of the energy levels and their occupancies will also change that will allow identification of nucleon emission. Besides that this will change the dependence of potential energy on R.
2. Determination of dynamic deformation of DNS fragments that will change DNS potential energy, and as a consequence evolution on R, A and Z.
3. Processes associated with different energies of nuclei excitation will be taken into account; this will lead mainly to change in duration of DNS existence and as a consequence to the processes of redistribution of mass and energy dependences of output channels.

It should be noted that the proposed model will be applied for description of processes of fusion - quasifission of heavy nuclei with initial excitation of target nucleus with neutrons and ions.

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ДИНАМИКА ДЕЛЕНИЯ ТЯЖЕЛЫХ ЯДЕР С ИСПОЛЬЗОВАНИЕМ КОНЦЕПЦИИ ДВОЙНОЙ ЯДЕРНОЙ СИСТЕМЫ

В.А. Бомко, А.Ф. Кобец, К.В. Павлий, Б.В. Зайцев

Предложена динамическая модель для описания деления тяжелых ядер, основанная на концепции двойной ядерной системы (ДЯС). Из анализов ядерных потенциалов (ОПСВ, folding-1, folding-2 и proximity) выбран proximity потенциал, который наиболее реалистически описывает потенциальную энергию системы при делении ядер, при низких энергиях возбуждения. Для реакций $U^{235}+n$, $Pu^{239}+n$, $U^{238}+n$ и $Pu^{241}+n$ найдено аппроксимационное выражение для критического расстояния в момент образования ДЯС. Определены начальные условия образования ДЯС, наиболее вероятная комбинация Z_1 и Z_2 при фиксированных значениях A_1 и A_2 и вероятность образования для всевозможных пар Z_1+Z_2 для всех комбинаций по A_0 (массовое число составного ядра), а также вычислены потенциальная, кулоновская и скрытая энергии связи.

ДИНАМІКА ДІЛЕННЯ ВАЖКИХ ЯДЕР З ВИКОРИСТАННЯМ КОНЦЕПЦІЇ ПОДВІЙНОЇ ЯДЕРНОЇ СИСТЕМИ

В.О. Бомко, А.П. Кобецъ, К.В. Павлій, Б.В. Зайцев

Запропонована динамічна модель для опису ділення важких ядер, заснована на концепції подвійної ядерної системи (ПЯС). З аналізів ядерних потенціалів (ОПСВ, folding-1, folding-2 і proximity) вибраний proximity потенціал, який найреалістичніше описує потенційну енергію системи при діленні ядер, при низьких енергіях збудження. Для реакцій $U^{235}+n$, $Pu^{239}+n$, $U^{238}+n$ і $Pu^{241}+n$ знайдено вираз апроксимації для критичної відстані у момент утворення ПЯС. Визначені початкові умови утворення ПЯС, найбільш вірогідна комбінація Z_1 і Z_2 при фіксованих значеннях A_1 і A_2 і вірогідність появи для всіляких пар Z_1+Z_2 для всіх комбінацій по A_0 (масове число складеного ядра), а так само обчислені потенційна, кулонівська і прихована енергії зв'язку.