

The analysis of reactions leading to synthesis of super heavy elements within the dinuclear system concept

E A CHEREPANOV

Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
Email: cher@jinr.ru

Abstract. The dinuclear system concept of complete fusion of nuclei has been applied to the analysis of superheavy elements synthesis. The optimal excitation energy of compound nuclei and production cross sections in the cold synthesis of heavy elements with charge $Z = 102 - 112$ have been calculated. The possibility of synthesizing the element with magic number $Z = 114$ in cold and hot fusion reactions has been considered.

Keywords. Fusion; fission; superheavy elements; quasi-fission; deexcitation.

PACS Nos 24.75+i; 25.85.-w; 25.85.Jg; 27.90.+b

1. Introduction

The application of heavy ions of large mass is necessary for the decision of problems of the synthesis of new elements. Especially important in planning the experiments on the synthesis of new elements is to know the cross section of complete fusion. The cross sections of complete fusion in reactions with heavy ions up to values $Z_p \cdot Z_t = 1600$ are well described by the existing theoretical models. For $Z_p \cdot Z_t > 1600$ values the cross section of complete fusion dramatically fell.

There are different models for the description of complete fusion of massive nuclei. Most popular of them is the macroscopic dynamical model of Swiatecki [1]. However, a lot of experimental data for reactions of cold synthesis cannot be explained even qualitatively within the framework of this model. For instance, new elements with $Z = 107 - 112$ were produced in GSI using targets close to Pb (see, for example, ref. [2]). In these reactions the maxima of the excitation functions for the evaporation of one neutron lie below the Bass barrier. Complete fusion for these reactions in framework MDM required a large excess (several tens of MeV) of the collision kinetic energy above the entrance Coulomb barrier B_{Bass} . In Japan, an approach is being developed on the basis of the fluctuation–dissipation model (see, for example ref. [3]), for the description of the fusion of heavy symmetric systems leading to the formation of transfermium nuclei. Estimation of the formation cross sections of SHE in standard statistical model taking into account the limitations on fusion from empirical systematics were made in ref. [4].

In all listed models, as it seems, there is no systematic comparison with the existing experimental data. Such a comparison could give significant weight to the theoretical predictions. In FLNR (JINR) a new approach has been developed for the description of complete fusion of massive nuclei based on dinuclear system (DNS) concept [6]. In the present work an attempt is undertaken to describe the existing data on cold synthesis of new elements on the basis of the DNS concept. We analysed various ('cold' and 'hot') reactions leading to the synthesis of the new element with charge number 114.

2. Description of the theoretical approach

2.1 Basic assumptions of the DNS-concept

The motivation of the DNS-concept and its comparison with MDM have already been presented in [5,6]. Therefore, here we point out only the basic assumptions used in the analysis of the SHE-synthesis reactions. According to the DNS-concept the complete fusion process proceeds in the following way. On the capture stage, after full dissipation of the collision kinetic energy, a dinuclear system is being formed (well known from deep inelastic transfer reactions). Complete fusion is an evolution process in which the nucleons of one nucleus sequentially are transferred to the second nucleus. The main characteristic of the DNS, determining its evolution, is the potential energy of the system $V(Z, L)$, which calculated according to the equation:

$$V(Z, L) = B_1 + B_2 + V(R^*, L) - [B_{\text{CN}} + V_{\text{rot}}^{\text{CN}}(R^*, L)], \quad (1)$$

where B_1 , B_2 and B_{CN} are the nuclear binding energies of the DNS nuclei and the compound nucleus, and Z is the atomic number of one of the nuclei in the DNS, L is the spin of the system. The value of $V(Z, L)$ was normalized to the energy of rotating compound nucleus by $B_{\text{CN}} + V_{\text{rot}}^{\text{CN}}(R^*, L)$. The nucleus–nucleus potential $V(R, L)$ incorporates the nuclear, Coulomb and centrifugal potentials:

$$V(R, L) = V_n(R) + V_c(R) + V_{\text{rot}}(R, L), \quad (2)$$

where R is the distance between the centers of the nuclei in the DNS.

In calculating $V(R, L)$, the DNS was assumed to have the shape of two slightly overlapping nuclei. R^* is the value of R , at which the DNS is to be found at the bottom of the 'pocket' in the potential $V(R, L)$. The nuclear potential $V_n(R)$ was calculated using the double folding method (see details in ref. [7]). The centrifugal potential was calculated for the case of the rigid rotor moment of inertia.

2.2 Peculiarities in the complete fusion of two massive nuclei within the DNS concept

Figure 1 presents the potential energy of the DNS, curve $V(Z, L = 0)$ exhibits two minima: the first one $Z = 0$ corresponding to complete fusion and the second one $Z = Z_{\text{CN}}/2 = (Z_p + Z_t)/2$ corresponding to the formation of a symmetric DNS. During the evolution DNS can decay into two nuclei. viz. quasi-fission takes place.

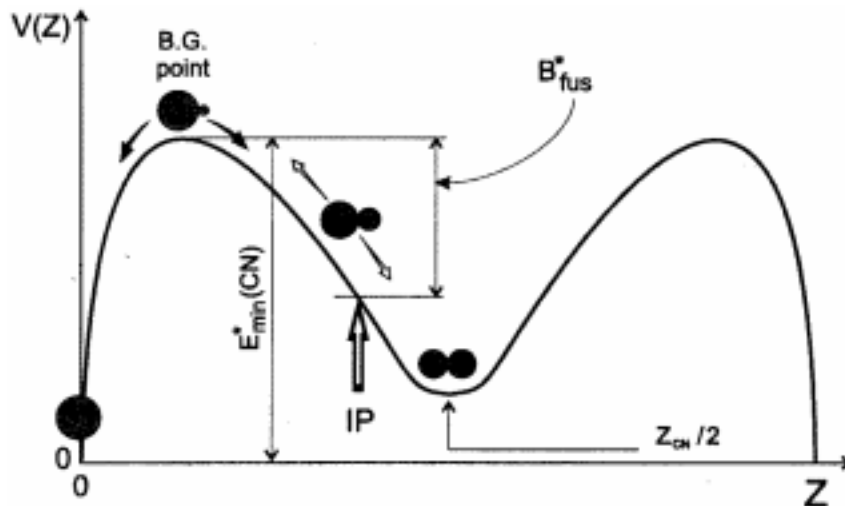


Figure 1. Schematic illustration of driving potential as a function of atomic number of the DNS nuclei. The possible moving of DNS and reaction input point are indicated with arrows.

The synthesis of super heavy elements (SHE) is usually performed at projectile energies leading to excitation energies of the compound nucleus as low as possible. This ensures higher survival probability of the compound nucleus during its deexcitation. As can be seen from figure 1, the main ‘heating’ of the compound nucleus takes place during the descent of the DNS from the BG point. It is at this evolution stage that the greater part of the system’s potential energy is transformed into thermal excitation. However, whether the DNS will reach the state of a compound nucleus or will undergo quasi-fission is determined already when approaching the BG point. At the same time, exactly at this evolution stage the DNS excitation energy is lowest. Thus, one can say that during the most important step to complete fusion, the DNS is in a cold state. This peculiarity in the evolution of the DNS in SHE-synthesis reactions required using real masses in calculating the potential energy $V(Z, L)$ in eq. (1). The deformation of the DNS nuclei formed during its evolution to the compound nucleus was taken into consideration. The deformation of the heavy nucleus was taken in the ground state, the deformation of the light nucleus – in the 2^+ state.

If the injection point of the reaction is situated to the right of the maximum in $V(Z, L = 0)$ (the Businaro–Gallone (BG) point), the initial DNS may follow either of the two possible evolution paths: to a larger or smaller charge asymmetry. On the contrary, on the way to the compound nucleus the DNS has to overcome the potential barrier, B_{fus}^* , which is equal to the difference in $V(Z, L)$ at the BG point and at the injection point of the reaction. The appearance of the inner fusion barrier B_{fus}^* [6] is due to the endothermic character of the process of nucleon rearrangement in the massive DNS, which leads the system in the direction of the compound nucleus. The energy necessary for this rearrangement is supplied from the DNS excitation energy E . The formation of the compound nucleus is not possible, if the DNS excitation energy is less than the value of B_{fus}^* .

2.3 Optimal energy for synthesis of SHE

Figure 2 demonstrates excitation energies at maximum of experimental and theoretical excitation functions of compound nuclei of elements with charge numbers Z from 102–114 produced in cold fusion (HI,1n) reactions. The curve indicates the value $E_{\min(\text{CN})}^*$ calculated on the Bass barrier [9]. From figure 2 one can see that our calculated values of E_{1n}^* are close to the experimental data.

2.4 The role of quasi-fission in the reactions of synthesis of SHE: Competition between complete fusion and quasi-fission

Another important characteristic of the fusion of massive nuclei, which manifests itself only in the DNS-concept, is the competition between complete fusion and quasi-fission. Due to the statistical character of the exchange of nucleons between the DNS nuclei, a certain probability exists that either the system reaches and overcomes the BG point, which leads to the formation of a compound nucleus, or the dinuclear system decay into two nuclei (undergoes quasi-fission). The more symmetric the reaction, the higher the inner fusion barrier B_{fus}^* which has to be overcome by the DNS on its way to the compound nucleus and, also, the stronger is the quasi-fission channel.

In most known models of the complete fusion of nuclei, the formation cross section of compound nuclei σ_{fus} is not different from the capture cross section σ_c . In our approach the fusion cross section σ_{fus} is a part of the capture cross section σ_c

$$\sigma_{\text{fus}} = \sigma_c \cdot P_{\text{CN}} = \pi \lambda_0^2 \sum_{l=0}^{l_{\text{cr}}} (2l + 1) T(l, E_{\text{cm}}) \cdot P_{\text{CN}}. \quad (3)$$

Here λ_0 is the de Broglie wavelength of the relative motion of interacting nuclei, E_{cm} is the bombarding energy in the center-of-mass system, $T(l, E_{\text{cm}})$ is the penetration coefficient of the l th partial wave through the potential barrier. $T(l, E_{\text{cm}})$ is approximated by the

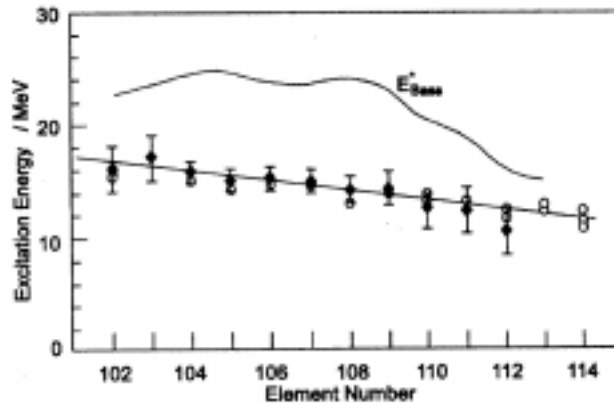


Figure 2. Excitation energies at the maximum of the excitation functions of (HI,1n) reactions leading to nuclei with $Z = 102$ –114, \circ – theoretical (see table 1) and \bullet – experimental data [8].

Table 1. Results of our calculations for cold fusion reactions. The references on experimental values for reactions with $Z_{CN} = 104-112$ (see in Review [2] and references therein).

Reactions	E_{th}^* MeV	E_{exp}^* MeV	P_{CN}	σ_{1n}^{th} mb	σ_{1n}^{exp} mb	Ref.
$^{48}\text{Ca}+^{208}\text{Pb} = ^{256}102$	15.6	16.0	$2.9 \cdot 10^{-1}$	$5.8 \cdot 10^{-4}$	$(1.3^{+0.4}_{-0.4})10^{-4}$	[20]
$^{48}\text{Ca}+^{206}\text{Pb} = ^{254}102$	16.1	24.0	$3.3 \cdot 10^{-1}$	$1.9 \cdot 10^{-4}$	$(6.0^{+1.6}_{-1.6})10^{-5}$	[21]
$^{50}\text{Ti}+^{208}\text{Pb} = ^{258}104$	15.2	15.0	$7.7 \cdot 10^{-2}$	$2.8 \cdot 10^{-5}$	$(1.0^{+0.13}_{-0.13})10^{-5}$	[2]
$^{50}\text{Ti}+^{209}\text{Bi} = ^{259}105$	14.7	15.0	$7.9 \cdot 10^{-3}$	$2.1 \cdot 10^{-6}$	$(4.5^{+0.9}_{-0.9})10^{-6}$	[2]
$^{54}\text{Cr}+^{208}\text{Pb} = ^{262}106$	14.5	15.0	$5.5 \cdot 10^{-4}$	$3.4 \cdot 10^{-7}$	$(5.0^{+1.4}_{-1.4})10^{-7}$	[2]
$^{54}\text{Cr}+^{209}\text{Bi} = ^{263}107$	14.4		$3.2 \cdot 10^{-4}$	$1.6 \cdot 10^{-7}$	$(2.0^{+1.3}_{-1.2})10^{-7}$	[2]
$^{58}\text{Fe}+^{208}\text{Pb} = ^{266}108$	12.9	14.0	$8.8 \cdot 10^{-5}$	$1.3 \cdot 10^{-7}$	$(6.7^{+0.75}_{-0.75})10^{-8}$	[2]
$^{58}\text{Fe}+^{209}\text{Bi} = ^{267}109$	14.0	14.0	$2.9 \cdot 10^{-5}$	$1.8 \cdot 10^{-8}$	$(7.5^{+5.0}_{-3.5})10^{-9}$	[2]
$^{62}\text{Ni}+^{208}\text{Pb} = ^{270}110$	13.9	13.8	$7.7 \cdot 10^{-6}$	$5.5 \cdot 10^{-9}$	$(3.5^{+2.7}_{-1.8})10^{-9}$	[2]
$^{64}\text{Ni}+^{208}\text{Pb} = ^{272}110$	13.1	12.2	$2.5 \cdot 10^{-5}$	$2.4 \cdot 10^{-8}$	$(1.5^{+0.9}_{-0.6})10^{-8}$	[2]
$^{64}\text{Ni}+^{209}\text{Bi} = ^{273}111$	13.2	13.5	$1.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-8}$	$(3.5^{+4.6}_{-2.3})10^{-9}$	[2]
$^{70}\text{Zn}+^{208}\text{Pb} = ^{278}112$	11.8	10.0	$7.3 \cdot 10^{-6}$	$1.4 \cdot 10^{-9}$	$(1.0^{+1.3}_{-0.7})10^{-9}$	[2]
$^{68}\text{Zn}+^{208}\text{Pb} = ^{276}112$	12.3	10-12	$1.4 \cdot 10^{-5}$	$2.2 \cdot 10^{-9}$	$< 1.3 \cdot 10^{-9}$	[2]
$^{70}\text{Zn}+^{209}\text{Bi} = ^{279}113$	12.7	10-12	$1.3 \cdot 10^{-6}$	$6.4 \cdot 10^{-10}$	$< 6.0 \cdot 10^{-10}$	[22]
$^{68}\text{Zn}+^{209}\text{Bi} = ^{277}113$	12.8		$2.6 \cdot 10^{-6}$	$1.1 \cdot 10^{-9}$		
$^{76}\text{Ge}+^{208}\text{Pb} = ^{284}114$	10.8		$3.3 \cdot 10^{-8}$	$1.2 \cdot 10^{-10}$		
$^{74}\text{Ge}+^{208}\text{Pb} = ^{282}114$	10.8		$1.1 \cdot 10^{-7}$	$1.2 \cdot 10^{-10}$		
$^{72}\text{Ge}+^{208}\text{Pb} = ^{280}114$	11.6		$3.5 \cdot 10^{-7}$	$9.5 \cdot 10^{-11}$		
$^{70}\text{Ge}+^{208}\text{Pb} = ^{278}114$	12.4		$3.8 \cdot 10^{-7}$	$1.9 \cdot 10^{-11}$		

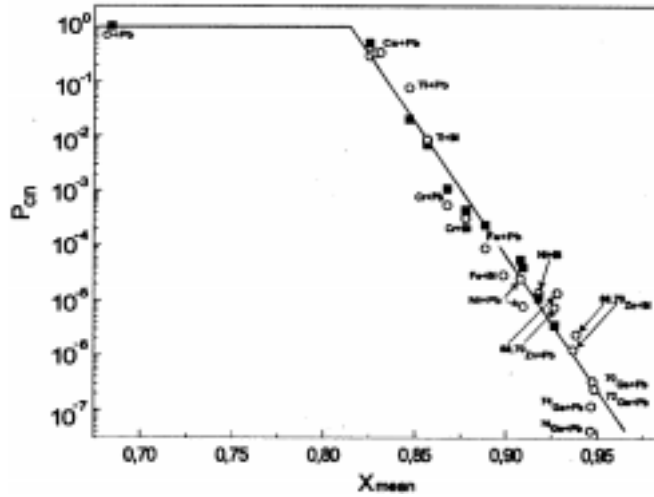


Figure 3. Probability of compound nucleus formation for different reactions as a function of the fissility parameter x_{mean} . Solid squares (■) represent the P_{CN} values extracted from experimental data [12], open circles (○) represent our calculations based on the model describing the competition between complete fusion and quasi-fission [6].

penetration factor of a parabolic barrier. P_{CN} is the probability of forming a compound nucleus in competition with quasi-fission [6]. In figure 3 are shown the values of P_{CN} , calculated for different reactions with ^{208}Pb and ^{209}Bi targets.

The ratio of repulsive Coulomb forces and the attractive nuclear forces governs the moving of two nuclei into one. For a monosystem this ratio is given by the fissility parameter x . For two touching sphere configuration, taking into account that the proton and neutron ratio between the two partners is equilibrated very quickly ($\approx 10^{-22}$ sec), a modified parameter x_{mean} describing the ratio of Coulomb and nuclear forces has been defined according to [13] and [14].

2.5 Capture cross section

The capture cross section σ_c makes up a part of the total inelastic cross section

$$\sigma_c/\sigma_R = \frac{\sum_{l=0}^{l_{kr}} (2l+1)T(l, E)}{\sum_{l=0}^{\infty} (2l+1)T(l, E)}. \quad (4)$$

The l_{kr} is the critical angular momentum, at which the capture of a heavy ion occurs and an excited DNS is formed. The value of l_{kr} was taken from empirical systematics of the ratio σ_c/σ_R [10]. In the figure 4 one can see the experimental data and our calculations σ_c for two type of reactions: with a ^{208}Pb target (left) and a ^{238}U target (right). The rather good agreement between the calculations and the experimental data is obvious.

2.6 Survival probability

The production cross section for evaporation residues with emission of x neutrons from heavy compound nuclei can be written in the following form as

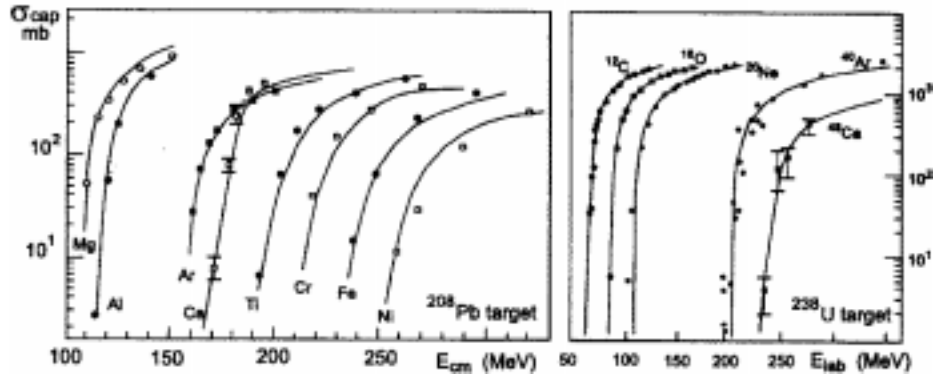


Figure 4. Capture cross sections for two targets Pb (left) and U (right) as a function of bombardment energy and different heavy ions. Points are experimental data, curves are result of calculations.

$$\sigma_{xn}(E^*) \approx \sigma_{\text{fus}} \cdot P_{xn}(E^*) \cdot W_{\text{sur}}(E^*), \quad (5)$$

where σ_{fus} is the compound nucleus formation cross section; E^* the excitation energy of compound nucleus; P_{xn} is the probability of evaporation of exactly x neutrons from the excited compound nuclei [11]; W_{sur} is the probability of survival of the heavy ($\Gamma_n/\Gamma_{\text{tot}} \approx \Gamma_n/\Gamma_f$) compound nucleus during its deexcitation

$$W_{\text{sur}}(E^*) = \prod_{k=1}^x \left(\frac{\Gamma_n(E_k^*)}{\Gamma_f(E_k^*)} \right)_k, \quad (6)$$

where x is the number of evaporated neutrons, k the index of the evaporation step. For the partial widths of neutron emission and fission the following expressions have been used [9]:

$$\Gamma_n(E^*, L) \approx \frac{(2s + \mu)}{(\pi\hbar)^2 \rho_m(U)} \int_0^{U-B_n} \sigma_{\text{inv}}(E_n) \rho_d(U - B_n - E_n) E_n dE_n, \quad (7)$$

$$\Gamma_f(E^*, L) \approx (2\pi\rho_m(U))^{-1} \int_0^{U_s-B_f} \rho_s(U_s - B_f - \varepsilon) d\varepsilon, \quad (8)$$

where U is the thermal energy of the mother nucleus, s the spin of the emitted particle and μ is the reduced mass of the system (particle neutron plus daughter nucleus). The symbols m and d indicate the mother and the daughter nuclei, respectively. The inverse cross section σ_{inv} is calculated within the model described in [10].

In expression (8) the thermal energy U_s and the rotational energy E_r^s are connected at the saddle point by the relation $U_s = E^* - E_r^s$. This form of the width Γ_f takes into account the change of the fission barrier of the rotating nucleus so far as $B_f(I) = B_f(0) - (E_r - E_r^s)$ (see details in [15]).

To describe the level density as a function of the excitation energy, the well known Fermi-gas expression (see, for example, book [16])

$$\rho(E^*) = \frac{\sqrt{\pi}}{12} \frac{1}{a^{1/4} (E^* - \delta)^{5/4}} \exp[S(E^*)] \quad (9)$$

has been used. In (9) the dependence of the nucleus entropy S on the excitation energy E^* is determined by the relation: $S = 2at$, using the connection of the temperature with the excitation energy of the nucleus $E^* = at^2$, here δ is correction accounting for even-odd effects [18]. The parameter of the level density $a = \pi^2 g_0/6$ is expressed through the density of single particle states near the Fermi energy $g_0 = f(E_f) = \text{constant}$. The decrease of the influence of shell effects on the level density with increasing excitation energy is taken into account by the phenomenological expression [16]:

$$a(E^*) = \tilde{a} [1 + f(E^*) \Delta W / E^*]. \quad (10)$$

Here $f(E^*) = 1 - \exp(-\gamma E^*)$, ΔW is the shell correction in the nuclear mass formula, $\tilde{a} = A(\alpha + \beta A)$ is the Fermi-gas value of the level density parameter, A is the mass

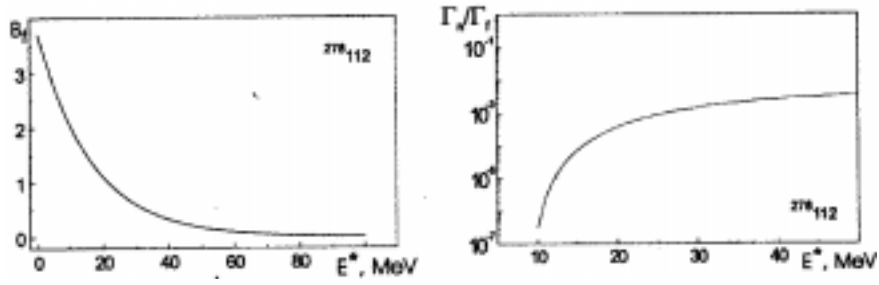


Figure 5. Fission barrier and Γ_n/Γ_f values for element 112 as a function of excitation energy.

number of nucleus. The empirical values of the parameters $\alpha = 0.134 \text{ MeV}^{-1}$, $\beta = -1.21 \cdot 10^{-4} \text{ MeV}^{-1}$, $\gamma = 0.061 \text{ MeV}^{-1}$ have been obtained in ref. [18] from the analysis of the data on the level density taking into account the contribution of the collective states to the total level density.

The fission barrier B_f is a sum of liquid drop B_f^{LD} and shell correction ΔW parts $B_f = B_f^{\text{LD}} + \Delta W$. To calculate W_{sur} , we need the fission barrier of compound nuclei. For transfermium region of compound nuclei the B_f^{LD} is very small. To include effect of washing of shell corrections we used the next equation $B_f(E^*) = \Delta W \cdot \exp(-\gamma E^*)$. For our calculation we used the value of $B_f(E^* = 0) = B_f^{\text{st at}}$ from ref. [17].

In figure 5 one can see that the dependence of the fission barrier and ratio Γ_n/Γ_f on E^* in region of maximum of excitation functions for (HI,1n) reactions (10 – 20 MeV) is very strong.

3. The analysis of reactions used for the synthesis of the transfermium and super-heavy elements

3.1 Reactions of cold fusion

The ‘cold’ method of synthesis of heavy elements where evaporation of one neutron has higher probability, named ‘cold fusion’ (was proposed in Dubna by Oganessian [19]), was successfully used to produce new transfermium elements up to $Z = 112$.

One can see from figure 6 that our approach allows rather good description of the experimental data on cold fusion (HI,1n) reactions.

3.2 Hot fusion reactions

As one can see from figure 6, that σ_{1n} of reactions which leads to synthesis of the super-heavy element with magic number $Z = 114$ with Pb target is less than 1 pb.

Therefore we analysed another reaction $^{48}\text{Ca} + ^{244}\text{Pu} = ^{292}114$, which was chosen for the synthesis of element 114 in FLNR (Dubna) (see, for example, ref. [23]). There are experimental data in which a ^{48}Ca -beam was used to bombard targets of Pb, Th, U. For the

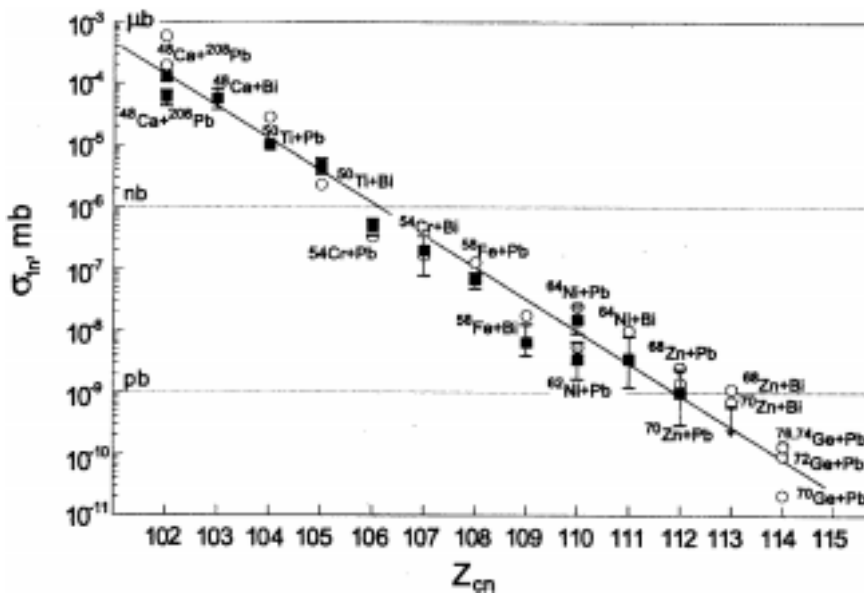


Figure 6. Experimental data (black squares) and theoretical calculations (open circles) for synthesis of elements from 102 to 114 in cold fusion reactions (HI, $1n$), the combinations are noted in the figure. The line has been drawn to guide the eyes. The references on experimental data σ_{1n} are given in table 1.

reaction $^{48}\text{Ca} + ^{208}\text{Pb} = ^{256}102$ measurements of the excitation functions for the evaporation of 1, 2, 3, 4 neutrons, as well as the fusion–fission cross section [20], which for heavy compound nuclei coincides with the fusion cross section, have been measured. Therefore it seemed very interesting to analyse these reactions in the framework of the DNS concept.

In figure 7 one can see calculations based on the DNS-concept for two reactions. For the $^{48}\text{Ca} + ^{208}\text{Pb} = ^{256}102$ reaction (left panel) our calculation rather well describes the experimental data for evaporation residue cross sections. For the $^{48}\text{Ca} + ^{232}\text{Th} = ^{280}110$ reaction (right panel), for which only σ_{3n} has been measured, our calculation is not in disagreement with the experimental point.

As one can see from figure 8 our calculations for the $^{48}\text{Ca} + ^{238}\text{U} = ^{286}112$ reaction agree with the experimental values. The right panel of figure 8 shows our estimations for the cross sections for the $^{48}\text{Ca} + ^{244}\text{Pu} = ^{292}114$ reaction.

Comparing our estimations (see figure 6) for the $^{76,74,72,70}\text{Ge} + ^{208}\text{Pb} = ^{284,282,270,278}114$ reaction with these for the reaction $^{48}\text{Ca} + ^{244}\text{Pu} = ^{292}114$ (see figure 8), it follows that the latter one is more preferable.

There exist also other estimations of cross section for the combination $^{48}\text{Ca} + ^{244}\text{Pu} = ^{292}114$ (see table 2). One can see that our estimation is in rather good agreement with value of cross sections from ref. [4].

Now in the FLNR an experiment is running to produce the isotope of element 114, in the reaction $^{48}\text{Ca} + ^{244}\text{Pu} = ^{292}114$. This experiment is very important, since it would give a possibility to reach the island of stability, about which physicists of the whole world dream for more than 30 years.

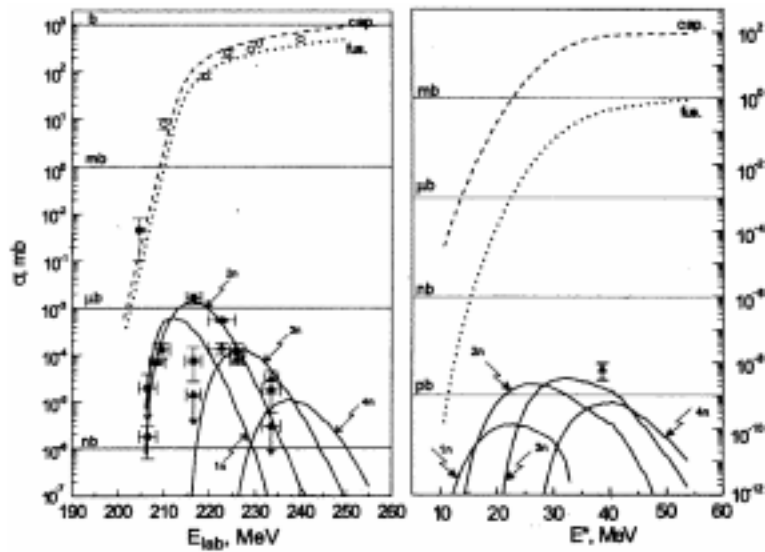


Figure 7. Results for the two reactions $^{48}\text{Ca} + ^{208}\text{Pb} = ^{256}102$ (left) and $^{48}\text{Ca} + ^{232}\text{Th} = ^{280}110$ (right). (\circ) denote the experimental values of fusion–fission cross sections [20], solid points (\bullet) experimental values of σ_{xn} [20], the experimental value σ_{3n} for the right reaction was taken from ref. [24], curves are the result of our estimations: dashed curves are calculations for σ_c , dotted curves are for σ_{fus} , and solid curves are for σ_{xn} .

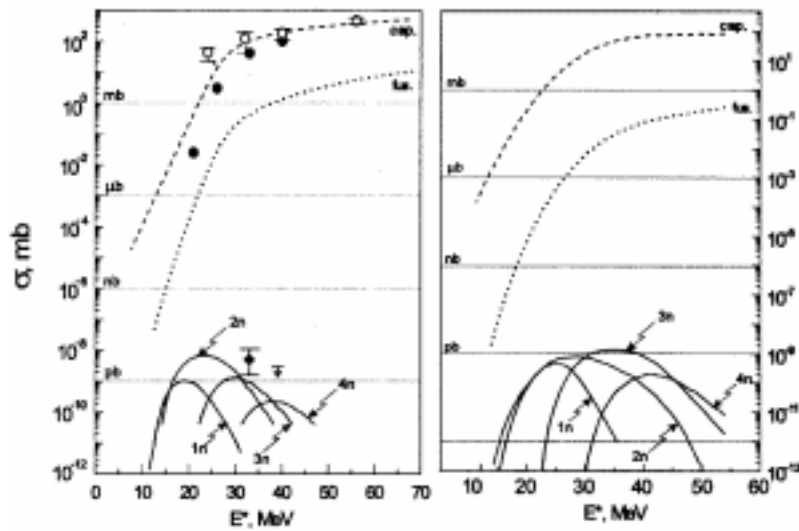


Figure 8. Cross sections for the reactions $^{48}\text{Ca} + ^{238}\text{U}$ (left) and $^{48}\text{Ca} + ^{244}\text{Pu}$ (right) leading to compound nuclei with $Z = 112$ and $Z = 114$, respectively. On the left, open and solid circles are capture cross sections from refs [25] and [26] correspondingly. Experimental data for σ_{xn} was taken from [27]. Different curves are theoretical calculations (explanation see in the caption of figure 7).

Table 2. Results of different estimations (maximal quantities) for cross section values for $^{48}\text{Ca} + ^{244}\text{Pu} = ^{292-xn}114$ reaction.

Channel	E^*	Value	Ref.
σ_{3n}	35 MeV	3.5 pb	[4]
σ_{3n}	26 MeV	100 pb	[28]
σ_{ER}	37 MeV	10 pb	[29]
σ_{3n}	32 MeV	20 pb	[23]
σ_{3n}	35 MeV	1.5 pb	Present work

4. Conclusions

The DNS concept was used in the analysis of existing experimental data on reactions leading to the synthesis of elements 102 and 112. The attempt to synthesize element 114 was also analysed. The method applied in this article describes well a wide set of experimental data on reactions of cold synthesis (reactions with evaporation of one neutron (HI,1n)) concerning the maxima of the excitation functions (figure 2), and their absolute values (figure 6). The DNS concept allows to carry out calculations of the inner fusion barrier B_{fus}^* for synthesis reactions, which in turn gives an estimation of the threshold ΔE for complete fusion. The DNS concept allows to estimate competition between complete fusion and dominant quasi-fission in SHE synthesis reactions, which gives the probability P_{cn} of forming a compound nucleus after capture. In ‘cold’ fusion reactions, the quasi-fission is the main factor determining the decrease of SHE-production cross sections when increasing the atomic number of the synthesized SHE. It was shown that the reaction $^{48}\text{Ca} + ^{244}\text{Pu} = ^{292}114$ for the synthesis of element 114, suggested in FLNR [23], is more preferable compared with the reaction of a Ge-beam on a Pb-target.

Acknowledgements

The author thanks Professors Yu Ts Oganessian and M G Itkis for support and constant attention to the given work and Prof. A Sobczewski and Drs A V Antonenko, A K Nasirov and R Kalpakchieva for useful discussions and interest. I am indebted to Prof. V V Volkov and Dr G G Adamian, for help, fruitful discussions, valuable remarks and useful suggestions during the whole period of preparing of this article. I express my special gratitude to Dr B I Pustyl'nik for the long-term cooperation and fruitful discussions on the mechanism of interaction of heavy nuclei and decay of the excited compound nucleus.

References

- [1] W J Swiatecki, *Phys. Scr.* **24**, 113 (1981)
S Bjornholm and W J Swiatecki, *Nucl. Phys.* **A391**, 471 (1982)
- [2] S Hofmann, *Rep. Prog. Phys.* **61**, 639–689 (1998)
- [3] Y Abe, Y Aritomo, T Wada and M Ohta, *J. Phys. Nucl. Part. Phys.* **23(10)**, 1275–1284 (1997)
- [4] B I Pustyl'nik, *VI Int. School-Seminar Heavy Ion Physics, 22–27 September* (Dubna, Russia, Word Scientific), pp. 431–433

- [5] V V Volkov, *Izvestiya AN USSR ser. fiz.* **50**, 1879 (1986)
- [6] A V Antonenko, E A Cherepanov, A K Nasirov, V P Permjakov and V V Volkov, *Phys. Lett.* **B319**, 425 (1993); *Phys. Rev.* **C51**, 2635 (1995)
G G Adamian, N V Antonenko, W Scheid and V V Volkov, *Nucl. Phys.* **A627**, 361–378 (1997)
- [7] G G Adamian, N V Antonenko, R V Jolos, S P Ivanova and O I Melnikova, *Int. J. Mod. Phys.* **E5**, 191–216 (1996)
- [8] A G Popeko, *Proc. 174 WE-Heraeus-Seminar 'New Ideas on Clustering in Nuc. and Atomic Phys.'*, *Rauischholzhausen, Germany*, June 9–13, 1997, p. 1137–1142
- [9] R Bass, *Nuclear Reactions with Heavy Ions* (Springer, New York, 1980)
- [10] E A Cherepanov, *Proc. Int. Symp. on In Beam Nuclear Spectroscopy* (Debrecen, Hungary, May 14–18, 1984) p. 499–506
- [11] T Sikkeland, *Phys. Rev.* **169**, 1232 (1968)
- [12] P Armbruster, GSI-Preprint-98-96, 1998
- [13] H Gaggeler, T Sikkeland, G Wirth, W Bruchle, W Bogl, G Franz, G Herrmann, J V Kratz, M Schaedel, K Summerer and W Weber, *Z. Phys.* **A316**, 291 (1984)
- [14] K-H Schmidt and W Morawek, *Rep. Prog. Phys.* **54**, 949–1003 (1991)
- [15] M Blann and F Plasil, *Phys. Rev. Lett.* **29**, 303 (1972)
- [16] A V Ignatyuk, *Statistical properties of excited nuclei* (Energoizdat, Moskva, 1983)
- [17] R Smolanczuk, J Skalski and A Sobiczewski, *Phys. Rev.* **C52**, 1871 (1995)
- [18] E A Cherepanov and A S Iljinov, *Nucleonika* **25**, 611–621 (1980)
- [19] Yu Ts Oganessian, *Lecture Notes in Phys.* (Springer, Heidelberg, 1975) vol. 33, p. 221
- [20] A V Yeremin, V I Chepigin, M G Itkis, A P Kabachenko, S P Korotkov, O N Malyshev, Yu Ts Oganessian, A G Popeko, J Ronac, R N Sagaidak, M L Chelnokov, V A Gorshkov and A Yu Lavrentev, *Rapid Comm. JINR* **6**, (92)-98
- [21] Yu Ts Oganessian, V K Utyonkov, Yu V Lobanov, F S Abdulin, A N Polyakov, I V Shirokovsky, Yu S Tsyganov, S Iliev, V G Subbotin, A M Sukhov, G V Buklanov, A N Mezencev, O V Ivanov, K Subotik, R W Loughheed, K J Moody, M A Stoyer, M J Stoyer and J F Wild, *Proc VI Int Conf. on Dynamical Aspects on Nuclear Fission* (Slovak Republic, Casta-Paperchichka, October 19–23, 1998)
- [22] F P Hessberger, S Hofmann, V Ninov, P Armbruster, H Folger, A Lavrentev, M E Leino, G Muenzenberg, A G Popeko, S Saro and A N Yeremin, *Proc. VI Int. Conf. on Dynamical Aspects on Nuclear Fission* (Slovak Republic, Casta-Paperchichka, October 19–23, 1998)
- [23] Yu Ts Oganessian, *Proc. Int. Conf. Structure of Vacuum and Elementary Matter* (Wilderness, South Africa, March 10–16, 1996) p. 11–24
- [24] Yu Ts Oganessian and A V Yeremin, *Proc. VI Int. Conf. on Dynamical Aspects on Nuclear Fission* (Slovak Republic, Casta-Paperchichka, October 19–23, 1998)
- [25] M G Itkis, Yu Ts Oganessian, E M Kozulin, N A Kondratiev, L Krupa, I V Pokrovsky, A N Polyakov, V A Ponamarenko, A Ya Rusanov and V I Vakotov, Submitted to *Nuovo Cimento*.
- [26] W Q Shen, J Albinski, A Gobbim, S Gralla, K D Hildenbrand, N Herrmann, J Kuzminski, W F J Muller, H Stelzer and J Toke, *Phys. Rev.* **C36**, 115–142 (1987)
- [27] Yu Ts Oganessian, A V Yeremin, G G Gulbekian, S L Bogomolov, V I Chepigin, B N Gikal, V A Gorshkov, M G Itkis, A P Kabachenko, V B Kutner, A Yu Lavrentev, O N Malyshev, A G Popeko, J Rohas, R N Sagaidak, S Hofmann, G Muenzenberg, M Veselsky, S Saro, N Iwasa and K Morita, preprint JINR E7-98-212, 1998 (submitted to *European Phys. J.*)
- [28] G Giardina, A D'Arrigo and R Sturiale, *Proc. VIII Int. Conf. on Nuclear Reactions Mechanisms* (Varenna, June 9–14, 1997) p. 435–443
- [29] T Wada, Private communication