INFLUENCE OF INTERACTING HEAVY NUCLEI MASS ASYMMETRY ON CAPTURE CROSS-SECTION IN FUSION REACTIONS

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The effect of beam and target isotope configuration on the capture cross-section is considered using dynamic-statistical description of the first stage of heavy nuclei fusion reactions. It demonstrates that the isotopic configuration of heavy nucleus renders insignificant effect on the capture cross-section. Cross-section decreases by decreasing mass asymmetry due to the change of light nuclei isotope configuration. The capture cross-section increases by increasing charge asymmetry for constant number of nucleons in the compound nucleus. For odd-odd interacting nuclei capture cross-section is from 1.5 to 6 times greater than for even-even nuclei in the same value of protons and neutrons in the compound nucleus.

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1. INTRODUCTION

The choice of the initial isotope beam-target combination is one of the determining factors for experimental work on the accelerator to study the fusion-quasifission of heavy nuclei. The successful synthesis of super-heavy elements initiated the development of theoretical works aimed at detailed study of these reactions. For the description of these processes few models were developed [1-3], which more or less describe these processes and can predict the optimum initial features and most probable reaction channels. Description of the processes of fusion-quasifission of interacting nuclei is proposed in the Dinuclear System Concept (DNSC) [4,5], on the basis of which were built. According to the DNSC, this process can be divided into three stages, the cross-section of several models evarpolation residues, leading to the formation of super-heavy elements, is written as follows [5-7]:

$$\sigma_{\rm ER}(E_{cm}) = \sum_{L=0} \sigma_c(E_{cm}, L) \cdot P_{CN}(E_{cm}, L) \cdot \\ \cdot W_{sur}(E_{cm}, L)\,, \tag{1}$$

where σ_c - partial capture cross-section; P_{CN} - probability of formation of the compound nucleus after capture, which depends on the competition between fusion and quasifission; W_{sur} - survival rate of the compound nucleus. The partial capture cross-section is determined by the transition probability of the colliding nuclei through the Coulomb barrier $T(E_{cm}, L)$ [8,9]:

$$\sigma_c = \frac{\pi\hbar^2}{2\mu E_{cm}}(2L+1)T(E_{cm}, L)\,, \tag{2}$$

where L-angular momentum, which is measured in $\hbar$ units, E_{cm} - beam kinetic energy, μ - reduced mass.

This work examines the influence of mass and charge asymmetry on capture cross-section. Dependence of the capture cross-section from the isotope configuration of interacting nuclei had been received on the basis of calculations of some reactions.

2. FORMALISM

Choice of nucleus-nucleus potential plays an important role in the description of interaction dynamics, calculation of probability and capture cross-section. The interaction potential of two nuclei can be represented as follows [5, 6]: $V_{nn} = V_{Coul} + V_n + V_{rot}$, where V_{Coul} - Coulomb potential, V_n - nuclear potential, V_{rot} - axifigal potential, respectively. Short-range forces potential (proximity), which has practically no fit parameters [10, 11] was used in order to calculate nuclear potential.

In [12], the expression, averaged for all possible angular momenta $L_{\max}$ involved in the reaction was used to describe capture cross-section:

$$\sigma_c = \frac{\pi\hbar^2}{2\mu E_{cm}} \cdot \frac{1}{L_{\max}(E_{cm})} \cdot \\ \cdot \sum_{L_{0i}}^{L_c} (2L_{0i}+1)\, P_{1i} P_{2i}\,(E_{cm}, L_{0i})\ , \tag{3}$$

where $P_{2i}(E_{cm}, L)$ - colliding nuclei probability of transition through the Coulomb barrier. As shown in [12], it suffices to consider only Coulomb barrier transfer energy because increase of excitation energy causes capture probability (P_{1i}) zero. $L_{\max}(E_{cm})$

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- angular momentum maximum value for a given kinetic energy E_{cm}, which may be involved in the fusion-quasifission. Maximum value of angular momentum can easily be obtained from energy balance at the contact point of the interacting nuclei: $E_{cm} - V_n^{cont} - V_{Coul}^{cont} - V_{rot}^{cont} = \mu\dot{R}^2/2$. Angular momentum is determined [13]: $L = \mu R\dot{R}\sin\theta$, where $R = R_1 + R_2$, $\dot{R}$ - velocity at the contact point, θ - angle between axis of the beam and the distance between the centers of interacting nuclei, which is equal to $\pi/2$ in order to determine the maximum value, then: $L_{\max} = R\sqrt{2\mu(E_{cm} - V_{Coul}^{cont} - V_n^{cont})}$. L_{0i} - initial value of angular momentum, which contributes to capture cross section. $L_{0i} < L_{\max}$, as this quantity is limited by the difference between excitation energies of light and heavy nuclei. The expression [12] is used to determine the capture probability:

$$P_{1i}(L_i, E_{cm}) = 1 - \exp\left(-\frac{E_{qf}(L_i) - \Delta E^*(L_i, E_{cm})}{T(L_i, E_{cm})}\right), \tag{4}$$

where $T(L_i, E_{cm}) = \sqrt{12E^*(L_i, E_{cm})/A_0}$ - temperature of the nuclei, after the dissipation of kinetic energy in excitation energy $E^*(L_i, E_{cm})$, A_0 - interacting nuclei nucleons sum, $E_{qf}(L_i)$ - energy required for overcome quasifission barrier, determined from the dynamics of interaction, $\Delta E^*(L_i, E_{cm})$ - difference between excitation energies of heavy and light nuclei.

For dynamic description of capture process classical Newton equations for collective coordinates of relative distance between nuclei mass centers R and relative angular momentum L, which contains radial and tangential friction forces [12] were used. For interacting nuclei the description of relative motion and change of angular momentum, the following system of equations can be written [13]:

$$\begin{cases} \mu\frac{d\dot{R}(t)}{dt} + \gamma_R(R)\dot{R}(t) = F_{nn}(R, L) \\ \mu\frac{dL(t)}{dt} + \gamma_\theta(R)L(t) = 0 \end{cases} \tag{5}$$

where
$F_{nn}(R, L) = -\frac{\partial V_{nn}(R,L)}{\partial R}$, $\gamma_R(R) = k_R\left(\frac{\partial V_n(R)}{\partial R}\right)^2$, $\gamma_\theta(R) = k_\theta\left(\frac{\partial V_n(R)}{\partial R}\right)^2$, k_R and k_θ radial and tangential friction coefficients, which were chosen [4] $k_R = (0.5...5)\cdot 10^{-23}\,s/MeV$ and $k_\theta = 0.01\cdot 10^{-23}\,s/MeV$. Dependences which characterize the capture process or the process of quasifission - $R(t)$, $V(t)$, $E_{cm}(t)$, $L(t)$ were obtained in solving (5), by Gere, where nuclei interaction, leading to their capture is considered as dynamic process in the range of R, from contact moment till capture moment of the nuclei (the formation DNS), or before system goes in quasifission channel. After the full dissipation of kinetic energy inertial moment of system is $\mu R^2 + j_1 + j_2$, where j_1 and j_2 - interacting nuclei inertial moments. The change of kinetic energy and angular momentum relative the distance between interacting nuclei centers is shown in Fig. 1 and 2 for $^{56}Fe + ^{244}Pu$ reaction. It follows that system enter to capture channel occurs at minimum of nucleus-nucleus potential and at $L_0 = 70$ there is no Coulomb barrier overcome, for all other values of angular momentum system is in capture process. This process is accompanied by intensive dissipation of kinetic energy which is converted into internal excitation of nuclei. From the calculations for these radial friction coefficients the most appropriate, in our opinion, is $k_R \approx (1 \div 1.5)\cdot 10^{-23} s/MeV$, because the capture time is equal $(5 \div 30)\cdot 10^{-22} s$ that corresponds data from [8, 13]. At higher radial friction coefficients capture time is larger by orders and there is a situation of stopping the process by R at the descent to the nucleus-nucleus potential after Coulomb barrier. Other calculations were made at $k_R = 1\cdot 10^{-23} s/MeV$, $k_\theta = 0.01\cdot 10^{-23} s/MeV$. Comparison of calculated and experimental excitation energy values are given in the Table.

The experimental and calculated data of excitation energy

Reaction	Kinetic energy, MeV	Excitation energy, MeV	
		Calc	Exp. [14-16]
$^{48}_{20}Ca + ^{238}_{92}U$	230	32.5...33.4	29.3...33.5
	234	33.3...36.5	32.9...37.2
	240	36.2...42.5	37.7...41.9
$^{48}_{20}Ca + ^{237}_{93}Np$	244	37.5...44	36.9...41.2
$^{48}_{20}Ca + ^{244}_{94}Pu$	231	30.5...31	29.3...33.5
	235	32.4...33.5	30.4...34.7
	236	32.9...34.5	32.9...37.4
	238	33.7...36.5	33.1...37.4
	243	36.1...41.5	38.9...43
	244	36.6...42.5	38...42.4
	250	40...48.5	43...47.2
	257	44.2...55.5	50.4...54.7
$^{48}_{20}Ca + ^{243}_{95}Am$	248	37.8...44	38...42.3
	253	40.4...49	42.4...46.5
$^{48}_{20}Ca + ^{247}_{96}Cm$	240	33.8...35.3	30.4...35.8
	243	35.2...38.3	30.9...35
	247	37.2...42.3	36.8...41.1
	249	38.2...44.3	35.9...39.9
	255	41.5...50.3	40.7...44.8
$^{48}_{20}Ca + ^{251}_{98}Cf$	245	35.4...37.3	26.6...31.7
	251	35.2...38.3	32.1...36.6

As the quasi-steady process of reducing of kinetic energy and angular momentum with an almost complete dissipation of kinetic energy (Fig. 1,2) is established with time, the process of counting stopped for all analyzed reactions with this condition. Therefore, in calculation of capture cross-sections $L = Const$ cannot be used because change of quasifission barrier leads to changes of energy needed to overcome it, and thus to change in capture probability. From the definition of capture cross-sections (3) and capture probability (4), it follows that it is necessary to know the Coulomb energy (E_{Coul}) and quasifission energy (E_{qf}) required to overcome quasifission barrier, when system leaves in quasifission channel.

These energies were determined from the solution of

(5), increment of kinetic energy was selected 1 MeV with accuracy determination E_{Coul} and E_{qf} 0.1 MeV.

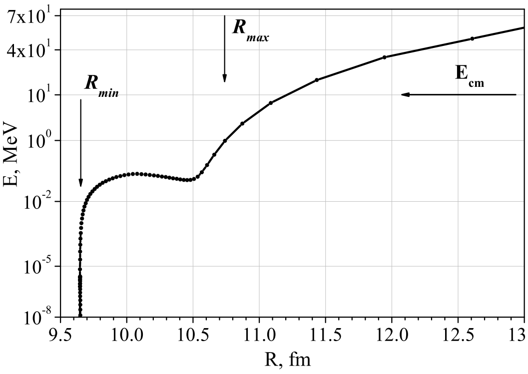

Fig.1. Dependence of kinetic energy from distance between nuclei centers in $^{56}Fe+^{244}Pu$ *reaction. Dynamics of process occurs from right to left. Maximum and minimum values of nucleus-nucleus potential are specified with arrows*

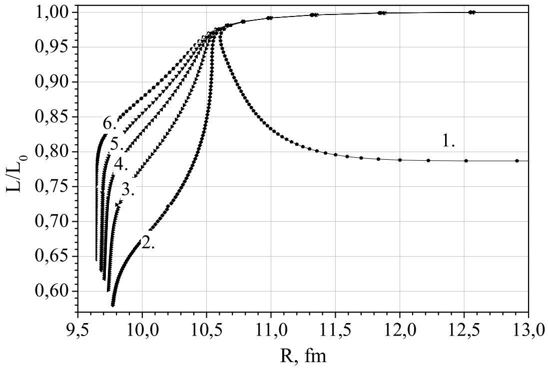

Fig.2. Dependence of relative angular momentum from distance between nuclei centers in $^{56}Fe+^{244}Pu$ *reaction. Dynamics of process occurs from right to left. 1.-*L_0*=70, 2.-*L_0*=60, 3.-*L_0*=50, 4.-*L_0*=40, 5.-*L_0*=30, 6.-*L_0*=10*

3. RESULTS

Main characteristics that define heavy nuclei fusion process are: beam energy and the excitation energy which are related to fusion barrier, and, consequently, probabilities of fusion and the survival of the compound nucleus; ratio of nuclear and Coulomb potentials which determines the probability of fusion and capture, and depends on interacting nuclei asymmetry; relative angular momentum involved in reactions, which defines capture and fusion probability; ratio of nucleons and γ-rays emission probability to fission probability; etc. Study of influence of interacting nuclei charge and mass asymmetry on capture cross-section will help to choose the isotopic characteristics of beam and target for experimental work planning. Fig.3 shows the capture cross-section from beam kinetic energy of light for nuclei-^{48}Ca and different heavy nuclei, such dependencies were obtained for a number of reactions. It follows from it that changes in the number of protons and neutrons in heavy nucleus changes capture cross-section for less than 10 percents. This is not essentially compared to the influence of light fragment.

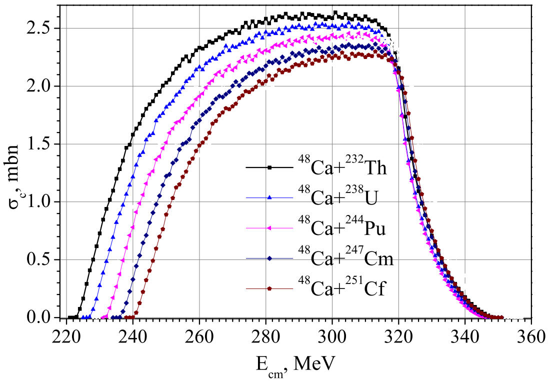

Fig.3. Dependence of capture cross-section from beam kinetic energy with a change of heavy nuclei mass asymmetry

Fig. 4 shows dependence of capture cross-section from beam kinetic energy for the Zn isotopes and the "constant" heavy fragment, such relationships were obtained for number of reactions. Figure shows that the capture cross-section decreases from 0.47 mb for ^{70}Zn up to 0.03 mbn for ^{64}Zn, so that, the contribution of changes in neutron amount of light nuclei in capture cross-section is essential and this should be considered in planning of experimental work on the accelerator. From executed calculations it also follows that if the number of neutrons in light nuclei decrease range of kinetic energy at which capture occurs, decreases from ΔE=335...375 MeV for ^{70}Zn up to ΔE=345...355 MeV for ^{64}Zn. This can make serious additional requirements for adjusting the beam energy at accelerator during the experimental work.

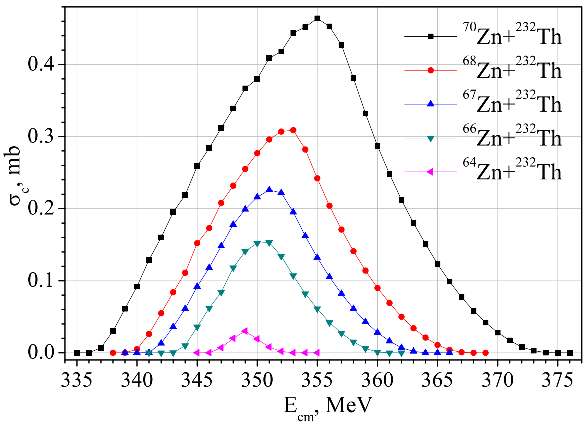

Fig.4. Dependence of capture cross-section from beam kinetic energy with a change of light nuclei mass asymmetry

Fig. 5 shows dependence of the capture cross-section from mass asymmetry for various interacting nuclei isotopic configurations. It shows that for $(Z_1 - Z_2)/Z_0 = Const$ (curves 1-6) with increasing mass asymmetry, i.e. the decreasing of neutrons in light fragment, the capture cross section decreases, this is due to reduction of the nuclear potential, Coulomb potential remains constant. Basic tendency, when $(Z_1 - Z_2)/Z_0$ and $(A_1 - A_2)/A_0$ increases, the capture cross-section also increases, because, in this situation, the nuclear potential faster than Coulomb, i.e., quasifission barrier increases. This can be seen from the following data, when $(Z_1 - Z_2)/Z_0 = 0.467$ and $(A_1 - A_2)/A_0 = 0.51$ $\sigma_c = 0.2mbn$ and when $(Z_1 - Z_2)/Z_0 = 0.6$ and $(A_1 - A_2)/A_0 = 0.65$ $\sigma_c = 1.2mbn$, and besides Z_0 and Z_0 for both cases. That is, in the second case, capture cross-section is 6 times higher than in the first. The same trend is observed for all considered reactions.

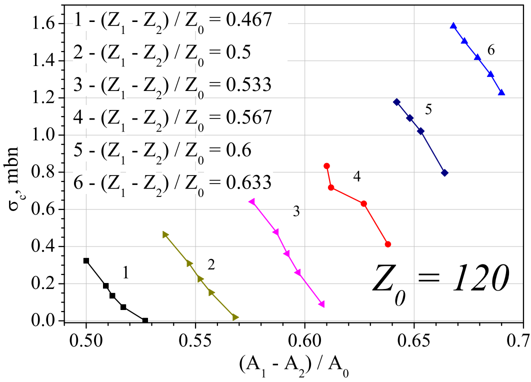

Fig.5. Dependence of capture cross-sections from interacting nuclei mass asymmetry for reactions: 1 - $^{70,72,73,74,76}_{32}Ge + ^{226}_{88}Ra$, 2 - $^{64,66,67,68,70}_{30}Zn + ^{232}_{90}Th$, 3 - $^{58,60,61,62,64}_{28}Ni + ^{238}_{92}U$, 4 - $^{54,56,57,58}_{26}Fe + ^{244}_{94}Pu$, 5 - $^{50,52,53,54}_{24}Cr + ^{248}_{96}Cm$, 6 - $^{46,47,48,49,50}_{22}Ti + ^{251}_{98}Cf$

Fig. 6 shows dependence of capture cross-sections from charge asymmetry for various $A_0 = Const$ from which it follows that capture cross section increases with increasing of charge asymmetry.

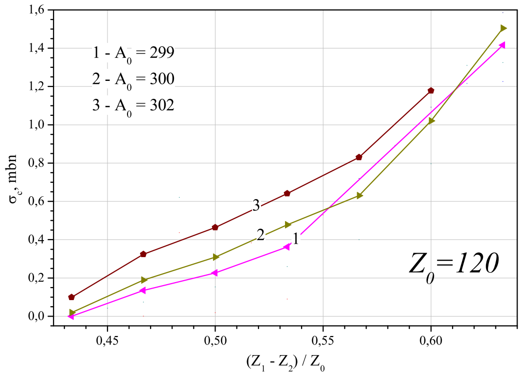

Fig.6. Dependence of capture cross-sections from interacting nuclei charge asymmetry

Special attention should be given to capture cross-sections dependencies of even-even and odd-odd interacting nuclei. Fig. 7 shows such dependence. The figure follows that for odd-odd interacting nuclei capture cross-section is from 1.5 to 6 times greater than for even-even nuclei with the same values of Z_0 and A_0. This enables to choose right beam and target isotope configuration while planning of experimental work on accelerator to receive superheavy elements.

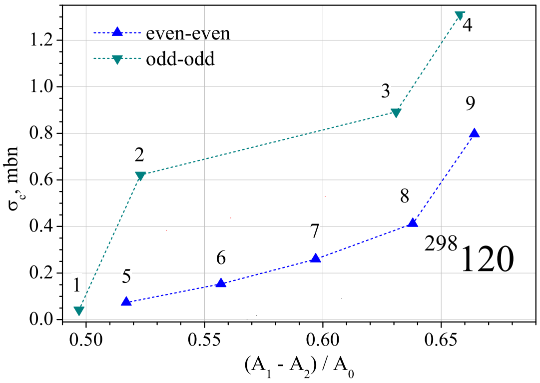

Fig.7. Dependence of capture cross-sections from interacting nuclei mass asymmetry for compound nucleus $Z_0 = 120$, A_0=298. 1 - $^{75}_{33}As + ^{223}_{87}Fr$, 2 - $^{71}_{31}Ga + ^{227}_{89}Ac$, 3 - $^{55}_{25}Mn + ^{243}_{95}Am$, 4 - $^{51}_{23}V + ^{247}_{97}Bk$, 5 - $^{72}_{32}Ge + ^{226}_{88}Ra$, 6 - $^{66}_{30}Zn + ^{232}_{90}Th$, 7 - $^{60}_{28}Ni + ^{238}_{92}U$, 8 - $^{54}_{26}Fe + ^{244}_{94}Pu$, 9 - $^{50}_{24}Cr + ^{243}_{96}Cm$

4. CONCLUSIONS

Over 80 reactions leading to super-heavy elements compound nucleus have been calculated using dynamic-statistical description of capture cross-sections - the first stage of fusion reactions of heavy nuclei. It was demonstrated that heavy nucleus isotopic configuration had less affects on capture cross-section than the light isotope configuration had. Increasing of charge and mass asymmetry increases capture cross-section, due to decrease of the Coulomb component of the interaction potential and increase of the angular momentum values number contributing to reaction. Odd-odd nuclei should be used when planning experimental work to receive element 120 near the closed shell $N_0 = 184$, it will lead to a higher capture cross-sections value. However, the compound nucleus formation and survival probability may contribute significantly to formation of super-heavy elements.

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ВЛИЯНИЕ МАССОВОЙ АСИММЕТРИИ ВЗАИМОДЕЙСТВУЮЩИХ ЯДЕР НА СЕЧЕНИЕ ЗАХВАТА ПРИ ИХ СЛИЯНИИ

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Используя динамико-статистическое описание первой стадии реакции слияния тяжелых ядер, рассматривается влияние изотопной конфигурации пучка и мишени на сечение захвата. Показано, что изотопная конфигурация тяжелого ядра незначительно влияет на сечение захвата. При уменьшении массовой асимметрии за счет изменения изотопной конфигурации легкого ядра сечение уменьшается и при увеличении зарядовой асимметрии, для постоянного количества нуклонов в составном ядре, сечение захвата увеличивается. Для нечетно-нечетных взаимодействующих ядер сечение захвата в 1,5...6 раз больше, чем для четно-четных ядер при одном и том же значении протонов и нейтронов в составном ядре.

ВПЛИВ МАСОВОЇ АСИМЕТРІЇ ВЗАЄМОДІЮЧИХ ЯДЕР НА ПЕРЕРІЗ ЗАХОПЛЕННЯ ПРИ ЇХ ЗЛИТТІ

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Використовуючи динаміко-статистичний опис першої стадії реакції злиття важких ядер, розглядається вплив ізотопної конфігурації пучка та мішені на переріз захоплення. Показано, що ізотопна конфігурація важкого ядра незначно впливає на переріз захоплення. При зменшенні масової асиметрії за рахунок зміни ізотопної конфігурації легкого ядра переріз зменшується і при збільшенні зарядової асиметрії, для постійної кількості нуклонів в складеному ядрі, переріз захоплення збільшується. Для непарно-непарних взаємодіючих ядер переріз захоплення в 1,5...6 разів більше, ніж для парно-парних ядер при одному і тому ж значенні протонів та нейтронів в складеному ядрі.