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POSSIBILITIES OF SYNTHESIS OF SUPERHEAVY NUCLEI IN HOT FUSION REACTIONS

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The actinide-based hot fusion reactions with stable projectiles heavier than ^{48}Ca are analyzed within the dinuclear system model for compound nucleus formation. Predictions for several reactions with radioactive beams for the synthesis of heaviest elements are also presented for the future interest. Possibilities of production of new isotopes of superheavy nuclei with charge numbers 104 -108 in incomplete fusion reactions are studied.

Introduction

The ^{48}Ca-induced hot fusion reactions with some actinide targets were carried out in Dubna [1] in order to approach to "the island of stability" of superheavy elements (SHE) predicted at charge numbers $Z = 114 - 126$ and neutron numbers $N = 172 - 184$ by the nuclear shell models [2, 3] The further experimental extension of the region of SHE is limited by the number of available projectiles and targets, and by very low production cross section. Since the intensive radioactive ion beams are not available so far, the possible way to synthesize new SHE is to use the actinide-based reactions with projectiles heavier than ^{48}Ca.

There is a large gap of unknown isotopes between the neutron-deficit isotopes obtained in cold fusion and heaviest isotopes formed in hot fusion. With incomplete fusion in transfer-type reactions leading to the nuclei with charge number larger than charge number of the heavy target one can produce the isotopes which can not be synthesized in complete fusion reactions. The actual possibilities to create the neutron-rich isotopes of superheavy nuclei via multinucleon transfer processes must be carefully examined.

Complete fusion reactions

The most important collective coordinate for the description of fission and heavy ion reactions at low collision energy is the mass asymmetry degree of freedom which was at first time introduced by V. M. Strutinsky et al. [4]. The fusion is described by the dinuclear system (DNS) model [5 - 8] in which the evaporation residue cross section is factorized as follows:

$$\sigma_{\rm ER}(E_{\rm c.m.}) = \sigma_{cap}(E_{\rm c.m.}) P_{\rm CN}(E_{\rm c.m.}) W_{\rm sur}(E_{\rm c.m.}). \qquad (1)$$

Here $\sigma_{cap} = \pi\lambda\!\!\!^{-2}(J_{\max}+1)^2 T(E_{\rm c.m.})$ is the effective capture cross section for the transition of the colliding nuclei over the entrance (Coulomb) barrier with the transmission probability T [6], P_{CN} is the fusion probability and W_{sur} is the survival probability of excited compound nucleus in the de-excitation process. The contributing angular momenta in the evaporation residue cross section are limited by W_{sur} with $J_{\max} \approx 10$ when highly fissile excited superheavy nuclei are produced for energies $E_{\rm c.m.}$ above the Coulomb barrier [6, 7]. Since the actinide targets are deformed, the value of $E^{\min}_{\rm c.m.}$, at which the collisions of nuclei at all orientations become possible, is larger than the Coulomb barrier calculated for the spherical nuclei. In the collisions with smaller $E_{\rm c.m.}$ the formation of the DNS is expected to be strongly suppressed.

In the DNS fusion model the compound nucleus is reached by a series of transfers of nucleons from the light nucleus to the heavy one [5 - 8]. The DNS has two main degrees of freedom: the mass asymmetry $\eta=(A_1-A_2)/(A_1+A_2)$ (A_1 and A_2 are the mass numbers of the DNS nuclei) and the relative distance R between the centers of the DNS nuclei. The dynamics of the DNS is considered as a combined diffusion in coordinates η and R. The diffusion in R occurs towards the values larger than the sum of the radii of the DNS nuclei and finally leads to the quasifission (decay of the DNS in R). The basic assumption of the DNS model that the touching nuclei are hindered by a repulsive potential to amalgamate directly in R into compound nucleus. The fusion probability P_{CN} gives the probability that the DNS crosses the inner fusion barrier B^*_{fus} in η and forms the compound nucleus P_{CN} can be calculated by solving diffusion equations like the Fokker-Planck and master equations in coordinates η and R or by using the Kramer's approximation [9]. The probability of complete fusion is calculated in the following way:

$$P_{CN}=\lambda_\eta^{Kr}/(\lambda_\eta^{Kr}+\lambda_{\eta_{\text{sym}}}^{Kr}+\lambda_R^{Kr}). \tag{2}$$

Since the initial DNS is in the conditional minimum of potential energy surface, we use two-dimensional Kramer's-type expression for the quasi-stationary rates λ_η^{Kr} of the fusion, $\lambda_{\eta_{\text{sym}}}^{Kr}$ of the symmetrization of the DNS with the following decay and λ_R^{Kr} of the quasifission from the initial DNS through the fusion barrier B^*_{fus} in η, through the barrier $B_{\eta_{\text{sym}}}$ in η in the direction to more symmetric DNS configurations and through the quasifission barrier B_{qf} in R, respectively [7, 8]. The main factor which prohibits the complete fusion of heavy nuclei is the evolution of the initial DNS to more symmetric configurations ($B_{\eta_{\text{sym}}}\approx$ (0,5 - 1,5) MeV and (4 - 5) MeV for hot and cold fusion, respectively) and decay of the DNS during this process or the decay of the initial DNS. In hot fusion reactions, the decay of DNS takes place mainly outside of the initial conditional minimum because $B_{\text{qf}}>B_{\eta_{\text{sym}}}$ in contrast to the case of cold fusion reactions. The local temperature Θ of the initial DNS calculated with the Fermi-gas model expression Θ ($a=A_{CN}/12$ MeV^{-1}, $A_{CN}=(A_1+A_2)$ and E^* is the excitation energy of the DNS) is used in λ_η^{Kr}, $\lambda_{\eta_{\text{sym}}}^{Kr}$ and λ_R^{Kr} [7].

The barriers B^*_{fus}, $B_{\eta_{\text{sym}}}$ and B_{qf} are given by the potential energy of the DNS which is calculated as the sum of binding energies B_i of the nuclei (i = 1,2) and of the nucleus-nucleus potential V [5 - 7]: $U(R,\eta,J)=B_1+B_2+V(R,\eta,J)$. V is calculated with the double-folding procedure with a nuclear radius parameter $r_0=1.15$ fm and a diffuseness $a_0=0{,}54-0{,}56$ fm depending on the mass number of the isotope. The variations of the potential in η are caused by both shell effects and odd-even effects included into the calculations through realistic binding energies [10 - 13]. The isotopic composition of the nuclei forming the DNS is obtained with the condition of a N/Z equilibrium in the system. The potential of the DNS depends on the ground state deformations [14] of the nuclei assumed in the pole-pole orientation. The survival probability under the evaporation of x neutrons is treated according to [7, 8, 15] as

$$W_{sur}=P_{xn}(E^*_{CN})\prod_{i=1}^{x}\frac{\Gamma_n((E^*_{CN})_i)}{\Gamma_n((E^*_{CN})_i)+\Gamma_f((E^*_{CN})_i)},$$

$$\frac{\Gamma_n}{\Gamma_f}=\frac{0.41A^{2/3}a_fU_n}{2[a_nU_n]^{1/2}-1}\exp[2a_n^{1/2}U_n^{1/2}-2a_f^{1/2}U_f^{1/2}], \tag{3}$$

where P_{xn} is the probability for the realization of the xn channel at the excitation energy $E^*_{CN}=E_{\text{c.m.}}+Q$ of the compound nucleus and i is the index of the evaporation step [16]. $(E^*_{CN})_i$ is the mean value of excitation energy of the compound nucleus at the beginning of step i with $(E^*_{CN})_1 = E^*_{CN}$. We used the analytical expression for the ratio of the partial widths of neutron emission (Γ_n) and fission (Γ_f) in Eq. (3), and $U_n = E^*_{CN} - B_n - \delta$, $U_f = E^*_{CN} - (B_f - \delta)\exp[-E^*_{CN}/E_d] - \delta$). The neutron binding energies B_n and the absolute values of microscopic corrections [4] of fission barriers $B_f(E^*_{CN} = 0)$ are taken from mass table [11]. In Fermi-gas approximation B_f value depends on E^*_{CN} The pairing corrections $\delta = 22/A_0^{1/2}$ and $11/A_0^{1/2}$ for even-even and odd-even nuclei (odd-even effect), respectively, were taken into consideration. In U_f a double counting of pairing in the fission barrier, which is a purely shell correction, was avoided. In Fermi-gas approximation B_f value depends on E^*_{CN} as $B_f = B_f(E^*_{CN} = 0)\exp[-E^*_{CN}/E_d]$ where E_d= 25 MeV is the shell-damping energy [15]. At the excitation energies of (30 - 50) MeV in hot fusion reactions the damping of the shell corrections [4] reduces the difference between the results obtained with various predictions of the properties of superheavies. The ratio of the level density parameters in the fission and neutron evaporation channels is chosen as a_f/a_n=1,07 and 1,045 ($a_n = a$) for the predictions of Ref. [11] and Refs. [12, 13], respectively, in order to describe the experimental evaporation residue cross section for the reaction ^{48}Ca + ^{244}Pu $\longrightarrow$ $^{288}114 + 4n$ [8].

The calculated evaporation residue cross sections σ_{ER} at the maxima of excitation functions and the corresponding excitation energies E^*_{CN} of the compound nuclei are plotted in Fig. 1 for various ^{238}U-based reactions. In Fig. 1 σ_{ER} and E^*_{CN} are estimated using the predictions of the properties of superheavies from Ref. [11]. The extraordinary low excitation energy in the ^{48}Ca+^{238}U reaction is due to the gain in the Q-value. With projectiles heavier than ^{48}Ca E^*_{CN} becomes smaller with increasing charge Z_{CN} and mass A_{CN} numbers of compound nucleus. The predicted cross sections are almost independent within the factor of 2–5 on the choice of the mass table. The advantage of ^{48}Ca beam is evident. The calculated evaporation residue cross sections decrease by about 3 orders of magnitude with increasing the charge number of projectile from 20 to 26. The main reason of fall-off of σ_{ER} is the strong decrease of fusion probability P_{CN}. The competition between complete fusion and quasifission in the DNS becomes stronger with increasing charge number of compound nucleus. Besides ^{48}Ca, only the projectiles ^{40,42}Ar and ^{50}Ti result the cross section on the level of the present experimental possibilities. The same dependence of σ_{ER} on the projectile one can observe with other actinide targets.

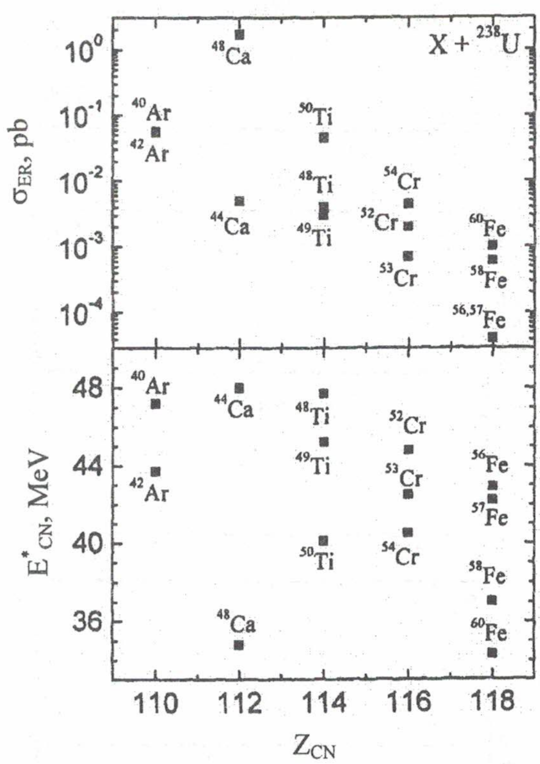

Fig. 1. The calculated maximal evaporation residue cross sections (upper part) at the corresponding optimalexcitation energies of the compound nuclei for the ^{238}U-based hot fusion reactions. The predictions of Ref. [11] were used in the calculations.

From Fig. 1 one can conclude that the stable isotopes of projectile-nucleus with the largest neutron excess are favorable for the most cases of hot fusion. At fixed charge asymmetry in the entrance channel, the fusion probability P_{CN} and excitation energy E^*_{CN} of compound nucleus decrease with increasing neutron excess in the projectile. The gain in the survival probability W_{sur} is not compensated by the loss in P_{CN}.

From Fig. 2 one can see that the reactions with smaller neutron excess in the target within certain interval of A are even more favorable for producing of SHE than those with larger neutron excess. The value of P_{CN} becomes larger with decreasing A in most cases. In these reactions the Q-value and, thus, E^*_{CN} decrease with A in the considered intervals. This behaviour was also observed within a certain small interval of A in the case of ^{48}Ca-induced Ra-, Th-, U-, Pu-, Cm-and Cf-based fusion reactions [8].

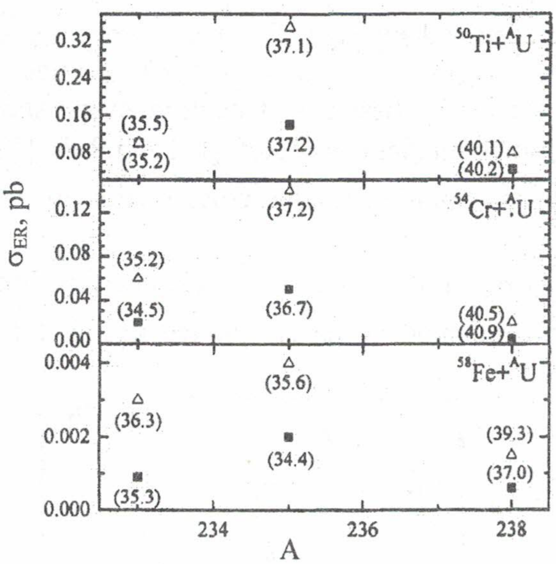

Fig. 2. The calculated maximal evaporation residue cross sections at the corresponding optimal excitation energies of the compound nuclei (in parenthesis) for the hot fusion reactions as a function of mass number A of the target. The results obtained with the predictions of Ref. [11] and Ref. [13] are shown by closed squares and open triangles, respectively.

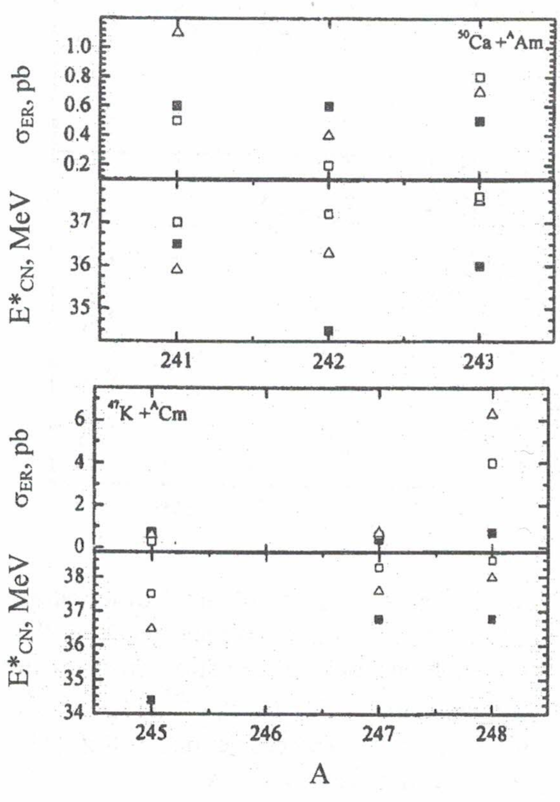

Fig. 3. The calculated maximal evaporation residue cross sections at the corresponding optimal excitation energies of the compound nuclei (in parenthesis) for the hot fusion reactions ^{50}Ca+^{A}Am and ^{47}K+^{A}Cm as a function of A. The results obtained with the predictions of Ref. [11], Ref. [12] and Ref. [13] are shown by closed squares, open squares and open triangles, respectively.

The radioactive beams of ^{47}K and ^{46}Ar are likely produced with high intensities in near future. In the actinide-based reactions the use of neutron-rich projectiles of ^{47}K and ^{50}Ca leads to the values of σ_{ER} comparable with one for the reactions with ^{48}Ca (Fig. 3). However, with projectile ^{47}K one can produce new odd SHE with the neutron number closed to N = 184. For the reaction ^{46}Ar+^{248}Cm, we obtained σ_{ER} = 9 pb at E^*_{CN} = 38 MeV using the predictions of Ref. [11].

Incomplete fusion reactions

The formation and decay of the DNS more asymmetric than the DNS in the entrance channel, the asymmetry-exit-channel quasifission (AECQ) reactions, as well as the quasifission are ruled by the same mechanism in the sense that both of them are diffusion processes in the same relevant collective coordinates: mass and charge asymmetries and relative distance. The cross section $\sigma_{Z,N}$ of the production of primary heavy nucleus in the AECQ reaction is the product of the capture cross section σ_{cap} in the entrance reaction channel and formation-decay probability $Y_{Z,N}$ of the DNS configuration with charge and mass asymmetries given by Z and N: $\sigma_{Z,N} = \sigma_{cap} Y_{Z,N}$. Since this nucleus is excited, one should take into account its survival probability W_{sur} in the deexcitation process to obtain the evaporation residue cross section

$$\sigma_{ER}(Z, N-x) = \sigma_{Z,N}(Z,N) W_{sur}(xn) . \tag{4}$$

Here x is the number of evaporated neutrons from the excited primary heavy nucleus. $W_{sur}(xn)$ is treated as in Ref. [15, 16]. The predicted properties of superheavies are taken from Ref. [11]. Assuming the thermal equilibrium in the DNS, we define the excitation energy $E^*_H(Z,N)$ of primary heavy nucleus proportionally to its mass number.

The primary charge and mass yield $Y_{Z,N}$ of the decay fragments can be expressed as in Ref. [17]

$$Y_{Z,N} = \Lambda^{qf}_{Z,N} \int_0^{t_0} P_{Z,N}(t) dt , \tag{5}$$

where $P_{Z,N}$ is the probability of formation of the corresponding DNS configuration and the decay rate $\Lambda^{qf}_{Z,N}$ of this configuration in R is associated with the one-dimensional Kramer's rate. The time of reaction t_0 is defined from the normalization condition $\sum_{Z,N} Y_{Z,N} = 1$. Using the microscopical method suggested in Ref. [17], one can find $P_{Z,N}(t)$ from the master equation

$$\begin{aligned} \frac{d}{dt} P_{Z,N}(t) &= \Delta^{-,0}_{Z+1,N} P_{Z+1,N}(t) + \Delta^{+,0}_{Z-1,N} P_{Z-1,N}(t) + \\ &+ \Delta^{0,-}_{Z,N+1} P_{Z,N+1}(t) + \Delta^{0,+}_{Z,N-1} P_{Z,N-1}(t) - \\ &- (\Delta^{-,0}_{Z,N} + \Delta^{+,0}_{Z,N} + \Delta^{0,-}_{Z,N} + \Delta^{0,+}_{Z,N} + \Delta^{qf}_{Z,N}) P_{Z,N}(t) \end{aligned} \tag{6}$$

with initial condition $P_{Z,N}(0) = \delta_{Z,Z_i} \delta_{N,N_i}$ and the microscopically defined transport coefficients for proton $\Lambda^{\pm,0}_{Z,N}$ and neutron $\Lambda^{0,\pm}_{Z,N}$ transfers between the DNS nuclei. In the reactions considered the probability of fission of heavy nucleus in the DNS is small to be disregarded in (6).

For $102 < Z < 110$, the potential energy decreases with total number of neutrons of the DNS and the larger primary yield of superheavy nuclei is expected in the reactions with ^{244,246}Cm than with ^{248}Cm. In the reaction ^{48}Ca + ^{248}Cm $\longrightarrow$ ^{40}S + (^{254}Fm + 2n) the calculated σ_{ER} for ^{254}Fm is about 0,5 μb in two approaches that is close to the experimental result presented in Refs. [18 - 20] where the yields of nuclei above Fm were not measured. In Fig. 4 the excitation energies of primary heavy nuclei correspond to $E_{\text{c.m.}}$ = 204 - 207 MeV, close to $E^{\min}_{\text{c.m.}}$. In this case $E^*_H(Z,N)$ are related to the maxima or to the right sides of excitation functions for one neutron emission. For example, for ^{262}No and ^{274}Hs E^*_H = 16 ($W_{sur}(1n) = 2,4\cdot 10^{-4}$) and 11 MeV ($W_{sur}(1n) = 1,6\cdot 10^{-2}$), respectively. While $Y_{Z,N}$ decreases by about 3 orders of magnitude with increasing Z from 102 to 108, the evaporation residue cross section decreases only by about 30 times due to the increase of W_{sur} with Z. The experimental data [20] as well as our treatment indicate the preference of projectile-target combination with smaller number of neutrons to produce superheavy nuclei. If one increases $E_{\text{c.m.}}$, the larger values of $Y_{Z,N}$ are overcompensated by smaller values of W_{sur} and thus σ_{ER} become smaller. One can see that with the AECQ reactions on actinide targets the unknown isotopes of superheavy nuclei can be produced with suitable cross sections. In Fig. 4 the nuclei ^{261}No and ^{264}Lr, and all nuclei with $Z > 103$ were not yet produced in complete fusion reactions. Therefore, the AECQ leads to the superheavies with mass numbers which are between those produced in the cold and hot fusion reactions [1, 3]. The production of these isotopes is also important for the experimental identification of superheavy nuclei. For example, for the reaction ^{243}Am(^{48}Ca, xn)$^{291-x}$115 α-decay chains end at ^{267,268}Db [1] which can be directly obtained in AECQ reactions ^{48}Ca + ^{246,248}Cm. Note that the methods elaborated for describing AECQ are suitable for the analysis of production of various exotic nuclei, for example, of neutron-rich light nuclei.

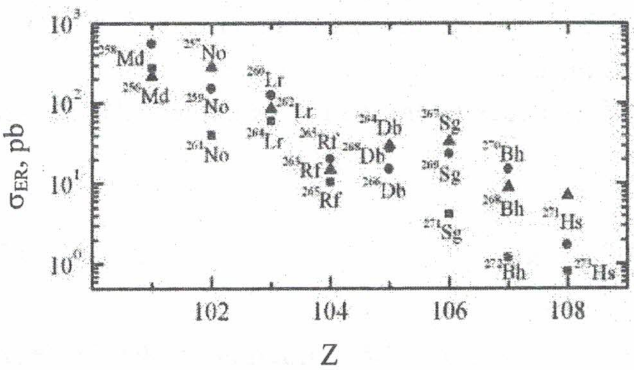

Fig. 4. The calculated evaporation residue cross sections σ_{ER} are shown by triangles, circles and squares for the reactions ^{48}Ca + + ^{244,246,248}Cm ($E_{\text{c.m.}}$ = 207, 205.5, 204 MeV), respectively. The heavy fragments after 1n evaporation are indicated. The results obtained with the predictions of Ref. [11].

Summary

1. The actinide-based reactions with stable projectiles heavier than ^{50}Ti projectile are not much promising for further synthesis of SHE.

2. The products of asymmetry-exit-channel quasifission reactions can fill a gap of unknown isotopes between the isotopes of heaviest nuclei obtained in cold and hot complete fusion reactions.

REFERENCES

1. *Oganessian Yu. Ts. et al.* // Physical Review. - 2000. - Vol. C62. - P. 041604(R); Ibid. - 2004. - Vol. C69. - P. 021601(R); Ibid. - 2004. - Vol. C69. - P. 054607.
2. *Sobiczewski A., Gareev F.A., Kalinkin B.N.* // Physics Letter. - 1966. - Vol. B22. - P. 500; *Möller P., Nix J.R.* // Journal Physics G: Nuclear and Particle Physics. - 1994. - Vol. 20. - P. 1681.
3. *Hofmann S., Münzenberg G.* // Review of Modern Physics. - 2000. - Vol. 72. - P. 733.
4. *Brack M., Damgaard J., Jensen A.S. et al.* // Review of Modern Physics. - 1972. - Vol. 44, No. 2. - P. 320.
5. *Volkov V.V.* // Izv. AN SSSR. Ser. fiz. - 1986. - Vol. 50. - P. 1879; *Antonenko N.V. et al.* // Physics Letter. - 1993. - Vol. B319. - P. 425; Physical Review. - 1995. - Vol. C51. - P. 2635.

6. *Adamian G.G., Antonenko N.V., Scheid W.* // Nuclear Physics. - 1997. - Vol. A618. - P. 176; *Adamian G.G., Antonenko N.V., Scheid W., Volkov V.V.* // Nuclear Physics. - 1997. - Vol. A627. - P. 361; Ibid. - 1998. - Vol. A633. - P. 409.
7. *Adamian G.G., Antonenko N.V., Scheid W.* // Nuclear Physics. - 2000. - Vol. A678. - P. 24.
8. *Adamian G.G., Antonenko N.V., Scheid W.* // Physical Review. - 2004. - Vol. C69. - P. 011601(R); Ibid. - 2004. - Vol. C69. - P. 014607; Ibid. - 2004. - Vol. C69. - P. 044601.
9. *Fröbrich P., Lipperheide R.* Theory of Nuclear Reactions. - Clarendon, Oxford, 1996.
10. *Audi G., Wapstra A.H.* // Nuclear Physics. - 1993. - Vol. A565. - P. 1.
11. *Möller P., Nix J.R.* // Atomic Data and Nuclear Data Tables. - 1988. - Vol. 39. - P. 213; LANL Preprint LA-UR-86-3983, 1986.
12. *Möller P., Nix J.R., Myers W.D., Swiatecki W.J.* // Atomic Data and Nuclear Data Tables. - 1995. - Vol. 59. - P. 185.
13. *Myers W.D., Swiatecki W.J.* // Nuclear Physics. - 1996. - Vol. A601. - P. 141; Report LBL-36803 (1994).
14. *Raman S., Nestor C.W., Tikkanen P.* // Atomic Data and Nuclear Data Tables. - 2001. - Vol. 78. - P. 1.
15. *Adamian G.G., Antonenko N.V., Ivanova S.P., Scheid W.* // Physical Review. - 2000. - Vol. C62. - P. 064303; *Zubov A.S. et al.* // Physical Review. - 2002. - Vol. C65. - P. 024308.
16. *Cherepanov E.A., Iljinov A.S.* // Nucleonika. - 1980. - Vol. 25. - P. 611.
17. *Adamian G.G., Antonenko N.V., Scheid W.* // Physical Review. - 2003. - Vol. C68. - P. 034601.
18. *Gäggeler H. et al.* // Physical Review. - 1986. - Vol. C33. - P. 1983.
19. *Hoffman D.C. et al.* // Physical Review. - 1985. - Vol. C31. - P. 1763.
20. *Türler A. et al.* // Physical Review. - 1992. - Vol. C46. - P. 1364.

ПРО МОЖЛИВОСТІ СИНТЕЗУ НАДВАЖКИХ ЯДЕР У РЕАКЦІЯХ ГАРЯЧОГО ЗЛИТТЯ

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У рамках моделі подвійної ядерної системи аналізуються реакції гарячого злиття між актинідами та ядрами важчими, ніж ^{48}Ca. Зроблено прогноз для реакцій злиття з радіоактивними пучками. Вивчено можливості отримання нових ізотопів надважких ядер із зарядовими номерами 104 - 108 у реакціях неповного злиття.

О ВОЗМОЖНОСТЯХ СИНТЕЗА СВЕРХТЯЖЕЛЫХ ЯДЕР В РЕАКЦИЯХ ГОРЯЧЕГО СЛИЯНИЯ

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В рамках модели двойной ядерной системы анализируются реакции горячего слияния между актинидами и ядрами тяжелее, чем ^{48}Ca. Сделаны предсказания для реакций слияния с радиоактивными пучками. Изучены возможности получения новых изотопов сверхтяжелых ядер с зарядовыми номерами 104 - 108 в реакциях неполного слияния.

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