

Superheavy element production, nucleus-nucleus potential and μ -catalysis

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Abstract. The semi-microscopic potential between heavy nuclei is evaluated for various colliding ions in the approach of frozen densities in the framework of the extended Thomas-Fermi approximation with \hbar^2 correction terms in the kinetic energy density functional. The proton and neutron densities of each nucleus are obtained in the Hartree-Fock-BCS approximation with SkM* parameter set of the Skyrme force. A simple expression for the nuclear interaction potential between spherical nuclei is presented. It is shown that muon bound with light projectile induces the superheavy elements production in nucleus-nucleus collisions.

INTRODUCTION

Knowledge of the nucleus-nucleus interaction potential is a key ingredient in the analysis of nuclear reactions. By using the potential between nuclei we can estimate the cross sections of different nuclear reactions [1].

The nucleus-nucleus interaction potential related to the Coulomb repulsion force and the nuclear attraction force has, as a rule, the barrier and the capture potential well near a touching point. The Coulomb part of the ion-ion potential is well-known. In contrast, the nuclear part of the nucleus-nucleus potential is less defined. There are many different approaches to the nuclear part of the interaction potential [1-6]. Unfortunately, barriers evaluated within different approaches for the same colliding system differ considerably, especially when both nuclei are very heavy or one nucleus is very heavy and another is light [7, 8]. The uncertainty of the interaction potential between heavy ions near the touching point gives rise to a variety of proposed nuclear reaction mechanisms. So, there is a need to reduce the uncertainty of the interaction potential around the touching point, especially between heavy nuclei used for the synthesis of superheavy elements (SHEs).

The production cross section of SHEs with $Z \geq 112$ is very low and close to the limit of current experimental possibility [9-13]. Due to this it is of interest to find new types of reactions, which can induce fusion of two heavy nucleus.

In second section of the paper we briefly discuss our semi-microscopic approach for the nucleus-nucleus interaction potential and present some new numerical results. The simple analytical expression for the nuclear potential between two heavy spherical nuclei is presented in section 3. We show in section 4 that muon bound with light nucleus induce SHE formation during nucleus-nucleus fusion reaction.

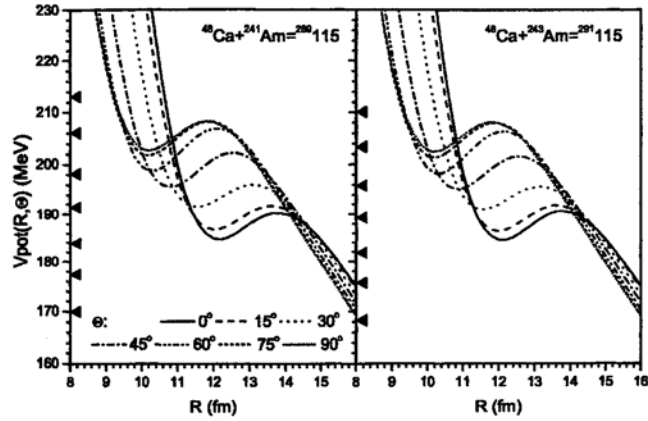


FIGURE 1. The SMPs for the collisions ^{48}Ca on $^{241,243}\text{Am}$ evaluated with the SkM* Skyrme force. The SMPs are evaluated for different angular orientations of the heavy deformed nuclei. The ground-state Q-values are indicated by the lowest triangle at the left vertical axis. The other 6 triangles mark arc, respectively, the thresholds for the emission of 1, 2, 3, 4, 5 and 6 neutrons.

SEMI-MICROSCOPIC POTENTIAL AND SHE PRODUCTION

We evaluate the nuclear part of interaction potential between heavy nuclei in the semi-microscopic frozen density approximation due to a short reaction time [7]. The frozen (or sudden) approximation is good for evaluation of the nucleus-nucleus potential near the touching point at collision energies above the barrier height. The shape of each ion cannot appreciably change and the energy of relative motion cannot be strongly transferred to another degrees of freedom during the short reaction time.

The interaction energy between ions is obtained with the help of a local energy density functional. The extended Thomas-Fermi (ETF) approximation with \hbar^2 correction terms is used for the evaluation of the kinetic energy density functional [14]. The Skyrme and Coulomb energy density functionals are employed for the calculation of the potential energy. These energy density functionals depend on the proton and neutron densities. These densities in each nuclei are obtained in the microscopic Hartree-Fock-BCS approximation with the Skyrme force. Our approximation is semi-microscopic because we use the microscopic density distributions and the ETF approximation for the calculation of the interaction energy of nuclei. Note that the binding energies of nuclei evaluated in the ETF approximation with the help of microscopic density distributions well agree with those obtained in the fully microscopic Hartree-Fock-BCS model [7, 8]. Therefore, our semi-microscopic method for evaluation of the interaction potential between various nuclei is quite accurate. The details of our method and results for various even-even projectiles and targets are discussed in [7-8,15-16]. Due to this we present here only some new results obtained in our approximation and discussions.

At the beginning we consider the semi-microscopic potentials (SMPs) for hot fusion

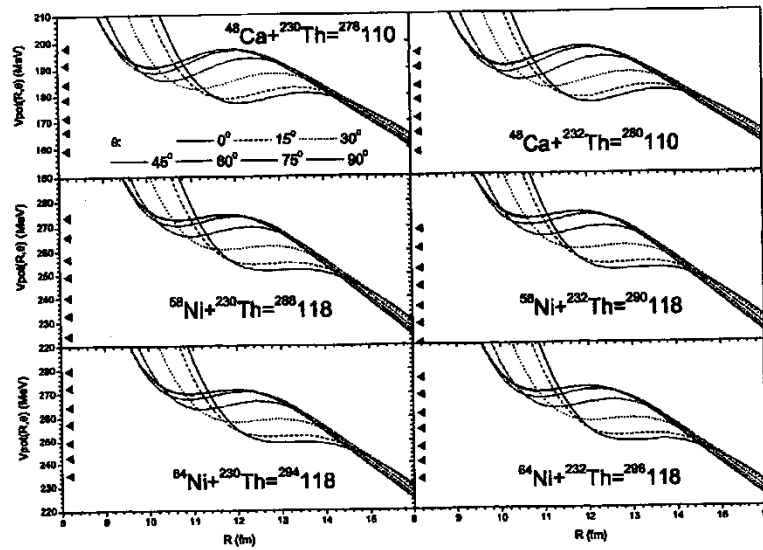


FIGURE 2. The SMPs for the collisions ^{48}Ca on $^{230,232}\text{Th}$ and $^{58,64}\text{Ni}$ on $^{230,232}\text{Th}$ evaluated with the SkM* Skyrme force. The notations are the same as in Fig. 1.

reactions which was used for the formation of element with 115 protons in Dubna very recently [11]. In Fig. 1 we presented SMPs for reactions $^{48}\text{Ca}+^{241,243}\text{Am}=\text{289,291}115$ evaluated for SkM* Skyrme force [17]. We see that the potential shape (radial positions of both the barriers and the capture wells for various orientations of deformed $^{241,243}\text{Am}$ and the depths of capture wells) for these reactions are very similar to the ones for reactions between ^{48}Ca and other closest even-even targets ^{238}U , $^{236,238,240,242,244}\text{Pu}$, ^{248}Cm and ^{252}Cf [7, 15, 16]. However the positions of both the barriers and the capture wells relatively the ground state of compound nucleus for various orientations $^{241,243}\text{Am}$ are slightly lower than the ones evaluated for nearest even-even projectiles $^{240,242,244}\text{Pu}$, see Fig. 1 in [16]. This is favorable for the SHE formation in reaction with $^{241,243}\text{Am}$.

A choice of light isotope is very important for the SHE production [7, 15, 16]. A SHE formation reactions induced by ^{48}Ca projectile are limited by availability of heavy transuranic elements in the nature. Due to this it is practically impossible to synthesize element with $Z \geq 120$ by using ^{48}Ca beam. By using Fig. 2 and Figs. 4-7 in [7] and analyzing the chart of nuclides we may conclude that ^{64}Ni is the nearest nuclide heavier than ^{48}Ca , which we may recommend to use for the SHE production, because of (1) ^{64}Ni is easily available as a projectile, (2) ^{64}Ni is sufficiently neutron rich, (3) ^{64}Ni produces relatively low-excited compound nuclei during fusion with easily available set of target nuclei and (4) the number of protons in ^{64}Ni is magic as that in ^{48}Ca . Therefore, reactions with ^{64}Ni projectile ($^{64}\text{Ni}+X \rightarrow \text{SHE}$) should play similar role as reactions with ^{48}Ca ($^{48}\text{Ca}+X \rightarrow \text{SHE}$), which are successfully used now in Dubna [11]. However the

capture well for reactions with ^{64}Ni is more shallow than the one for reactions with ^{48}Ca , see Fig. 2. This may reduce the capture probability for reactions with ^{64}Ni projectile.

By analyzing SMPs for reactions presented in Figs. 1,2 and for other reactions considered in [7, 15, 16] we observe the common features of SMPs for various reactions and make conclusions for reactions leading to the SHEs:

- (1) The depth of the pockets is important for the fusion probability. We observe correlation between pocket depth and experimentally observed reduction of SHE formation with increasing size of the projectile.
- (2) The pocket depth should be as large as possible for the SHE production, because the deeper pocket has larger the capture window and, therefore, better chance for fusion. Due to this hot fusion reactions has better chance for capture than cold fusion reactions leading to the same SHE.
- (3) For the subsequent formation of a compound nucleus it is best to have a most compact capture configuration. Due to this both the cold fusion systems are more preferable than more symmetric systems leading to the same compound nucleus and the side orientation of deformed nucleus is more preferable for the SHE formation than the tip orientation of deformed nucleus in the case of the hot fusion reactions.
- (4) The observed fusion windows lie systematically about 5 to 10 MeV below our barriers.
- (5) The isotopic composition of heavy transuranic nuclei only weakly affects both the shape of the capture well and barrier heights for different orientations relatively the ground-state fusion reaction Q -value.
- (6) The capture properties of SMP and compound-nucleus excitation energy in the hot fusion reactions strongly depend on the isotopic composition of light nuclide.
- (7) The difference between the capture barrier position and the ground-state fusion reaction Q -value decreases with increasing as charge as number of neutrons of the projectile for reactions with the same target.
- (8) Pocket depth is vanished with increasing size of the projectile. For example in the case of ^{208}Pb target, there are no pocket for $^{96}\text{Zr}+^{208}\text{Pb}$ and more heavy projectiles.
- (9) The potential pockets for system leading to SHE are much shallower than the ones for more lighter colliding systems.
- (10) The interaction potentials obtained by using different standard expressions [1-6] are spread over large interval for heavier systems.

ANALYTICAL EXPRESSION FOR POTENTIAL

The numerical evaluation of SMP is very accurate for determination of interaction potential between nuclei around the touching point. Unfortunately, it is not so convenient for any practical application because one needs to evaluate numerically the microscopic Hartree-Fock-BCS nucleonic densities of interacting nuclei, derivatives of these densities and integrals [7, 8]. It is better to find analytical expression for the potential. To solve this task we choose 119 spherical or near spherical nuclei along the β -stability line from ^{16}O to ^{212}Po and perform numerical calculations of the interaction potentials between

all possible nucleus-nucleus combinations in the semi-microscopic approximation. We evaluate potential for any nucleus-nucleus combinations at 15 distances between ions around the touching point. By using database for 7140 nucleus-nucleus potentials at 15 points each, we find a simple analytical expression for the potential between spherical nuclei in the form [8]

$$V(R) = -1.989843 C f(R - R_{12} - 2.65) \quad (1)$$

$$\times \left[1 + 0.003525139(A_1/A_2 + A_2/A_1)^{3/2} - 0.4113263(I_1 + I_2) \right],$$

where R is the distance between mass centers of colliding nuclei, $C = R_1 R_2 / R_{12}$, R_i is the effective nuclear radius, $R_{12} = R_1 + R_2$,

$$f(s) = \left\{ 1 - s^2 \left[0.05410106 C \exp\left(-\frac{s}{1.760580}\right) - 0.5395420 (I_1 + I_2) \right. \right. \quad (2)$$

$$\left. \left. \times \exp\left(-\frac{s}{2.424408}\right) \right] \right\} \times \exp\left(\frac{-s}{0.7881663}\right), \text{ for } s \geq 0,$$

$$f(s) = 1 - \frac{s}{0.7881663} + 1.229218s^2 - 0.2234277s^3 - 0.1038769s^4 \quad (3)$$

$$- C(0.1844935s^2 + 0.07570101s^3)$$

$$+ (I_1 + I_2)(0.04470645s^2 + 0.03346870s^3), \text{ for } -5.65 \leq s \leq 0,$$

A_i is the number of nucleon in nucleus i ($i = 1, 2$), $I_i = (N_i - Z_i)/A_i$, Z_i and N_i are numbers of protons and neutrons in nucleus i . The effective nuclear radius is given by

$$R_i = R_{ip}(1 - 3.413817/R_{ip}^2) + 1.284589(I_i - 0.4A_i/(A_i + 200)), \quad (4)$$

where the proton radius is determined as in [18] $R_{ip} = 1.24A_i^{1/3}(1 + 1.646/A_i - 0.191I_i)$. The last term in (4) takes into account deviation of the nuclear radius from the proton radius when the neutron number in nucleus deviates from the β -stability value for given A . The line of β -stability is described by Green's approximation $I = (N - Z)/A = 0.4A/(A + 200)$ [19]. Note that the potentials obtained by means of the analytical expression well agree with semi-microscopic one [8].

The "empirical" fusion barrier B_{empir} and "empirical" barrier radius R_{empir} between heavy nuclei are extracted by means of a special analysis of the experimental data for subbarrier fusion reactions in Ref. [20]. The absolute and relative differences between "empirical" fusion barrier and barrier evaluated by using various analytical expressions [1-6,8] B_{theor} are presented in Fig. 3. In Fig. 4 we present the absolute and relative differences between "empirical" barrier radius and radii of barrier evaluated by using various analytical expressions [1-6,8] R_{theor} . The barriers B_{theor} and radii R_{theor} evaluated by using Eqs. (1)-(4) well agree with "empirical" the ones respectively, see Figs. 3-4. The distributions of deviations $B_{\text{empir}} - B_{\text{theor}}$, $(B_{\text{empir}} - B_{\text{theor}})/B_{\text{empir}}$, $R_{\text{empir}} - R_{\text{theor}}$ and $(R_{\text{empir}} - R_{\text{theor}})/R_{\text{empir}}$ are almost symmetric with respect to the lines $B_{\text{empir}} - B_{\text{theor}} = 0$ or $R_{\text{empir}} - R_{\text{theor}} = 0$ correspondingly for the case of using analytical expression for SMP, see Figs. 3-4. This also suggests the reliability of A - and Z -dependencies of our expression for the nucleus-nucleus potential. In contrast to this similar distributions

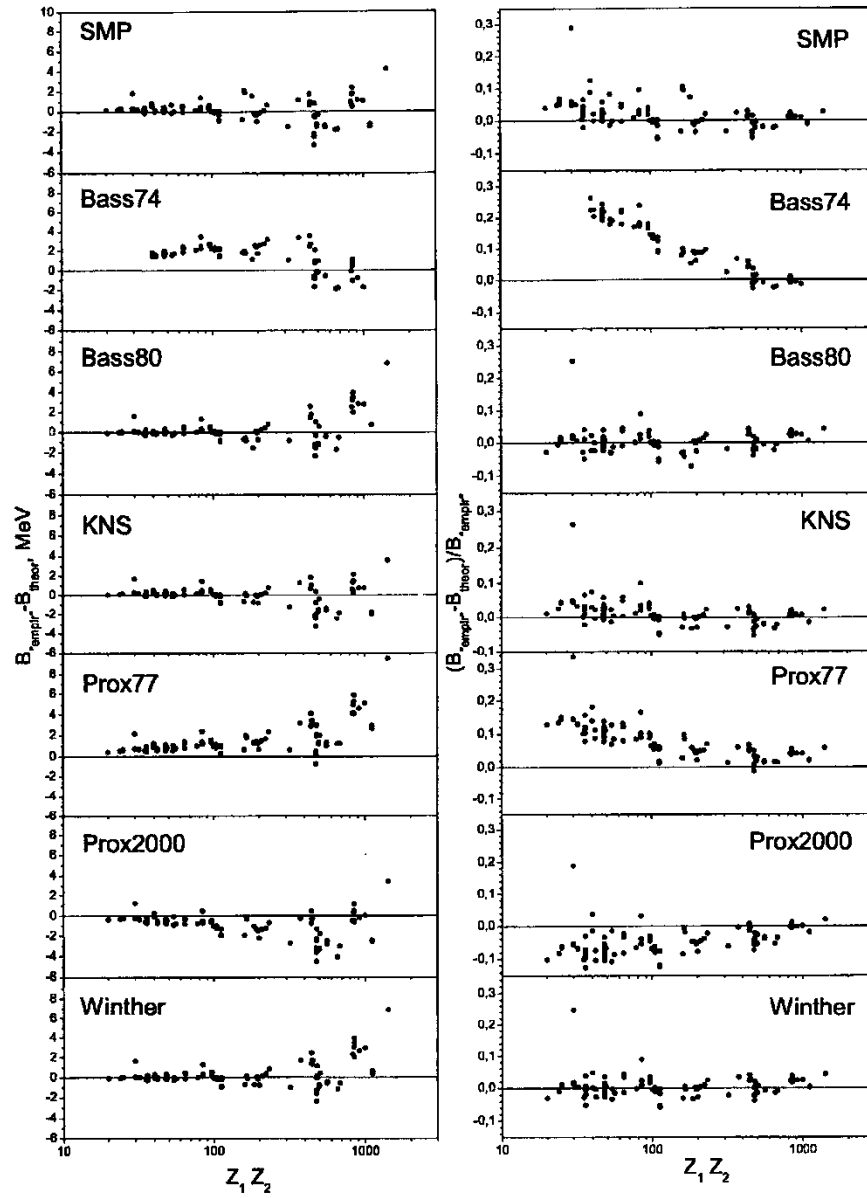


FIGURE 3. The absolute (left panels) and relative (right panels) differences between the "empirical" fusion barrier and the barrier evaluated by using various analytical expressions (SMP - [8], Bass74 - [2], Bass80 - [1], Prox77 - [3], Prox2000 - [5], KNS - [4] and Winther - [6]).

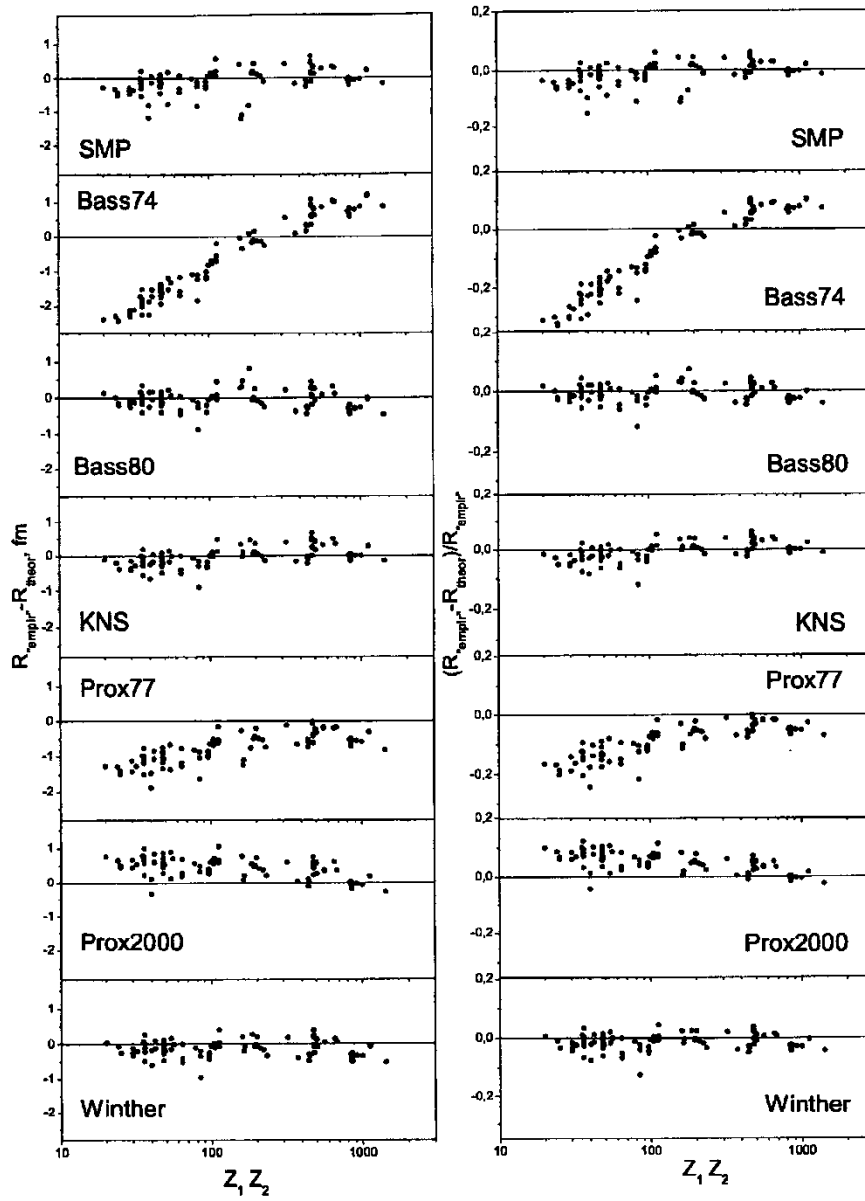


FIGURE 4. The absolute (left panels) and relative (right panels) differences between the "empirical" radius of barrier and the barrier radius evaluated by using various analytical expressions (SMP - [8], Bass74 - [2], Bass80 - [1], Prox77 - [3], Prox2000 - [5], KNS - [4] and Winther - [6]).

for the proximity-1977 [3], proximity-2000 [5] and Bass-1974 [2] potentials have no symmetry with respect to the lines $B_{\text{empir}} - B_{\text{theor}} = 0$ and $R_{\text{empir}} - R_{\text{theor}} = 0$, see corresponding panels in Figs. 3-4. Note that it is impossible to evaluate both the depth and the width of capture well by using Bass-1974 [2], Bass-1980 [1], Krappe-Nix-Sierk [4] and Winther [6] potentials because the shape of these potentials are unrealistic or unknown at distances smaller than the touching point distance of two nuclei.

CATALYSIS OF THE SHE SYNTHESIS BY MUON

It is easy to understand qualitatively a influence of muon μ^- on the SHE fusion process, if we recollect that the wave function of $1s$ state of μ^- in a very heavy nucleus is located inside the nucleus [21]. Therefore, negatively-charged muon inside heavy nucleus should effectively reduce the Coulomb repulsion between protons. Due to this the forces, inducing fission of compound nucleus and preventing fusion of two nuclei should decrease. Consequently, the SHE formation probability should rise due to μ^- .

Let's we consider in detail the catalysis of the SHE production by μ^- . The process of SHE formation is subdivided into three steps [22-27]: (1) The capture of two nuclei in an entrance-channel potential well and formation of a common nuclear system of two touching nuclei. (2) The formation of a spherical or nearly spherical compound nucleus during shape evolution from the common nuclear system of two touching nuclei to a compound nucleus. (3) The surviving of the excited compound nucleus due to evaporation of neutrons and γ -ray emission in competition with fission.

The capture process depends on both the barrier thickness and pocket shape of entrance-channel potential between nuclei [7]. The shape evolution step is determined by a potential-energy landscape between the touching configuration of two colliding nuclei and the compound-nucleus shape [22-27]. Decay properties of the compound nucleus drastically depend on the fission barrier height [22-27]. Therefore, enhancement of the SHE production in fusion reaction may be achieved by processes which (1) make capture pocket dipper and barrier of entrance-channel potential thinner, (2) increase the slope or reduce both barrier height and thickness of the potential-energy landscape between touching configuration of two colliding nuclei and compound nucleus, (3) increase the fission barrier height. Below we show that these three conditions can be met in a reaction between a light nucleus with captured μ^- -meson L_μ and a heavy nucleus T .

The potential energy of $L_\mu+T$ system before touching can be approximated as

$$E_{L_\mu T}(R) = B_L + B_T + B_{L_\mu} + V_{LT}(R) + V_{T_\mu}(R), \quad (5)$$

where B_L and B_T are the binding energies of light L and heavy T nuclei, respectively, B_{L_μ} is the binding energy of muon in the light nucleus L , $V_{LT}(R)$ is the interaction potential between the light and heavy nuclei related to Coulomb and nuclear forces at distance R between their mass centers [7, 8], and $V_{T_\mu}(R) = -e^2 Z_T / R$ is the Coulomb interaction between Z_T protons in the heavy nucleus and the muon. The potential energy of the compound nucleus with bound μ^- is connected with the binding energy of the compound nucleus B_{CN} and with that of muon in the compound nucleus $B_{CN\mu}$, i.e., $E_{CN} = B_{CN} + B_{CN\mu}$.

The potential-energy landscape evaluated relatively to the ground state of compound nucleus with bound μ^- , which formed during $L_\mu+T$ fusion reaction, is related to

$$\delta(R) = E_{L_\mu T}(R) - E_{CN} = \delta_N(R) + \delta_{N\mu}(R). \quad (6)$$

Here we split $\delta(R)$ into contributions of pure nuclear $\delta_N(R)$ and muon-nuclear $\delta_{N\mu}(R)$ subsystems, where

$$\delta_N(R) = B_L + B_T - B_{CN} + V_{LT}(R), \quad \delta_{N\mu}(R) = B_{L\mu} - B_{CN\mu} + V_{T\mu}(R). \quad (7)$$

We see that the Coulomb interaction between muon and protons modifies the potential-energy landscape of fusing system. (Note that realistic landscape of potential-energy surface of fusing system depends on a great number of various collective coordinates. However, we take into account only the most important collective coordinate, which describes the distance between mass centers of separated nuclei or elongation of fusing system upon the capture step.)

Note that $\delta_{N\mu}(R) = B_{L\mu} - B_{CN\mu} - Z_T e^2/R$ is decreased with reduction of R . At distance R_{CN} , which corresponds to the distance between left and right mass centers of compound nucleus, $\delta_N(R_{CN}) = \delta_{N\mu}(R_{CN}) = 0$ because we evaluate $\delta(R)$ relatively to the ground state of compound nucleus with bound μ^- . Note that $B_{L\mu} - B_{CN\mu} > 0$, therefore $\delta_{N\mu}(R)$ is mainly reduced with R . Consequently if $\delta_{N\mu}(R)$ continuously decreases with reducing of R , then muon induces the SHE formation due to three effects:

- (1) A more dipper capture pocket is formed as a result of such R dependence of $\delta_{N\mu}(R)$. Therefore, the capture state formation probability increases.
- (2) The potential-energy landscape of the muon-nuclear system becomes more favorable for shape evolution from captured states of two touching nuclei to the compound nucleus.
- (3) The muon-nuclear system exhibits a larger fission barrier height as compared to pure nuclear system, see also [28] and papers cited therein. Note that variation of the fission barrier height on 0.3 MeV lead to change of SHE production cross section on approximately 30% [22]. Due to muon the fission barrier of heavy nucleus is increased near to 1 MeV [28]. Consequently, the fission or quasi-fission probability of muon-nuclear system get reducing approximately on one order as compared to the pure nuclear system. Therefore only due to this effect the SHE production cross section may rise to one order.

μ^- is a convenient particle for inducing compound-nucleus formation in reactions $L_\mu + T \rightarrow SHE + xn + e^- + \bar{\nu}_e + \nu_\mu$, because its lifetime ($\approx 2.2 \times 10^{-6}$ s [21]) is sufficient for making $1s$ bound state with a light projectile nucleus just before the collision with a target and induce fusion reaction. The process of SHE formation during nucleus-nucleus collision is fast relatively typical μ^- dynamic time. Therefore there is high probability of population of $1s$ bound state of μ^- in SHE during nuclear reaction time. The compound nucleus relatively rarely excited during the decay μ^- ($\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ [21]). It is possible to make beam of muonic projectile L_μ by merging beams of strongly ionized projectile nucleus L and of μ^- at the same velocities before the target.

Note that muon catalysis of thermonuclear reactions is also related to effective reduction of the Coulomb repulsion between protons and is well studied both theoretically

and experimentally (see [21] and papers cited therein). Muon catalysis of thermonuclear reactions between two hydrogen isotopes is mainly related to reduction of both fusion barrier heights and thickness. In contrast to this muon catalysis of SHE production is connected with more complex processes as reduction of fusion barrier thickness, modification of capture pocket, variation of potential-energy landscape between capture and compound-nucleus shapes and rising of the fission barrier height.

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