Muon catalysis of superheavy element production in nucleus-nucleus fusion reaction

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I. INTRODUCTION

The synthesis of superheavy elements (SHEs) was and still is an outstanding research object. The production cross section of SHEs with Z ≥ 112 is very low and close to the limit of current experimental possibility [1-4]. Due to this it is of interest to find new types of reactions, which can induce fusion of two heavy nucleus. We show in the next section that muon bound with light nucleus induce SHE formation during nucleus-nucleus fusion reactions.

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 3. 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−.

II. CATALYSIS OF THE SHE SYNTHESIS BY MUON

The process of SHE formation is subdivided into three steps. 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 3. The shape evolution step is determined by potential-energy landscape between the touching configuration of two colliding nuclei and the compound nucleus 3. Decay properties of the compound nucleus drastically depend on the fission barrier height 3. 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 Lµ and a heavy nucleus T.

The potential energy of Lµ+T system before touching can be approximated as

\[ E_{Lµ,T}(R) = B_L + B_T + B_{Lµ} + V_{LT}(R) + V_{Tµ}(R), \]  

where B_L and B_T are the binding energies of light L and heavy T nuclei, respectively, B_{Lµ} 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, and \( V_{Tµ}(R) = -e^2Z_T/R \) 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_{CNµ}, i.e.,

\[ E_{CN} = B_{CN} + B_{CNµ}. \]

The potential energy evaluated relatively to the ground state of compound nucleus with bound µ−, which formed during Lµ+T fusion reaction, is related to difference

\[ δ(R) = E_{Lµ,T}(R) - E_{CN}. \]

It is useful to split δ(R) into contributions of pure nuclear δ_N(R) and muon-nuclear δ_{Nµ}(R) subsystems

\[ δ(R) = δ_N(R) + δ_{Nµ}(R), \]

where

\[ δ_N(R) = B_L + B_T - B_{CN} + V_{LT}(R), \]

\[ δ_{Nµ}(R) = B_{Lµ} - B_{CNµ} + V_{Tµ}(R). \]

We see in (3)-(6) 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, in (1),(3)-(6) 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.) At distance $R_{CN}$, which corresponds to the mass distance between left and right parts of compound nucleus, $\delta N(R_{CN}) = \delta N_p(R_{CN}) = 0$. 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 [11] and papers cited therein. Consequently, the fission or quasi-fission probability of muon-nuclear system get reducing as compared to the pure nuclear system.

In Table 1 we evaluate $\delta N_\mu(R)$ around barrier for several colliding systems, which can be used to the SHE production. The muon binding energies in muonic atoms is obtained by using Pustovalov parametrization [8] with nucleus charge radius $R = 1.2A^{1/3}$ fm, where $A$ is the number of nucleons in the nucleus. The entrance-channel fusion barriers $B_{gs}$ and $B_{gs,\mu}$, depths of entrance-channel capture potential well $D_{pw}$ and $D_{pw,\mu}$ and bottom of capture pocket $B_{cp}$ and $B_{cp,\mu}$ for the pure nuclear $B_{gs}$ and muon-nuclear systems, respectively, are given in Table 1. Quantities $B_{gs}$, $B_{gs,\mu}$, $B_{cp}$ and $B_{cp,\mu}$ are evaluated relatively to the compound-nucleus ground state. The parameters of entrance-channel potential wells for pure nuclear systems $B_{gs}$, $D_{pw}$ and $B_{cp}$, presented in Table 1, are taken from [8].

| Pure nuclear reaction | $B_{gs}$ | $D_{pw}$ | $B_{cp}$ | $\delta N_\mu(R)$ |
|----------------------|----------|----------|----------|------------------|
| $^{70}$Zn$+^{208}$Pb$\rightarrow^{278}$112 | 16.7 | 4.0 | 12.7 | $\approx 0$ |
| $^{70}$Zn$+^{208}$Pb$\rightarrow^{278}$112$_p$ | 20.3 | 5.3 | 15.0 | 13.19 | 218.08 $R$ |
| $^{78}$Ge$+^{208}$Pb$\rightarrow^{286}$114 | 12.8 | 2.9 | 9.9 | $\approx 0$ |
| $^{78}$Ge$+^{208}$Pb$\rightarrow^{286}$114$_p$ | 16.4 | 3.8 | 12.6 | 13.21 | 218.08 $R$ |
| $^{86}$Kr$+^{208}$Pb$\rightarrow^{294}$118 | 5.3 | 1.1 | 4.2 | $\approx 0$ |
| $^{86}$Kr$+^{208}$Pb$\rightarrow^{294}$118$_p$ | 9.1 | 1.9 | 7.2 | 13.28 | 218.08 $R$ |

The muon induce fusion reactions, because as we see in Table 1 $\mu^-$ is a convenient particle for inducing compound-nucleus formation in reactions $L_\mu + T \rightarrow$ SHE + $xn + e^- + \nu_\mu + \nu_\mu$, because its lifetime $(\approx 2.2 \times 10^{-6} s)$ 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 $\mu^-$ dynamic time. Therefore there is high probability of population of $1s$ bound state of $\mu^-$ in SHE during nuclear reaction time. Due to this we can use estimates for $\delta N_\mu$, presented in Table 1. The compound nucleus relatively rarely excited during the decay $\mu^- (\mu^- \rightarrow e^- + \nu_\mu + \nu_\mu)$ [13]. It is possible to make beam of muonic projectile $L_\mu$ by merging beams of strongly ionized projectile nucleus $L$ and of $\mu^-$ at the same velocities before the target. At such conditions nuclei should capture $\mu^-$ with high probability and $\mu^-$ should quickly populates $1s$ state.

III. CONCLUSIONS

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 [8] 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 fission barrier height. The reduction of fusion barrier height, evaluated relatively to the ground state of two colliding nuclei, is also taken place in SHE production reactions with muonic projectiles.

Here we have briefly discuss main features of the muon
catalysis of SHE production. Detail theoretical and experimental studies of the muon catalysis of heavy nucleus formation are needed.

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