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Entrance-channel potentials for hot fusion reactions

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Abstract. The semi-microscopic entrance-channel potentials for the reactions $^{48}\mathrm{Ca} + {}^{247,249}\mathrm{Bk} \to {}^{295,297}117$ and $^{48}\mathrm{Ca} + {}^{254}\mathrm{Es} \to {}^{302}119$ are evaluated in the approach of frozen nucleon densities within the framework of the extended Thomas-Fermi approximation.

PACS. 25.60.Pj Fusion reactions – 25.70.Jj Fusion and fusion-fission reactions

1 Introduction

The hot fusion reactions of superheavy element (SHE) formation are observed in collisions of the spherical projectile ^{48}Ca with deformed transuranic targets [1]. The population of capture states settled at the capture pocket of the entrance-channel potential depends on detailed behavior of the potential as a function of both the distance R between the nuclei and the orientation of a deformed nucleus. Many quasi-bound states are populated during the collision if the relative kinetic energy is slightly higher then the fusion barrier and the capture pocket is deep and wide. Because of their crucial role at the initial stage of the hot fusion process a precise knowledge of the interaction potentials between the colliding nuclei is needed.

In order to determine nucleus-nucleus interaction potentials various methods were suggested in [2,3,4,5,6,7,8]. However, the barriers evaluated within these approaches for the same colliding system leading to SHE differ considerably [6,7]. Uncertainty of the interaction potential near the touching point gives rise to a variety of the proposed nuclear-reaction mechanisms. So, it would be nice to decrease this uncertainty.

Recently, an accurate and reliable semi-microscopic method for evaluation of the nucleus-nucleus potential has been proposed [6,7,8]. Therefore, we evaluate the entrance-channel semi-microscopic potentials for hot fusion reactions leading to SHE with 117 and 119 protons.

2 Semi-microscopic potentials

We evaluate the interaction potential between heavy nuclei within the semi-microscopic frozen-density approximation. The density distribution and the shape of colliding nuclei are perturbed when the nuclear surfaces are close and nucleons possessed by different nuclei interact strongly enough. In the case of hot fusion reactions the time of passing the distances of strong interaction between nuclei can be approximated as $t_\mathrm{s} \approx (2\mu R^2 s/(Z_1 Z_2 e^2))^{1/2} \approx 10^{-22}\,\mathrm{s}$, where Z_1 and Z_2 are the charges of colliding nuclei, respectively, e is the charge of proton, μ is the reduced mass of colliding nuclei, R is the sum of radii of colliding nuclei, $s \approx 3\,\mathrm{fm}$ is the range of strong interaction between nuclear surfaces. The relaxation time of the intrinsic nuclear state arising from nucleon-nucleon interactions, see [9], can be estimated as $t_\mathrm{r} \gtrsim 10^{-20}\,\mathrm{s}$ for the case of hot fusion reactions [6]. Since $t_\mathrm{r} \gg t_\mathrm{s}$ the frozen approximation is good for evaluation of the nucleus-nucleus potential near the touching point at collision energies around the barrier height.

The nucleus-nucleus potential is obtained with the help of the energy density functional. The extended Thomas-Fermi (ETF) approximation with $\hbar^2$ corrections is used for evaluation of its kinetic energy part [10]. The Skyrme and Coulomb energy density functionals are employed for the calculation of the potential energy. These functionals depend on the proton and neutron densities. The latter are obtained in the microscopic Hartree-Fock-BCS approximation with SLy4 parametrization of the Skyrme forces [11]. 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 model with help of the microscopic density distributions are in good agreement with those obtained in the fully microscopic Hartree-Fock-BCS model [6]. Therefore, our semi-microscopic method for evaluation of the interaction potential between various nuclei is quite accurate.

Semi-microscopic potentials (SMP) for the reactions $^{48}\mathrm{Ca} + {}^{247,249}\mathrm{Bk} \to {}^{295,297}117$ and $^{48}\mathrm{Ca} + {}^{254}\mathrm{Es} \to {}^{302}119$ are presented in fig. 1. As seen from fig. 1, the isotopic

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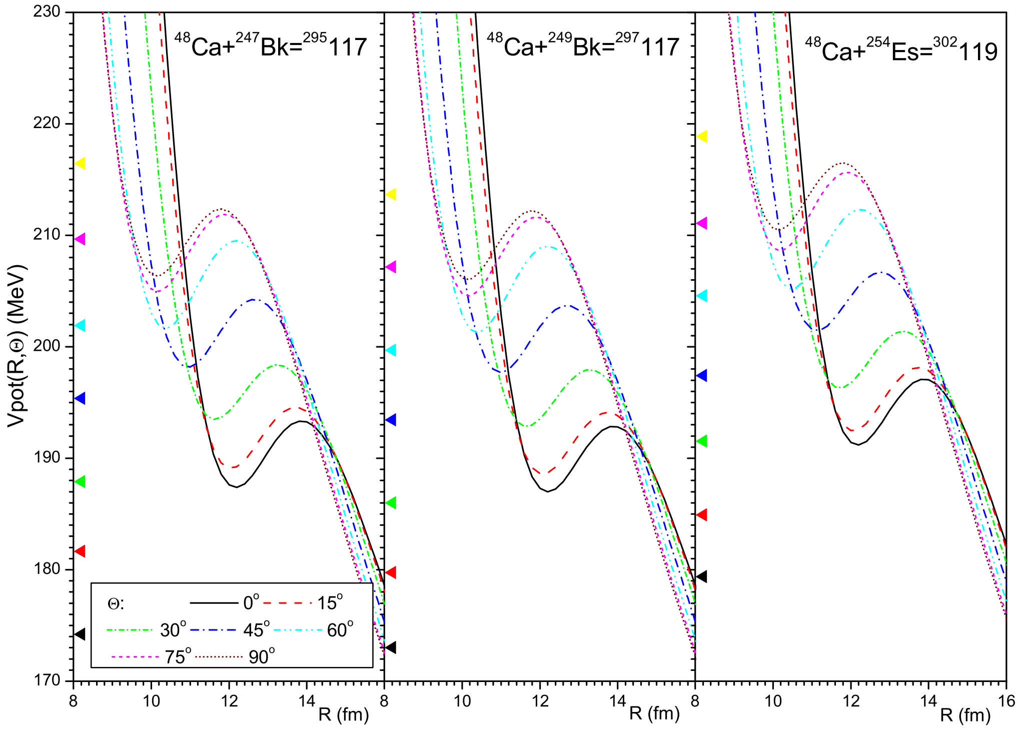

Fig. 1. Entrance-channel SMPs for reactions $^{48}\mathrm{Ca} + {}^{247,249}\mathrm{Bk} \rightarrow {}^{295,297}117$ and $^{48}\mathrm{Ca} + {}^{254}\mathrm{Es} \rightarrow {}^{302}119$. The ground-state Q-values are indicated by the lowest triangle at the left vertical axis. The other 6 triangles mark, respectively, the thresholds for the emission of 1, 2, 3, 4, 5 and 6 neutrons evaluated by using [12].

composition of berkelium has only a minor influence on the shape of SMP. The SMP barrier heights B_{gs} evaluated with respect to the ground-state energy of the compound nucleus, slightly increase with growing number of neutrons in berkelium.

The SMP are shown in fig. 1 for various orientations of the deformed nuclei. For these systems the lowest barriers are obtained for the tip orientation ($\Theta = 0°$). However, the side orientation ($\Theta \approx 90°$) is relevant to the SHE formation [6,7]. This conclusion is supported by the experimental analysis of fusion reactions between lighter nuclei [13]. It is shown there that fusion through the tip orientation is strongly suppressed by quasi-fission.

Shapes of SMP in fig. 1 are very similar to the ones for hot fusion reactions between $^{48}\mathrm{Ca}$ and various isotopes of U, Pu, Am, Cm and Cf, see figures in [6,7] and in the papers cited therein. Moreover, the SMP barrier heights B_{gs} for side orientation, the neutron separation energies [12] and the fission barriers of compound nuclei are also comparable to the ones for other hot fusion reactions [6,7]. Both the capture properties of reactions $^{48}\mathrm{Ca} + {}^{247,249}\mathrm{Bk} \rightarrow {}^{295,297}117$ and $^{48}\mathrm{Ca} + {}^{254}\mathrm{Es} \rightarrow {}^{302}119$ and the decay characteristics of compound nuclei $^{295,297}117$ and $^{302}119$ are similar to the ones for other hot fusion reactions. Therefore it is possible to use these reactions for successful synthesis of elements 117 and 119 at collision energies close to 212 MeV and 216 MeV, respectively.

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