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Production of compound nuclei in heavy-ion collisions and super-heavy nuclei in hot-fusion reactions

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The statistical model for the calculation of the compound nucleus formation cross section and the probability of compound nucleus formation in heavy-ion collisions is discussed in detail [1]. Light, heavy, and superheavy nucleus-nucleus systems are considered in this model within a unified approach. In this model, the compound nucleus is formed in heavy-ion collisions through two consecutive steps.

The first step involves overcoming the capture barrier, formed by the nuclear, Coulomb, and centrifugal interactions of two separated incident nuclei. The capture barrier is associated with colliding nuclei in their ground state or with a shape slightly different from the ground state due to the rapid passage of the capture barrier at high collision energies. After passing the barrier, the incident nuclei enter the capture well. The collision energy is quickly transferred into the intrinsic energy of the stuck-together nuclei due to strong dissipative forces at the overlap of their densities. The relaxation time for the dissipation of radial kinetic energy is short, allowing the kinetic energy to be rapidly transferred to the intrinsic energy of both nuclei. Consequently, the temperatures of the nuclear matter in the contacting nuclei become uniform and equal by the end of the first step. Thus, a system of stuck-together nuclei with zero radial velocity is formed in the capture well. This zero or near-zero radial velocity leads to the dissipation of memory effects on the future dynamics of the system.

The second step involves the evolution of the system of stuck-together nuclei in the capture well. The nuclear matter in the capture well has a uniform temperature and zero velocity. The stuck-together system may be considered a quasistationary state located in the well between barriers of different natures. The further evolution of the system is driven by competition between penetration through these barriers.

The capture well is limited by the compound nucleus formation barrier $B_{\rm cnf}$ at smaller internuclear distances. The barrier $B_{\rm cnf}$ arises during the smooth shape evolution from the stuck-together incident nuclei to a spherical or near-spherical compound nucleus. The compound nucleus is formed once the system passes $B_{\rm cnf}$.

The capture well is confined by other barriers in the case of larger distances between nuclei, i.e., on the way from the stuck-together nuclei to the well-separated deformed nuclei. These barriers are formed by the nuclear, Coulomb, and centrifugal interactions of two separated nuclei as well as the contributions of the surface deformation energies of both nuclei. The quasielastic barrier $B_{\rm qe}$ is associated with the evolution of the stuck-together nuclei into deformed versions of the incident nuclei after separation.

The penetration through the different barriers can be considered statistically using the Bohr-Wheeler transition state approximation, which was proposed for the calculation of the width of passing through the fission barrier. As a result, the evolution of the system in the model is linked to the ratio of the widths related to the penetration of the corresponding barriers.

It is shown that the compound nucleus is formed in competition between passing through the compound-nucleus formation barrier and the quasielastic barrier. It is shown that the compound nucleus formation cross section is suppressed when the quasielastic barrier is lower than the compound nucleus formation barrier. The critical value of angular momentum, which limits the compound nucleus formation cross-section values for light and medium-mass ion-ion systems at above-barrier collision energies, is discussed in the model. The suppression of the compound nucleus formation cross section, even at small partial waves for very heavy ion-ion systems, is obtained in the model.

The values of the capture and compound nucleus formation cross sections calculated for various light, heavy, and superheavy nucleus-nucleus systems as well as the probability of the compound nucleus formation for superheavy nuclei agree well with the available experimental data.

A model for hot-fusion reactions leading to the synthesis of superheavy nuclei is discussed [2]. The values of the hot-fusion cross sections obtained in the model agree with the available experimental data. The hot-fusion cross sections are found for two different models of the fission barrier heights of superheavy nuclei.

The superheavy production cross sections consist of three steps. The first and second steps, as described above, lead to compound-nucleus formation. The third step involves the survival probability of the compound nucleus, associated with the evaporation of x neutrons in competition with fission.

The available experimental data for the superheavy nuclei production cross section are well described in the model. The calculations of the cross sections for the various hot-fusion reactions leading to the 119 and 120 elements are presented.

Simple expressions useful for qualitative analysis of the cross-section for forming superheavy nuclei are obtained. It is shown that the superheavy nuclei production cross section is proportional to the transmission coefficient of the capture barrier, realization probability of the xn-evaporation channel, and exponentially depends on the quasielastic barrier, fusion reaction Q value, compound nucleus formation barrier, neutron separation energies, and fission barrier heights.

1. V. Yu. Denisov. Phys. Rev. C 109 (2024) 014607
2. V. Yu. Denisov. Phys. Rev. C 109 (2024) 044618

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