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ScienceDirect
Nuclear Physics A 834 (2010) 212c–216c
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

# Extraction of probability of compound-nucleus formation

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We propose an empirical barrier distribution for a unified description of heavy-ion fusion and quasi-elastic scattering based on the Skyrme energy-density functional approach. The capture (fusion) cross sections and the quasi-elastic scattering cross sections of a large number of reactions can be well reproduced. Based on these systematic studies and the HIVAP calculations for the survival probability, the probability $P_{\rm CN}$ of the compound-nucleus formation is extracted from the measured evaporation residue cross sections for "cold" and "hot" fusion reactions.

## 1. INTRODUCTION

Heavy-ion fusion reactions have received great attention in recent years. It is because that to investigate the mechanism of heavy-ion fusion reaction is crucial for synthesis of super-heavy nuclei, and heavy-ion fusion reaction provides an opportunity to explore the nucleus-nucleus potential and the barrier distribution. It is known that the simplified version of the evaporation residue cross section of reaction leading to super-heavy nuclei is given by

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

Here, $\sigma_{\rm cap}$, $P_{\rm CN}$ and $W_{\rm sur}$ are the capture cross section, the formation probability and the survival probability of the compound nucleus, respectively. There could be several parameters in the practical models for description of each component of the right side of Eq.(1) which are hardly unambiguously determined by a very limited number of measured evaporation residue cross sections of super-heavy nuclei. Therefore, it is very necessary to test and determine the interaction and parameters adopted in each component of Eq.(1) individually to reduce the uncertainty in the estimates of the evaporation residue cross section.

In our recent work [1–3], we proposed an approach for a unified description of the heavy-ion fusion, quasi-elastic scattering and fusion-fission reactions based on the Skyrme energy-density functional approach. In this talk, we first give a brief review of this approach.

*We thank Prof. Shan-Gui Zhou for valuable suggestions. This work is supported by National Natural Science Foundation of China, No. 10875031, 10847004.


doi:10.1016/j.nuclphysa.2009.12.043

Then, the model will be checked from different reactions: heavy-ion fusion, quasi-elastic scattering and fusion-fission reactions, and some results will be discussed. Finally, we attempt to extract the formation probability $P_{\rm CN}$ of the compound nucleus from the measured evaporation residue cross sections of super-heavy nuclei combining the proposed approach.

## 2. THE MODEL FOR A UNIFIED DESCRIPTION OF HEAVY-ION FUSION, QUASI-ELASTIC SCATTERING AND FUSION-FISSION REACTIONS

Based on the Skyrme energy density functional together with the extended Thomas-Fermi (ETF) approximation, the total energy of a nuclear system can be expressed as a functional of proton and neutron densities. By minimizing the total energy of a nucleus, the proton and neutron densities can be obtained. Based on the obtained density distributions of the reaction partners and density sudden approximation, the entrance channel potential $V(R)$ between the reaction partners and the fusion barrier $B_0$ can be further obtained without any adjustable parameters [1].

For heavy-ion fusion reactions, we assume that the one-dimensional fusion barrier is replaced by a barrier distribution $D(B)$ which empirically takes into account the coupling to internal degrees of freedom of the binary system. Motivated by the shape of the barrier distribution extracted from experiments, we consider the weight function to be a superposition of two Gaussian functions $D_1(B)$ and $D_2(B)$. The peaks and the widths of $D_1(B)$ and $D_2(B)$ only depend on the barrier height $B_0$ of the entrance channel potential except a factor $g$ in $D_1(B)$. The quantity $g$ empirically takes into account the structure effects and is determined by an empirical formula in which the Q-value and neutron shell closure are involved. With the empirical barrier distribution the capture (fusion) cross sections [1] and the large-angle quasi-elastic scattering cross sections [3] can be calculated,

$$\sigma_{\rm cap}(E_{\rm c.m.}) = \frac{1}{F_0}\int_0^\infty D(B)\; \sigma_{\rm fus}^{\rm Wong}(E_{\rm c.m.},B)dB, \tag{2}$$

and

$$\frac{d\sigma_{\rm qel}}{d\sigma_R}(E_{\rm c.m.}) = \frac{1}{F_0}\int_0^\infty D(B)\frac{d\sigma_{\rm el}}{d\sigma_R}(E_{\rm c.m.},B)dB + P_{\rm corr}, \tag{3}$$

with the normalization constant $F_0 = \int D(B)dB$. Where, $\sigma_{\rm fus}^{\rm Wong}$ denotes Wong's formula [5] for penetrating an one-dimensional parabolic barrier. $\frac{d\sigma_{\rm el}}{d\sigma_R}$ is the ratio of the elastic cross section $\sigma_{\rm el}$ to the Rutherford cross section $\sigma_R$ which can be obtained by the semi-classical perturbation theory [6]. $P_{\rm corr}$ is a small correction term to empirically take into account the additional contribution of nucleon transfer [3].

Through a systematic study of heavy-ion fusion reactions, quasi-elastic scatting reactions and fusion-fission reactions [1–3,7], we find: 1) A large number of measured fusion excitation functions for light and medium-heavy fusion systems at energies around the Coulomb barriers can be reproduced well. In the calculated fusion (capture) excitation functions of 120 fusion reactions at energies near and above the barrier, about 70% systems have very small deviations from the experimental data. 2) All of calculations adopt the same parameters (with the Skyrme force SkM* and several parameters in the empirical barrier distribution and without any adjustable parameters). 3) The shell effects and neutron-rich effects which influence the fusion cross sections at sub-barrier energies have been taken into account by the structure effect factor $g$ empirically. 4) The elastic scattering angle distributions of a series of reactions at energies much higher than the Coulomb barrier can be reasonably well reproduced by the entrance channel potential which is based on the frozen density approximation systematically. 5) With the same empirical barrier distribution and taking into account the correction term that mainly comes from the nucleons transfer, the calculated large-angle quasi-elastic scattering cross sections of these reactions are in good agreement with the experimental data. 6) The shapes of the fusion barrier distributions extracted from experimental data are reasonably well reproduced by the empirical barrier distribution. 7) The fusion cross sections depend more strongly on the shape of the left side of the barrier distribution while the quasi-elastic scattering cross sections depend more strongly on the right side [7]. 8) Incorporating a statistical model HIVAP for describing the decay of the compound nuclei, the evaporation residue (and fission) cross sections of 51 fusion-fission reactions have been systematically studied simultaneously to investigate and refine some key parameters of the HIVAP code. The experimental data can be systematically reproduced reasonably well. Based on these studies, the formation probabilities $P_{\rm CN}$ of the compound nuclei in reactions leading to superheavy nuclei are further studied.

## 3. EXTRACTION OF FORMATION PROBABILITY OF COMPOUND NUCLEUS AND DISCUSSIONS

With the above formula for the capture cross sections $\sigma_{\rm cap}$ and the HIVAP code for the survival probabilities $W_{\rm sur}$ of the compound nuclei, the formation probabilities $P_{\rm CN}$ of the compound nuclei could be extracted from the measured evaporation residue cross sections $\sigma_{\rm ER}$ of superheavy nuclei produced in "cold" fusion or "hot" fusion according to Eq.(1). Because the dependence of $P_{\rm CN}$ on the incident energy of the reaction system is not so clear and the available experimental data are very limited in present, it is difficult (even impossible) to obtain the exact values of $P_{\rm CN}$ presently. Here, we just give some rough estimation of the mean values of $P_{\rm CN}$ in the region $B_{\rm m.p.} \leq E_{\rm c.m.} \leq B_0$ [8]. Here, $B_{\rm m.p.}$ denotes the most probable barrier height based on the effective barrier distribution $D_{\rm eff}(B)$ [1]. $B_0$ is the barrier height of the entrance channel potential. Fig.1 shows the deduced mean values of logarithm of $P_{\rm CN}$ (which gives the order of magnitude of $P_{\rm CN}$) as a function the charge number of the compound nucleus. The squares denote the results with the "cold" fusion, i.e., the reactions with Pb and Bi targets [11,12,15]. The open circles denote the results with the "hot" fusion, i.e., the reactions with $^{48}$Ca bombarding on actinite targets [13,14]. The error bars are roughly estimated by the systematic errors in calculating the $\sigma_{\rm cap}$ and $W_{\rm sur}$, and the error bars of the measured $\sigma_{\rm ER}$. One can see that the $P_{\rm CN}$ exponentially decreases with the charge number generally in the "cold" fusion reactions. However, the decrease of the $P_{\rm CN}$ with $Z$ is not very obvious in the region $Z \geq 114$ in the "hot" fusion reactions. The star denotes the result of the deduced mean value of logarithm of $P_{\rm CN}$ around the Coulomb barrier for $^{50}$Ti+$^{208}$Pb in [9]. The open triangles denote the results of Oganessian [10]. It is encouraging to note that the different

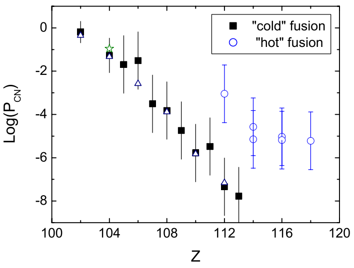


Figure 1. (Color online) The extracted mean value of logarithm of $P_{\rm CN}$ as a function of compound-nuclear charge number. The star and open triangles denote the extracted $P_{\rm CN}$ in [9] and [10], respectively. The experimental data of evaporation cross sections are taken from refs. [11–15]

methods of deducing $P_{\rm CN}$ give similar results for "cold" fusion reactions.

In summary, we proposed an empirical barrier distribution for a unified description of heavy-ion fusion and quasi-elastic scattering reactions based on the Skyrme energy-density functional approach. The model has been checked carefully and extensively from different reactions: heavy-ion fusion, quasi-elastic scattering and fusion-fission reactions, and a large number of experimental data can be reproduced reasonably well. Based on these studies, the mean values of the formation probabilities $P_{\rm CN}$ of compound nuclei in "cold" and "hot" fusion reactions have been roughly extracted from the measured evaporation residue cross sections.

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