Threshold energy for sub-barrier fusion hindrance phenomenon

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The relationship between the threshold energy for a deep sub-barrier fusion hindrance phenomenon and the energy at which the regime of interaction changes (the turning-off of the nuclear forces and friction) in the sub-barrier capture process, is studied within the quantum diffusion approach. The quasialastic barrier distribution is shown to be a useful tool to clarify whether the slope of capture cross section changes at sub-barrier energies.

The experiments with various medium-light and heavy nuclei have shown that the experimental slopes of the complete fusion excitation function keep increasing at low sub-barrier energies and may become much larger than the predictions of standard coupled-channel calculations. This was identified as the fusion hindrance with the threshold energy $E_s$.\textsuperscript{4} More experimental and theoretical studies of sub-barrier fusion hindrance are required to improve our understanding of its physical reason, which may be especially important in astrophysical fusion reactions.\textsuperscript{4}

As shown within the quantum diffusion approach\textsuperscript{3,8}, due to a change of the regime of interaction (the turning-off of the nuclear forces and friction) at deep sub-barrier energies, the curve related to the capture cross section as a function of bombarding energy has smaller slope. In the present paper we try to demonstrate the relationship between the threshold energy $E_s$ for a deep sub-barrier fusion hindrance phenomenon and the energy $E_{ch}$ at which the regime of interaction changes in the sub-barrier capture process.

In the quantum diffusion approach the capture of nuclei is treated in terms of a single collective variable: the relative distance between the colliding nuclei. The neutron transfer and nuclear deformation effects are taken into consideration through the dependence of the nucleus-nucleus potential on the isotopic compositions, deformations and orientations of interacting nuclei. Our approach takes into consideration the fluctuation and dissipation effects in collisions of heavy ions which model the coupling with various channels (for example, coupling of the relative motion with low-lying collective modes such as dynamical quadrupole and octupole modes of target and projectile\textsuperscript{10}). We have to mention that many quantum-mechanical and non-Markovian effects\textsuperscript{11–13} accompanying the passage through the potential barrier are taken into consideration in our formalism\textsuperscript{3,8}. The details of used formalism are presented in our previous articles\textsuperscript{3,8}. With this approach many heavy-ion capture reactions at energies above and well below the Coulomb barrier have been successfully described.

Within the quantum diffusion model\textsuperscript{3,8} the nuclear forces start to play a role at relative distance $R_{int} = R_b + 1.1$ fm ($R_b$ is the position of the Coulomb barrier at given angular momentum and orientations of the interacting nuclei) where the nucleon density of colliding nuclei approximately reaches 10% of saturation density. If the colliding nuclei approach the distance $R_{int}$ between their centers, the nuclear forces start to act in addition to the Coulomb interaction. Thus, at $R < R_{int}$ the relative motion may be more coupled with other degrees of freedom. At $R > R_{int}$ the relative motion is almost independent of the internal degrees of freedom. Depending on whether the value of external turning point $R_{ex}$ is larger or smaller than interaction radius $R_{int}$, the impact of coupling with other degrees of freedom upon the barrier passage seems to be different. So, two regimes of interaction at sub-barrier energies differ by the action of nuclear forces and, respectively, of nuclear friction. Due to the switching-off the nuclear interaction at external turning point $R_{ex}$, the cross sections falls with the smaller rate at a deep sub-barrier energies.

FIG. 1: The experimental threshold energy $E_s$ for a deep sub-barrier fusion hindrance phenomenon\textsuperscript{1} and the calculated energy $E_{ch}$ at which the regime of interaction changes in the indicated sub-barrier capture reactions as a function of $Z_1Z_2[A_1A_2/(A_1 + A_2)^{1/2}]$.

As seen in Fig. 1, for the reactions $^4$He + $^{208}$Pb, $^{58}$Ni + $^{54}$Fe, $^{48}$Ca + $^{48}$Ca, $^{90,96}$Zr, $^{40}$Ca + $^{90,96}$Zr, $^{58}$Ni + $^{58,60,64}$Ni, $^{60}$Ni + $^{89}$Y, $^{64}$Ni + $^{64}$Ni, $^{106}$Mo, $^{90}$Zr + $^{90}$Zr, and $^{16}$O + $^{208}$Pb, $^{238}$U, there is a good agreement be-
tween the threshold energy $E_s$ for a deep sub-barrier fusion hindrance phenomenon and the energy $E_{ch}$ at which the regime of interaction changes in the sub-barrier capture process. The values $E_s$ and $E_{ch}$ almost coincide and linearly increase with $Z_1Z_2[A_1A_2/(A_1 + A_2)]^{1/2}$.

and the capture cross section is the sum of the fusion and quasifission cross sections, from the comparison of calculated capture cross sections and measured fusion cross sections one can extract the hindrance factor and the threshold incident energy for a deep sub-barrier fusion hindrance phenomenon. The small fusion cross section at energies well below the Coulomb barrier may indicate that the quasifission channel is preferable and the system goes to this channel after the capture [3, 4]. So, the observed hindrance factor may be understood in term of quasifission. At deep sub-barrier energies, the quasifission event corresponds to the formation of a nuclear-molecular state or dinuclear system with small excitation energy that separates (in the competition with the compound nucleus formation process) by the quantum tunneling through the Coulomb barrier in a binary event with mass and charge close to the colliding nuclei. In this sense the quasifission is the general phenomenon which takes place in the reactions with the massive [14–17], and medium-mass nuclei [6].

Since the quasielastic measurements are usually not as complex as the capture (fusion) measurements, and they are well suited to survey the decreasing rate of fall of the sub-barrier capture cross section. There is a direct relationship between the capture and the quasielastic scattering processes, because any loss from the quasielastic channel contributes directly to the capture (the conservation of the reaction flux):

$$P_{qe}(E_{c.m.}, J) + P_{cap}(E_{c.m.}, J) = 1$$

and

$$dP_{cap}/dE_{c.m.} = -dP_{qe}/dE_{c.m.},$$

where $P_{qe}$ is the reflection probability and $P_{cap}$ is the capture (transmission) probability. The quasielastic scattering is the sum of elastic, inelastic, and transfer processes. The reflection probability

$$P_{qe}(E_{c.m.}, J = 0) = \frac{d\sigma_{qe}}{d\sigma_{Ru}}$$

for angular momentum $J = 0$ is given by the ratio of the quasielastic differential cross section and Rutherford differential cross section at 180 degrees [18–23]. The barrier distribution is extracted by taking the first derivative
of the $P_{qe}$ with respect to $E_{c.m.}$, that is,
\[ D_{qe}(E_{c.m.}) = -dP_{qe}(E_{c.m.}, J = 0)/dE_{c.m.} = \]
\[ = dP_{cap}(E_{c.m.}, J = 0)/dE_{c.m.}. \]

Thus, one can observe the change of the fall rate of $P_{cap}(E_{c.m.}, J = 0)$ at sub-barrier energies by measuring the barrier distribution $D_{qe}$. By employing the quantum diffusion approach and calculating $dP_{cap}(E_{c.m.}, J = 0)/dE_{c.m.}$, one can obtain $D_{qe}(E_{c.m.})$. In addition to the mean peak position of the $D_{qe}$ around the barrier height, we predict the sharp change of the slope of $D_{qe}$ below the threshold energy because of a change of the regime of interaction in the sub-barrier capture process (Figs. 2–4). The effect seems to be more pronounced in the collisions of spherical nuclei (Figs. 3 and 4). The collisions of deformed nuclei occurs at various mutual orientations on which the value of $R_{int}$ depends. Thus, the deformation and neutron transfer effects can smear out this effect. The reactions $^4$He+$^{16}$O, $^4$He+$^{144}$Sm, $^{208}$Pb and $^{48,40}$Ca+$^{36}$S+$^{90}$Zr with the spherical nuclei are preferable for the experimental study of $D_{qe}(E_{c.m.})$.

In conclusions, employing the quantum diffusion approach, we demonstrated the relationship between the threshold energy for a deep sub-barrier fusion hindrance phenomenon and the energy at which the regime of interaction changes in the sub-barrier capture process. We predicted the sharp change of the slope of the quasielastic barrier distribution below the threshold energy. This is expected to be the experimental indication of a change of the regime of interaction in the sub-barrier capture. One concludes that the quasielastic technique could be an important tool in capture (fusion) research.

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