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Effects of Nuclear Intrinsic Degrees of Freedom on Heavy-Ion Fusion Reactions

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Abstract

It has been well recognized that heavy-ion fusion reactions at energies near and below the Coulomb barrier are strongly influenced by the coupling of the relative motion between the colliding nuclei to their intrinsic degrees of freedom, such as low lying collective excitations and deformations of various multipolarity. Recently developed high precision experimental data are thus opening a new door to probe nuclear intrinsic degrees of freedom.

I discuss the role of β_6 deformation and low-lying vibrational excitations of a deformed target nucleus in its fusion with a structureless projectile. To this end, I analyzed the high precision data of the ^{16}O+^{154}Sm, ^{16}O+^{186}W and ^{16}O+^{238}U fusion reactions by a coupled-channels framework. It is shown that the inclusion of β_6 deformation in the coupled-channels calculations leads to a considerable improvement of the fit of the theoretical results to the experimental data concerning the fusion excitation function and the so called fusion barrier distribution for all of these reactions. I compare the optimum values of the deformation parameters obtained by the χ^2 fitting of the fusion data with those obtained from inelastic $\alpha-$, p and n scatterings and the ground state mass calculations. A problem is that the sign of β_6 obtained from the analysis of the fusion data is opposite to that obtained by the other analyses except for ^{186}W. It is then shown that the octupole vibration of the target nucleus significantly affects the fusion barrier distribution and the optimum values of the deformation parameters for the ^{16}O+^{154}Sm and ^{16}O+^{238}U reactions. Especially, the sign problem of β_6 mentioned above is resolved by including the octupole vibration in the coupled-channels analysis. The coupled-channels analyses are then further extended to include the β and γ bands of the target nucleus as well. It is shown that the effect of β band is negligible in all the three reactions, while the γ band causes a non-negligible effect on the barrier distribution at energies above the main fusion barrier. Another important ingredient of nuclear intrinsic degrees of freedom is the exchange of nucleons between the colliding nuclei. In this respect, I discuss the effect of two neutron transfer reactions on the ^{16}O+^{238}U fusion reactions, and show that the two neutron transfer reaction ^{238}U(^{16}O,^{18}O)^{236}U, which has a positive Q-value, influences the fusion cross section at sub-barrier energies.

In these studies, I use the conventional Coulomb interaction potential which is valid only outside the Coulomb radius. In my thesis, I present analytic expressions of the Coulomb interaction between a spherical and a deformed nuclei which are valid for all separation distance. I demonstrate their significant deviations from commonly used formulae in the region inside the Coulomb radius, and show that they remove various shortcomings of the conventional formulae.

As often done, I use the so called orientation average formulation in studying the role of β_6 deformation. I examine the validity of this approximate treatment by analyzing the excitation function of the fusion cross section as well as the fusion barrier distribution for the reactions of the ^{154}Sm target with various projectiles ranging from ^{12}C to ^{40}Ar. I show that the orientation average procedure gradually looses its accuracy with increasing charge product of the projectile and target nuclei because of the effects of finite excitation energy of the target nucleus. The relevance of such inaccuracy in analyzing the experimental data is also discussed.

Finally, I apply the coupled-channels formalism to discussing characteristics of the fusion reactions induced by unstable nuclei. As concrete examples I study the ^{9,11}Be $+^{209}$Bi and ^{19,25,37}Na$+^{208}$Pb fusion reactions. The cross sections of the first example have been recently measured experimentally. I show that the deformation and the associated rotational excitation of ^{9}Be significantly enhances the fusion cross section at sub-barrier energies, while those of ^{11}Be play only a small role, though one needs more detailed studies for the case of ^{11}Be. These effects have been overlooked in previous studies, but are important to properly identify the characteristic effects of the loosely bound nature of ^{11}Be. The study of Na induced fusion reactions has been partly motivated by the relativistic mean field calculations, which indicate a large difference between the charge and the matter deformations in Na isotopes far from the β stability line. I show that the large difference between the charge and the matter deformations noticeably affects the fusion barrier distribution for the ^{19}Na and ^{37}Na induced reactions, while its effect is compensated by the large and opposite difference of the charge and matter radii for ^{25}Na induced reactions.