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Understanding the barrier distribution function derived from backward-angle quasi-elastic scattering

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It is shown that the "barrier distribution" derived from quasi-elastic backscattering of heavy ions gives us, in fact, information about the "total reaction threshold distribution" and not about the "fusion barrier."

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Heavy ion collisions at near-barrier energies and, in particular, fusion reactions have been of increased interest from experimental and theoretical points of view during the last several years. Among other things, these reactions are used for synthesis and study of new superheavy elements. The mechanism of nucleus-nucleus interaction at low energies is rather complicated due to coupling of many degrees of freedom and has not been understood quite clearly up to now. The interaction potential of two heavy ions is a fundamental characteristic of low-energy nuclear dynamics. The coupling of the relative motion to other nuclear degrees of freedom leads to an effective multidimensional nucleus-nucleus potential energy surface instead of a one-dimensional two-body potential with quite definite height and position of the Coulomb barrier.

To get experimental information about the coupling with different internal degrees of freedom and, thus, about the multidimensional Coulomb barrier, a method was proposed [1] for extracting the "barrier distribution" from an accurate measurement of the fusion excitation function by taking the second derivative with respect to the center-of-mass energy of the quantity $E\sigma_{\rm fus}(E)$. This method turns out to be quite effective to derive the height of the fusion barrier and a role of the surface deformations and rotation of nuclei in the sub-barrier fusion reactions (see, for example, articles in Ref. [2] and numerous references therein).

However, experimental measurement of the fusion excitation function is rather difficult, especially for the heavy nuclear combinations used for synthesis of superheavy elements. In this connection, the idea to derive the barrier distribution function from the quasi-elastic scattering cross section at backward angles [3] (which can be measured much more easily) seems very attractive. In a simple one-dimensional model the idea looks very clear. A part of the incoming flux penetrates the barrier (fusion) with the transmission probability $T_0(E)$, whereas the remaining part reflects from the barrier (elastic scattering). The height of the barrier, B, can be obtained both from the transmission coefficient (the derivative dT_0/dE is maximal at $E \approx B$) and from the reflection coefficient $R_0(E) = 1 - T_0(E)$, $dR_0/dE = -dT_0/dE$. Nothing changes if we include in this simple model several quasi-elastic channels and assume, as before, that fusion is proportional to the total penetration probability $T^{\rm fus}(E) = \sum_\nu T_\nu^{\rm fus}(E)$ and quasi-elastic scattering is proportional to the total reflection coefficient $R^{\rm QE}(E) = \sum_\nu R_\nu^{\rm QE}(E)$. Due to unitarity,

$$R^{\rm QE}(E) = 1 - T^{\rm fus}(E) \quad (1)$$

and $dR^{\rm QE}/dE = -dT^{\rm fus}/dE$. This method found its experimental confirmation for near-barrier collisions of medium nuclei, such as ^{16}O + ^{154}Sm [3].

Recently the "barrier distribution functions" have been obtained from the experimentally measured quasi-elastic scattering of heavy projectiles (^{48}Ti, ^{54}Cr, ^{56}Fe, and ^{64}Ni) on a ^{208}Pb target at backward angles [4]. The authors found that the centroids of the derived distribution functions are significantly deviated from the predicted fusion barrier heights (by $3 \div 10$ MeV) toward the low-energy side. The same conclusion was also reached in Ref. [5] where the backward-angle quasi-elastic scattering was used to obtain the barrier distribution for the reaction ^{86}Kr + ^{208}Pb leading to element 118. There are no doubts that the measurements are correct. The question arises what does this low-energy shift mean?

It is well known that for heavier combinations, besides quasi-elastic scattering and fusion, more and more reaction channels appear, mainly deep inelastic scattering, and instead of Eq. (1) we have

$$R^{\rm QE}(E) = 1 - P^R(E), \quad (2)$$

where $P^{\rm R}(E)$ denotes the probability for *all* the reaction channels except the quasi-elastic scattering. Fusion is the largest part of $P^R(E)$ for light projectiles and it is a smaller one for heavy projectiles. Moreover, in collisions of very heavy nuclei (for example, Xe + Pb) an interaction potential is repulsive everywhere; there is no potential pocket and no barrier at all in the strict sense. Nevertheless, in such collisions the quasi-elastic scattering can also be measured and relation (2) is definitely fulfilled.

This means that the derivative $dR^{\rm QE}/dE = -dP^R/dE$ gives us information not about the barrier distribution but about the reaction threshold distribution. For light nuclear systems these distributions are quite close, but for heavy ones (when interaction of nuclei becomes more and more complicated and the potential barrier can disappear completely) they may significantly differ. The same should hold also for weakly bound neutron-rich projectiles, for which the neutron transfer and breakup reaction channels play a most important role at near-barrier energies.

Obviously, the reaction threshold distribution should be shifted to the low-energy side relative to the barrier distribution just because at all incident energies the total reaction cross section is larger (by definition) than the cross section of any specific channel (like fusion or capture). For very heavy nuclear combinations the barrier distribution loses its meaning altogether whereas the reaction threshold distribution maintains its correct physical meaning in accordance with its definition given by Eq. (2). However, we cannot use different names for the same quantity, $dR^{\mathrm{QE}}/dE = -dP^{\mathrm{R}}/dE$, depending on combinations of colliding nuclei.

Note in conclusion that this is not a terminology problem but an important finding, because experiments on the measurement of backward-angle quasi-elastic scattering for deriving the barrier distributions for heavy nuclear systems (which may be used for the production of superheavy elements) are planned to be performed in several laboratories. In this connection we should realize quite clearly what the quantity dR^{QE}/dE really means.

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