Existence of a one-body barrier revealed in deep subbarrier fusion

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Abstract. We propose a two-step model for heavy-ion fusion reactions based on the adiabatic approach in order to account for steep fall-off of fusion cross sections at deep subbarrier energies. The two-step model consists of the capture process in the two-body potential pocket, which is followed by the penetration of the adiabatic one-body potential to reach a compound state after the touching configuration. We argue that although the sudden and adiabatic approaches provide a similar result to each other for the fusion cross section, the two approaches can be discriminated by detecting average angular momenta of a compound nuclei.

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INTRODUCTION

For medium-heavy mass systems, fusion cross sections at deep-subbarrier energies decrease much faster than the results of standard coupled-channel (CC) calculations, as the incident energy decreases [1, 2, 3, 4, 5]. Those unexpected deviations, often referred to as the fusion hindrance, take place at incident energies below a certain threshold. The threshold incident energies have been extensively investigated by the energy E_s at which the experimental astrophysical S-factor takes a maximum. Although the systematics of E_s may have been experimentally established, the physical origin of the fusion hindrance has not been clarified.

One important aspect of the deep subbarrier fusion is that the inner turning point of the Coulomb barrier becomes inside of the touching point for projectile and target [6, 7]. That is, the projectile and target overlap with each other during tunneling process [see the arrow in Fig. 2]. In this point of view, the threshold incident energies should be correlated with the potential energy at the touching point, $V_{\rm Touch}$, because the density overlap during tunneling process takes place at incident energies below $V_{\rm Touch}$. We will show below that this situation actually takes place, indicating that the steep falloff is a result of the overlap process after colliding nuclei touch with each other.

In order to describe such overlap process, either of the sudden or adiabatic approaches have been employed. The former is justified if fusion reactions take place rapidly, and the frozen density approximation becomes valid. Based on this approach, Mişicu and Esbensen proposed the potential energy with a shallow pocket due to the short range repulsive force in the overlap region [8]. The adiabatic approach, which is the opposite limit to the sudden approach, assumes dynamical changes of matter densities during the

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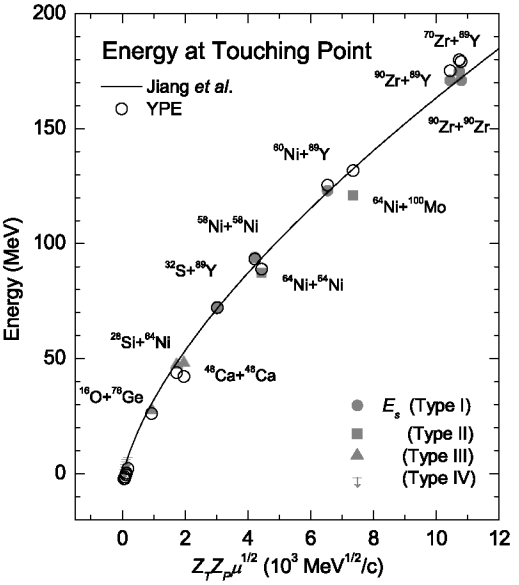

FIGURE 1. Potential energy at the touching point calculated using the Yukawa-plus-exponential model. The open circle is the result of the YPE model. The filled circle, squares, triangles, and the horizontal line show the experimental threshold energy taken from Ref. [5]. the solid curve denotes the systematics of threshold energy by Jiang *et al.* [5].

reaction process. Umar and Oberacker calculated the adiabatic potential energy for the ^{64}Ni+^{64}Ni reaction using the density-constrained time-dependent Hartree-Fock method, and showed that the colliding nuclei evolve with neck formations at near the touching point [9]. In order to determine which approach is more reasonable, it is important to investigate both of them. In this talk, we investigate the adiabatic approach in explaining the steep falloff phenomenon and discuss the difference between the two approaches.

CORRELATION BETWEEN E_S AND ENERGIES AT THE TOUCHING POINT

We systematically evaluated the potential energies at the touching point using a phenomenological potential model, in order to clarify a correlation between those and the threshold incident energies [7]. Figure 1 shows the energies at the touching point calculated with the Yukawa-plus-exponential (YPE) model [10], denoted by the open circle. The experimental threshold energy, E_s, is denoted by the filled circles, the filled squares, the filled triangles and the horizontal lines, depending on the types of the system as defined in Ref. [5]. Notice that energy E_s for the type III was estimated by extrapolation, and that for the type IV is only an upper limit. The systematics for the energy E_s proposed by Jiang *et al.* [5] is also shown by the solid line.

In the figure, it is remarkable that the result of the YPE model follows closely to

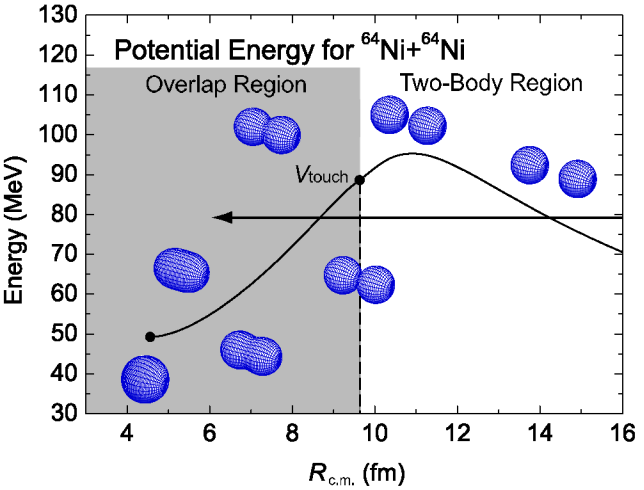

FIGURE 2. One- and two-body potential energy for ^{64}Ni+^{64}Ni calculated using the Yukawa-plus-exponential model. $V_{\rm Touch}$ is the energy at the touching point for target and projectile. We assume that the shape configuration in the one-body system is described by the lemniscatoid parametrization.

the systematic curve, and is consistent with E_s, except for the asymmetric reaction of ^{64}Ni+^{100}Mo. In order to check the correlation in other asymmetric reactions, we also examine the energy at the touching point for ^{16}O+^{208}Pb. For this system, the result of the YPE model is consistent with E_s [3, 7]. Therefore, it is unlikely that the large difference between $V_{\rm Touch}$ and E_s for the ^{64}Ni+^{100}Mo can be attributed to the model assumption of the YPE potential. For this system, there may exist some peculiar nuclear structure effect because the coupled-channels calculation reported in Ref. [11] does not seem to account well for the experimental fusion cross sections even above the threshold energy E_s. A further investigation is necessary for this system concerning the threshold energy. We conclude that the energy at the touching point strongly correlates with the threshold incident energy E_s. Notice that our analysis is fairly independent of the modelings, since both our adiabatic approach and the sudden one of Ref. [8] provide a similar potential energy to each other at the touching point.

TWO-STEP MODEL

We now show our two-step model based on the adiabatic approach. Figure 2 shows how our adiabatic approach works. The solid line is the potential energy for the ^{64}Ni+^{64}Ni reaction calculated using the YPE model [10]. Assuming neck formation after the colliding nuclei touch with each other, we smoothly joint the energy at the touching point to that of the compound state. The dynamical neck formations are described by the lemniscatoid parametrization [12], as shown in the inset in Fig. 2. Notice that this adiabatic potential already includes a large part of the channel coupling (CC) effects. Although the standard CC formalism has been well established in describing subbarrier

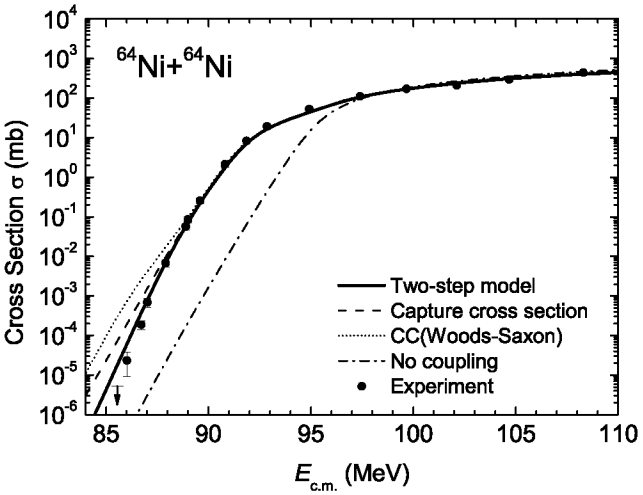

FIGURE 3. Fusion cross sections for the ^{64}Ni+^{64}Ni calculated by the two-step model. The solid line is the result of the two-step model. the filled circle is the experimental data. the dashed line is the corresponding capture cross section. The dotted line is obtained with the Woods-Saxon potential, while the dash-dotted line is the result in the absence of the channel coupling effect.

fusion reactions, its direct application to the deep subbarrier region would therefore result in the double counting of the CC effect.

In order to avoid this difficulty, we propose a simple phenomenological model, in which the two- and one-body processes are defined independently and time-sequentially. Details of this model are discussed in Ref. [13]. The fusion cross section in this two-step model then takes the form

$$\sigma(E) = \frac{\pi\hbar^2}{2\mu E}\sum_{\ell}(2\ell+1)T_{\ell}(E)P_{\rm lbd}(E,\ell), \tag{1}$$

where μ and E denote the reduced mass and the incident energy in the center-of-mass system, respectively. T_ℓ is the capture probability in the two-body system from a large distance to the touching point, estimated using the standard CC formalism. For the calculation of T_ℓ, we modify the computer code `CCFULL` [14] in order to apply the YPE potential. $P_{\rm lbd}$ is the penetrability for the adiabatic one-body potential from the touching point to the inner turning point, estimated using the WKB approximation. An important point in this model is that the one-body penetration works only at incident energies below $V_{\rm Touch}$. We applied the two-step model to the ^{64}Ni+^{64}Ni reaction.

Figure 3 shows the fusion cross section thus obtained. In the figure, the result of the two-step model is denoted by the solid line. The result is remarkably in good agreement with the experimental data, denoted by the solid circle. The corresponding capture cross section, obtained by setting $P_{\rm lbd} = 1$ in Eq. 1, is denoted by the dashed line. As a comparison, the result of the CC calculation with the Woods-Saxon (WS) potential is also shown by the dotted line. We see that the discrepancy between the capture

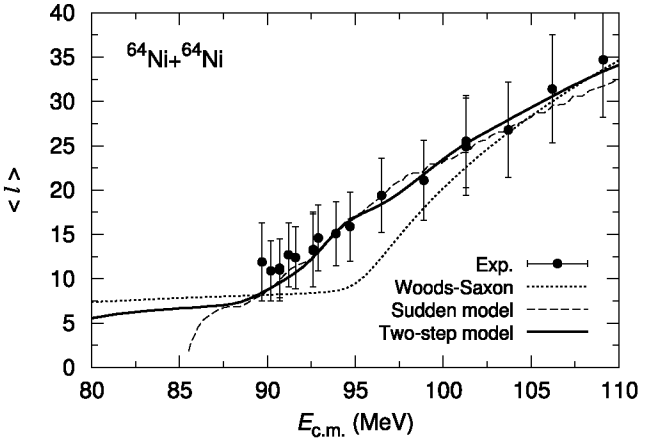

FIGURE 4. Calculated average angular momenta of the compound nuclei for the ^{64}Ni+^{64}Ni reaction. The solid line is the result of the two-step model, while the dashed line is the result of the sudden model by Mişicu and Esbensen taken from [8]. The dotted line is the result of the standard coupled-channel calculation with the Woods-Saxon potential.

cross section obtained with the WS potential and the experimental data is improved by the YPE potential, because the YPE model simulates the saturation property of the nuclear matter. A further improvement has been achieved by taking into account the one-body barrier inside the touching point. We have applied the two-step model also to the ^{58}Ni+^{58}Ni reaction. We found that the agreement with the experimental excitation function is as good as for the ^{64}Ni+^{64}Ni system shown in Fig. 3.

DIFFERENCE BETWEEN THE ADIABATIC AND THE SUDDEN APPROACHES: MEAN ANGULAR MOMENTA

As long as fusion cross section is concerned, both the sudden approach of Mişicu and Esbensen [8] and our adiabatic approach provide similar results for each other. However, the origin of the fusion hindrance is different between the two approaches. In our two-step model, the fusion hindrance takes place due to the penetration of the inner one-body potential. On the other hand, in the sudden model, which uses a shallow potential, the hindrance occurs because of the cut-off of the high angular-momentum components in the fusion cross section. The average angular momentum of the compound nuclei estimated by the sudden model therefore is much smaller than that of the present adiabatic model, as shown in Fig. 4. It is thus interesting to measure the average angular momentum of the compound nucleus at deep subbarrier energies, in order to discriminate between the two approaches.

SUMMARY

We have shown that the energies at the touching point strongly correlate with the experimental incident threshold energies E_s. This observation indicates that the steep falloff phenomena originate from the dynamics after two colliding nuclei touch with each other. In order to describe such dynamics in terms of the adiabatic approach, we proposed the two-step model, which phenomenologically supplements the standard coupled-channel model with the process for penetration of the one-body region. We applied the two-step model to the ^{64}Ni+^{64}Ni and ^{58}Ni+^{58}Ni reactions and obtained that the results are consistent with the experimental data. The effect of the one-body potential is important only at energies below the potential energy at the touching point. In this way, the two-step model provides a natural origin of the threshold energy for fusion hindrance discussed in Refs. [1, 2, 3, 4, 5]. On the other hand, the origin of the fusion hindrance for the sudden approach is attributed to the cutoff of high angular momentum components. The deference between the two approaches thus emerges typically in the average angular momentum of the compound nucleus. It would be an interesting future experiment to measure the average angular momenta, in order to discriminate between the two approaches.

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