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著者	Ichikawa Takatoshi, Hagino Kouichi, Iwamoto Akira
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Existence of a one-body barrier revealed in deep subbarrier fusion

Takatoshi Ichikawa,¹ Kouichi Hagino,² and Akira Iwamoto³

¹*RIKEN Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan*

²*Department of Physics, Tohoku University, Sendai 980-8578, Japan*

³*Japan Atomic Energy Agency, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan*

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Based on the adiabatic picture for heavy-ion reactions, in which the neck formation in the one-body system is taken into account, we propose a two-step model for fusion cross sections at deep sub-barrier energies. This 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 describe the former process with the coupled-channels framework, while the latter with the Wentzel-Kramers-Brillouin (WKB) approximation by taking into account the coordinate dependent inertia mass. The effect of the one-body barrier is important at incident energies below the potential energy at the touching configuration. We show that this model well accounts for the steep fall-off phenomenon of fusion cross sections at deep sub-barrier energies for the $^{64}\text{Ni}+^{64}\text{Ni}$ and $^{58}\text{Ni}+^{58}\text{Ni}$ reactions.

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Heavy-ion fusion reactions at low incident energies provide a good opportunity to study the quantum tunneling phenomena of many-particle systems. Because of a strong cancellation between the repulsive Coulomb interaction and an attractive short-range nuclear interaction between the colliding nuclei, a potential barrier, referred to as the Coulomb barrier, is formed, which has to be overcome in order for fusion to take place. In heavy-ion reactions, because of a strong absorption inside the Coulomb barrier, it has been usually assumed that the compound nucleus is automatically formed once the Coulomb barrier has been overcome. The coupled-channels (CC) approach based on this picture has been successful at energies close to the Coulomb barrier, where the inner turning point of the Coulomb barrier is well outside the touching point of the colliding nuclei [1].

Recently, fusion cross sections have been measured for the first time at deep sub-barrier energies for medium-heavy mass systems, such as $^{64}\text{Ni}+^{64}\text{Ni}$, $^{58}\text{Ni}+^{58}\text{Ni}$, and $^{64}\text{Ni}+^{89}\text{Y}$ [2,3]. The experimental data indicate that fusion cross sections fall off much faster than the exponential energy dependence expected from a usual tunneling picture, as the incident energy decreases. Although it has been argued that this hindrance of fusion cross sections may be explained if one phenomenologically introduces a considerably diffuse nuclear potential [4], the physical origin of the steep fall-off phenomenon has not yet been understood (see also Ref. [5]).

At energies well below the Coulomb barrier, the inner turning point is comparable to, or even smaller than, the touching point. In that situation, the frozen density approximation, which has often been employed in constructing the internucleus potential [6], breaks down, and one has to treat explicitly the dynamics after the touching configuration. In this connection, Mişicu and Esbensen have recently proposed a potential energy with a shallow pocket based still on the frozen density approximation [7,8]. That is, the outer region of the potential is constructed with the double folding procedure [6], while the phenomenological repulsive core due to the

saturation property of nuclear matter is taken into account in the inner region [7,8]. It was shown that the CC calculation with such shallow potential well reproduces the steep fall-off phenomenon for the $^{64}\text{Ni}+^{64}\text{Ni}$ reaction [7,8].

The approach of Mişicu and Esbensen is based on the sudden picture for nuclear reaction, that is, the reaction takes place so rapidly that the colliding nuclei overlap with each other without changing their density. However, it is not obvious whether the fusion dynamics at deep sub-barrier energy is close to the sudden limit or to the adiabatic limit, where the nuclear reaction is assumed to take place much more slowly than the dynamical density variation of colliding nuclei. Since one would not know *a priori* which approach is more reasonable, it is important to investigate both the possibilities [9].

In this Brief Report, we investigate the adiabatic approach in explaining the steep fall-off phenomenon of fusion cross sections. Notice that both the sudden and the adiabatic approaches would lead to a similar result to each other in the region where the colliding nuclei do not significantly overlap. Our model here is to consider the fission-like adiabatic potential energy surface with the neck configuration after the colliding nuclei touch to each other. This one-body potential acts like an inner barrier which has to be overcome to reach the compound state. It is this residual effect which we would like to discuss in connection to fusion cross sections at deep sub-barrier energies.

In order to illustrate how the adiabatic approach works, Fig. 1 shows the potential energy for the $^{64}\text{Ni}+^{64}\text{Ni}$ reaction obtained with the Krappe-Nix-Sierk (KNS) model [10] as a function of the center-of-mass distance R . In the KNS model, the saturation property of nuclear matter is phenomenologically taken into account. It has also been shown that the KNS model is consistent with the potential obtained with the energy density formalism with the Skyrme SkM* interaction [11]. The parameters in the KNS model are taken as $a_0 = 0.68$ fm, $a_s = 21.33$ MeV, and $\kappa_s = 2.378$ from FRLDM2002 [12]. The radius parameter is fine-tuned as $r_0 = 1.204$ fm in order

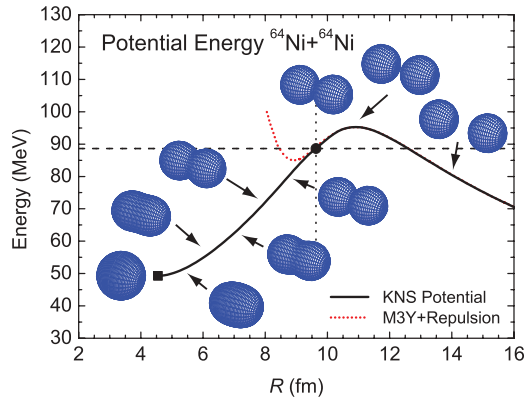


FIG. 1. (Color online) One- and two-body potential energies for $^{64}\text{Ni}+^{64}\text{Ni}$ obtained with the KNS model as a function of the center-of-mass distance. The shape for the one-body configuration described by the Lemniscatoids parametrization is also shown. The filled circle and square denote the touching configuration and the ground state of the compound system, respectively. The dotted line is the sudden potential taken from Ref. [7].

to fit the experimental fusion cross section at high incident energies. The touching configuration is denoted by the filled circle in the figure. For distances larger than the touching point, the potential energy for the two-body system is calculated as the sum of the Coulomb energy for two point charges and the nuclear energy given by Eq. (17) in Ref. [10]. For the one-body system after touching two nuclei, we assume that the shape configuration is described by the Lemniscatoids parametrization (see the inset in the figure) [13], and calculate the Coulomb and surface integrals for each configuration [10].

We find that the value of the potential energy at the touching configuration V_{touch} is 88.61 MeV. This is exactly the energy E_s at which the experimental fusion cross section start to fall off abruptly in this reaction [2]. This strongly suggests a correlation between the observed fusion hindrance and a process after the two nuclei overlap each other. For a comparison, the sudden potential which Mişicu and Esbensen considered [7] is denoted by the dotted line in the figure. We find that the adiabatic KNS potential and the sudden potential almost coincide with each other outside the touching radius.

In order to describe the two-body process from a large distance to the touching point, we employ the standard CC formalism by taking into account inelastic excitations in the colliding nuclei. However, it is not straightforward to extend this treatment to the one-body process. In the CC formalism, the total wave function is expanded with the asymptotic intrinsic states of the isolated nuclei, in which one usually restricts the model space only to those states which are coupled strongly to the ground state. Apparently, such asymptotic basis is not efficient to represent the total wave function for the one-body dinuclear system, and in principle one would require to include all the intrinsic states in the complete set. This is almost impossible in practice. Moreover, the adiabatic one-body potential with the neck configuration already includes a large part of the channel coupling effects, and the application of the standard CC formalism would result in the double counting of the CC effect.

In order to avoid these difficulties, we here propose a simple phenomenological model, in which the two- and one-body processes are defined independently and time-sequentially. The fusion cross section in this two-step model then reads

$$\sigma(E) = \frac{\pi \hbar^2}{2\mu E} \sum_{\ell} (2\ell + 1) T_{\ell}(E) P_{1\text{bd}}(E, \ell), \quad (1)$$

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 for the two-body process estimated with the CC method. $P_{1\text{bd}}$ is the penetrability for the adiabatic one-body potential to reach the compound state after the touching of two-body potential, which plays an important role at energies below V_{touch} (i.e., below the dashed line in Fig. 1). At these energies, the fusion reaction is described not only by the two-body potential, but the potential which governs the fusion dynamics is switched from the two-body to the adiabatic one-body potential at the touching configuration. Only after overcoming (or penetrating through) these two- and one-body barriers, the system can form a compound nucleus. One may regard the one-body penetrability $P_{1\text{bd}}$ as a *fusion spectroscopic factor*, which describes the overlap of wave function between the scattering and the compound states.

In order to estimate the capture probability T_{ℓ} within the two-step model, we cut the two-body potential at the touching configuration as shown in the upper panel of Fig. 2. The capture probability does not depend strongly on how to cut the potential, since only the lowest two-body eigenpotential, which is obtained by diagonalizing the coupling Hamiltonian [1,14,15], is relevant at deep sub-barrier energies. As indicated by the dashed line in the figure, the inner turning point for the lowest eigenpotential is still far outside the touching distance. Thus, the actual shape of the original potential in the inner-barrier region influences little on the penetrability. Another view is that the incoming wave boundary condition

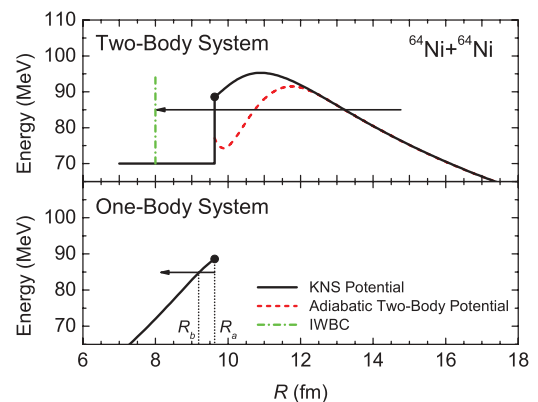


FIG. 2. (Color online) The internucleus potential used in the two-step model. The solid line in the upper panel denotes the KNS potential for the two-body process, which is cut at the touching configuration, while the dashed line denotes the lowest two-body eigenpotential. The dash-dotted line denotes the position at which the incoming wave boundary condition (IWBC) is imposed in the CC calculation. The solid line in the lower panel denotes the adiabatic one-body potential inside the touching distance.

(IWBC) is imposed in the CC calculation at the touching distance so that the capture probability is defined at the touching configuration, although in the actual calculations we impose the IWBC at a distance somewhat smaller than the touching point in order to avoid the numerical error. For simplicity, we employ a sharp cutoff of the two-body potential in this paper.

In order to estimate the one-body probability P_{1bd} , we use the WKB approximation. We assume that the reflected flux in this process does not return to the two-body system, but exits through the multidimensional potential energy surface in the one-body system. The penetrability then reads $P_{1bd}(E, \ell) = e^{-2S(E, \ell)}$, where $S(E, \ell)$ is the action integral with the coordinate dependent inertia mass $M(R)$,

$$S(E, \ell) = \int_{R_a}^{R_b} dR \sqrt{\frac{2M(R)}{\hbar^2} (E - V_{1bd}(R, \ell))}. \quad (2)$$

Here, R_a and R_b are the inner and the outer turning points, respectively (see the lower panel of Fig. 2). V_{1bd} is the adiabatic one-body potential energy given by

$$V_{1bd}(R, \ell) = V_C(R) + V_S(R) + \frac{\ell(\ell + 1)\hbar^2}{2I(R)} + \frac{2}{7}E_R, \quad (3)$$

where V_C , V_S , and I are the Coulomb and the surface energies and the moment of inertia for the rigid body, respectively. E_R denotes the centrifugal energy at the touching configuration. Note that the last term in Eq. (3) comes from the conservation of the energy and angular momentum between the two- and one-body systems in the sticking limit [16].

We now apply the present two-step model to the fusion reaction of the $^{64}\text{Ni}+^{64}\text{Ni}$ system. To this end, we use the KNS potential energy already shown in Fig. 1. In the energy region discussed in this paper, we expect that the the Lemniscatoids parametrization provides a reasonable approximation, because the neck formation is still small as shown in the inset of Fig. 1. This parametrization has an advantage in that the configuration is described with only one parameter for a symmetric system. In addition, one obtains a smooth connection between the one- and two-body potential energy curves, since the change of the configuration shape across the touching point is rather natural. As for the inertia mass M , we take the linear combination between the irrotational-flow mass in the Werner-Wheeler approximation [17], M_0 , and the reduced mass, μ . That is, $M(R) = k(M_0(R) - \mu) + \mu$, where k is the normalized factor. The renormalization factor is necessary, since the liquid drop model with the irrotational-flow mass M_0 overestimates the vibrational excitation energy $\hbar\omega_0$ for the first 2^+ state [18]. In the calculations presented below, we use the normalization factor, $k = 46$, which leads to the vibrational energy of $0.2\hbar\omega_0$. Notice that the inertia mass M is in agreement with the reduced mass μ at the touching configuration.

In order to compute the capture probability T_ℓ with the CC framework with a sharp-cut KNS potential, where the form of the coupling potential is not known, we modify the computer code CCFULL [19] and estimate the nuclear coupling term with the numerical derivative of the nuclear potential up to the second order. The coupling scheme included in the calculations, as well as the deformation parameters, are

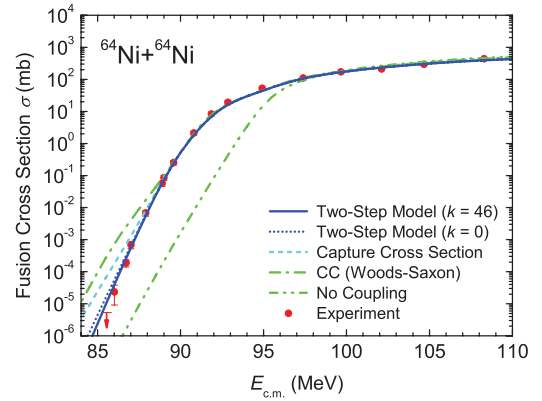


FIG. 3. (Color online) Fusion cross sections for the $^{64}\text{Ni}+^{64}\text{Ni}$ reaction calculated with the two-step model. The filled circles denote the experimental fusion cross section, taken from Ref. [2]. The solid and dotted lines denote the fusion cross section obtained with the normalization factor for the mass inertia of $k = 46$ and 0 , respectively. The dashed line denotes the corresponding capture cross section. The dash-dotted line is obtained with the Woods-Saxon potential, while the dash-dot-dotted line shows the result in the absence of the channel coupling effect.

the same as in Ref. [2]. To be more specific, we include the coupling to the low-lying 2^+ and 3^- phonon states, two-phonon quadrupole excitations, and all possible mutual excitations both in target and projectile nuclei. The potential depth in the inner-barrier region for the sharp-cut KNS potential and the position of the IWBC are chosen as $V_0 = 70$ MeV and $R_{IWBC} = 8.0$ fm, respectively. These values are determined using the the Woods-Saxon (WS) potential with $V_{WS} = 75.98$ MeV, $r_{WS} = 1.19$ fm, and $a_{WS} = 0.676$ fm. We have checked the numerical stability of the calculations at extremely low incident energies by comparing the obtained result with the one in the multichannel WKB approximation [20].

Figure 3 shows the fusion cross sections thus obtained. It is remarkable that the fusion cross section obtained with $k = 46$ for the coordinate dependent mass is in good agreement with the experimental data (see the solid line). The corresponding capture cross sections, obtained by setting $P_{1bd} = 1$ in Eq. (1), is denoted by the dashed line. As a comparison, the result with the WS potential is also shown by the dash-dotted line. We see that the discrepancy between the capture cross section obtained with the WS potential and the experimental data is improved by taking into account the saturation property simulated by the KNS potential, and a further improvement has been achieved by taking into account the one-body barrier inside the touching configuration. The result with $k = 0$ is denoted by the dotted line. The difference between the solid and the dotted line is small, indicating the negligible effect of the coordinate dependence of mass inertia in the energy region discussed in this paper. We have applied the two-step model also to the $^{58}\text{Ni}+^{58}\text{Ni}$ system. We found that the agreement with the experimental excitation function [21] is as good as for the $^{64}\text{Ni}+^{64}\text{Ni}$ system shown in Fig. 3.

The present two-step model is in the opposite limit to the recent sudden model of Mişicu and Esbensen [7,8]. As

long as the fusion cross sections are concerned, both the models provide similar results, at least for the $^{64}\text{Ni}+^{64}\text{Ni}$ reaction. However, the origin for 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 cutoff of the high angular-momentum components in the fusion cross section. The average angular momentum of the compound nuclei estimated with the sudden model would therefore be much smaller than that of the present adiabatic model. It is thus interesting to measure the average angular momentum of the compound nucleus at deep sub-barrier energies, in order to discriminate the two approaches.

We would next like to comment on the recent experimental data for $^{16}\text{O}+^{197}\text{Au}$, where the fusion hindrance was not observed [22]. We estimate the potential energy at the touching configuration, V_{touch} , to be 68.23 MeV if we use $r_0 = 1.2$ fm in the KNS potential. This is nearly equal to the lowest incident energy performed in the experiment. Thus, the fusion cross sections have to be measured at lower energies in order to observe the fusion hindrance for this system, as has been speculated in Ref. [22].

To summarize, we have proposed the adiabatic two-step model for fusion cross sections at deep sub-barrier energies. By

applying this model to the $^{64}\text{Ni}+^{64}\text{Ni}$ and $^{58}\text{Ni}+^{58}\text{Ni}$ reactions, we have shown that the penetration of the adiabatic one-body potential with the neck configuration after the touching of two colliding nuclei is responsible for the steep falloff of fusion cross sections observed recently in the experimental data. The effect of the one-body potential is important only at energies below the potential energy at the touching configuration. In this way, the two-step model provides a natural origin for the threshold energy of fusion hindrance discussed in Refs. [2,3].

In Ref. [5], it was shown that the experimental fusion cross sections for the $^{16}\text{O}+^{208}\text{Pb}$ system follow the exponential energy dependence at deep sub-barrier energies. This is in contrast to the behavior in the medium-heavy systems discussed in Refs. [2,3]. It would be an interesting future work to apply the present two-step model to this reaction and to clarify the difference between the mass asymmetric and symmetric systems.

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