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Influence of heavy-ion transfer on fusion reactions

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The influence of inelastic excitations on heavy-ion fusion is well established and can be quantitativly described by coupled-channels calculations. The influence of transfer channels, however, is still under debate. We have analyzed a large set of heavy-ion-induced fusion excitation functions involving nuclei with similar structures and show that there is a universal correlation between the shape (and enhancement) of the excitation function and the strength of the total neutron-transfer cross sections for systems ranging from light to heavy masses.

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Fusion reactions play an important role in nuclear physics since they enable production of nuclei away from the valley of stability. For this reason, many experimental and theoretical studies of heavy-ion-induced fusion have been performed during the past few decades. In order to understand the underlying reaction mechanism, fusion excitation functions have been measured from high energies, where fusion dominates the total reaction cross section, down to low energies, where fusion proceeds via tunneling through a barrier. Recent results in this field are summarized, e.g., in Ref. [1]. In addition to the Coulomb barrier, heavy-ion fusion is known to be influenced by quasielastic reaction channels. While the effect of inelastic excitations on heavy-ion fusion is well established, the possible importance of transfer processes is still under debate.

The influence of transfer channels was first discussed by Broglia *et al.* [2,3], who suggested that transfer reactions with positive Q values are needed to explain the behavior of low-energy fusion data for the Ni + Ni systems. Measurements of quasielastic neutron transfer for ^{58}Ni + ^{58,64}Ni confirmed this suggestion [4]. The first quantitative treatment of the interplay between transfer and fusion reactions within a coupled-channel approach was performed for the system ^{58}Ni + ^{124}Sn [5,6]. Other systems treated with the same approach include ^{40}Ca + ^{90,96}Zr [7,8], ^{40,48}Ca+ ^{48}Ca [9,10], and ^{32,36}S + ^{48}Ca [11]. The effect of transfer reactions on fusion is also discussed in Refs. [12–15]. Some of these systems have been measured in sufficiently small energy steps to extract the underlying barrier distributions, $B(E)$, and to study the contribution from transfer channels to $B(E)$ [8,16,17].

While all these measurements give evidence for an enhancement of the fusion cross sections through transfer reactions, a recent study of ^{58,64}Ni + ^{132}Sn fusion [18,19] stated that no enhancement due to transfer channels was seen in these systems. This led the authors to the conclusion that there is a "dramatically different influence" of positive Q-value transfer channels in fusion reactions between Ni and Sn isotopes, when compared to fusion between lighter nuclei. On the other hand, subsequent measurements of fusion in the ^{40,48}Ca + ^{124,132}Sn systems by the same group [20] indicated fusion enhancement due to neutron transfer. In the present paper, we analyze a large set of fusion excitation functions involving medium-mass and heavy nuclei and show that there is no difference in the fusion behavior between light and heavy systems. A comparative way to estimate the influence of transfer is also provided.

In order to simplify the discussion, we restrict the selection of the systems of interest to those where the excitation energy of the projectile and/or the target is above 1 MeV. By this choice, we eliminate systems dominated by Coulomb excitation, which is known to strongly influence the magnitude of fusion at energies in the vicinity of the Coulomb barrier. We first discuss a general isotopic effect in fusion reactions which has been studied for many years (e.g., Ref. [21]) but is still being debated, i.e., the different enhancement observed for fusion of nuclei with the same Z_1,Z_2 but different masses, A_1,A_2, where the couplings of transfer reactions to the fusion channel play an important role.

In this analysis, we do not use the so-called reduced coordinate representation [22] for the fusion excitation functions. While reduced coordinates eliminate the trivial size factors, they introduce, on the other hand, additional, model-dependent parameters. Furthermore, it is known that nuclear radii do not always follow the standard $A^{1/3}$ systematics. As an example, α-scattering experiments on ^{40}Ca and ^{48}Ca indicate a matter-radius difference of 0.12 ± 0.06 fm while from standard $A^{1/3}$ systematics, a value of 0.27 fm is expected [23].

We start by discussing the Ni + Ni and Ca + Zr systems, which both populate compound nuclei in the mass 116–144 region. The fusion excitation functions for ^{58}Ni + ^{58}Ni, ^{64}Ni + ^{64}Ni, and ^{58}Ni + ^{64}Ni [21,24,25] and for ^{40}Ca + ^{90}Zr, ^{48}Ca + ^{96}Zr, ^{40}Ca + ^{96}Zr, and ^{48}Ca + ^{90}Zr [7,10,26] are presented in Figs. 1(a) and 1(c), respectively. The fusion excitation functions between neutron-poor and neutron-poor, or neutron-rich and neutron-rich projectile and target combinations (i.e., ^{58}Ni + ^{58}Ni and ^{64}Ni + ^{64}Ni or ^{40}Ca + ^{90}Zr and ^{48}Ca + ^{96}Zr) have very similar shapes, but they are shifted towards higher and lower energies due to their slightly different Coulomb barriers. For the same reason, the cross sections at energies above the Coulomb barrier between neutron-rich beams and targets are higher than the ones between neutron-poor beams and targets. The most noticeable difference in the excitation functions, however, is the shallower slope observed for systems involving a neutron-poor beam (^{58}Ni or ^{40}Ca) on a neutron-rich target (^{64}Ni or ^{96}Zr) at energies close to the Coulomb barrier. As a result, these systems exhibit the largest fusion cross sections at the lowest energies. This enhancement is caused by couplings to transfer reactions, as is discussed in more detail below.

Heavy-ion-induced transfer reactions, at energies close to the Coulomb barrier, follow the so-called Q-value systematics, which predicts that the preferred states in the outgoing channel are those located inside the so-called Q window, a Gaussian-shaped distribution with a centroid at the optimum value, Q_{opt} given by [2,27]

$$Q_{opt} = Q_{gg} - E_x = E\left(\frac{B_f}{B_i} - 1\right), \quad (1)$$

where Q_{gg} is the ground-state Q value, E_x is the excitation energy in the outgoing channel, E is the c.m. energy, and $B_{i,f}$ is the Coulomb barrier energies in the entrance or exit channel, respectively. The width of the Gaussian distribution depends on the incident energy, the system parameters (Z_1, Z_2, A_1, A_2), the number of transferred nucleons, etc., and is typically around 6–10 MeV.

Since the c.m. energies discussed here are all close to the Coulomb barrier B_i, we can rewrite Eq. (1) as

$$E_x \sim Q_{gg} - (B_f - B_i). \quad (2)$$

By definition, E_x has to be positive, as negative values in Eq. (2) are energetically forbidden and, thus, these reactions should have small transfer cross sections. For energies at and below the Coulomb barrier, proton transfer is reduced relative to neutron transfer; therefore in the following we concentrate on the neutron-pickup channels. The excitation energies resulting from the transfer of one to six neutrons calculated with Eq. (2) for the systems Ni + Ni and Ca + Zr are presented in Figs. 1(b) and 1(d), respectively. A FWHM of 8 MeV for the Q-value distribution is indicated by the vertical bars. As can be seen, positive excitation energies and, thus, larger transfer yields are expected for the systems ^{58}Ni + ^{64}Ni and ^{40}Ca + ^{96}Zr and these are the same reactions that exhibit a shallower slope in the fusion excitation functions.

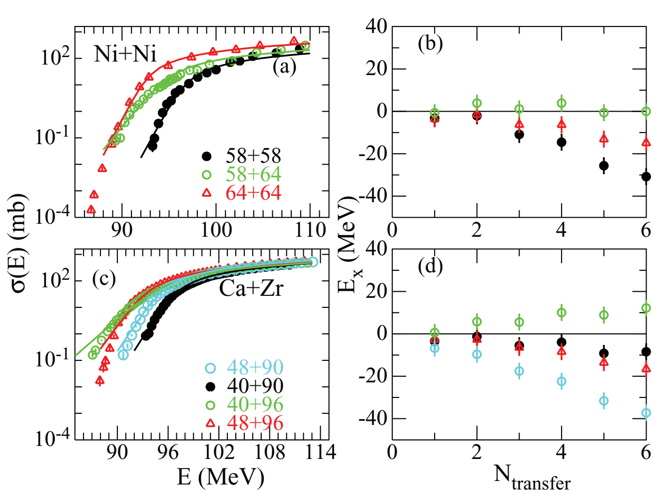

FIG. 1. (Color) Fusion excitation functions for the systems Ni + Ni (a) and Ca + Zr (c). The solid curves are fits using Wong's formula. Panels (b) and (d) are the average excitation energies of the residual nuclei following neutron pickup reactions. See text for details.

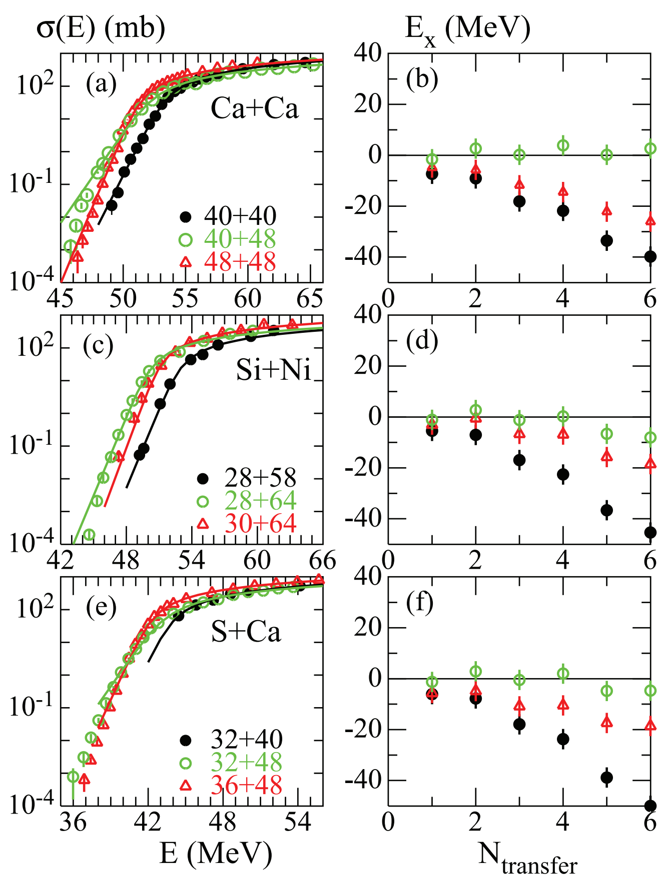

FIG. 2. (Color) Same as Fig. 1, but for the systems S + Ca (a), Ca + Ca (c), and Si + Ni (e). Panels (b), (d), and (f) are average excitation energies of neutron pickup reactions for the same systems.

A similar behavior is found for other light and heavy systems. Three lighter systems are introduced in Fig. 2. For the systems S + Ca [11,28,29] and Ca + Ca [9,10,30], the fusion excitation functions for ^{32}S + ^{48}Ca and ^{40}Ca + ^{48}Ca again exhibit a shallower slope correlated with positive excitation energies, when compared to the other cases such as ^{40}Ca + ^{40}Ca or ^{48}Ca + ^{48}Ca. For another system in Fig. 2, Si + Ni [31,32], the excitation energies for the one- and two-neutron pickup reactions in ^{28}Si + ^{64}Ni and ^{30}Si + ^{64}Ni are rather similar. This observation in turn correlates with a smaller difference in the slopes of the two fusion excitation functions.

The results for the heavier systems ^{40,48}Ca + ^{124,132}Sn [20,33] and ^{58,64}Ni + ^{124,132}Sn [18,19] are found in Fig. 3. In the literature, there are also measurements of fusion excitation functions between ^{58,64}Ni and other stable even-even Sn isotopes [34,35]. Most of these excitation functions, however, were only measured down to the 1- or even 20-mb regions. The same is true for the reactions involving ^{132}Sn, where the fusion excitation functions could only be measured to cross sections of ∼1 mb due to the low beam intensities available at present-day radioactive-beam facilities. Because of the limited range of the experimental data for the stable Sn isotopes only the fusion data for system ^{58}Ni + ^{124}Sn are shown in Fig. 3. A new measurement of the fusion cross sections for this and

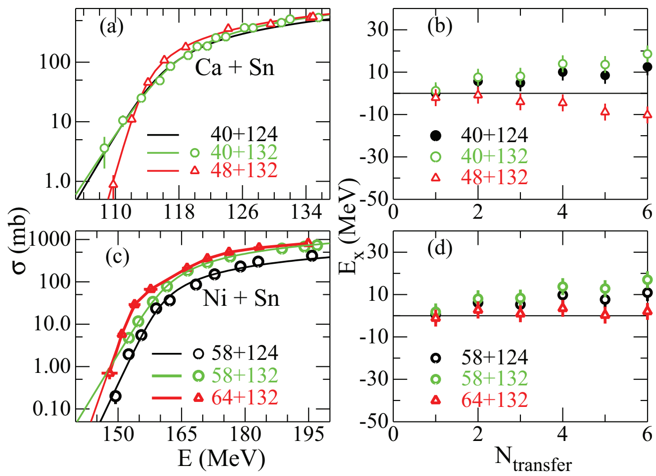

FIG. 3. (Color) Fusion excitation functions for the systems Ca + Sn (a) and Ni + Sn (c). For ^{40}Ca + ^{124}Sn, there are too many data points, so only a fit curve is shown. Panels (b) and (d) are average excitation energies of neutron pickup reactions for the same systems.

other neighboring Sn isotopes extending to sufficiently low cross sections would be worthwhile.

At first glance, the correlations discussed above seem less pronounced for the Ni + Sn systems. However, for both the Ca + Sn and the Ni + Sn systems, a shallower slope of the fusion excitation function is again correlated with positive excitation energies for neutron-pickup reactions. It is also interesting to note that the excitation functions for ^{40}Ca + ^{124,132}Sn are almost identical, with both systems showing positive E_x values [see Fig. 3(a)]. As can be seen in Figs. 1 and 2, the influence of transfer reactions is more pronounced at lower cross sections ($\leqslant$1 mb), and, thus, an extension of the fusion excitation functions for these heavy systems towards lower energies is desirable.

As discussed above, common to all systems in Figs. 1–3 is the shallower slope observed for the fusion excitation functions between neutron-poor beams and neutron-rich targets. In the following, we provide a more quantitative description of this effect.

For a theoretical description of the data presented above, coupled-channels calculations would be the appropriate approach (see, e.g., Ref. [6]). However, a coupled-channel treatment introduces many new parameters such as $B(EL)$ values, deformation lengths, and the need to include multiphonon excitations and multinucleon transfers. Thus, we have analyzed the excitation functions using the Wong formula [36], which describes the fusion excitation functions with the equation:

$$\sigma = \left(R_C^2/2E\right)\hbar\omega \ln\{\,1 + \exp[(2\pi/\hbar\omega)(E - V_C)]\}, \qquad (3)$$

where R_C, V_C, and $\hbar\omega$ correspond to the radius, the height, and the curvature of the fusion barrier, respectively. It is well known that large $\hbar\omega$ values correspond to thin barriers, a signature of a strong fusion enhancement. The solid lines in Figs. 1–3 are the results of least-squares fits with Eq. (3) to the measured excitation functions. They provide a good description of the data in the 1- to 1000-mb cross-section range.

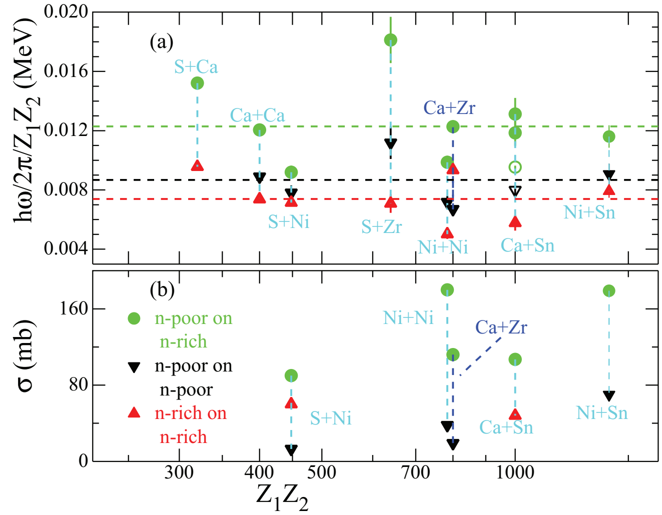

FIG. 4. (Color) (a) Plot of $\hbar\omega/Z_1Z_2$ vs Z_1Z_2 for various systems ranging from S + Ca to Ni + Sn. (b) Plot of total neutron-transfer cross sections, σ vs Z_1Z_2. For Ni + Sn, the assignments of the symbols are (a) green, ^{58}Ni+^{132}Sn; black, ^{58}Ni+^{124}Sn; red, ^{64}Ni+^{132}Sn; (b) green, ^{58}Ni+^{124}Sn; black, ^{58}Ni+^{112}Sn. For Ca + Ni, (a) two upper green-filled circles, ^{40}Ca+^{132}Sn and ^{40}Ca+^{124}Sn [20]; open green, ^{40}Ca+^{124}Sn [33]; open black, ^{40}Ca+^{116}Sn [33]; red, ^{48}Ca+^{132}Sn [20]; (b) green, ^{40}Ca+^{124}Sn; red, ^{48}Ca+^{124}Sn.

A similar analysis of fusion data has been performed previously by Jahnke *et al.* [37] for Ar- and Kr-induced fusion reactions. In that study, it was noticed that the curvature of the fusion barrier, $\hbar\omega$, increases for the heavier systems, which is caused by the larger Coulomb barrier. In order to correct for this size effect, we have therefore divided the $\hbar\omega$ values by the product Z_1Z_2. Values of the ratio $\hbar\omega/(Z_1Z_2)$ obtained from least-squares fits to several systems ranging from S + Ca to Ni + Sn are plotted in Fig. 4(a) as a function of Z_1Z_2. The error bars in Fig. 4(a) represent the uncertainties associated with the least-squares fits only. While these uncertainties are often quite small ($\sim$1%), there is an additional systematic uncertainty of about 20%, as found for the system ^{40}Ca + ^{124}Sn. The data were measured at two different laboratories, resulting in $\hbar\omega$ values differing by 21.5% [20,33].

From Fig. 4(a), it can be seen that all green symbols, which represent systems with a neutron-poor projectile and a neutron-rich target, have larger values of $\hbar\omega/(Z_1Z_2)$ than the other two cases, i.e., neutron-poor projectile and neutron-poor target (black) and neutron-rich projectile and neutron-rich target (red). The three dashed lines in Fig. 4(a) are the average values of the data points with the same color. It should also be noticed that, in this representation, the rescaled values of $\hbar\omega$ for the systems Ca + Sn and Ni + Sn follow the same systematics as found in the lighter systems.

While there are many measurements of fusion excitation functions for systems ranging from S + Ca to Ni + Sn, studies of transfer reactions in these systems are more sparse. There are only a few excitation functions of transfer reactions in the literature. In Fig. 4(b) we have plotted total neutron-transfer cross sections measured at energies close to the Coulomb barrier as a function of Z_1Z_2 [4,5,38–43]. The color code in Fig. 4(b) is the same as used in Fig. 4(a); i.e., green for a neutron-poor projectile on a neutron-rich target, black for a neutron-poor projectile on a neutron-poor target, and red for a neutron-rich projectile on a neutron-rich target. Again, quasielastic neutron-transfer reactions between neutron-poor beams and neutron-rich targets have the largest cross sections, as expected from the Q-value systematics discussed above. The similarity between the plots of $\hbar\omega/(Z_1Z_2)$ and the total neutron-transfer cross sections are a strong indicator that transfer reactions influence fusion. This was demonstrated for ^{58}Ni + ^{124}Sn in Ref. [6] and for the ^{40}Ca + ^{96}Zr and ^{40}Ca + ^{48}Ca systems in Refs. [8–10]. This seems to be an universal behavior for all reactions which are not dominated by Coulomb excitation. The discussion presented here is limited to the energy region close to the Coulomb barrier, where data can be analyzed by the Wong formula. While the influence of transfer reactions is expected to increase at lower energies, fusion hindrance [24,44] comes into play in this energy range, which complicates the analysis. A recent measurement in the ^{40}Ca + ^{96}Zr system [8] gave no indication of fusion hindrance down to cross sections of 2 μb, while the measurement and calculations of ^{40}Ca + ^{48}Ca indicate that both the transfer channels and the hindrance contribute in a significant way in the μb cross-section range [9].

To summarize, we have found that fusion excitation functions between neutron-poor projectiles and neutron-rich targets always exhibit a shallower slope than those between pure neutron-rich or neutron-poor projectile-target systems. By analyzing the data with the Wong formula, shallower slopes are found to result in a larger curvature $\hbar\omega$ of the fusion barrier. The latter is a sign of strong fusion enhancement. In a plot of the ratio $\hbar\omega/(Z_1Z_2)$, which takes standard size effects into account, it is found that, contrary to the conclusions of Ref. [18], this enhancement is the same for light and heavy fusion systems. The slopes of the fusion excitation functions and, thus, the fusion enhancement, are found to be correlated with the strength of the total neutron-transfer cross sections, pointing to the need to include these processes in coupled-channel calculations.

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