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Transfer reactions as a doorway to fusion

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Abstract. This paper discusses the role played by transfer reactions on the sub-barrier fusion enhancement. A semiclassical formalism is used to derive the transfer form factors, that are used in coupled-channel calculations. It is shown that transfer reactions that take place at small distances may be an important doorway to fusion. The relation between this formalism and the long-range absorptive fusion potential is also discussed. Results of calculations for the $^{16}O + {}^{A}Sm$, $^{32}S + {}^{100}Mo$ and $^{16}O + {}^{59}Co$ systems are presented.

1. Introduction

It is well understood that the fusion cross section enhancement at sub-barrier energies, relative to the unidimensional barrier penetration model predictions, is due to the splitting and lowering of the Coulomb barrier, when macroscopic collective degrees of freedom such as the deformation of the nuclei and their surface vibrations, or the coupling of inelastic channels of the colliding nuclei, are taken into account. The fusion enhancement may also arise by the additional attraction in the incident channel. Transfer channels may act as a doorway to fusion in a complex multistep process, where the point of no return from fusion may be situated at distances larger than the position of the barrier. At low energies, and for heavy systems, the semiclassical approximations are suitable to be used in the description of the transfer process and in the derivation of transfer form factors. Although there are some signatures that transfer channels with large Q-values or large cross sections may couple with the fusion and contribute to its enhancement at sub-barrier energies, the relation between fusion and transfer reactions is not so clear, because they take place at different distances. This paper is concerned with the role played on the fusion, by the distance where the transfer mechanisms take place.

2. The derivation of transfer form factors from a semiclassical formalism

At the near and sub-barrier energy range, the semiclassical approximations are suitable to be used for the derivation of transfer form factors [1, 2]. The transfer probability may be written as

$$P_{\rm tr} = \left\{ (1/\hbar) \int_{-\infty}^{+\infty} F(r(t)) \exp[{\rm i}t(Q - Q_{\rm opt})/\hbar]\, {\rm d}t \right\}^2 \qquad (1)$$

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where $F(r(t))$ is the transfer form factor, η is the Sommerfeld parameter and Q and Q_{opt} are the ground state and optimum Q-values, respectively. At energies below the Coulomb barrier, the following ansatz is made [1, 2]:

$$F(r) = F_0(\varphi(r)/r)\exp[-\alpha(r - D_c)] \tag{2}$$

where D_c is the core distance, deduced from the elastic scattering data, α is the slope factor, F_0 is a normalization factor and $\varphi(r)$ is a smooth function that limits $F(r)$ towards a maximum close to the Coulomb barrier position [3]. With some additional approximations, the transfer probability can be written as [1, 2]

$$P_{\text{tr}}/\sin(\theta/2) = A\exp(-2\alpha D) \tag{3}$$

where D is the distance of closest approach.

The slope parameters α of the form factors can be extracted experimentally from the plot of the logarithm of the transfer probability versus the distance of closest approach. The normalization factors F_0 are derived from the fits of the Q-integrated experimental angular distributions at small angles (or large distances of closest approach), when these reaction mechanisms are supposed to be simple one-step processes. Then, one can derive the transfer cross sections for very backward angles.

3. The coupling of the fusion and transfer mechanisms

Coupled-channel calculations are widely used in the study of the sub-barrier fusion problem. Low-lying collective state couplings are used in all the calculations. Usually, only when these couplings are not enough to explain the experimental fusion excitation function, one tries to couple additional transfer channels. As the transfer form factors very often are not available, authors sometimes indicate [4] that transfer couplings should be responsible for the extra enhancement needed to fit the data, without performing the calculations. However, when there are available transfer angular distribution data for individual transfer channels and for elastic scattering data, the formalism described in section 2 can be used to derive the transfer form factors. A computer code [5], called SBTRANS, performs the calculations.

The analysis of the fusion excitation functions of the ^{33}S + $^{90-92}$Zr systems [2] showed that the fusion enhancements were much larger than the predictions of coupled-channel calculations including only inelastic channels. Measurements of the transfer differential cross sections of the most important channels were made for these systems. Following the procedure described in section 2, the form factors were determined. The results of the calculations have shown that for some channels the theoretical predictions for the transfer angular distributions fit the whole angular range of the data, while for some other channels, the theoretical predictions for backward angles are much larger than the data. In this last situation there is a 'missing' transfer cross section at backward angles. When coupled-channel calculations, including transfer channels, were performed, the experimental fusion excitation functions could be fitted.

An intriguing question came to us: What happens when one applies this formalism for systems where the fusion had already been explained by the coupling of inelastic channels? We did that for the ^{16}O + ^{144,148,150,152,154}Sm systems [6]. The transfer angular distributions for the main channels were analysed by this method. Ten transfer channels were studied: stripping of one α and stripping of two protons for each system. For only one of them, the stripping of two protons for $A = 144$, it was observed a very small 'missing' cross section at backward angles. For the other nine channels, good fits of the whole angular range were obtained. Figure 1 shows the results for the stripping of 2p and 1α channels for $A = 144$.

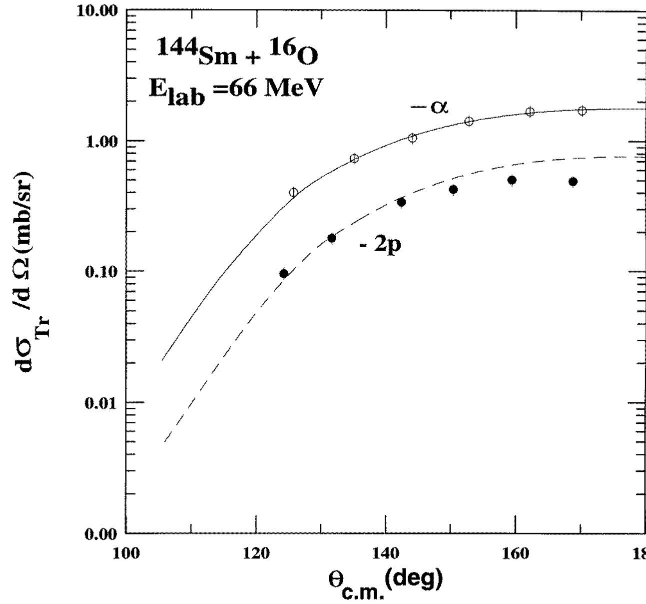

Figure 1. Transfer differential cross sections for the (−2p) and (−1α) channels for the ^{16}O + ^{144}Sm system. The symbols represent experimental data and the lines are obtained by fitting the data for the smallest angles.

The reduced average transfer distances for all the channels were calculated to be of the order of 1.57 fm, much larger than the position of the Coulomb barrier ($r_B = 1.38$ fm). Simplified coupled-channel calculations, including the transfer channels, were performed by the CCFUSB code [5, 7]. The results showed no contribution of the transfer channels to the fusion cross section enhancement. The conclusion is that the channels for which there are 'missing' transfer cross sections contribute to the fusion enhancement, whereas the others give no contribution to the fusion cross section.

Liang *et al* [4] measured differential cross sections for the most important transfer channels in the ^{32}S + ^{92,98,100}Mo systems, at near barrier energies. Large transfer cross sections were observed for the ^{98,100}Mo, while small values were observed for the ^{92}Mo. The large fusion cross section enhancement for the ^{32}S + ^{98,100}Mo [4, 8] could not be explained by coupling just the inelastic channels. This was only possible for the small enhancement of the ^{32}S + ^{92}Mo fusion excitation function [4, 8]. The formalism described before is being applied for these systems. So far we have performed preliminary calculations for ^{32}S + ^{92,100}Mo systems, at near-barrier energies ($E_{\mathrm{lab}} = 116$ MeV). The main transfer channels for the ^{32}S + ^{100}Mo are the stripping of one and two protons (−1p and −2p) and the pick-up of one and two neutrons (+1n and +2n). For the ^{32}S + ^{92}Mo system the same stripping channels are important, but there are no measurementes of the neutron transfer channels. Table 1 shows the results of the calculations. There, Q_{gg} is the ground-state Q-value, $\langle\alpha\rangle_{\mathrm{exp}}$ is the form factor slope parameter, $F(r_B)$ is the form factor value at the barrier and $\langle d_{\mathrm{Trans}}\rangle$ is the average transfer distance. One can see that the +2n channel has the largest Q and $F(r_B)$ values and the smallest average transfer distance, not far from the position of the Coulomb barrier ($r_B = 1.38$ fm). Figure 2 shows the results of the calculations for the ^{32}S + ^{100}Mo system. In all of them there are 'missing cross sections' at backward angles, although this effect is most impressive for the +2n channel. For the

Table 1. Results of the calculations from the SBTRANS code, for the $^{32}S + ^{100}Mo$ system.

Channel	Q_{gg} (MeV)	$\langle\alpha\rangle_{exp}$ (fm^{-1})	$F(r_B)$ (MeV)	$\langle d_{Trans}\rangle$ (fm)
$-1p(^{100}Mo)$	1.3	0.87	0.39	1.50
$-2p(^{100}Mo)$	−1.4	0.85	0.48	1.48
$+1n(^{100}Mo)$	0.35	0.82	0.39	1.48
$+2n(^{100}Mo)$	5.8	1.47	0.84	1.44
$-1p(^{92}Mo)$	−4.8	0.80	0.34	1.53
$-2p(^{92}Mo)$	−5.8	0.86	0.44	1.49

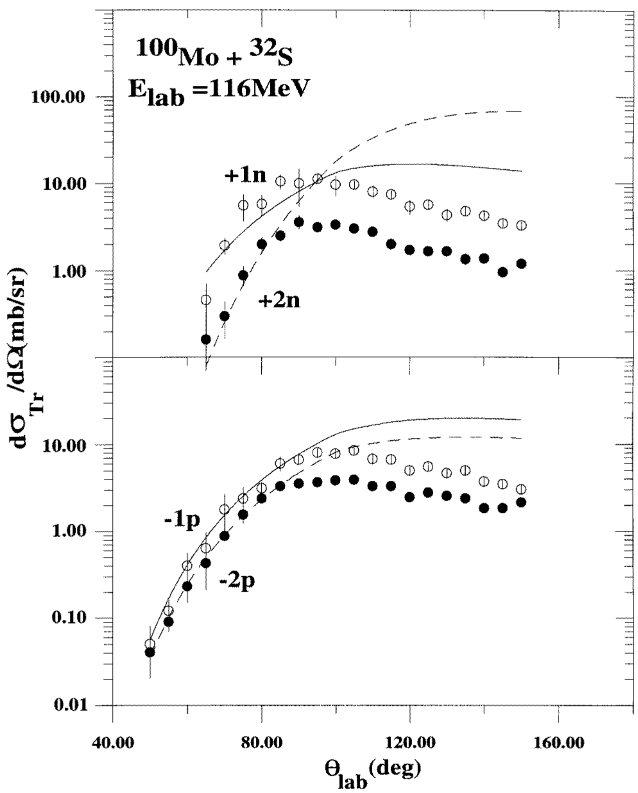

Figure 2. Transfer differential cross sections for the −2p, −1p, +1n and +2n channels for the $^{32}S + ^{100}Mo$ system. The symbols represent experimental data and the curves are obtained by fitting the data for the smallest angles.

$^{32}S + ^{92}Mo$ system, this effect was found to be much smaller.

Then, the coupled-channel calculations were performed by the CCFUSB code. The potential parameters for this code were determined in order to agree with the parameters obtained from the elastic scattering data [4]. The results for the $^{32}S + ^{100}Mo$ system show some small contributions to the fusion cross section enhancement due to the coupling of the −1p, −2p and +1n channels, and a large contribution from the +2n channel, at the low-energy limit. The overall results, including the 2^+ and 3^- inelastic channels of projectile and target, and the four transfer channels, are shown by the full curve in figure 3. At the

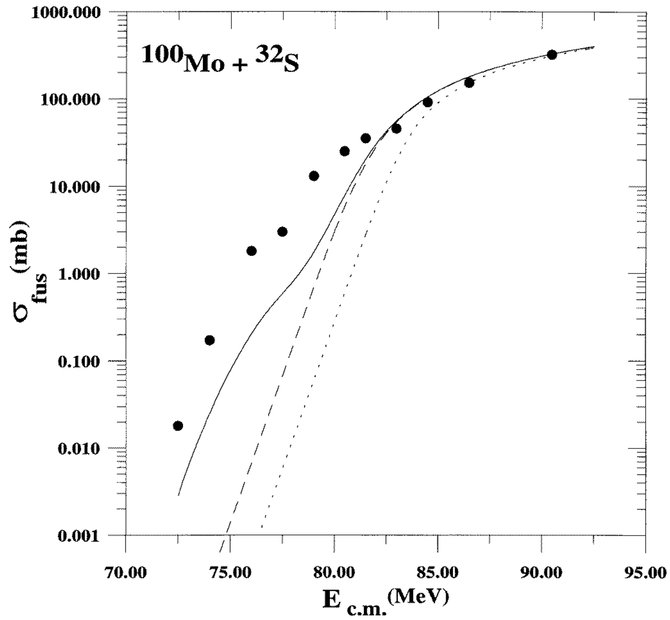

Figure 3. Coupled channel calculations for the $^{32}S + ^{100}Mo$ system. The dotted curve is the uncoupled calculation, the broken curve is the result considering just inelastic couplings and the full curve is obtained when the transfer channels are also coupled.

near-barrier energy region, the enhancement is not yet enough to explain the fusion cross section data. For the $^{32}S + ^{92}Mo$ system, the additional contribution to the fusion from the -1p and -2p transfer channels can hardly be distinguished from the inelastic couplings.

These results confirm the previous interpretation obtained from other systems, that transfer reactions which occur at distances not so far from the position of the Coulomb barrier are the natural candidates to behave as a doorway to fusion.

4. Connections between different approaches, concerning transfer and fusion

From the previous analysis one can conclude that the fusion process may start before the Coulomb barrier is transposed, since the transfer reaction may behave as a doorway to fusion. This means that the absorption of flux from the elastic channel, leading to fusion, may start at distances even larger than the position of the Coulomb barrier. A macroscopic picture of that may be thought of as the neck formation between the pair of colliding nuclei. This is also in agreement with the predictions of the direct reaction formalism developed by Udagawa *et al* [9]. The simultaneous analysis of elastic scattering and fusion data for several systems indicate a long-range fusion absorptive potential. Our group has applied this formalism for the $^{16}O + ^{59}Co$ system [10], for which a previous analysis of the fusion excitation function [11] had shown the need of the coupling of transfer channels, in order to fit the data. Following this formalism, the imaginary part of the optical potential W_A is divided into two terms: W_F is the part that accounts for the absorption into the fusion channel, and W_D corresponds to the absorption into direct superficial channels. One assumes $W_A = W_F$ for $r < R_F$, where R_F is the range of the fusion potential and the only free parameter in the fitting procedure of the fusion excitation function. We have found a result

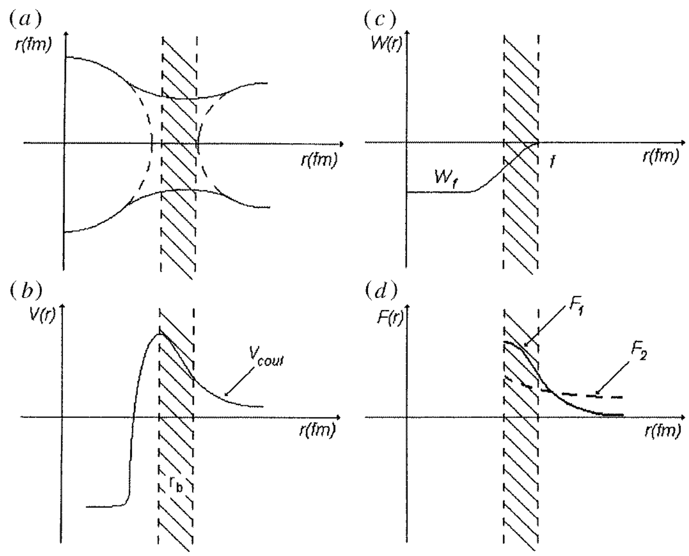

Figure 4. Schematic representation of different reaction quantities as a function of the distance of the separation between the colliding nuclei. (*a*) The neck formation between the two nuclei. (*b*) The Coulomb barrier of the system. (*c*) The long-range fusion absorptive potential. (*d*) The form factors of two different transfer channels: F1 (full curve) corresponds to a steep form factor, large at the barrier position and a doorway to fusion; F2 (broken curve) should not contribute to the fusion enhancement. The shadow region represents the region where the point of no return from fusion has been reached, before the barrier is penetrated.

similar to those obtained by Udagawa *et al* [9], with the range of the fusion potential slightly larger than the Coulomb barrier position. Figure 4 shows, schematically, the interpretation of a complex reaction mechanisms, as a function of the separation distance of two colliding nuclei. In figure 4(*d*), the F1 curve corresponds to a very steep transfer form factor, with a large value near the barrier, as the +2n channel for the $^{32}S + {}^{100}Mo$ system—the associated transfer channel should be an important doorway to fusion. The F2 curve corresponds to the opposite situation.

5. Conclusions

This paper is concerned with the role played by transfer channels as a doorway to the fusion process. From the semiclassical formalism and the calculations performed, one can say that, at large distances, transfer is a simple direct one-step process, with no strong interplay with fusion. However, when the transfer reactions take place at small distances, there might be a ‘missing’ cross section at backward angles, relative to the theoretical predictions. This can be interpreted as follows. Part of the flux that would react as a transfer, actually goes to fusion in a multistep process. The channels for which this effect happens should be strongly coupled to fusion and could contribute significantly to enhance the fusion cross section. This interpretation has been confirmed for the different systems studied, and it is compatible with the neck formation picture and the long-range fusion absorptive potential and the neutron flow model [12]. From these approaches one concludes that the point of no return from fusion may be reached at distances beyond the position of the Coulomb barrier. The fusion enhancement arises not just by the splitting of the barrier, but also by the additional attraction in the incident channel, as a result of the strong absorption under or even outside the barrier.

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