Theory of transfer reactions in peripheral heavy-ion collisions

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(Received 26 April 1989; revised manuscript received 5 October 1989)

The total absorption from the elastic channel due to transfer and inelastic processes in peripheral heavy-ion collisions at low bombarding energies is calculated in a microscopic coupled-channel approach. It is demonstrated for the first time that considering the depopulation of the entrance channel as an incoherent depopulation due to transfer processes is a good approximation. Using the corresponding absorptive potential within the framework of the Born approximation to calculate the transfer to individual channels, the results of full coupled-channels calculations are accurately reproduced.

In the past few years it has become more and more apparent that the coupling among different channels is essential to describe the dynamics of heavy-ion reactions at energies around the Coulomb barrier. The observed large fusion cross sections below the barrier,[1] the effect of the polarization potential in elastic scattering,[2] and the fluctuations observed in the excitation function of deep-inelastic reactions[3] are typical phenomena testifying to the interweaving of inelastic and transfer processes in reactions between heavy ions.

Unfortunately, even the most ambitious microscopic calculations, in the various versions of coupled channel Born approximation, time-dependent Hartree-Fock theory, etc., cannot explicitly treat all the channels involved in these phenomena. The vast majority of these channels are dealt with in an average fashion by introducing an absorptive potential describing the depopulation of the entrance channel.[4] The understanding of the mechanisms which determine the absorptive potential and its use in the description of heavy-ion reactions is an essential issue for a general theory of these phenomena.

Microscopic calculations indicate that the nuclear reactions which are most effective in depopulating the entrance channel are transfer processes.[5] The resulting potentials compare well with empirical potentials extracted from the analysis of the experimental data.[6] A complete microscopic theory of the absorptive potential is, however, still missing. In particular the role played by quantal coherence leading to memory-conserving processes is still an open question. Furthermore, in most theoretical analyses of quasielastic heavy-ion reactions, the absorptive potential is obtained by fitting the corresponding elastic cross section. The range of validity of this prescription has never been checked quantitatively in realistic cases.

In the present paper microscopic coupled-channel calculations of peripheral heavy-ion collisions are carried out taking into account the single particle degrees of freedom, and the quantal probabilities for the system to remain in the entrance (elastic) channel are determined. These calculations are used to check the reliability of the method for calculating the total absorption from the elastic channel introduced in Ref. 5 and shortly summarized below. This absorptive potential is then used to determine quantitatively the accuracy of the Born approximation for calculating transfer reaction probabilities in a realistic case of complex reactions among heavy ions. The results support the procedure of extracting a local absorptive potential from the probabilities of individual transfer processes taking place between the two ions. According to Ref. 5, in fact, once the total absorption is known as a function of the impact parameter, one can construct an ion-ion absorptive potential as a function of the relative distance between the two nuclei.

Making the ansatz that the transfer processes are independent of each other, the total probability of remaining in the ground state can be written as

$$P_0=\prod_n(1-p_n)\approx\exp\left[-\sum_n p_n\right], \tag{1}$$

where p_n is the probability associated with the transfer

channel n in the collision. We have here furthermore assumed that many transitions n contribute to the depopulation. This assumption also implies that we may calculate P_0 assuming the transfer probabilities p_n to be small compared to unity. Consequently they can be estimated making use of first order perturbation theory.

Within the same scheme, the probability for the system to be in a particular transfer channel s is given by

$$P_s = p_s \prod_{n \neq s} (1-p_n) \approx p_s \exp\left[-\sum_n p_n \right] . \quad (2)$$

This formula has been at the basis of all studies of transfer processes to individual channels. We have relied on its range of validity to obtain nuclear structure information from heavy-ion reactions. It is not first order perturbation theory, but relies upon the assumption that the transfer channel singled out for detailed study is one out of many. For small impact parameters, where the assumption that p_s and p_n are small breaks down, the expressions (1) and (2) are quite unreliable. In this region, however, the probabilities P_0 and P_s are quite negligible and the error is of no consequence for the cross section.

Although the potentials calculated following the above prescription seem to provide a correct overall picture of the data,[6] the theory still lacks a solid foundation, which can only come by comparing the prediction of the model against more exact results, e.g., as obtained from time-dependent Hartree-Fock theory (TDHF).[7] No calculation, however, exists within this framework, at least to our knowledge, projected on a single channel. An economic yet accurate approximation to the TDHF, at least for peripheral collisions where one does not expect the nuclei to deform appreciably, is provided by the time-dependent shell model proposed by Bertsch and Schaeffer[8] and further developed in Ref. 9. The two colliding nuclei are described by Saxon-Woods potentials which move on classical trajectories of relative motion. Nucleons can be excited and exchanged between the two nuclei, leading to a treatment of the time-dependent many-particle system which resembles quite accurately TDHF except for the fact that the self-consistent shell model potentials are not modified during the collision.

The Hamiltonian describing the intrinsic degrees of freedom is

$$H(t) = H_0 + V(t) , \quad (3)$$

where $H_0 = H_a + H_A$ is the sum of the Hamiltonians of the two colliding nuclei, while

$$V(t) = \begin{pmatrix} W_a & Z \\ Z^\dagger & W_A \end{pmatrix} \quad (4)$$

describes the interaction between them. The inelastic excitations inside nucleus i are taken into account by W_i, while transfer processes between the two nuclei are described by Z and $Z^\dagger$. Solving the time-dependent equation

$$i\hbar\dot{\rho} = [H,\rho] \quad (5)$$

for the one-body density matrix, one can calculate the expectation value for one-body observables along the classical trajectory. Moreover, one can calculate the probability that the system is in a definite configuration.[10] In particular the probability for the system to remain in the entrance channel is given by the expression

$$P_0 = \det[\rho_{b_0 b_0'}(t)] , \quad (6)$$

where b_0 and b_0' indicate the set $\{b_0\}$ of occupied orbitals in the initial configuration.

As an example, we have studied the collision ^{60}Ni+^{60}Ni at $E_{lab}=240$ (and 360) MeV, as a function of the impact parameter ranging from very peripheral $b=8.2$ (10.) fm down to more central collisions with $b=4.7$ (7.) fm. For simplicity only transfer processes have been considered. The ion-ion potential of Ref. 11, obtained through a folding potential, has been used to calculate the elastic trajectories. The level scheme shown in Table I was used to describe the motion of neutrons and protons in the single particle states and microscopic form factors describing the transfer among these levels

TABLE I. Scheme of the single particle levels used for the calculations.

$^{60}_{28}$Ni				
Neutrons		Protons		
Level	Energy (MeV)	Level	Energy (MeV)	
$1g_{9/2}$	−3.0			
$2p_{1/2}$	−8.0			
$if_{5/2}$	−8.8	$2p_{3/2}$	−0.6	
				E_F
$2p_{3/2}$	−9.35	$1f_{7/2}$	−3.8	
$1f_{7/2}$	−12.8	$2s_{1/2}$	−9.8	
		$1d_{3/2}$	−10.3	
		$1d_{5/2}$	−13.0	

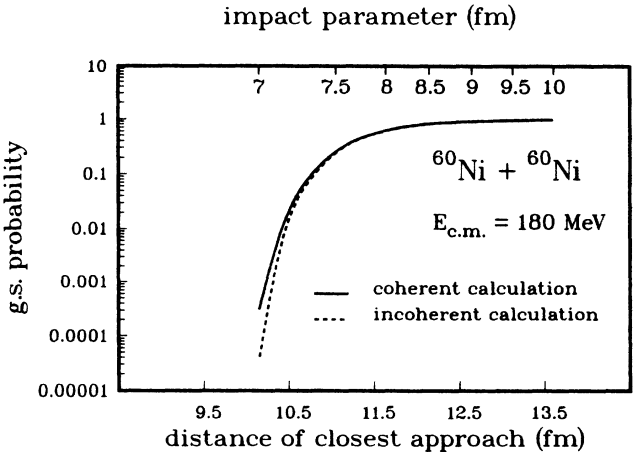

FIG. 1. The probability to remain in the entrance channel is shown as a function of the distance of closest approach. The corresponding impact parameter is indicated in the upper part of the figure. The solid curve is the coupled-channel calculation taking into account coherence and higher-order effects, while the dashed one is the estimate obtained using the procedure of Ref. 5 and first order perturbation theory. The two curves are discontinued close to the orbiting trajectory.

have been calculated.[12]

In Fig. 1 the probability given by Eq. (6) to remain in the ground state is shown as a function of the distance of closest approach for the reaction at $E_{lab}=360$ MeV. The solid curve gives the exact result of the time-dependent shell model, while the dashed curve displays the calculation obtained making use of Eq. (1) and calculating the quantities p_n in first order perturbation theory. The two estimates are in good agreement as long as the trajectory is peripheral, i.e., for distances of closest approach larger than ~ 10.5 fm (the sum of the radii being 9.15 fm). From there on, decreasing the impact parameter, higher-order effects diminish the depopulation in the entrance channel. When the distance of closest approach is 10.15 fm the result of the shell model calculation, $3.1\cdot 10^{-4}$, is a factor of 8 larger than the outcome of calculations carried out making use of Eq. (1), $4.\cdot 10^{-5}$: In any case, both values are very small.[13]

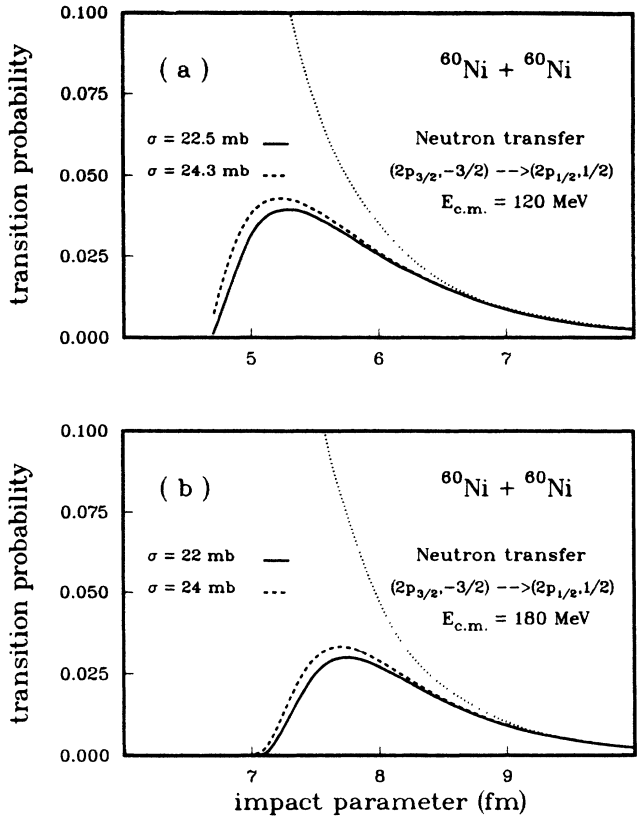

FIG. 2. The transition probability for the most intense neutron transfer process is shown as a function of the impact parameter. The single particle transition is indicated as (nlj,m) where m is the magnetic quantum number in a coordinate system with z axis along the angular momentum of relative motion. The solid curve is the coupled-channel calculation, while the dashed one is the estimate obtained through Eq. (2). The dotted curve is the first order transition probability estimate of p_s. Two different incident energies are considered. The angular momenta corresponding to the maximum of the probability at $b=5.3$ fm for $E_{c.m.}=120$ MeV and $b=7.7$ fm for $E_{c.m.}=180$ MeV are 70. $\hbar$ and 124. $\hbar$, respectively. The cross sections obtained by integrating over the impact parameter are also indicated.

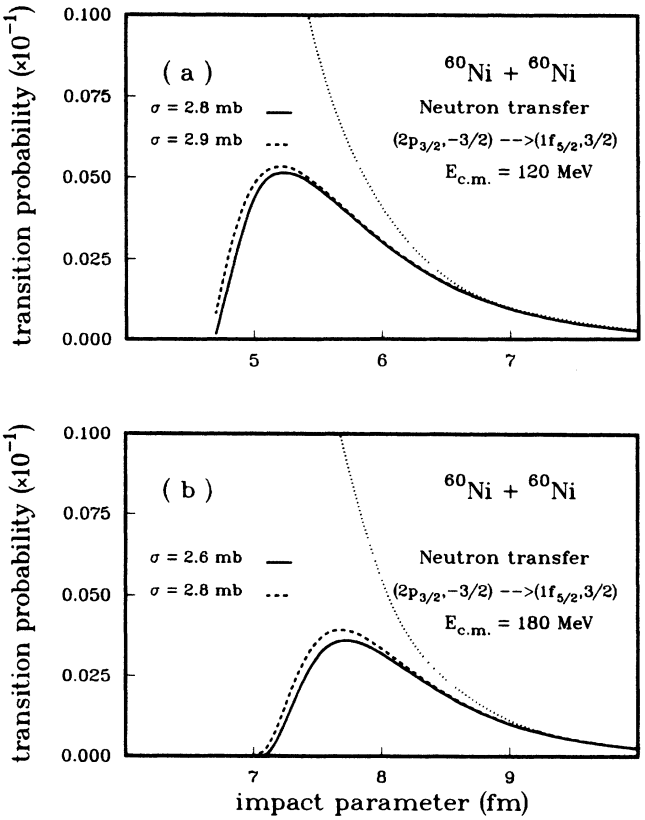

FIG. 3. The same as Fig. 2, but for a less intense neutron transfer process.

In Figs. 2 and 3 single particle transition probabilities for neutron stripping to individual states are shown as a function of the impact parameter and for the two energies considered. The solid curve represents the coupled-channel calculation obtained multiplying the probability of having a specific configuration s for neutrons $P_s^{neut}=\det[\rho_{b_s b_s'}(t)]$ with that of remaining in the entrance channel for protons $P_0^{prot}=\det[\rho_{b_0 b_0'}(t)]$. The dashed curve is the result obtained using Eq. (2). As was to be expected the simple approximation breaks down for small distances where p_s (dotted curve) approaches unity. In this region the contribution to the cross section is, however, small due to a large absorption. The more important deviation close to the maximum is governed by the magnitude of p_s for the corresponding impact parameter. For the (strong) transition $2p_{3/2,-3/2}\rightarrow 2p_{1/2,1/2}$ where the second subindex corresponds to the magnetic quantum number, one finds at the maximum $p_s\sim 0.1$, which accounts for the error slightly smaller than 10%, while for the other transition both p_s and the error are smaller. The estimated values of the transfer cross section are also shown in the figures.

We conclude that, in peripheral heavy-ion collisions, the total absorption depopulating the elastic channel can be accurately described taking into account the coupling to the transfer channels assuming that they are independent of each other and calculating the corresponding probabilities making use of first order perturbation theory. Within the same physical situation the Born approximation provides a description of transfer processes to individual states which is quite accurate.

We would like to acknowledge several fruitful discussions with G. Pollarolo and J. H. Sørensen.

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[12]In these calculations for the form factors a code written by G. Pollarolo, in the small recoil approximation, was used.

[13]The more serious discrepancy which we obtained in a previous work (Ref. 9) for the system $^{40}Ca+^{40}Ca$ was due to an inconsistency in the form factors used for the comparison. New calculations for $^{40}Ca+^{40}Ca$ show the same behavior as for $^{60}Ni+^{60}Ni$.