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Interplay of break-up and transfer processes in reactions involving weakly-bound systems ¹

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Abstract. In this note we illustrate some applications of a simple model which has been devised to clarify the reaction mechanism and the interplay of different reaction channels (elastic, inelastic, transfer, break-up) in heavy-ion collisions. The model involves two potential wells moving in one dimension and few active particles; in spite of its simplicity, it is supposed to maintain the main features, the properties and the physics of the full three-dimensional case. Special attention is given to the role of continuum states in reactions involving weakly-bound systems, and different approximation schemes (as first-order or coupled-channels) as well as different continuum discretization procedures are tested. In the case of two active particles the reaction mechanism associated with two-particle transfer and the effect of pairing interaction are investigated.

1. Introduction

One- and two-particle transfer induced by heavy ions are rather complex processes, difficult to describe from the point of view of the underlying nuclear structure as well as the point of view of the reaction mechanism. This latter is essentially due to the coupling of the transfer channels to the other competing and interplaying channels, starting from the elastic to the inelastic, break-up and fusion ones. For these reasons one typically uses the expedient of resorting to a number of reaction models and approximation schemes (such as coupled-channels, first-order approximation, space truncation, limitation to two-body processes, “effective” optical potentials and form factors, etc).

Particularly critical in the case of weakly-bound systems is the treatment of continuum states and the associated procedures of continuum discretization. For nuclear structure models the coupling to continuum states is popularly included by discretization procedures (box, HO, THO, etc), all aiming at providing a set of confined and square-integrable states with positive energy. These procedures are rather successful as long as one is describing structure properties of isolated systems. In the case of reaction processes that naturally involve asymptotic scattering conditions, the popular choice is provided by the CDCC approach, in which the basis states are obtained by properly “bunching” true scattering states.

¹ Work done in collaboration with Antonio Moro and Kouichi Hagino

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The control of all the approximations embedded in these approaches is not an easy task. For this reason we will simplify the problem by assuming particles to move just in a one dimension, and projectile to follow a classical fixed trajectory. In spite of the drastic assumption, the problem may maintain the main features, the properties and the physics of the full three-dimensional case. On the other side, due to its simplicity the scattering problem can be in many cases solved “exactly” and therefore serves as a benchmark for all approximation schemes. In addition this simplified scheme can shed some light on the “reaction mechanism”, namely on the description of the process in terms of single or repeated action of the external field in a perturbative expansion. In particular our choice allows us to properly treat in a simple way the action of the pairing correlations and therefore to clarify the long-standing issue of their connection with two-particle transfer (or two-particle break-up processes) and of the competition of sequential vs simultaneous process.

Additional applications of the model to one and two-particle systems can be found in Refs.[1, 3]. A similar line of research, in one and three dimensions, has been also successfully carried out by Samarin and collaborators [2].

2. Systems with one active particle

We first consider processes involving just one active particle, initially sitting on a single-particle level of a one-body potential and feeling the action of a second moving potential, as exemplified in Fig. 1.

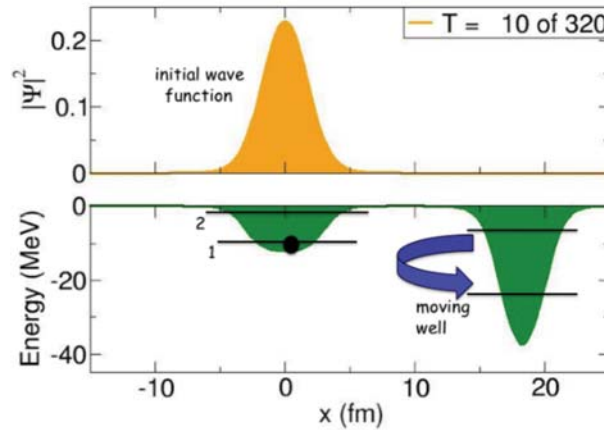


Figure 1. Schematic picture of the process. The upper frame gives the initial wave function probability, while the fixed and moving wells are shown in the lower frame.

Therefore, we have to solve the single-particle time-dependent equation

$$i\hbar \frac{\partial}{\partial t} \Psi(x, t) = \mathcal{H}(x, t) \Psi(x, t) \quad \text{with} \quad \mathcal{H}(x, t) = -\frac{\hbar^2}{2\mu} \frac{\partial^2}{\partial x^2} + V_T(x) + V_P(x - x_P(t)). \quad (1)$$

The choice of the parameters entering in the calculation will lead to different structural and kinematical conditions, corresponding to rather different physical situations and simulating different bombarding energy regimes, impact parameters, and Q-values for particle transfer: essentially one has to fix the parameters characterizing the two wells V_T and V_P (consequent energies of single-particle states in both potentials), initial condition (selecting one of the single particle state in target potential), and input for the projectile trajectory $x_P(t)$.

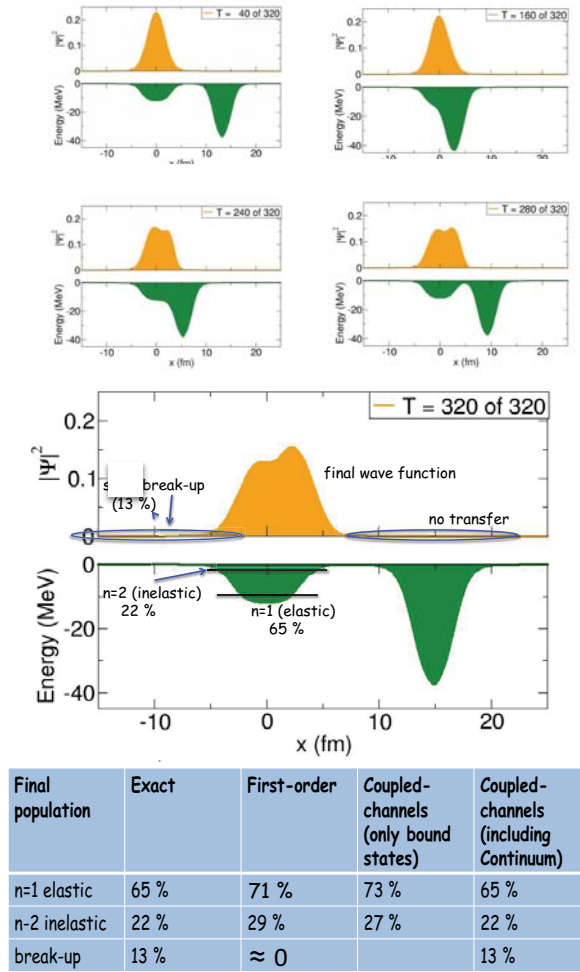


Figure 2. Evolution of the single-particle wave function (and corresponding evolution of the two wells) at different times. The final situation is better shown in the enlarged frame at the bottom of the figure. The parameters for this calculation are given in text. The table at the bottom refers to different models and approximation schemes.

As a first example of the evolution of the wave function we chose a case in which both the target and the projectile potential wells admit two bound levels (with binding energies energies at 2.0 and 9.0 MeV for the fixed target and 27.0 and 9.0 MeV for the moving one). Initially, the particle is sitting in the target ground state and the projectile trajectory is $x_p(t) = x_0 + vt + \frac{1}{2}at^2$; initial energy, reduced mass μ , distance of closest approach x_0 and acceleration³ are given respectively as 1 MeV, 0.975 amu, 3 fm and $4500/\hbar^2$ fm/ps². The evolution of the wave function with time is illustrated in Fig. 2. The different frames refer to different times (the total collision time is divided in 320 steps and the corresponding time is quoted in each frame), and in each frame the upper part gives the square of the one-particle wave function while the lower frame gives the actual position of the two potentials at the same time. At the end of the process, by taking the overlap of the final wave function with the initial wave function and the wave functions of the single-particle states of each well one can determine the probability of elastic,

³ For this case time is expressed in unit of \hbar .

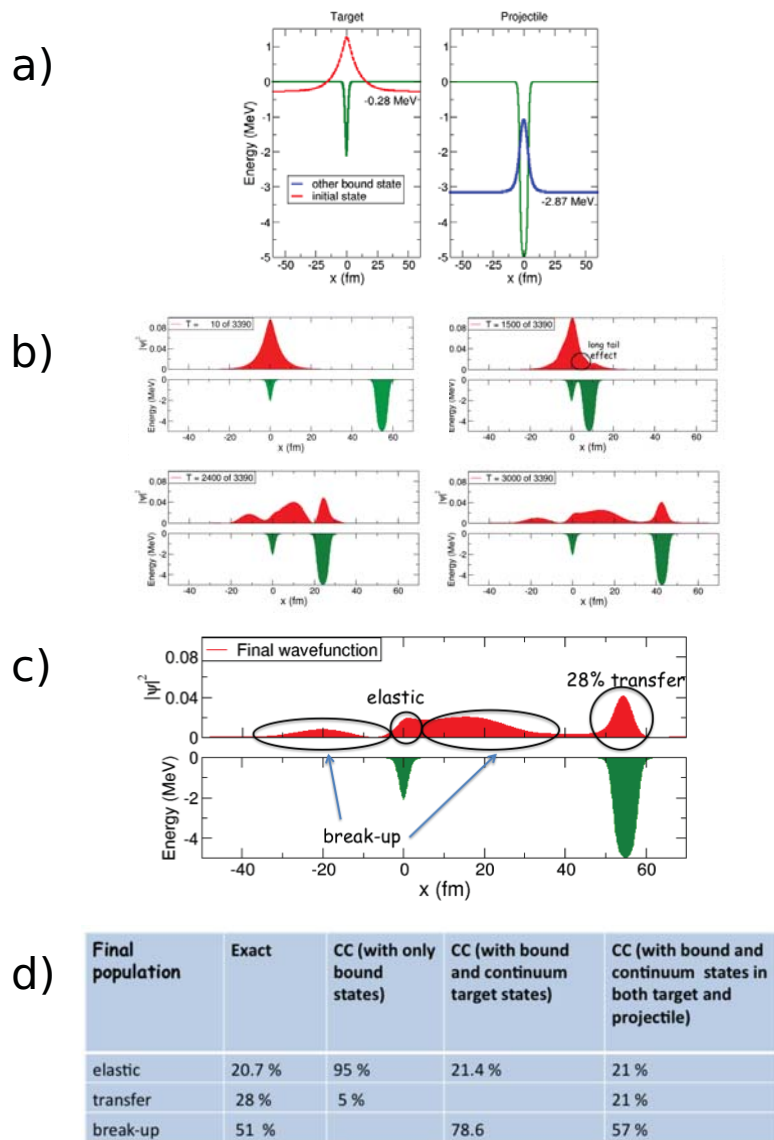


Figure 3. Cf. caption to Fig.2.

inelastic, break-up and of one-particle transfer process. Note that a part of the wave function (although not easily detectable in the figure) appears outside the two wells, indicating a not negligible break-up probability ($\approx 13\%$). On the other side with these kinematical parameters the condition of optimal Q-value seems to inhibit the transfer process.

The table at the bottom of Fig. 2 gives, in comparison with the “exact” values, the values obtained in first order approximation and in a coupled-channels scheme. This is done within the standard time-dependent coupled-channels formalism by constructing the non-diagonal transfer formfactors and expanding the wave function into the dual basis associated with the two wells (cf. Ref. [4]). The continuum is included via a set of pseudostates obtained by discretization procedure in a large box. Results obtained within other procedures are very similar [1].

The "first-order" population of the elastic channel is obtained from the flux conservation as $P_{el} = 1 - \sum_i P_i$ in terms of the first-order populations P_i of the different reaction channels. The importance of the full multistep couplings (including continuum, last column) is evidenced by the population of the continuum (break-up) states that, negligible in first order, can only be obtained via the excitation of the weakly-bound excited state.

As a second example we consider a physical situation in which the transfer and excitation to the continuum (breakup) play a more significant role. This is achieved considering as initial state a weakly-bound state of the target well ($E_b = -0.28$ MeV), as displayed in Fig. 3a. In this case the projectile well follows the trajectory $x_p(t) = x_0 + \sqrt{\rho^2 + (vt)^2} - \rho$ proposed by Ref. [4]; this trajectory differs from the previous one in the fact that the projectile is changing its acceleration over the distance ρ thus simulating the nuclear interaction with the target, in fact at $t = \pm\infty$ the trajectory tends to a uniform motion with zero acceleration. Incident energy, reduced mass μ , ρ and distance of closest approach x_0 are given respectively as 5 MeV, 1.001 amu, 2 fm and 4 fm. The corresponding evolution of the wave function is shown in the different frames of Fig. 3b. The weak-binding situation leads to an initial wave function with a longer tail than in the previous case. As a consequence, part of the wave function is already transferred to the second well even before the overlap of the two wells (second frame). At the end of the process (cf. Fig. 3c) there is a large transfer probability, but the weak-binding situation has also led to a large fraction of the wave function outside of the two wells, therefore associated to large break-up processes.

The table in Fig. 3d compares the "exact" final probabilities with those obtained within the time-dependent coupled-channels approach. Three different model spaces are compared. In the first calculation we have included only target and projectile bound states. The second includes the target bound levels plus the first 50 continuum pseudostates obtained with the BOX method with a radius equal to 500 fm (this corresponds to an energy cutoff in the continuum of 0.5 MeV). The last (and more complete) calculation uses the target and projectile bound states plus the first 100 pseudostates of target and projectile continuum obtained with the BOX method with a radius of 40 fm (this corresponds to an energy cutoff in the continuum of 300 MeV). It is evident that, even in the simple one-dimensional case, the complexity induced by the different competing channels and the strong role of continuum in the case of weakly-bound systems implies the necessity of a very large model space in order to obtain an acceptable agreement with the exact results.

3. Two-particle transfer processes and pairing interaction

We move now to the case of two-particle systems and two-particle transfer processes. Starting from the initial two-particle state generated by the fixed well we follow the time evolution of the two-particle wave function due to the action of the moving one-body potential. In addition to the one-body potentials the Hamiltonian includes a residual pairing-like interaction between the two particles, taken as a density-dependent delta interaction (i.e. acting only when the two particles are both inside the same well). Examples of the time evolution are given in Fig. 4, where initial and final wave functions are given as a contour plot as a function of x_1 and x_2 . The upper frames refer to the case in which the pairing interaction is switched off (uncorrelated case) and the two particles sit in one single-particle state. From the final wave function we can separate different final states: elastic/inelastic, one-particle transfer, one-particle break-up, two-particle transfer and finally two-particle break-up. In this specific case break-up processes (both one and two-particle) are negligible. The total one-particle probability P_1 amounts to about 40%, while the two-particle transfer probability P_2 amounts to about 4%. Due to the absence of correlations the transfer process is therefore produced by the successive transfer of single particles. In such a situation, in a perturbative approach, we expect a pair transfer probability $P_2 \approx (P_1)^2/4$, which is precisely the value obtained in our calculation.

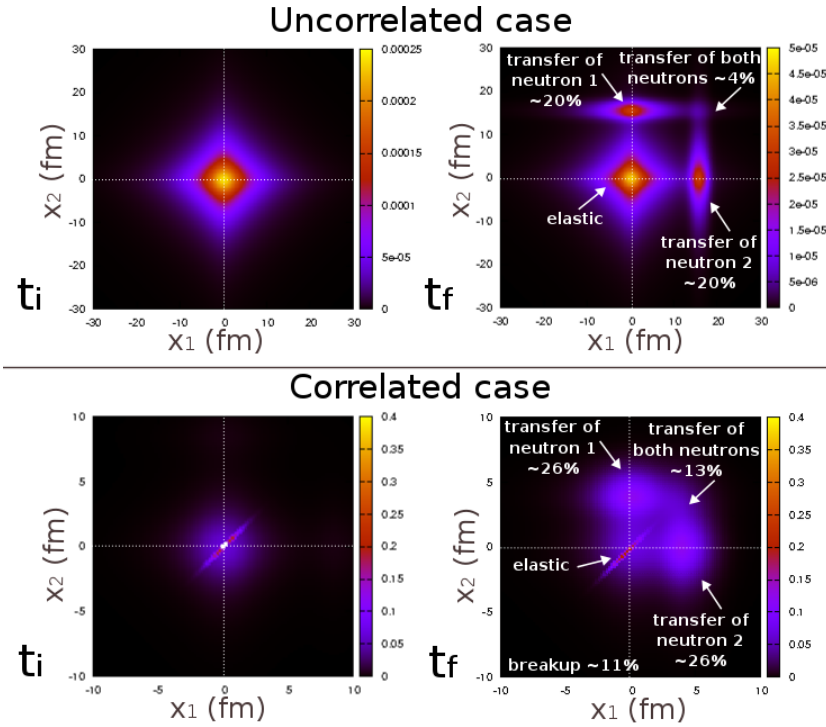


Figure 4. Square of the two-particle wave function shown as a contour plot as a function of x_1 and x_2 . The four frames refer to the uncorrelated (upper part) and correlated case (lower part). Initial wave functions in the left column, final ones in the right column.

We switch now to the case with correlations. The corresponding initial and final wave functions are shown in the lower frames of Fig. 4. The initial wave function has been obtained by diagonalizing the residual pairing interaction in the two-particle basis. Continuum states have been included by a discretization procedure (cf. Ref.[5]). Note that due to the correlation the probability of finding both particles on the same side is now clearly favored. The effect of this initial correlation will propagate during the scattering process and affect the final wave function (lower-right frame). At the end of the process one gets a total single-particle probability P_1 equal to 52 % and a pair transfer probability P_2 equal to 13%. This latter value is a factor 2 larger than the uncorrelated estimate $P_2 \approx (P_1)^2/4$. This factor 2 represents therefore the enhancement factor due to the pairing correlation. From the point of view of the reaction mechanism, the processes results from the coherent contribution of successive one-particle transfers via the full set of levels in the intermediate one-particle system (continuum states included).

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