Role of Transfer Channels in Heavy-ion Reactions

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Abstract. Transfer reactions constitute the dominant contribution to the back-angles quasi-elastic excitation functions measured in collisions between heavy-ions. This is shown by using a semiclassical model that incorporates both the excitation of surface modes and the particle transfer degrees of freedom.

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INTRODUCTION

Exploiting the very short wave length of the relative motion, one can use simple classical arguments to understand the main characteristics of a heavy ion reaction by introducing a potential that is function of the center-of-mass distance. With this simple ingredient it is, for example, possible to provide a reasonable estimation of the total reaction cross section and to predict at which angle the yields are mostly concentrated. The ion-ion potential has as its most conspicuous feature a barrier originating from the balance between a long-range repulsive Coulomb and a short-range attractive nuclear components.

Despite its merits this simple potential description has been readily recognised as leading to important shortcomings. From elastic scatterings one learned [1] that the potential must be energy dependent and must have an imaginary part. From fusion reactions one learned [2] that the simple potential description strongly under predicts fusion cross sections at very low energies.

To arrive at a consistent description of the data one has to include in the reaction mechanism couplings that take into account the intrinsic states of the two nuclei. These variables are associated to single particles and collective modes, surface vibrations and rotations. In the case of fusion reaction it has been shown that the couplings to surface modes [3] account for most of the missing cross section. For these reactions the effect of the couplings preclude us from talking about a single barrier but it is more convenient to talk about a distribution of barriers (several Mev wide) around the nominal Coulomb barrier of the ion-ion potential. These barrier distributions can be extracted directly from the fusion excitation functions by taking the second energy derivative of the energy weighted fusion cross section [4]. More ricently, it has been suggested that the same information on the barrier may be extracted from the energy dependence of the quasi-elastic cross section at backward angles [5]. In this case the barrier distributions are obtained by the energy derivative of the quasi-elastic excitation functions.

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The importance of transfer reactions, i.e. of couplings to single-particle degrees of freedom, in the description of a heavy-ion reaction has been underlined in several papers [6, 7, 8]. These transfer degrees of freedom are weak, very numerous and span a wide range of Q-values. They are governed by long range formfactors and are providing the main contribution to the absorptive and polarization potential. Unfortunately fusion reactions have been very elusive in pinning down the role of particle transfer, many good fits of the data could, in fact, be obtained by including only surface modes.

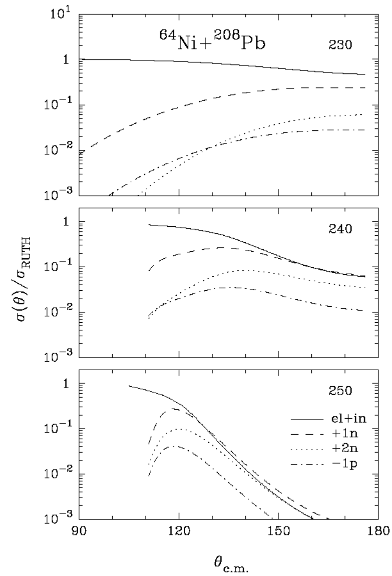

FIGURE 1. Center-of-mass angular distributions for elastic plus inelastic and some transfer channels. The cross section are plotted as ratio to the Rutherford cross section. The label in each frame indicates center-of-mass bombarding energy in MeV.

Quite recently quasi-elastic excitation functions have been measured [9] for several systems, whose use have been proposed for cold-fusion production of super-heavy elements, and the corresponding barrier distributions extracted. Because of the final energy, mass and charge resolution of the experiment, the quasi-elastic reactions, beside elastic and inelastic channels, receive contributions also from transfer channels, both neutrons and protons. As a consequence these reactions are providing a very interesting tool to investigate the role of transfer reactions at near barrier energies.

THE MODEL

To analyse the quasi-elastic reactions we use a semiclassical model, GRAZING [12, 13, 14, 15], that generalizes the well known theory for Coulomb excitation by incorporating the effects of the nuclear interaction in the trajectory and in the excitation process and by including the exchange of nucleons between the two partner of the reaction. The model solves, in an approximate way, the system of semi-classical coupled equations

$$i\hbar\dot{c}_\beta(t) = \sum_\alpha < \beta|V_{int}|\alpha > c_\alpha(t)e^{\frac{i}{\hbar}(E_\beta - E_\alpha)t + i(\delta_\beta - \delta_\alpha)} \tag{1}$$

where c_β gives the amplitude for the system to be, at time t, in channels β. This system of coupled equation derives from the Schrödinger equation by expanding the the total wave function in term of channels wave functions describing the states belonging to the different asymptotic mass partitions. The interaction V_{int} is responsible for the excitation of the surface modes and for the transfer of nucleons. The time-dependence of the matrix elements is obtained by solving the Newtonian equations of motion for the relative motion that develops in a nuclear plus Coulomb field. For the nuclear part the model uses the empirical potential of Ref. [16] and for the Coulomb component the two point charges expression is used.

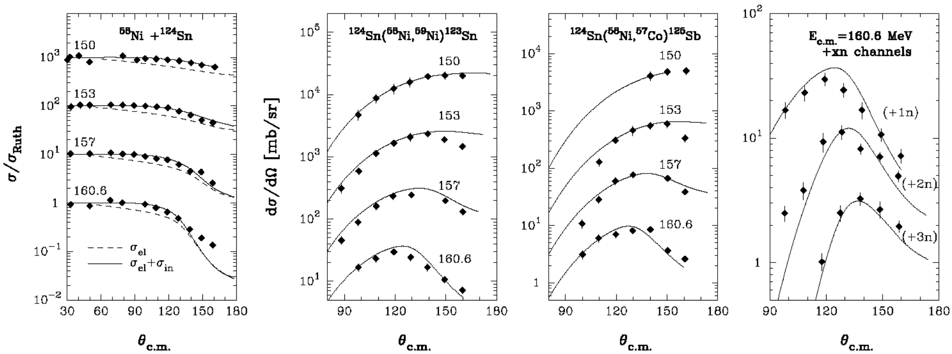

FIGURE 2. In the first column is shown the ratio to Rutherford of the elastic plus inelastic scattering (full line) in comparison with the experimental data. The pure elastic scattering (dash-line) is also shown. The following two columns display the calculated angular distributions of the inclusive one-neutron pick-up and one-proton stripping channels. The last column displays the angular distributions for some multi-neutron transfer channels at the indicated bombarding energy.

The model is able to calculate the distribution of the total reaction cross section among all binary final states but it is not able to follow the evolution of the di-nuclear complex up to the formation of the compound nucleus. All the flux that reaches the inner pocket of the potential is considered to lead to capture. The component of the interaction V_{int}, responsible for the exchange of nucleons, is constructed from the one-particle transfer formfactors calculated by using the parametrization of ref. [17]. This parametrization has been tested for several target and projectile combinations and it has been found to provide a quite good description of one-nucleon transfer reactions. The component of the interaction V_{int}, responsible for the excitation of the surface modes, is constructed by using formfactors that are proportional to the r-derivative of the ion-ion potential. In Fig. 1, for the ^{58}Ni plus ^{208}Pb system, are shown the calculated angular distributions for the elastic plus inelastic channels in comparison with the angular distributions of several transfer channels. It is clear from the figure that at large angles the quasi-elastic angular distribution (that is a sum over elastic, inelastic and transfer channels) receive sizable contributions from transfer channels. These transfer channels are the dominant one at the higher bombarding energies.

Before drawing conclusions one has to demonstrate that the above calculations describe adequately the main properties of grazing reactions. To this purpose we analyse the ^{58}Ni + ^{124}Sn system. This is one of the few systems for which we have complete measurements of all reaction channels in a wide energy range [18, 19, 20, 21, 22, 23, 24, 25, 26] and for which a coupled channels analysis [27], that includes inelastic and transfer channels, has been performed. From Fig. 2 is clear that the model gives, for all energies, a good description of the elastic angular distributions (first column), of the angular distributions for the inclusive cross sections of one-neutron pick-up, of one-proton stripping channels and of some multi-neutrons transfer channels (last three columns). In the case of elastic scattering the good description shown by the full line is obtained by adding to the true elastic (shown with a dash-line) all the inelastic channels. The shown results are very similar to the one obtained in ref. [27] where a quantum mechanical coupled-channels formalism has been used. This indicates that the semiclassical approximation (that is easily extensible to heavier systems) provides a quite good description of the reaction and gives reassurance over the present results.

QUASIELASTIC EXCITATION FUNCTION

To produce the excitation function of ref. [9] one calculates, for the different systems, the angular distributions of all the reaction channels shown in Fig. 1 in step of 1 MeV of bombarding energy and sums all the cross section taken at $\theta_{lab} = 172^o$. For all analyzed systems the quasi-elastic excitation functions are displayed in the top row of Fig. 3. The barrier distributions $B(E)$ obtained from the excitation functions with a three-point formula energy derivative, are shown in the central row. The points represent the experimental data of ref. [9]. Both barrier distributions and excitation functions are very well described by the theory. Interpreting the centroid of the barrier distributions as the position of the effective barrier E_B^{eff} one sees that the couplings give rise to a lowering of the Coulomb barrier of the entrance channels by 4$\sim$7 MeV depending on the systems. The full width-half-maximum of the barrier distributions, all of Gaussian-like shape, is of the order of 10$\sim$12 MeV and is almost constant for all the systems.

The contribution of the particle transfer channels is shown in the bottom row of Fig. 3 as the ratio of the transfer cross section to the total quasi-elastic one. It is clear that transfer channels give sizable contributions in all the energy range and are the dominant processes at the higher energies. The contribution of more massive transfer channels is at this angle negligible. The last column of Fig. 3 shows the prediction of the model for the collision of ^{76}Ge plus ^{208}Pb system that, in ref. [11], has been proposed for cold fusion production of superheavy elements.

An alternative illustration of the role of particle transfer channels is obtained by looking at the evolution of the barrier distribution as a function of the channels that are contributing to the quasi-elastic cross section. If for quasi-elastic we consider all the final states that belong to the entrance channel mass partition (i.e. only elastic plus inelastic channels) we obtain the quasi-elastic excitation functions and barrier distributions shown with dash-lines in Fig. 3. It is clear from the figure that the quasi elastic barrier distribution depends on what we consider quasi-elastic. It is thus difficult to have a direct comparison between quasi elastic and fusion barrier distributions, differences

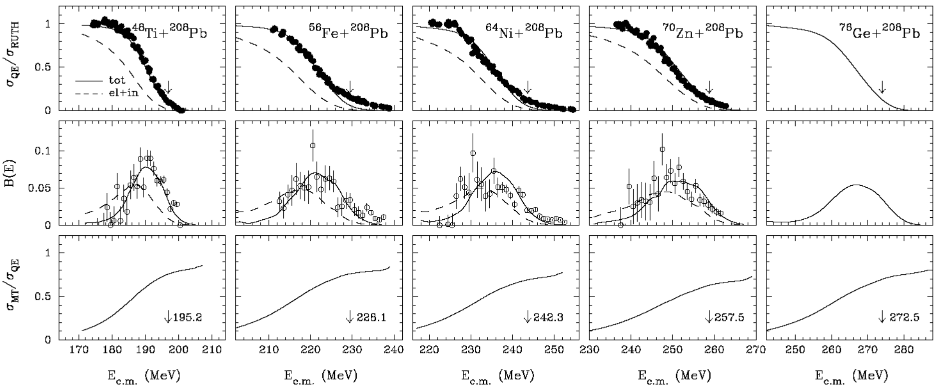

FIGURE 3. Quasi-elastic excitation function (top), barrier distribution (middle), ratio of transfer channels to the total quasi-elastic cross section (bottom). All the cross sections have been calculated at $\theta_{lab} = 172^o$. The down-arrows represent the Coulomb barrier for the entrance channels calculated with the empirical potential of ref. [16] and using a two points-charge Coulomb potential. The dash-lines are the results considering as quasi-elastic all the final channels belonging to the entrance channel mass partition. The data are from ref. [9]

may appear due to the different definition of what it is quasi-elastic. In pursuing these comparisons one should keep in mind that, while the barrier distribution extracted from fusion reactions gives an illustration of how the couplings modify the transmission coefficient through the barrier, the barrier distribution extracted from quasi-elastic scattering illustrates the modification of the reflection coefficient. For systems where fusion and quasi-elastic scattering exhaust most of the total reaction cross section, it is reasonable to expect equivalence between the two barrier distributions. This may not be the case for heavy system where the reaction is dominated by more complicated processes where the two reactants may overcome the Coulomb barrier but separate again with large energy losses and substantial exchange of mass and charge.

CONCLUSIONS

We have shown that the semi-classical theory offers a very powerful tool for the analysis of heavy-ion reactions. It allows a clear separation between relative motion variables and intrinsic degrees of freedom, surface vibrations and particle transfers. This separation is essential to pin down the relative role played by the different degrees of freedom in the large variety of nuclear processes. In this contribution we have seen that particle transfer channels give sizable contributions to the quasi-elastic cross sections in all the energy range. It has also been shown that the shape of the barrier distributions are related to the processes that are contributing to the quasi-elastic scattering.

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