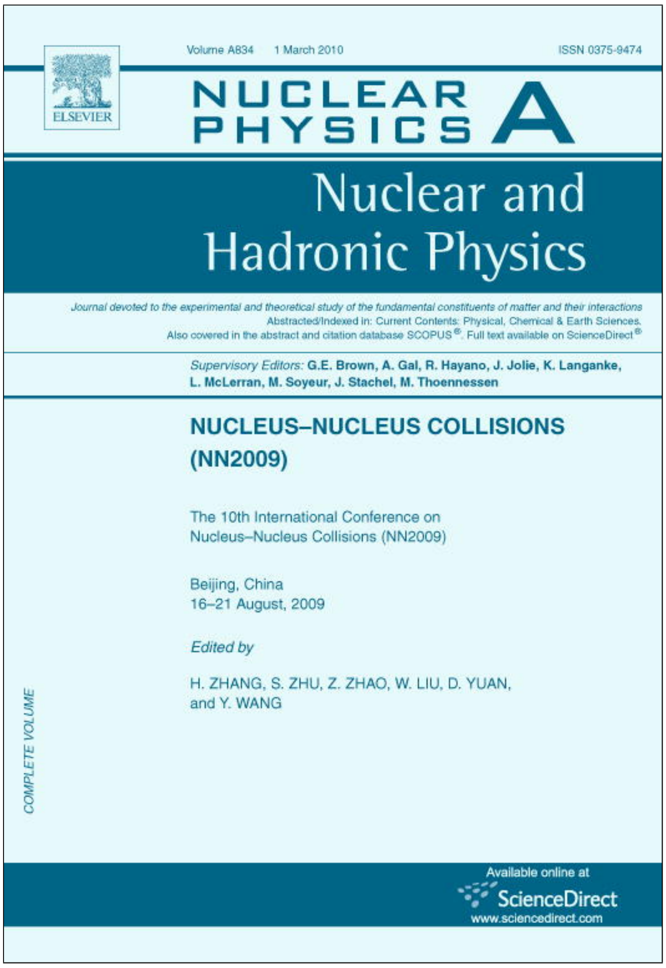
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Role of transfer reactions in heavy ion collisions: the quasi-elastic excitation function

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Transfer reactions constitute the dominant contribution to the back-angles quasi-elastic excitation functions 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.

1. INTRODUCTION

The collision between two ions may be modelled, in its simplest form, by replacing the complex ion-ion interaction with a potential function of their center-of-mass distance. This potential has two components a short-range nuclear attraction and a long-range Coulomb repulsion. These two components give rise to a barrier whose value plays an important role in the choice of the bombarding energy of any experiment. The simple potential model, despite is great merits, under-predicts the cross-section for fusion reactions. In Ref.[1] the concept of barrier distribution has been introduced to describe the large enhancements obtained in the estimation of the fusion cross section when the couplings to the intrinsic degrees of freedom are added in the model. Later on it has been shown [2] that this barrier distribution can be extracted from the experiment by taking the second order energy derivative of the energy weighted fusion excitation function.

For heavy systems, that may be important for the formation of super-heavy nuclei, one can not obtains directly the barrier distribution from fusion data (this process is very weak) but following the suggestion of ref. [3] it is possible to obtain the "same" information by exploiting the excitation function of quasi-elastic processes at backward angles (in this case the barrier distribution is obtained by taking the first energy derivative). Without entering in the discussion if quasi-elastic processes and fusion reactions will lead to the same barrier distributions [4] and leaving out its actual interpretation I will illustrate how the quasi-elastic excitation function can be calculated by using a semiclassical model that incorporate both surface degrees of freedom and transfer processes. After a short introduction to illustrate the model I will show the results [5] for several projectile and target combinations for which the quasi-elastic excitation function has been measured [6].

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2. GRAZING AND QUASIELASTIC EXCITATION FUNCTIONS

The semiclassical model, GRAZING [7–10] 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 partners of the reaction. The model solves, in an approximate way, the system of semi-classical coupled equations

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

beingc_β 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 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 [11] plus Coulomb field.

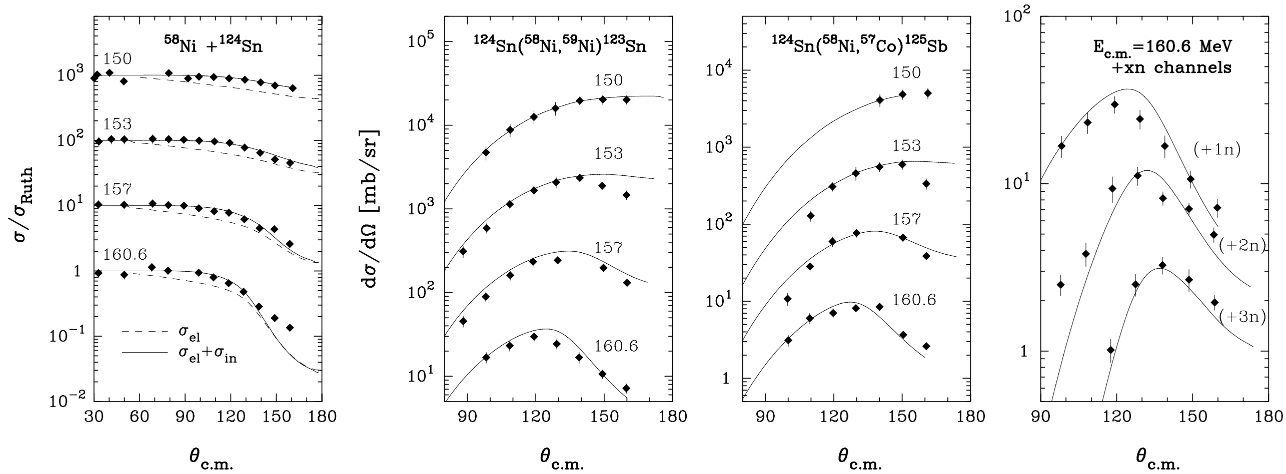

Figure 1. In the first column is shown the ratio to Rutherford of the elastic plus inelastic scatterings (full line) in comparison with the experimental data. The pure elastic scattering (dash-line) is also shown. The following two columns display the calculated angular distributions of the inclusive 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 data are from ref. [12]

The component of the interaction V_{int}, responsible for the exchange of nucleons, contains the well known one-particle transfer formfactors, while the one responsible for the excitation of the surface modes contains the inelastic formfactors that are proportional to the r-derivative of the ion-ion potential.

To show how well the model describes the nuclear collision I show in Fig. 1 the calculated angular distributions for elastic scattering, and for some transfer channels for the

^{58}Ni + ^{124}Sn system [12]. This being one of the few systems for which we have complete measurements of all reaction channels in a wide energy range and for which a coupled channels analysis [13], that includes inelastic and transfer channels, has been performed. These results indicate that the semiclassical approximation provides a quite good description of the reaction over a large energy range and for the full angular range so that one can relay on its calculation for the construction of the excitation function for quasielastic processes in the backward direction. The measured quasi-elastic excitation functions, beside the contributions from elastic and inelastic scattering contain also contributions from the transfer of few neutrons and protons since the experiments do not have good mass and charge resolutions.

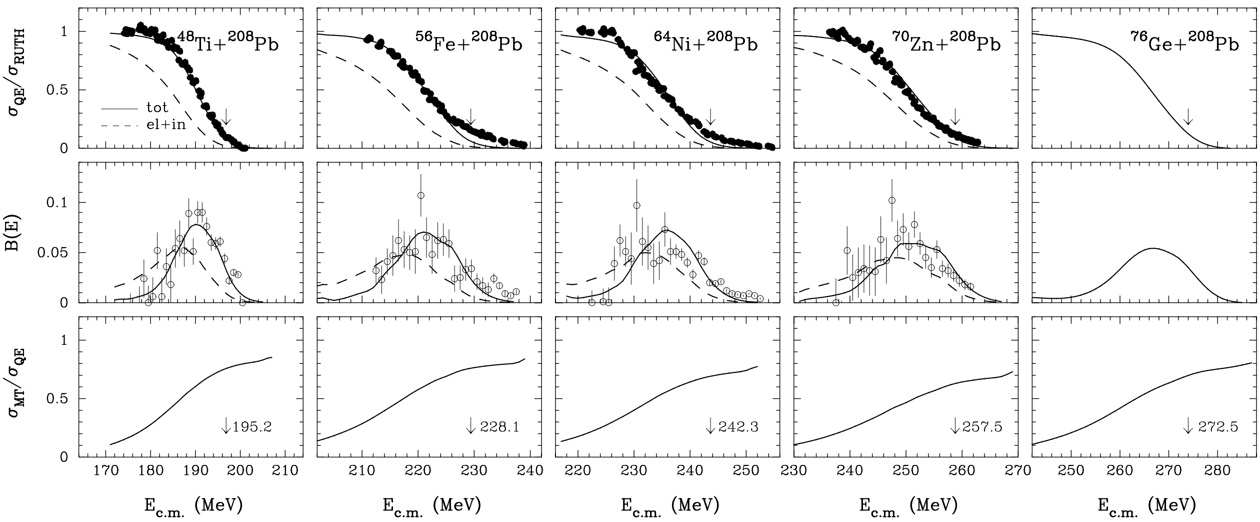

Figure 2. Quasi-elastic excitation function (top), barrier distribution (middle), ratio of transfer channels to the total quasi-elastic cross section (bottom). All the cross sections have been calculated at $\theta_{lab} = 172^o$. The down-arrows represent the Coulomb barrier for the entrance channels calculated with the empirical potential of ref. [11] 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. [6]

To produce the excitation functions, with GRAZING I calculate, for different systems, the angular distributions of several direct reaction channels, in step of 1 MeV of bombarding energy, and sum all the cross sections at $\theta_{lab} = 172^o$. For transfer I added the contributions of the transfer reactions up to the transfer of three neutrons and two protons. The more massive transfer channels are negligible in the interested angular range. For all analyzed systems the quasielastic excitation functions are displayed in the top row of Fig. 2 while the extracted (with a three point formula) barrier distributions $B(E)$ are shown in the central row. The contribution of the particle transfer channels is show in the bottom row as the ratio of the transfer cross section to the total quasielastic one. It is clear that transfer channels give sizable contribution in all the energy range and are the dominant processes at the higher energies.

If for quasielastic we consider all the final states that belong to the initial mass partition (i.e. only elastic plus inelastic channels) one obtains the quasielastic excitation function shown with a dash-line in Fig. 2. The corresponding excitation functions, shown in the same figure also with a dash-line, are much broader and with centroids that are even at smaller energies thus the quasi elastic barrier distribution depends on what we consider quasielastic or if you prefer depends on the experimental resolution of the experiment.

3. CONCLUSIONS

The semiclassical approximation provides a valuable tool to obtain a good description of ion-ion collisions. It provides a good description of the the quasi-elastic processes, it shows that the empirical potential describes correctly the relative motion of the two ions and it demonstrates that particle-transfer channels give sizable contribution to the quasielastic cross section in all the energy range.

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