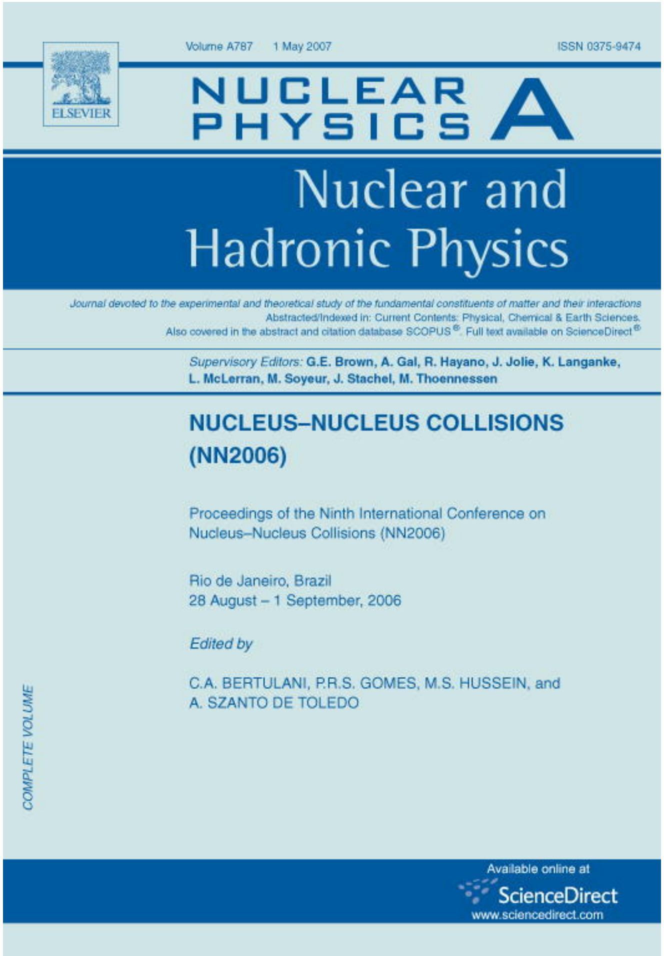
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NUCLEAR PHYSICS A

Hindrance in fusion heavy-ion reactions

Giovanni Pollarolo [a]

[a]Dipartimento di Fisica Teorica, Università di Torino and INFN, Sez. di Torino, Via Pietro Giuria 1, I-10125 Torino, Italy.

The behavior of heavy ion fusion reactions at energies larger than the Coulomb barrier is discussed by analyzing the energy dependence of all reaction channels in ^{58}Ni + ^{124}Sn and ^{16}O + ^{208}Pb systems. The analysis is done by using a semiclassical models that incorporate surface and particle transfer degrees of freedom. The observed hindrance factor may be understood in term of deep-inelastic collisions whose cross section should be added to the one of fission and evaporation to obtain a meaningful comparison with the calculated capture cross section.

1. Introduction

In the field of fusion heavy-ions reactions two main questions have emerged in the past few years, both related to the hindrance of fusion respect to theoretical predictions. In the extreme low energy domain it has been found [1,2] that fusion cross section does not follow the exponential fall-off predicted by the Wong [3] formula but drops more rapidly. In the high energy region the coupled-channel calculations, that successfully describe the large enhancements at energies lower than the Coulomb barrier, over-predict the fusion cross section by a considerable amount. These behaviors have been reconciled by modifications of the nuclear part of the ion-ion potential. While the low energy hindrance may be explained by modifying the nuclear potential in the interior [4,5] i.e. by using a shallower potential the high energy behavior requires [6–8] a nuclear potential with a very large diffusivity that is not compatible with the one extracted from elastic and inelastic scattering data.

This contribution deals only with the behavior of the fusion cross section at energy larger than the Coulomb barrier. The data are analyzed by using a semi-classical model, GRAZING [9–12], that treats on the same footing particle transfer and surface degrees of freedom. The model is able to estimate at the same time the cross sections for most of the processes that may appear in a heavy ion reaction from elastic scattering to deep-inelastic and capture. This overall description of the reaction is essential because the relative importance of the different reaction channels may only be obtained by knowing how the total reaction cross section is shared among the different final channels. The analysis will concentrate on the ^{58}Ni + ^{124}Sn and ^{16}O + ^{208}Pb systems since they are among the few for which beside the excitation function for fusion also many quasi-elastic channels are measured at several bombarding energies.

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2. Applications

The semi-classical model, GRAZING, solves in an approximate way, the well known system of semi-classical coupled equations

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

where c_β gives the amplitude for the system to be, at time t, in channels β. The interaction V_{int} contains the well known terms for the excitation of the surface modes and for the transfer of single 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. [13] whose parameters have been adjusted to describe elastic scattering data (for more details see to Refs. [9–12]).

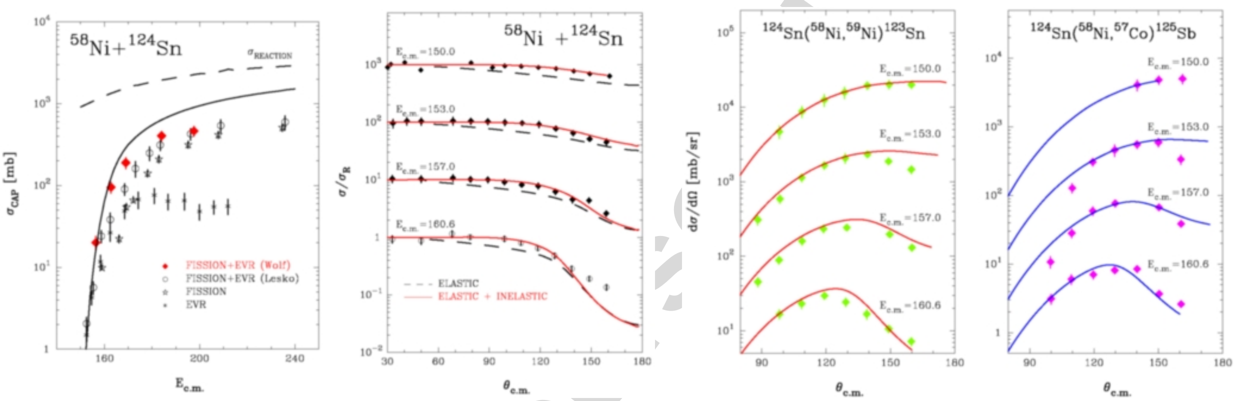

Figure 1. The calculated capture cross section (full line) and the total reaction cross section (dash line) are shown in comparison with the experimental data (first column). The ratio to Rutherford of the elastic angular distributions (dash-line for the pure elastic, full line for elastic plus inelastic) are shown in comparison with the experimental data (second column). The last two columns display the calculated angular distribution of the inclusive one-neutron pick-up and one-proton stripping channels.

The model is able to calculate the distribution of the total reaction cross section among all binary final states but, as all others coupled channels codes, 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.

Let's start the discussions with the ^{58}Ni + ^{124}Sn system. This is one of the few systems for which we have a complete measurements of all reaction channels in a wide energy range [14–22] and for which a coupled channels analysis [23] has been performed that includes inelastic and transfer channels.

In Fig. 1 (first column) are compared the calculated capture cross sections with the experimental data of the indicated references. The experimental data correspond to the sum of the fission and evaporation residue cross sections. At the higher energies a very large hindrance factor is seen since the theory largely over-predict the experimental data. However the model gives, for all energies, a very good description of the elastic angular distributions (second column) and of the angular distributions for the inclusive cross sections of one-neutron pick-up and one-proton stripping channels (last two 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.

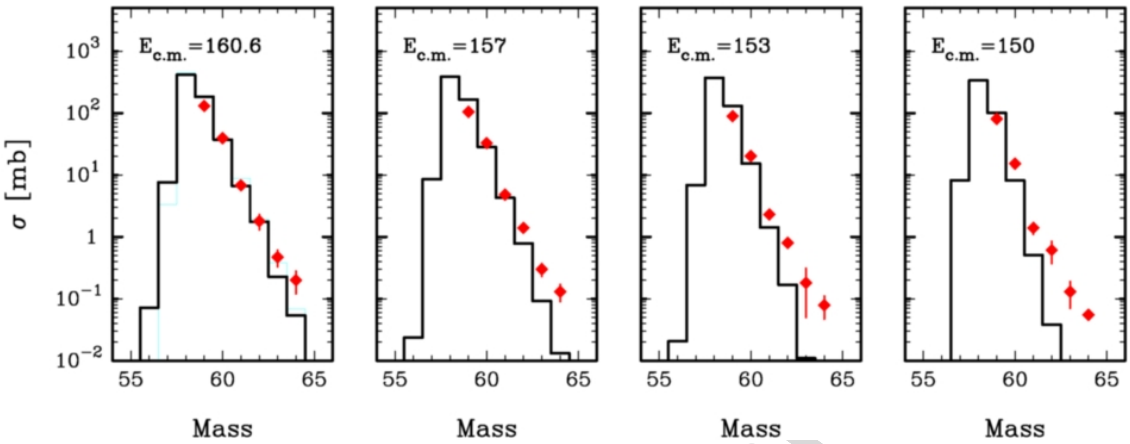

Figure 2. The total cross sections for pure neutron pick-up channels as a function of the mass of the detected fragment is shown for the indicated bombarding energies.

Also the energy dependence of the total cross section for the measured multi-neutrons transfer channels (Fig. 2) are quite well described almost up to the transfer of six neutrons. These results clearly indicate the capability of the model to describe the evolution of the collision. They also show that the empirical potential gives a good description of the relative motion and of the coupling matrix elements.

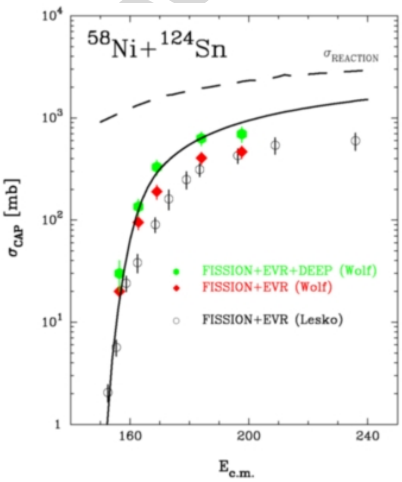

Figure 3. The energy dependence of the capture cross section in comparison with the experimental data. Here to obtain the measured capture we added to the evaporation residues and fission cross section also the contribution of the deep-inelastic component.

The discrepancies seen in the fusion excitation function have thus to be ascribed not to the inadequacy of the potential but to other reaction channels. Keeping in mind that the model estimates the cross section for capture and not for the formation of the compound-nucleus it is natural to try to compare the calculated capture cross section by adding the deep-inelastic component to the one for evaporation and fission. This is done in Fig. 3 and a good comparison is obtained in the full energy range.

It has been from the analysis of the fusion excitation function of the ^{16}O + ^{208}Pb system [6] that surfaced the problem of the high energy hindrance and emerged the need of a nuclear potential with a very large diffusivity [7,8] For this system we know the elastic scattering angular distributions in a very wide range of energy and the angular distributions of several inelastic and transfer channels. From the Optical Model analysis of elastic scattering one extracted good estimations of the total reaction cross section and from transfer and inelastic channels one could estimate the total quasi-elastic cross section [24]. This system constitutes thus an ideal case to check for the findings discussed above. The hindrance factor is, in this system, much smaller and it is clearly seen only in a linear scale as it is reported on the top-left panel of Fig. 4 that displays the fusion excitation function in comparison with experimental data from different experiments. The calculations have been done by using the standard parametrization of the empirical potential [13].

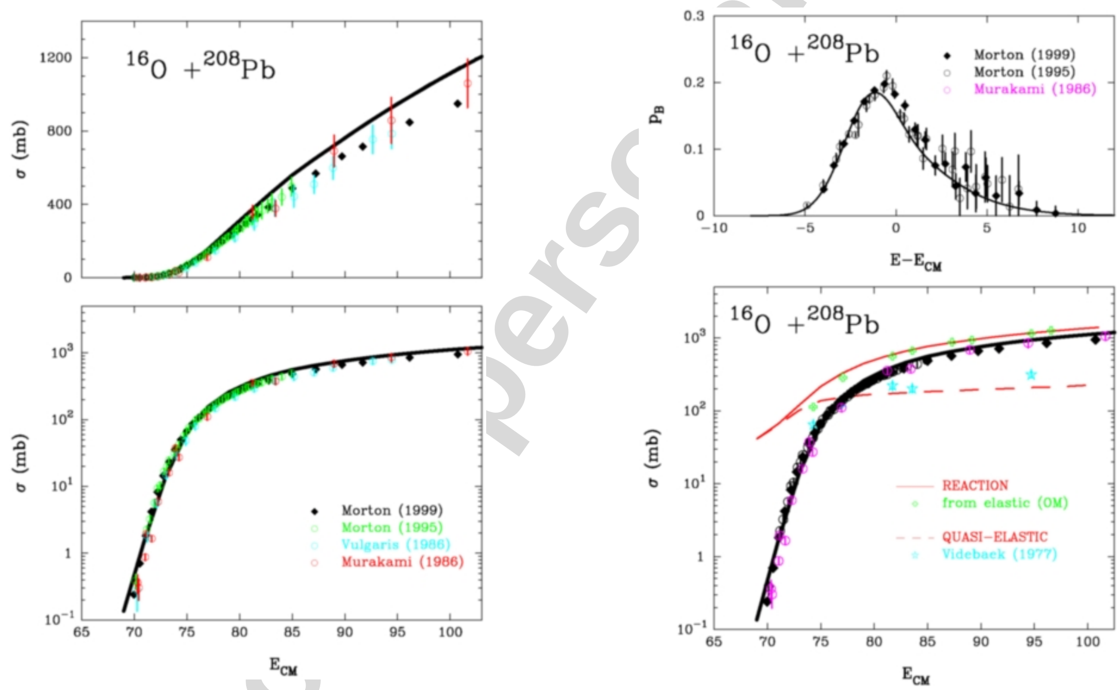

Figure 4. Fusion excitation function for the ^{16}O + ^{208}Pb in comparison with the experimental data of the quoted Refs. In the top row of the second column is also shown the barrier distribution.

For this system it is probably more illustrative to compare our quasi-elastic and total reaction cross sections with the one of Ref. [24] instead of showing angular distributions for elastic and transfer channels. This is done in the bottom panel at the right hand side of Fig. 4 where we display with a dash-line our calculated quasi-elastic cross sections and with a thin continuous line our calculated total reaction cross section. For completeness the same figure displays also the fusion cross sections. The figure illustrates a quite good description of the experimental data in all the energy range thus the diffusivity of the nuclear potential as provided by the empirical potential [13] is quite accurate also for this system.

3. Conclusions

From the semi-classical analysis one has to conclude that the hindrance to fusion, seen at energies above the Coulomb barrier in heavy-ion reactions, should be ascribed to deep-inelastic events that correspond to the formation of a di-nuclear system with large intrinsic angular momentum that very rapidly separates again in a binary event with mass and charge very close to the entrance channel. The potential that describe elastic scattering is adequate also for the calculation of the fusion (capture) cross section.

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