Presence of a deep inelastic component at bombarding energies close to the Coulomb barrier: The Ni+Sn case

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The origin of a rather large deep inelastic component in the total cross section for heavy-ion collisions at energies below or slightly above the Coulomb barrier is discussed. Calculations for the reactions $^{58}Ni+^{122,124}Sn$ show a quantitative agreement with recently obtained experimental data.

In early analysis of heavy-ion collisions it was assumed that the large range of energy losses characteristic of deep inelastic processes could be correlated with the incident partial waves. The underlying idea was that progressively larger energy losses would result as the two reactants were brought closer together in more central collisions. Working our way down in partial waves from a grazing situation, a monotonically increasing curve is thus obtained[1] for the energy loss.

The simple-minded picture summarized above has been the guideline of calculations whose aim was to describe reactions in terms of classical trajectories subject to dissipative forces.[2] As more elaborated schemes were introduced[3–5] it was soon realized that a description based on average trajectories alone was incomplete. Indeed, a proper account of fluctuations around the average behavior is essential to quantitatively describe the experimental data. Among these, the quantal ones associated with the couplings to intrinsic excitation channels have been shown to be especially important.[6]

A straightforward manifestation of the presence of these large fluctuations is the lack of correlation between impact parameters and energy losses. Indeed, low impact parameters are able to feed quasi-elastic events just as some of the higher partial waves may induce strongly inelastic processes. A broad range of partial waves is therefore involved in the transition between quasi-elastic, deep-inelastic, and fusion processes [cf. Fig. 1(a)].

Triangular distributions like the ones in Fig. 1(a) are typical for energies above the Coulomb barrier V_b. As the bombarding energy is lowered below V_b, it is clear that a classical range of impact parameters leading to fusion can no longer be sustained. Yet, when the quantal effects are taken into account, a characteristic feature of the tunneling mechanism is that the partial-wave distribution for fusion reaches a stable shape, independent of energy.[7] From this point down, the gradual reduction in cross sections is achieved maintaining a sizable content of angular momentum. Under these circumstances one

TABLE I. Multipolarity λ, excitation energy E, and percent of the energy weighted sum rule (EWSR) for the low-lying states of nickel and tin included in the calculation. For tin they are obtained from a systematics over all the tin isotopes, while for nickel they correspond to the experimental states.

	λ	E (MeV)	% EWSR
	2^+	1.45	10
^{58}Ni	3^-	4.47	9
	4^+	2.46	3.5
$^{112,114}Sn$	2^+	1.45	10
	3^-	2.28	13

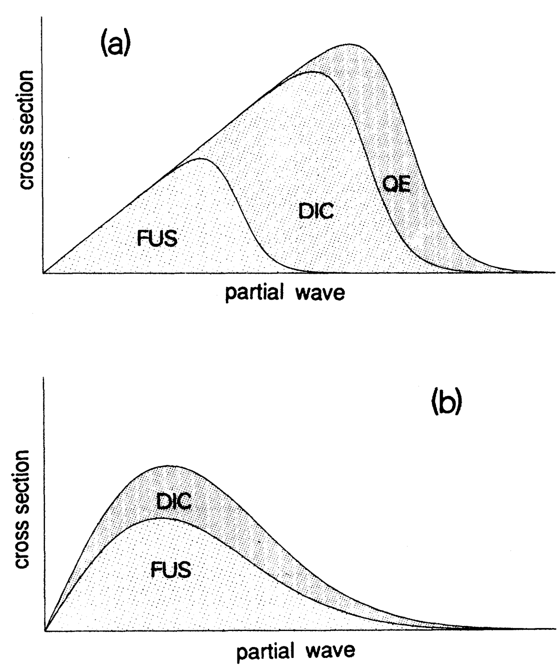

FIG. 1. Schematic representation of the partial-wave distribution of the cross sections for the different processes. (a) corresponds to energies above the Coulomb barrier while (b) corresponds to energies below.

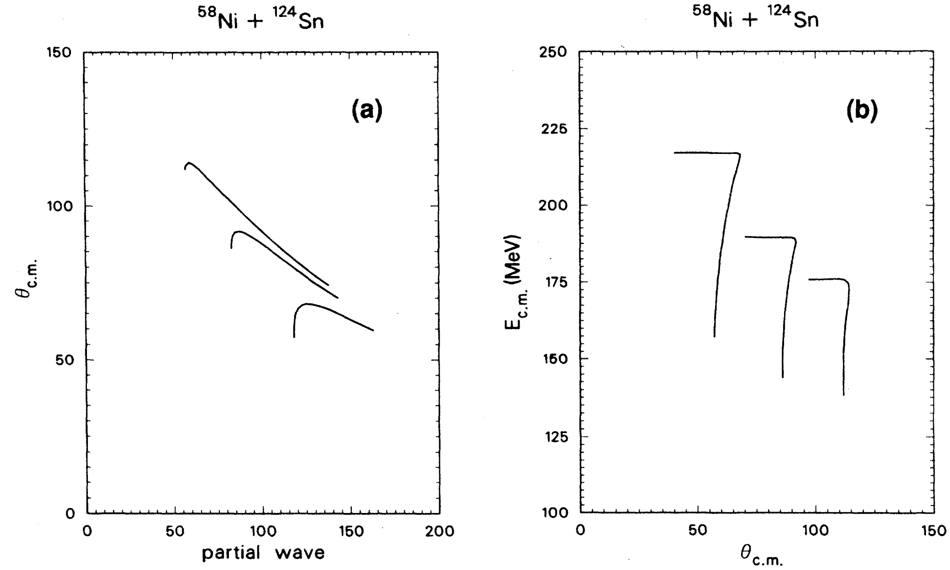

FIG. 2. Deflection functions (a) and correlation between scattering angle and final kinetic energy (b) for the collision of Ni on ^{124}Sn at 320, 280, and 260 MeV of laboratory energy. The curves represent results of average trajectory calculations.

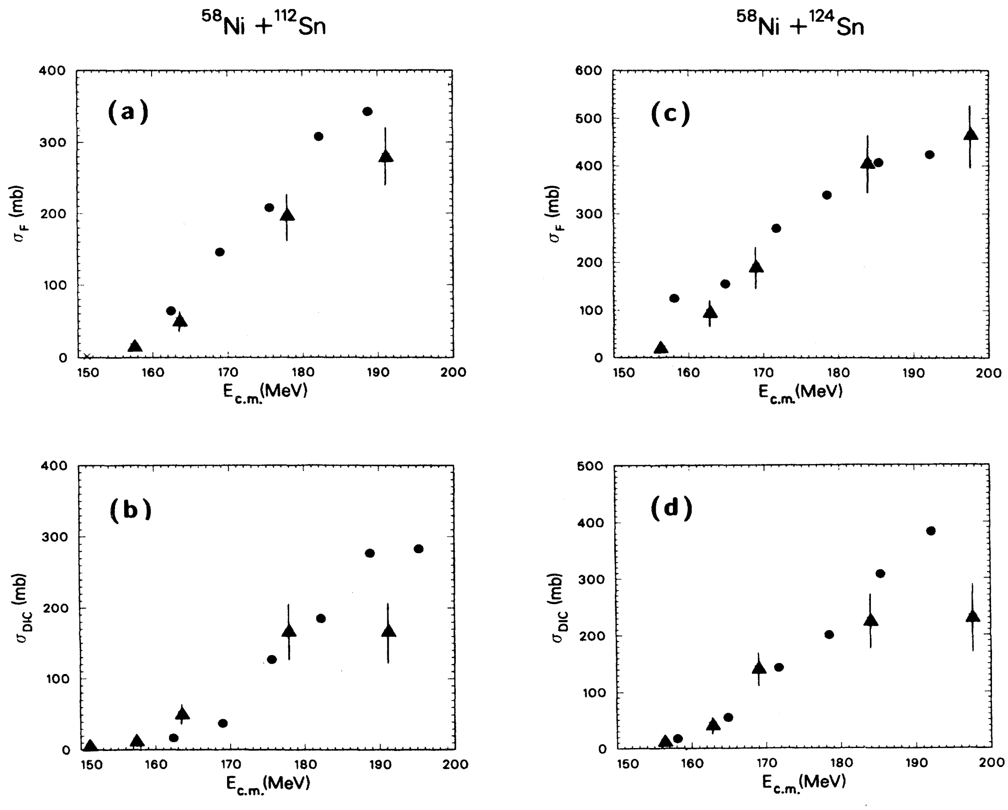

FIG. 3. Energy dependence of the fusion and deep-inelastic cross section for the indicated reactions. The solid circles represent the results of our calculation while the triangles with error bars correspond to the results of Refs. 8 and 9.

should expect that the same range of partial wave feeds both deep-inelastic and fusion processes and that the corresponding partial-wave distributions of cross section overlap, as shown in Fig. 1(b).

The preceding statements establish the plausibility of a regime of energies around the barrier in which deep-inelastic and fusion events should share in building up the reaction cross section. To bring these arguments into a quantitative form we have made an analysis of the reactions $^{58}Ni+^{122,124}Sn$, studied by Wolf *et al.*,[8,9] using the coherent surface excitation model of Ref. 5. This model takes explicitly into account the degrees of freedom associated with the collective surface modes of the two nuclei and incorporates, in the proximity approximation,[10] the dissipation due to the exchange of nucleons. The actual calculations are performed by using the program TORINO.[11]

The main input of the model is the response function of the two colliding nuclei. The low-lying states used in the calculation are shown in Table I. In the case of nickel they correspond to the experimental states, while for the 2^+ and 3^- states of tin we have used an average over all isotopes. To the low-lying states of Table I we have added the quadrupole and octupole giant resonances, in accordance with the universal response function of Ref. 12.

We start by doing a calculation with average trajectories, where the initial conditions for the deformation parameters and the conjugate momenta correspond to their quantal expectation values in the ground state. In Fig. 2(a) we show, for the listed bombarding energies, the deflection function. Low impact parameters do not yield any emerging trajectories, an orbiting situation that is interpreted as fusion. The correlation between the scattering angle and the final energy of the emerging nuclei is shown in Fig. 2(b). As it is seen, a sizable amount of energy loss can be obtained for impact parameters smaller than the grazing l.

As mentioned in the introduction, to construct the actual cross section one should incorporate in the calculation the effect of the quantal fluctuations. This is done by following the prescription explained in Refs. 5 and 11. Thus, for a range of impact parameters around the grazing, we have run a set of calculations with initial conditions for the deformation parameters and conjugate momenta chosen in accordance with the quantal distribution of these quantities in the ground state of the different modes. By keeping track of the events associated with the orbiting trajectories, one can compute the fusion cross section. As a function of the bombarding energy they are shown on the top of Fig. 3 for the two tin isotopes in comparison with the experimental data of Refs. 8 and 9. From the emerging trajectories with an energy loss greater than 20 MeV, an estimation of the deep-inelastic cross sections is also obtained. These are shown at the bottom of Fig. 3 in comparison with the experimental data.[8,9]

As is seen from the above mentioned calculations, a proper account of the quantal fluctuation is essential in order to describe the unexpected large deep-inelastic cross sections obtained at bombarding energies close to the Coulomb barrier.

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