Quasielastic Barrier Distributions: Role of Particle Transfer Channels

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(Received 13 December 2007; published 24 June 2008)

The barrier distributions extracted from quasielastic excitation functions are analyzed in terms of a semiclassical model that incorporates both the excitation of the surface degrees of freedom and the exchange of neutrons and protons. It is shown that quasielastic cross sections receive sizable contributions from transfer reactions in all measured energy range.

DOI: 10.1103/PhysRevLett.100.252701 PACS numbers: 25.70.Hi, 24.10.−i

Some of the basic features of a reaction between two heavy ions can be understood by introducing an interaction potential function of their center-of-mass distance, consisting of short-range attractive nuclear and long-range repulsive Coulomb components. Very readily it has been recognized that several aspects of the collision at near-barrier energies deviate considerably from the predictions of this simple potential model. For instance, fusion cross sections are greatly underpredicted [1], and elastic scattering indicates that the optical potential must have a marked energy dependence [2]. To reach a consistent description of the data one has to include in the reaction mechanism couplings with variables that describe the intrinsic states of the two nuclei. These variables are associated with single particles and collective modes, surface vibrations, and rotation.

In the case of fusion reactions, 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 may be depicted as giving rise to a smearing over several energies of the 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]. It has been suggested that the same information on the barrier may be extracted from the energy dependence of the quasielastic cross section at backward angles [5]. In this case the barrier distributions are obtained simply by the energy derivative of the quasielastic excitation functions. The barrier distributions obtained with these two complementary methods are in reasonable agreement although the ones extracted from quasielastic scattering are broader and have less structure. This equivalence has, however, been checked for only a few reactions and all involving light projectiles, like oxygen, that are characterized by low single-particle level density.

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 [6–8]. These transfer degrees of freedom are weak, are very numerous, and span a wide range of Q values. They are governed by long-range form factors and provide 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. The quasielastic reactions, beside elastic and inelastic channels, receive contributions also from transfer channels, both neutrons and protons. These reactions are thus providing a very interesting tool to investigate the role of transfer reactions at near-barrier energies. To this purpose we make use of the very recent data of Ref. [9] where, for systems that have been considered for cold-fusion production of superheavy elements [10], quasielastic excitation functions have been measured and the corresponding barrier distributions extracted. The measurements have been carried out in a very large energy interval that spans several tens of MeV below the nominal Coulomb barrier of the entrance channel.

As a guide for the discussion, in Fig. 1, for the ^{64}Ni plus ^{208}Pb system, are shown the calculated angular distributions (ratio to Rutherford cross section) for the elastic plus inelastic channels in comparison with the angular distributions of several transfer channels. It is clear from the figure that in the backward direction the quasielastic angular distributions (it is a sum over elastic, inelastic, and transfer channels) receive sizable contributions from transfer channels, and these are the dominant ones at the higher bombarding energies. The angular distributions of Fig. 1 are obtained by using a semiclassical model, GRAZING [11–14], that incorporates both particle transfer degrees of freedom and inelastic excitations of collective surface vibrations. The theory calculates how the incoming flux is divided among the different reaction channels by solving, in an approximate way, the well known system of coupled equations,

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

obtained from the time dependent Schrödinger equation by expanding the total wave function of the system in terms of channel wave functions $\psi_{\alpha} = \psi^{a}(t)\psi^{A}(t)e^{i\delta(\vec{R})}$ corre-

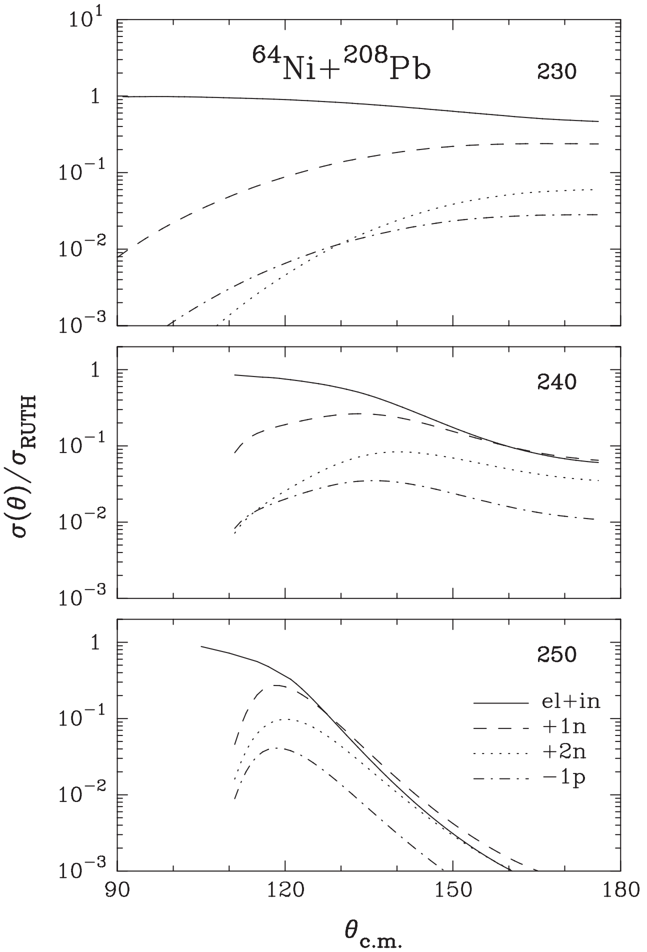

FIG. 1. Center-of-mass angular distributions for elastic plus inelastic and some transfer channels. The cross sections are plotted as a ratio to the Rutherford cross section. The label in each frame indicates center-of-mass bombarding energy in MeV.

sponding to the asymptotic mass partitions. The coefficient $c_\beta(t)$ gives the amplitude for the system to be in channel $\beta(b, B)$. The semiclassical phase $\delta(\vec{R})$ has been introduced in the definition of the channel wave function because the trajectory of relative motion is not a straight line. This phase is important for recoil effects and for the definition of the optimum Q value.

The residual interaction $H_{\rm int}$ is constructed by using the well known form factors for the inelastic excitation and for the transfer of a single nucleon (neutron and proton, stripping and pick-up). For the inelastic form factors the model uses the macroscopic expression, and this is proportional to the r derivative of the ion-ion potential. The form factors for the transfer processes are calculated by using the parametrization of Ref. [15] that provides a very good description of the actual form factors. The time dependence of the interaction is obtained by solving the classical equations of motion in a nuclear plus Coulomb field. For the nuclear potential U_{aA} it used the simple Wood Saxon parametrization of Ref. [16] whose parameters come from the knowledge of the nuclear densities and have been slightly adjusted through a systematic comparison of elastic scattering data. For the Coulomb component the two point charges expression is used. The model beside the transfer channels incorporates also the coupling to the surface modes 2^+ and 3^- of projectile and target. The energy and strength of these modes are obtained from the compilations of Refs. [17,18]. The surface modes are treated in the harmonic approximation. For very low bombarding energies and for very large impact parameters, this model reduces to the well known theory of Ref. [19] that provides a very accurate description of the Coulomb excitation process by assuming that the two ions move along a classical trajectory in a pure Coulomb field. GRAZING generalizes the Coulomb excitation model by incorporating the effects of the nuclear interaction in the trajectory, in the excitation process, and by including the exchange of nucleons.

To produce the excitation function of Ref. [9], one calculates, for the different systems, the angular distributions of all the reaction channels are shown in Fig. 1 in steps of 1 MeV of bombarding energy and sums all the cross sections taken at $\theta_{\rm c.m.} = 172°$. For all analyzed systems the quasielastic excitation function is displayed in the top row of Fig. 2. 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 $E_B^{\rm eff}$, one sees that the couplings give rise to a lowering of the Coulomb barrier of the entrance channels by 4–7 MeV depending on the systems. The full width at half maximum of the barrier distributions, all of Gaussian-like shape, is of the order of 10–12 MeV and is almost constant for all the systems. The contribution of the particle transfer channels is shown in the bottom row of Fig. 2 as the ratio of the transfer cross section to the total quasielastic 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. 2 gives the prediction of the model for the collision of ^{76}Ge plus ^{208}Pb system that, in Ref. [10], 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 quasielastic cross section. If for quasielastic we consider all the final states that belong to the initial mass partition (i.e., only elastic plus inelastic channels), we obtain the quasielastic excitation functions shown with dashed lines in Fig. 2. The corresponding barrier distributions, shown in the same figure also with dashed lines, are much broader and with centroids that are even at smaller energies. As expected, the quasielastic barrier

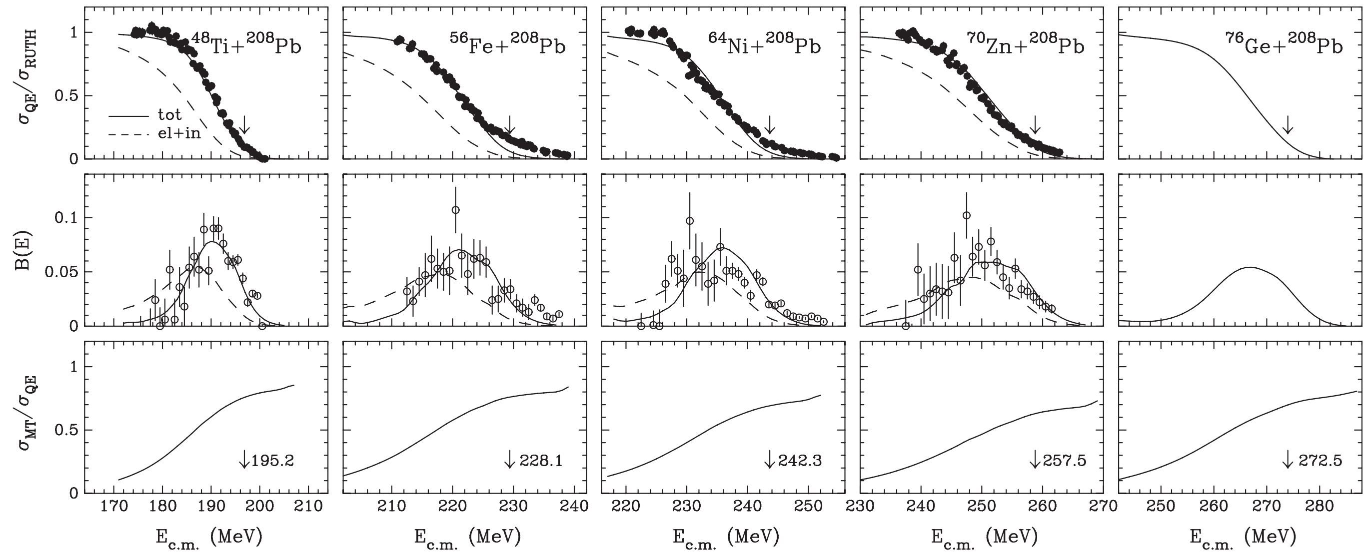

FIG. 2. Quasielastic excitation function (top), barrier distribution (middle) ratio of transfer channels to the total quasielastic cross section (bottom). All the cross section have been calculated at $\theta_{c.m.} = 172°$. The down arrows represent the Coulomb barrier for the entrance channels calculated with the empirical potential of Ref. [16] and using a two points charge Coulomb potential. The dashed lines are the results when considering as quasielastic all the final channels belonging to the entrance channel mass partition. The data are from Ref. [9].

distribution depends on what we consider quasielastic, and thus it should not be a surprise to see differences from this barrier distribution and the one extracted from fusion reactions. For this purpose 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 quasielastic scattering illustrates the modification of the reflection coefficient. For systems where fusion and quasielastic 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 a 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 a substantial exchange of mass and charge.

The abilities of the model to predict correctly the evolution of the reaction and to check the validity of the last assertion are well illustrated in Fig. 3 where for the ^{58}Ni plus ^{124}Sn system are shown the angular distributions of elastic plus inelastic channels, the angular distributions of several neutron transfer channels, and the excitation function for capture in comparison with the experimental data [20,21] (the capture cross section is here defined as the sum of the cross sections for evaporation residue, fission, and deep inelastic reactions). In the same figure are also compared the theoretical barrier distributions extracted from the quasielastic and capture excitation functions. The theory describes quite nicely the cross sections of all the channels and follows the energy evolution of the angular distributions and of the capture cross sections. Since capture and quasielastic processes exhaust most of the reaction cross section, the two barrier distributions are, as expected, very similar. Notice that GRAZING is not able to follow the evolution of the dinuclear complex up to the formation of the compound nucleus (the model uses the degrees of freedom of the asymptotic mass partitions) and assumes that all the flux reaching the inner pocket of the potential leads to capture.

The nice description of the reaction is a clear indication that the potential used for the relative motion is quite good and that the microscopic form factors [15] for one-neutron transfer are accurate (the transfer of many nucleons is incorporated into the model in the successive approximation). The model, contrary to all other coupled channels, does not use explicitly any absorptive potential. The depopulation of the entrance channel derives directly from the couplings with reaction channels. The same system has been analyzed in Ref. [22] in a quantum mechanical coupled-channels formalism [23] that incorporates the incoming wave boundary condition and, by exploiting the rotating frame approximation, includes both the excitation of surface modes and the particle transfer channels. To have a good description of the total reaction cross section, a very small imaginary potential had to be added in the description. The results are very similar and indicate that the semiclassical approximation (this is easily extensible to heavier systems) provides a quite good description of the reaction and gives reassurance over the present results.

We have shown that the semiclassical model of Refs. [11,12,14] gives a good description of the quasielastic processes in heavy-ion collision, that the empirical potential describes correctly the relative motion of the two ions, and that particle transfer channels give a sizable contribution to the quasielastic cross section in all the

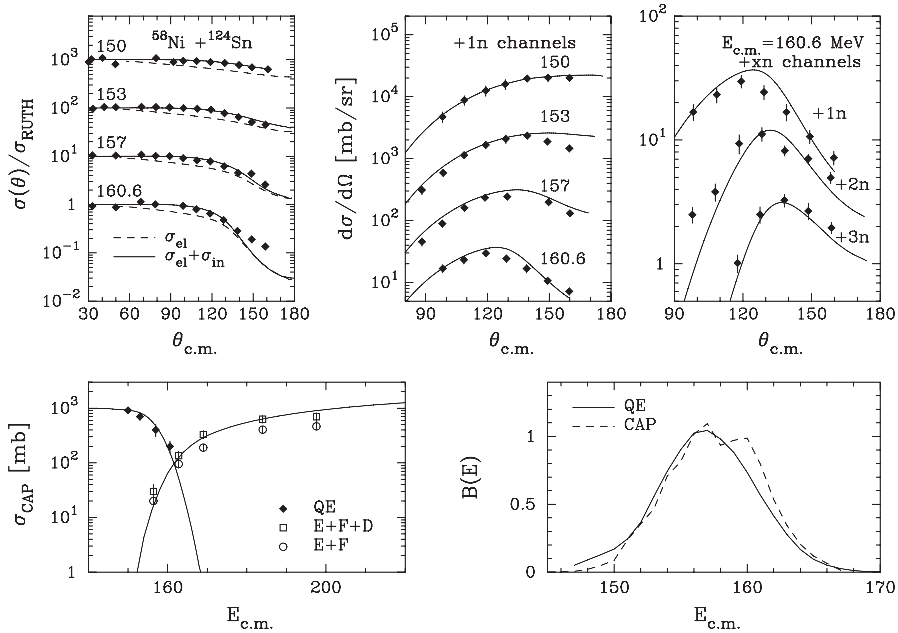

FIG. 3. (top row) Angular distributions for elastic plus inelastic scattering and inclusive (energy integrated) one-neutron pick-up reaction are shown for different bombarding energies. The dashed lines, in the first frame, correspond to the calculated true elastic. In the right-hand frame, for the highest bombarding energy, are shown the angular distributions of some multineutron pick-up channels. The data are from Ref. [21]. (bottom row) Excitation function for capture cross section ($E + F + D$) and quasielastic scattering (QE) (ratio to Rutherford cross section) are shown in comparison with the calculations (notice that the two excitation functions are plotted on the same scale being the quasielastic multiplied by a factor of 1000). The data for capture are from Ref. [20], while the ones for quasielastic have been derived from Ref. [21] by summing, at the most backward center-of-mass angle, 160°, all the measured channels. In the right-hand frame are shown the theoretical barrier distributions for capture and quasielastic excitation function, and the barrier distribution for capture has been arbitrarily normalized to the quasielastic one. The labels, E, F, and D, stand for evaporation residue, fission, and deep inelastic reactions, respectively.

energy range. It has also been shown that the shape of the barrier distribution is related to the processes that are contributing to the quasielastic scattering.

The author is grateful to Hiroshi Ikezoe for providing the experimental data.

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