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A TRANSPORT DESCRIPTION OF INTERMEDIATE PROCESSES IN HEAVY ION COLLISIONS

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Heavy ion collisions with bombarding energies sufficient to overcome the interaction barrier exhibit relaxation processes. These relaxation processes extend continuously from deep inelastic collisions all the way to compound nucleus formation. Deep inelastic collisions (DIC) occur in collisions with a wide range of orbital angular momenta between the grazing angular momentum and the critical angular momentum, ℓ_{cr}. In collisions with smaller angular momenta, the projectile and target interpenetrate sufficiently to result in a totally equilibrated compound nucleus (CN). The boundary between DIC and CN formation is not sharp. For a band of orbital angular momenta in the vicinity of ℓ_{cr}, collisions lead to processes which are intermediate between CN formation and DIC. These intermediate processes are characterized by complete energy damping and a broad fragment mass distribution. Measurements of the angular distributions and the kinetic energies of the emitted fragments indicate that the colliding ions are captured into a dinuclear molecular complex (DMC) and the observed fragments are emitted from this intermediate stage without going through the CN formation [1-2]. The interaction times associated with the intermediate processes are relatively long and, as a result, we observe the relaxation of the mass-asymmetry mode. In heavier systems, the intermediate processes are well established and called fast-fission or quasi-fission [1]. Similar data are available for a few light systems, (Si + C and Si + N), and these are referred to as orbiting processes [2].

Statistical descriptions of the collision processes in the framework of transport theories (diffusion and frictions models) have been quite successful in understanding the reaction mechanism of DIC and analyzing the experimental data [3-6]. The diffusion model for DIC provides a good description for the scattering processes, but it can not be applied to describe the intermediate processes. The intermediate processes involve the formation and evolution of a DMC, and its subsequent decay by fragmentation. Hence, these processes require a description of the two phases of the collision and the connection between them.

In the present work, we propose an extension of the diffusion model in order to describe the intermediate processes and the compound nucleus formation in heavy ion collisions [7-8]. The model describes the intermediate processes and fusion in terms of the formation and the evolution of a long-lived DMC and its subsequent decay by fragmentation. The colliding ions can be trapped into the pocket of the entrance channel nucleus-nucleus potential and a DMC is formed. This DMC acts as a doorway state towards formation of a completely equilibrated CN. It evolves through the exchange of nucleons to different dinuclear configurations. At each stage of its evolution, there is a finite probability for direct fragmentation into outgoing channels by thermal penetration over the barrier. The doorway states that do not fragment relax into a CN configuration and are identified as the fusion yield.

A full description of the collision process involves the dynamical and the statistical aspects of the reaction. We restrict ourselves here to a discussion of the statistical aspects alone and describe the evolution of the DMC on the basis of a transport theory. We assume that within a semi-classical treatment, the trajectory R(t) of the relative motion of the colliding ions is known such that we are left with the Schroedinger equation,

$$i\hbar \frac{\partial}{\partial t}|\Psi(t)\rangle = H(t)\ |\Psi(t)\rangle \tag{1}$$

for the intrinsic wave function $|\Psi(t)\rangle$. The Hamiltonian for the intrinsic motion depends on time through the relative distance (and also through deformation parameters, $H(t) = H[R(t)]$. We introduce the channel wave functions $|\chi_j\rangle$ as the eigenfunctions of the Hamiltonian $H_0 = H(R \to \infty)$ for the separated fragments with energies ε_j, and the wavefunctions $|\phi_\lambda\rangle$ for the dinuclear molecular states with the energies ε_λ. The solution of the Schroedinger eq. (1) can be expanded in terms of the set of dinuclear molecular states and the set of channel states,

$$|\Psi(t)\rangle = \sum_\lambda a_\lambda(t)\ |\phi_\lambda\rangle + \sum_j a_j(t)\ |\chi_j\rangle\ . \tag{2}$$

Inserting this expansion into eq. (1) and assuming the states are orthogonalized, we obtain a set of coupled equations

$$i\hbar \frac{d}{dt} a_\lambda = \sum_\mu [\varepsilon_\lambda\ \delta_{\lambda\mu} + V_{\lambda\mu}]\ a_\mu + \sum_j V_{\mu j}\ a_j \tag{3a}$$

for the occupation amplitudes $a_\lambda(t)$ of the dinuclear states, and

$$i\hbar \frac{d}{dt} a_j = \sum_i [\epsilon_j \delta_{ji} + V_{ji}] a_i + \sum_\mu V_{j\mu} a_\mu \tag{3b}$$

for the occupation amplitudes $a_j(t)$ of the channel states. These coupled eqs. involve the coupling between different dinuclear states, $V_{\lambda\mu}$, the coupling between different channel states, V_{ji}, and as well as the coupling between dinuclear states and channels, $V_{\lambda j}$.

In a statistical treatment, we are interested in a macrosopic description of the collision process. Therefore, we define averages over intrinsic dinuclear states by dividing the total space into subspaces (coarse-graining), [3-5]. Each subspace contains all the dinuclear states with the same values of some macroscopic variables, such as the excitation energy E, the charge and mass-asymmetry N, Z, the Z-component of the intrinsic angular momentum K, etc., D ≡ {N, Z, E, K, ..}. Accordingly, we define coarse-grained occupation probabilities of dinuclear states,

$$\Pi(D,t) = \sum_{\lambda\epsilon D} a_\lambda(t)\, a^*_\lambda(t) \tag{4a}$$

by summing the microscopic probabilities over subspaces. In a similar fashion, the coarse-grained fragmentation probabilities for the channel space are defined as

$$P(C,t) = \sum_{j\epsilon C} a_j(t)\, a^*_j(t) \tag{4b}$$

where C ≡ {N, Z, E, K, ..} is a set of macroscopic variables (similar to that of the DMC) characterizing the binary fragmentation channels. Using a well-known projection formalism of statistical mechanics, the set of eqs. for the amplitudes a_λ and a_j can be transformed into two coupled eqs. for the course-grained distribution functions (4a) and (4b), [3-7]. The first one describes the evolution of the DMC in terms of relevant macroscopic variables. The distribution function $\Pi(D,t)$ of the macroscopic variables of the DMC is determined by

$$\frac{d}{dt}\Pi(D,t) = \int_0^t d\tau\{\sum_{D'} K_{DD'}(t,\tau)\Pi(D',t-\tau) + \sum_{C'} K_{DC'}(t,\tau)P(C',t-\tau)\} \tag{5a}$$

The second equation describes the fragmentation probability from the DMC into the outgoing channels. The probability $P(C,t)$ of finding a binary exit channel with the macroscopic variables C is determined by

$$\frac{d}{dt} P(C,t) = \int_0^t d\tau\{\sum_{C'} K_{CC'}(t,\tau)P(C',t-\tau) + \sum_{D'} K_{CD'}(t,\tau)\Pi(D',t-\tau)\} \quad . \qquad (5b)$$

The collision terms $K_{DD'}$, $K_{CC'}$ and K_{CD} in these eqs. describe the coupling between dinuclear states; the coupling between fragmentation channels and the coupling between dinuclear states and channels, respectively. $K_{DD'}$ in eq. (5a) consists of gain terms ($D \neq D'$) which correspond to transitions from all states with $D \neq D'$ to the states D, and another term $D = D'$ which describes the loss from the subspace D. K_{DC} in eq. (5a) describes the gain from the channel space into the DMC. In a similar manner, $K_{CC'}$ in eq. (5b) consists of gain terms ($C \neq C'$) which correspond to transitions from all channels with $C \neq C'$ to the channels C, and another term $C = C'$ which describes the loss from the channels C. K_{CD} in eq. (5b) describes the loss from the DMC into the fragmentation channels. The eqs. (5a) and (5b) carry memory effects, due to the fact that the collision terms are non-local in time. The changes of distribution functions, $\Pi(D,t)$ and $P(C,t)$, at time t depend on the past history of the evolution.

The coupled eqs. (5a) and (5b) are in principle exact, and they provide a basis for introducing further approximations. The essential step in deriving transport equations is based on the assumption that the time scales associated with the macroscopic (collective) variables are much longer than the time scale associated with the intrinsic variables. As a result, the intrinsic variables equilibrate fast and remain close to a local equilibrium. The collision terms in eqs. (5a) and (5b) can be evaluated explicitly by introducing statistical approximations for the coupling matrix elements $V_{\lambda\mu}$, V_{ji}, and $V_{\lambda j}$ [3-7]. Furthermore, the memory effects in eqs. (5a) and (5b) can be neglected as a consequence of the separation of time scales (Markov approximation). Hence, within a statistical approximation, the coupled eqs. (5a) and (5b) reduce to coupled ordinary transport equations for the distribution function $\Pi(D,t)$,

$$\frac{d}{dt} \Pi(D,t) = \sum_{D'} W_{DD'}\{\rho_D \Pi(D',t) - \rho_{D'} \Pi(D,t)\} \qquad (6a)$$

and for the fragmentation probability $P(N,Z,t)$ into a binary exit channel (N,Z),

$$\frac{d}{dt} P(N,Z,t) = \sum_D \Pi(D,t)\, \Gamma_{D\rightarrow(N,Z)} - P(N,Z,t) \sum_D \Gamma_{(N,Z)\rightarrow D} \qquad (6b)$$

In eq. (6a) ρ_D is the level density of the DMC and $W_{DD'}$ is the average transition probability between dinuclear states. In eq. (6b) $\Gamma_{D\to(N,Z)}$ is the decay width for going from a DMC to the fragmentation (N,Z) and $\Gamma_{(N,Z)\to D}$ is the width for the inverse process. The decay widths are given by an average transition probability between the dinuclear states and the channel states multiplied by the level density of the final states. (In general, a loss term is present in eq. (6a), as a result of the coupling to the outgoing channels, and eq. (6b) contains another term due to the channel-channel coupling. Within a weak-coupling approximation, these terms are omitted here.) These coupled transport equations (6a) and (6b) provide a unified description for a wide range of relaxation processes observed in heavy ion collisions. In the DIC domain, a DMC is not actually formed, i.e., there is no barrier which separates the two phases of the collision process. In this case, the coupled transport equations reduce to the single master equation of the usual diffusion model. On the other hand, for angular momenta for which the entrance channel potential exhibits a pocket, the collision leads to the formation of a DMC. The coupled transport equations (6a) and (6b) describe the evolution of the DMC towards fully equilibrated CN formation and partially to fragmentation. The underlying reaction mechanism is, in a way, similar to the reaction mechanism of the pre-equilibrium particle emission, with a difference, that here, binary fragments are emitted in place of nucleons.

A particularly simple case emerges for the orbiting processes. Studies of orbiting in light systems (Si + C and Si + N collisions) show that the final kinetic energies of the fragments are fully relaxed and determined by the potential energy stored in the DMC. Furthermore, all the fragments have the same isotropic angular distributions. These observations indicate that the interaction times associated with the orbiting processes are sufficiently long so that during the interaction time the energy, angular momentum and the mass-asymmetry mode have reached equilibrium values. Yet the time needed for a totally equilibrated CN formation is much longer than the interaction times of the orbiting processes. Consequently, the fragments are emitted from an equilibrated DMC, before CN formation takes place. We, therefore, can use the local equilibrium solution of eqs. (6a) and (6b)

$$P_\ell(N,Z) = \sum_D \Pi_\ell^{eq}(D)\ \Gamma_{D\to(N,Z)} \Big/ \sum_D \Gamma_{(N,Z)\to D} \qquad (7)$$

for describing the orbiting and fusion processes. Using the fact that the local equilibrium solution $\Pi_{\ell}^{eq}(D)$ is determined by the level density of the DMC at the potential minimum for each partial wave ℓ, and the decay widths are proportional to the final level densities, the fragmentation probability can be expressed as

$$P_{\ell}(N,Z) = \rho_{\ell}(N,Z;R_B)/\sum_{N'Z'} \{\rho_{\ell}(N',Z';R_M) + \rho_{\ell}(N',Z';R_B)\} . \qquad (8)$$

Here $\rho_{\ell}(N,Z;R_B)$ and $\rho_{\ell}(N,Z;R_M)$ are the level densities of the DMC at the barrier $R = R_B$ and at the minimum $R = R_M$ of the entrance channel nucleus-nucleus potential.

Using the result (8), the total fragmentation probability (orbiting cross section) and the fusion cross section can be evaluated. This model is successfully applied to the analysis of Si + C collisions for which the fusion cross section and the orbiting data are available for a wide range of bombarding energies [2]. The detail of this analysis is reported in the contribution by D. Shapira, et al. [2].

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