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A STATISTICAL DESCRIPTION OF ORBITING AND FUSION

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We discuss in this contribution a statistical model for describing the orbiting and fusion processes in heavy ion collisions. A preliminary treatment of the model was given in ref. [1].

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 mementum and the critical angular momentum, ℓ_{cr}, for the onset of the capture processes. In collisions with smaller angular momenta, the projectile and and target interpenetrate deeper and, as a result, a totally equilibrated compound nucleus (CN) is formed. The boundary between the DIC and the CN formation is not sharp. For a band of orbital angular momenta in the vicinity of ℓ_{cr}, the collisions lead to the processes which are intermediate between CN formation and DIC. These intermediate processes are characterized by a 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 [2-3]. The interaction time 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 [2]. Similar data are available for a few light systems, (Si + C and Si + N), and these are referred to as orbiting processes [3].

Statistical descriptions of the collision processes in the framework of transport theories (diffusion and friction models) have been quite successful in understanding the reaction mechanism of DIC and analyzing the experimental data [4-5]. 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 for describing the intermediate processes and the compound nucleus formation in heavy ion collisions. 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 to emit fragments 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 within the framework of an extended diffusion model. Once a DMC is formed, it couples to complicated dinuclear states and direct fragmentation channels. A statistical treatment for the coupling between the dinuclear states and the fragmentation channels yields two coupled transport equations for a description of the intermediate processes [6]. The first one describes the evolution of the DMC in terms of relevant macroscopic variables, which characterize the dinuclear system, such as the charge and mass-asymmetry, the excitation energy, the z-component of intrinsic angular momentum, etc., D = {N, Z, E, K, ..}. Then the distribution function $\pi_\ell(D,t)$ (for each partial wave, ℓ) of the macroscopic variables of the DMC is determined by

$$\frac{d}{dt}\pi_\ell(D,t) = \sum_{D'} W_{DD'}\{\rho_D\,\pi_\ell(D',t) - \rho_{D'}\,\pi_\ell(D,t)\} \tag{1}$$

where ρ_D is the level density of the DMC and $W_{DD'}$ is the average transition probability between the dinuclear states. (In general, a loss term is present on the right hand side of this equation, as a result of the coupling to the outgoing channels. Within a weak coupling approximation, this term is omitted here.) The second transport equation describes the fragmentation probability from the DMC into the outgoing channels. The probability $P_\ell(N,Z,t)$ of finding a binary exit channel with an orbital angular momentum ℓ and fragmentation product (N,Z) is determined by

$$\frac{d}{dt}P_\ell(N,Z,t) = \sum_D \pi_\ell(D,t)\,\Gamma_{D\to(N,Z)} - P_\ell(N,Z,t)\sum_D \Gamma_{(N,Z)\to D} \tag{2}$$

Here $\Gamma_{D\to(N,Z)}$ 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. These coupled transport equations (1) and (2) 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 (1) and (2) describe the evolution of the DMC towards fully equilibrated CN formation and the fragmentation during this evolution. In contrast to the DIC, a single trajectory of the intermediate processes can lead partially to 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 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 suggest that the fragments are emitted from an equilibrated DMC. We, therefore, can use the local equilibrium solutions of the coupled transport equations (1) and (2) to describe the orbiting processes. The local equilibrium solutions of (1) and (2) can be expressed in terms of constrained equilibrium distribution functions. As a result, the fragmentation probability is given by

$$P_\ell(N,Z) = \rho_\ell(N,Z;R_B) / \sum_{N'Z'} \rho_\ell(N',Z';R_M) \tag{3}$$

where $\rho_\ell(N,Z;R_B)$ and $\rho_\ell(N,Z;R_M)$ are the level densities of the DMC at the excitation energies evaluated at the top of the potential barrier $R = R_B$ and at the potential minimum $R = R_M$. In obtaining the result (3), we also use the fact that a DMC predominantly decays into channels which have a similar fragmentation as the DMC. Total fragmentation probability (orbiting cross section) into an exit channel with a fragmentation product (N,Z) is calculated by summing over all partial waves up to an ℓ_{max},

$$P(N,Z) = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{max}} (2\ell+1)\, P_\ell(N,Z). \tag{4}$$

The fusion probability is obtained for each partial wave by subtracting from unity the probability for direct fragmentation. Hence, the fusion cross section is given by

$$\sigma_f = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{max}} (2\ell+1)[1-P_\ell] \tag{5}$$

where the total fragmentation probability for each partial wave is obtained by summing over all possible fragmentations, $P_\ell = \sum_{N,Z} P_\ell(N,Z)$. ℓ_{max} is the maximum angular momentum which leads to a trapping of the colliding ions into a DMC. It is determined from the requirements that the trajectories must surmount the entrance channel nucleus-nucleus potential, and furthermore, the potential energy surface must exhibit a pocket. Otherwise, the system can not be trapped into a DMC.

We apply this model 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 [3]. The density of states is approximated by the Fermi gas expression.

$$(N,Z) = C_\ell \exp[2\{a(E-U_\ell(N,Z))\}^{\frac{1}{2}}]/\{E-U_\ell(N,Z)\}^2 \tag{6}$$

where $a = A/8$ is the usual level density parameter. $U_\ell(N,Z;R)$ is the potential energy of the DMC in the sticking limit, and it consists of the nuclear and coulomb and rotational energies and a Q-value contribution. For the nuclear potential, the Bass proximity potential is used, and the parameters are adjusted to reproduce the observed kinetic energies of the emitted fragments. In figure 1, the prediction of the model for the absolute orbiting cross section is compared with data. The absolute cross sections for the two strongest channels O + Mg and C + Si are predicted rather well. The Fermi gas expression underpredicts the level density of the N + Al system, and as a result, the predicted yield in this channel is low. In figure 2 the prediction of the model for the fusion cross section is presented. The increase, saturation and the decrease as demonstrated by the recently measured data [7] are well reproduced.

In conclusion, a statistical description for the intermediate processes in heavy ion collisions is presented. The model, at the equilibrium limit, is successfully applied to analyze the orbiting and fusion data in Si + C collisions.

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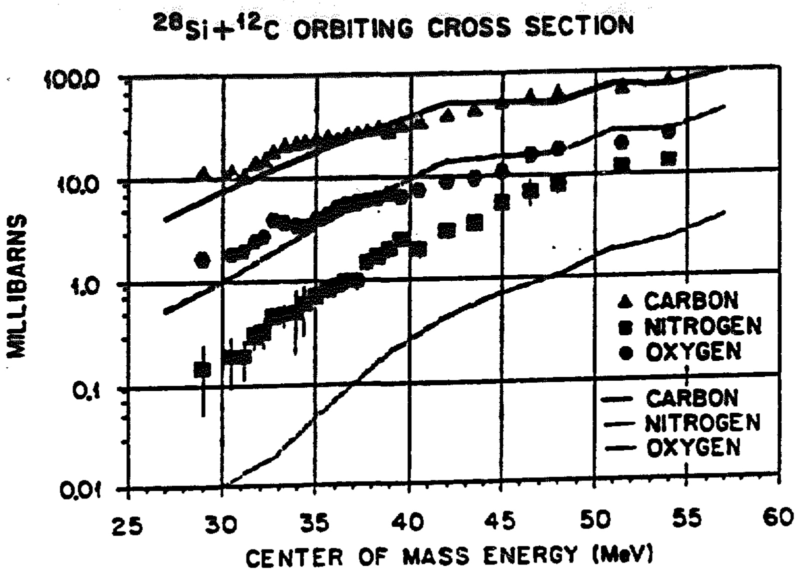

Figure 1

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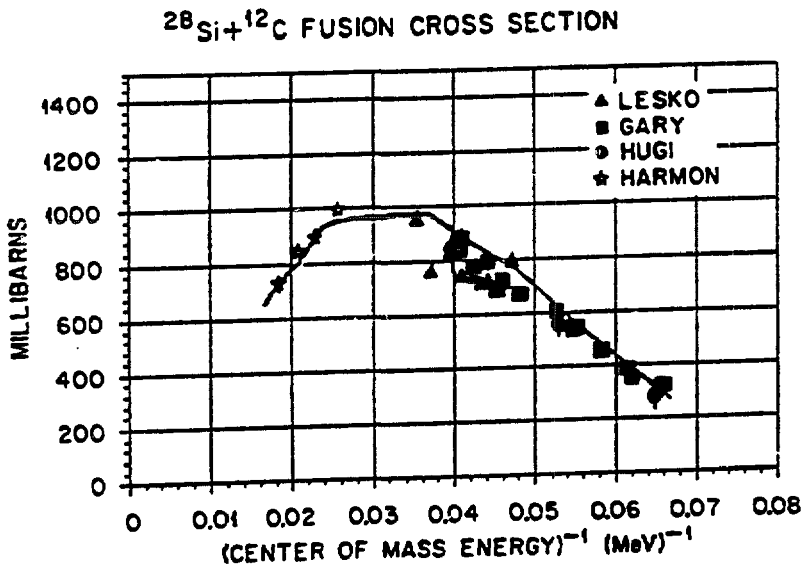

Figure 2

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