STATISTICAL ASPECTS OF DISSIPATIVE HEAVY-ION COLLISIONS

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ABSTRACT

The experimental results of dissipative heavy-ion collisions are summarized and the present status of theoretical developments is outlined. Time scales and successive steps of equilibration are discussed. Starting from a general formulation of a transport theory we discuss various approximations. Typical results of calculations are presented. Possible future developments of transport theories are indicated.

1. INTRODUCTION

During the past few years relaxation phenomena in dissipative heavy-ion collisions have become an interesting subject of experimental and theoretical studies. According to the classical picture ($\lambdabar \lesssim 0.1$ fm in dissipative collisions) these collisions correspond to impact parameters which lead to a strong overlap of the nuclei but not to a compound nucleus.

2. EXPERIMENTAL RESULTS

Dissipative collisions may be regarded as a precompound heavy-ion collision which provides us with a large variety of relaxation phenomena of nuclei. The experimental results[1-5] show the following salient features.

(1) Projectile and target are mostly rather heavy nuclei with mass number $A \gtrsim 40$.

(2) They are observed at incident energies of typically 1 to 3 MeV per nucleon above the Coulomb barrier.

(3) The identity of projectile and target is essentially preserved throughout, although

(4) a considerable amount of mass ($\Delta A \lesssim 20$) can be transferred during the collisions.

(5) The angular distribution is strongly non-isotropic which means that the mean time of nuclear interaction is significantly smaller than the time needed for a complete rotation of the composite system ($\tau_{rot} > 10^{-20}$s).

(6) A large amount of relative kinetic energy (typically more than 100 MeV) and relative angular momentum (up to ≈ 50 units of $\hbar$) is dissipated, i.e. transferred from relative motion into intrinsic excitation.

(7) Dissipative collisions cover the total range between direct reactions and compound-nucleus formation. Their share in the total cross-section increases with increasing bombarding energy and masses of the colliding nuclei. For heavy nuclei typical values for the dissipative cross-section are 1 to 2 barns.

(8) The measured cross-sections are inclusive cross-sections because not all reaction products can be observed. Frequently only the charge and

the energy of one fragment are detected. Since the excitation energies are large, the channels cannot be resolved and therefore, only averaged quantities are observed.

3. NUCLEAR INTERACTION TIMES AND SUCCESSIVE STEPS OF EQUILIBRATION

From the analysis of angular distribution (and energy spectra[1]) it is possible[1,6,7] to deduce nuclear interaction times τ_{int} as function of the impact parameter b or the corresponding incident angular momentum $l = kb$. These interaction times range from about 10^{-22}s for $l \approx l_{gr}$ up to several 10^{-21}s for small l values. The relaxation times for the loss of radial kinetic energy (τ_{rad}), for the dissipation of relative angular momentum (τ_{ang}) and for the evolution of fragment deformations (τ_{def}) have been determined in a simultaneous fit[7,8] to experimental energy sprectra and γ-multiplicities.

The result is

$$\begin{aligned} \tau_{rad} &\approx 0.3 \cdot 10^{-21}\text{s}, \\ \tau_{ang} &\approx 1.0 \cdot 10^{-21}\text{s}, \\ \tau_{def} &\approx 4 \cdot 10^{-21}\text{s} \quad . \end{aligned} \tag{1}$$

The values imply that the fast loss of radial kinetic energy is followed by the dissipation of relative angular momentum and finally, by the evolution of fragment deformations. The analysis of mass distributions[1,6-10] show that no equilibrium is reached in the mass asymmetry coordinate. The corresponding equilibration time is of the order $2 \cdot 10^{-20}$s, cf. ref.[11].

Of particular interest for the formulation of transport theories is the time interval τ_{mem} for the loss of phase memory. This time has been evaluated[12,13] to be of the order $\lesssim 0.5 \cdot 10^{-23}$s for excitation energies larger than 20 MeV and not too light systems. During the approach of the nuclei the loss of phase memory is expected to be somewhat larger[14] ($2 \cdot 10^{-22}$s). The initial stage of dissipative collisions is characterized by the mutual approach of projectile and target in their ground states. This gives rise to a specific correlation for the occupation probabilities of single-particle states. Local (i.e., for fixed values for the collective variables) equilibrium distribution for the single-particle occupation probabilities is reached only by residual interactions. The corresponding local equilibration time τ_{loc} is expected to be similar to the equilibration time observed in precompound reactions and hence, $\tau_{loc} \approx 10^{-21}$s. Consequences of the values for the characteristic times are discussed qualitatively.

4. TRANSPORT THEORIES

Transport theories of dissipative heavy-ion collisions have been formulated by several groups[15-18]. A recent review has been given by Weidenmüller[14]. We discuss here various approaches as different approximations to a more general formulation[19] of transport theory for dissipative collisions. Starting from a given separation of the degrees of freedom into slow collective (or macroscopic) variables and fast equilibrating "intrinsic" variables we derive the transport equation

$$\left\{\frac{\partial}{\partial t} + \frac{\vec{p}}{M_\nu} \cdot \vec{\nabla}_\nu - \left[\vec{\nabla}_r U_\nu(\vec{r})\right]\right\} f_\nu(\vec{r},\vec{p};t) = d_\nu \int_0^{t-t_0} d\tau \int d^3r' d^3p' \sum_\mu K_{\nu\mu} (\vec{r},\vec{p};\vec{r}',\vec{p}';\tau) f_\mu (\vec{r}',\vec{p}';t-\tau) \, . \tag{2}$$

The l.h.s. describes the change of the probability distribution $f_\nu(\vec{r},\vec{p};t)$ due to the velocity $\vec{p}/M_\nu$ and the force $-\vec{\nabla}_r U_\nu(\vec{r})$ within the subset ν. The quantities M_ν and $U_\nu(\vec{r})$ denote the corresponding mean reduced mass and the mean potential, respectively. The collision term on the r.h.s. of (2) describes the coupling to other subsets. Different approximations for the collision kernel $K_{\nu\mu}$ are discussed. The approximations are divided into weak-coupling[16,18] and strong-coupling[15,17,20] limits and according to the basis (adiabatic[16,20] and sudden or asymptotic[15,17,18,20]).

5. TYPICAL RESULTS

For a practical use, the transport equations are transformed to Fokker-Planck equations and/or simplified by a moment expansion. Microscopic transport coefficients[21] are compared with experimental values of transport coefficients. Numerical results[7,8,22-25] for various cross-sections are discussed.

6. CONCLUDING REMARKS

Dissipative heavy-ion collisions have become a new field of nuclear research. Transport theories have been developed for the description of these processes. The major restrictions and approximations of present formulations are critically discussed. Possible future developments are indicated.

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