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INCOMPLETE LINEAR MOMENTUM TRANSFER IN NUCLEAR REACTIONS : AN INTERPLAY BETWEEN ONE-BODY AND TWO-BODY DISSIPATION

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Abstract

An explanation for the experimentally observed linear momentum transfer in light and heavy-ion induced reactions is propounded by simple geometrical considerations in momentum space. We display explicitly the transition from *one-body to two-body dissipation*. We obtain a surprising agreement with the experiments over the whole measured energy range.

Introduction. The observation of a limitation of the linear momentum transfer is a current subject of study in experimental heavy-ion physics. A lot of results were recently obtained using the fission fragments angular correlation method [1, 2, 3, 4, 5, 6] or by the measurement of recoil products [7, 8]. The general trend is an almost linear decrease of the ratio of the transferred linear momentum over the available incident momentum during the collision. In other words, the fusion reactions are more incomplete when the incident energy above the Coulomb barrier increases. A few processes were already considered in order to understand this general behaviour. For instance, intranuclear cascade calculations were done in ref [8, 9]. Nevertheless, it appears, that some additional sophistications like the account of clusters are needed to predict the incomplete mechanisms. On the other hand, the non-linear character of the equations of motion have suggested [10] the presence of solitons in heavy-ion reactions. This picture is certainly appealing, but it might not account for the large amount of the missing transferred momentum. The aim of this letter is to present an analysis by looking at the evolution of a dinuclear system in the momentum space. As a matter of fact, the Wigner transform f(r,p) of the density matrix fulfills the Landau-Vlasov equation :

$$\frac{\partial f}{\partial t} + \frac{p}{m}\frac{\partial f}{\partial r} - \frac{\partial U}{\partial r}\frac{\partial f}{\partial p} = I\ (f) \qquad (1)$$

where r is the space coordinate, p the momentum, m the nucleon mass. U is the self-consistent field and I (f) a collision term. The Landau-Vlasov equation can be obtained within a semi-classical treatment [11]. The left-hand side term contains the so-called one-body dissipation as far as the interdistance D between the center of mass of each partner is concerned. Above the Coulomb barrier, the projectile is slowed down in the entrance channel through the window and the wall dissipation [12]. The dissipative processes can be understood by nucleon exchanges between the ions (window) and nucleon reflections on the mean field (wall). Since the interdistance D is a collective coordinate [13], the associated momentum can be already transferred to the intrinsic degrees of freedom by means of the one-body dissipation. The right-hand-side term is the collision term of the Boltzmann equation. It expresses the effect of the individual nucleon - nucleon collisions upon the system. At low relative velocity, the Pauli principle cancels this term, but in the high energy regime, it becomes the main slowing - down factor. Let us consider successively both (one- and two- body dissipation) momentum transfer processes.

One-body dissipation. The simplest way to study the linear momentum transfer is to consider the geometry of spheres in momentum space. Figure 1 shows the typical situation : the Fermi sphere of the projectile particles displaced from the Fermi sphere of the target particles by the relative momentum $\vec{p}_u$ of the two ions. This picture is extremely schematic since it restricts the form of the momentum distribution to a Fermi bisphere and, in addition to that, disregards its dependence on real space. The energy difference between the surfaces of the dashed sphere and the target Fermi sphere corresponds to the average binding energy E_b = 8MeV. Projectile particles within the dashed sphere (hatched area) are trapped inside the target potential well and transfer their momentum completely, whereas the particles outside will transfer no momentum at all as long as two-body collisions are neglected. In this limit of one-body dissipation, the momentum transfer is simply given by the probability to find the projectile particles trapped. The result is displayed as a function of the square-root of the available energy per nucleon above the Coulomb barrier on figure 2 by the dashed-dotted line. It is in this simple version independent of projectile and target combinations. As a matter of fact, the independence of the momentum transfer on the system is shown to a large extent by the experimental results.

Two-body dissipation. The collision integral in the equation (1) was obtained in an heuristic way as the difference between a loss and a gain term : $I(f) = G(f) - L(f)$ (2)

Contrary to the problem of the nucleon emission [14], the Pauli principle between the projectile nucleons might play here an important role [15] . The collective displacement of the momentum distributions requires a self-consistent treatment of the gain term. The loss term itself is simpler because it reads :

$$L(f) = \frac{p}{m} \frac{1}{\lambda(p)} f(\vec{p}) \qquad (3)$$

where $\lambda(p)$ is the local mean free path.

In order to add the two-body dissipation to the previous schematic picture with the one-body dissipation, we consider first the mean free path λ^* at the target escape surface p_e (dashed circle in figure 1). The value of λ^* is estimated in ref [14] and [16] to be equal to 15.5 fm. We can then assume that the projectile and target Fermi spheres approach each other according to the following equation for its mean relative momentum $\vec{p}_u$:

$$\frac{d\,p_u}{dt} = - \frac{Pe^2}{m\,\lambda_{eff}} \qquad (4)$$

which governs the motion of phase space cells on the target escape surface and can be obtained starting from eq. (2) ; λ_{eff} is an effective mean free path parametrized by :

$$\lambda_{eff} = g(p_u)\,\lambda^* \qquad (5)$$

with

$$g(p_u) = g_o / (p_f + p_u)^2 \qquad (6)$$

The factor $g(p_u)$ accounts for the gain term around the target escape surface and for the distortions of the Fermi spheres during the collision ; g_o is an adjustable parameter and p_f is the Fermi momentum.
The momentum transfer can then be computed according to the one-body picture plus the slowing-down of the displacement vector $\vec{p}_u$ due to the two-body dissipation. It depends slightly on the mean distance (essentially the diameter of the target nucleus) covered by the projectile nucleons in

the target. For the practical calculation of the distance, we use the mean velocity of the projectile nucleons which are virtually not yet trapped by the mean field.

Results. The fiqure 2 shows our results for the reactions $\alpha + {}^{238}U$ (full line) and $\alpha + {}^{59}Co$ (dotted). With $g_0 = 8\,p_f^2$, the agreement of the calculation with the experiments is excellent over the whole energy range. We verified thereby the weak dependence of the linear momentum transfer on the target size. As far as the projectile species is concerned, the description is only dependent on the energy per nucleon above the barrier. It renders the comparison between the model and the experiments meaningful also for the other systems. At low energies, the momentum transfer is practically entirely due to one-body dissipation. It becomes incomplete around the average nucleon binding energy E_b. The transition between one-body and two-body dissipation takes place around 40 MeV/nucleon above the barrier where each mechanism accounts for about 50 % of the transfer. Beyond 150 MeV/nucleon no momentum transfer can be ascribed any more to the one-body dissipation alone, because the initial Fermi spheres are disconnected.

Conclusion. The previous description which considers the dinuclear system in its momentum space predicts the limitation of the momentum transfer in nuclear reactions. One- and two-body dissipation define three regimes of incident energies with a transitional region between about 20 and 100 MeV/nucleon. The independence on the studied system refers to the basic momentum properties of the nucleons inside the nuclei. Finally, we exhibit the importance of the gain term in the collision integrals near the target escape surface, since the effective mean free path is larger than the local mean free path defined by the loss term alone. Self consistent treatments of the gain term might allow to extract this quantity microscopically [17].

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Figure Captions

Figure 1 : The Fermi spheres of the target and projectile particles displaced from each other by the relative momentum $\vec{p}_u$ of the colliding nuclei. The particles inside the dashed sphere p_e (Fermi energy E_f + nucleon binding energy E_b) are trapped by the mean field.

Figure 2 : The linear momentum transfer, calculated with one-body dissipation alone (dashed-dotted) and with one- and two-body dissipation for the reactions $\alpha + {}^{238}U$ (full line) and $\alpha + {}^{59}Co$ (dotted). The experimental data are indicated : ▼ from ref. [9] for $\alpha + {}^{238}U$, * from ref. [7] for $\alpha + {}^{232}Th$, ■ from ref. [18] for $\alpha + {}^{59}Co$ and ● from [2, 6, 19, 20, 21, 22, 23] for other systems.

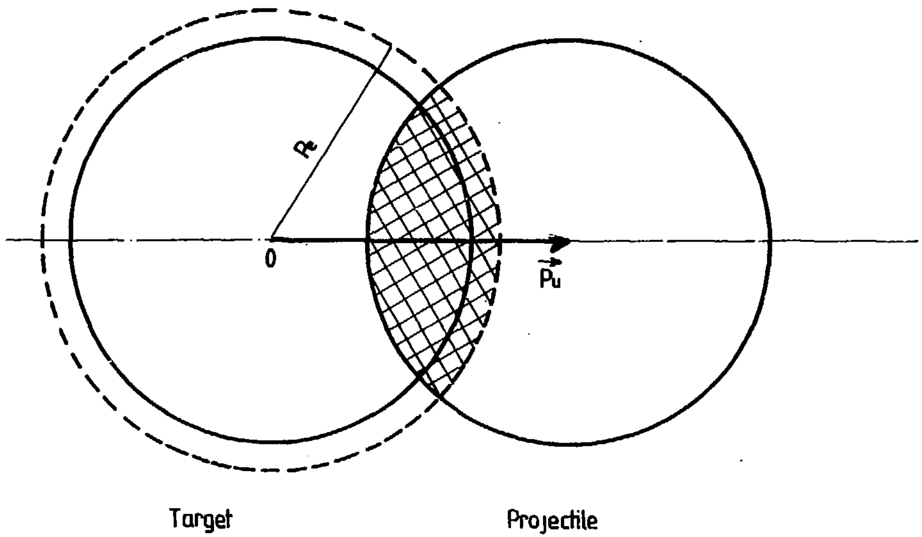
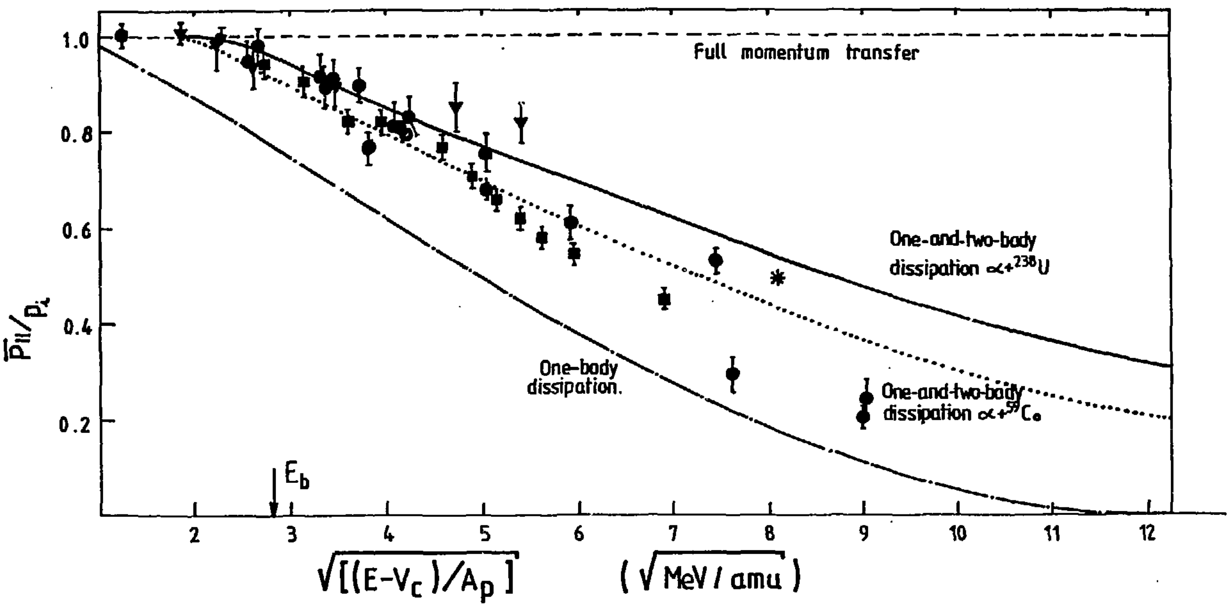


Figure 1


1.0
0.8
0.6
0.4
0.2
2
3
4
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7
8
9
10
11
12
Full momentum transfer
One-and-two-body dissipation α+238U
One-body dissipation.
One-and-two-body dissipation α+59Co
Eb
√[(E-Vc)/Ap]
(√MeV/amu)

Figure 2