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Dissipative processes in light heavy ion collisions

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Abstract. The characteristics of the dissipative processes in the collisions of light heavy ion systems at incident energies below 10 MeV/nucleon have been studied. The correlations between different experimental observables show similar trends as those known at much heavier systems and semiempirical relationships are established starting from assumptions on the nature of the microscopic mechanisms. The charge equilibration process in light systems is also studied.

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The idea of the formation of the dinuclear system, seen as a doorway to deep inelastic collisions, is supported by the experimental study of the statistical consequences of its presence, through the analysis of fluctuations in the excitation functions of the products formed in the collision of the systems with masses $A_1 + A_2 \leq 100$ [1]. While statistical concepts are more or less accepted to be valid for heavy nuclear systems, for those with a small number of nucleons involved, the situation is not so clear, as the existence of deep inelastic processes for light systems remained still insufficiently studied. In view of these considerations, it would be of interest to see, to what extent experimental data really show differences or, on the contrary, a noticeable similitude between these two extremes.

Continuous measurements in energy and angle for the projectile-like fragments identified in the reactions: ^{19}F (111.4, 125, 136.9 MeV) $+$ ^{27}Al, ^{19}F (111.4, 136.9 MeV) $+$ ^{12}C and ^{27}Al (140.14 MeV) $+$ ^{12}C, ^{27}Al have been carried out using the experimental device DRACULA [2], mounted at an extension of the 15 MV SMP Tandem from LNS, Catania, whose main components are two large area position sensitive ionization chambers, placed up and down relative to the horizontal reaction plane. Start and stop PPADs allowed to perform mass measurements too.

The double differential cross sections as a function of different experimental observables, show similar trends with those observed for much heavier systems. Thus, a complete dynamics from quasielastic to complete dissipation regime is evidenced even in the case of such light systems and microscopic models were able to describe it [3,4]. The double differential cross section as a function of the atomic number (Z) of the reaction product and the total kinetic energy (TKE) shows a continuous broadening of the charge distribution with increasing total kinetic energy loss (TKEL). Maxima centered approximately at the projectile and target Z values are present up to large TKEL. This shows that the interacting nuclei did not completely lose their identity, suggesting a statistically not equilibrated process.

The experimental angular distributions of the reaction products depend on the nature and time scale of the reaction. An estimate of the interaction time, for different degrees of inelasticity of the reaction process (windows of TKE), can be done from the angular distributions for any reaction product, in the frame of a Regge-pole model [5]. The representation of the interaction time as a function of Z and TKEL in figure 1 shows that, it is possible to populate more and more different Z values from that corresponding to the projectile, as the interaction time increases. Thus, the energy integrated angular distributions usually presented in the literature, becoming flatter as the atomic number difference between the detected product and the projectile increases, reflect the necessity of a longer interaction time in order to reach Z values far off from the projectile atomic number, but for the same degree of inelasticity of the reaction, the value of the average lifetime is independent of the specific fragment in the exit channel whose angular distribution has been used to deduce it. This behaviour is characteristic to a diffusion type process.

The natural logarithm of the charge distribution variance (σ_Z^2) obtained from a two-gaussian fit, in windows of TKE, as a function of the ratio of the total kinetic energy loss to the grazing angular momentum (TKEL/l_{gr}), follows a systematics which has been established for light, medium and heavy mass systems in [6], namely:

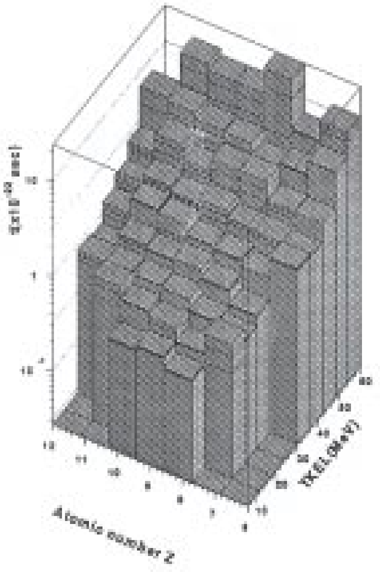

Figure 1. A typical contour plot of the interaction time as a function of Z and TKEL.

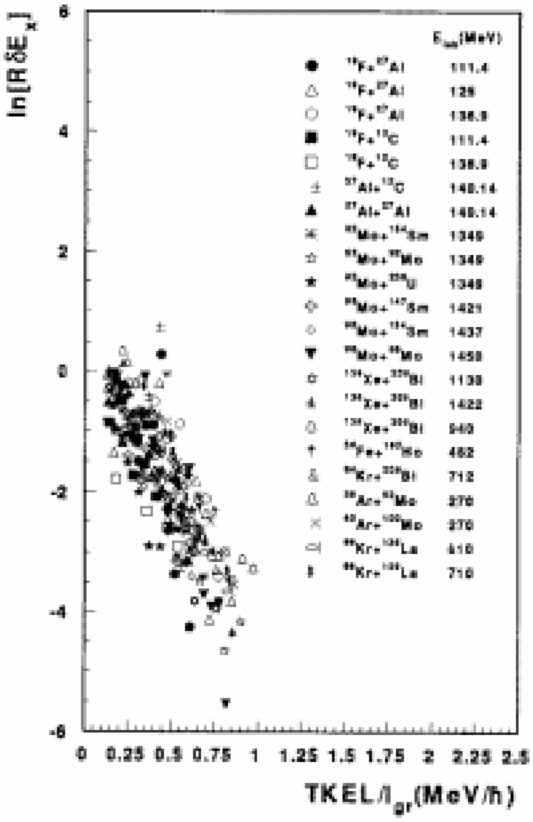

Figure 2. Dependence of energy dissipated per transferred nucleon on TKEL and l_{gr} for various systems.

$$\ln[F\sigma_Z^2] = s\left[\frac{\mathrm{TKEL}}{l_{\mathrm{gr}}} - \frac{\Delta}{l_{\mathrm{gr}}}\right], \qquad F = s\frac{m}{\mu}\alpha\frac{E_0}{l_{\mathrm{gr}}}\left(\frac{A}{Z}\right)^2. \tag{1}$$

This corresponds to an energy dissipation time rate assumed to be of the form [6]:

$$\frac{\mathrm{d}E}{\mathrm{d}\tau} = -2D_A\frac{m}{\mu}\alpha E_0\frac{\tau_0}{\tau}. \tag{2}$$

m is the nucleon mass; μ is the reduced mass of the system; $E_0 = E_{\mathrm{cm}} - V_{\mathrm{coul}}$ is the initial kinetic energy available over the Coulomb barrier; V_{coul} is the Coulomb potential evaluated at the interaction radius; α takes into account the Pauli exclusion principle in the process of nucleon exchange. D_A is the mass diffusion coefficient; A and Z refer to the composite system. A correlated exchange of nucleons is assumed: $\sigma_A^2 = (A/Z)^2\sigma_Z^2$. τ_0 represents the time when the statistical exchange of nucleons shows up and Δ the corresponding value of TKEL, which can be correlated to the change of slope more clearly observed in the experimental data from [7]. s is the universal value of the slope experimentally established for heavy (6.07 ħ/MeV) [8], medium (5.27 ħ/MeV) [7] and light (5.93 ħ/MeV) [6] systems.

Thus, the width of the charge distribution, measured experimentally as a function of TKEL, is limited by the size and incident energy of the system, as the expression of the abscissa in eq. (1) behaves like a system independent quantity. The relationship (2), the linear dependence of σ_Z^2 on the interaction time in a simple diffusion model and the exponential dependence of τ on TKEL [6], lead to the following expression for the amount of energy dissipated per transferred nucleon (δE_x):

$$\ln[R\delta E_x] = -s\left[\frac{\mathrm{TKEL}}{l_{\mathrm{gr}}} - \frac{\Delta}{l_{\mathrm{gr}}}\right], \qquad R = \frac{1}{\frac{m}{\mu}\alpha E_0}, \tag{3}$$

which can be followed in figure 2.

By considering in the TKEL range from 0 up to Δ, a mechanism of collective exchange of nucleons (corresponding to charge equilibration) and under the assumption that the number of exchanged nucleons is equal to the mass distribution variance, related to σ_Z^2 by a continuous evolution from uncorrelated to correlated exchange of nucleons, one obtains that the charge distribution variance scaled with a factor which depends on the system, follows the dependence:

$$F_\Delta \sigma_Z^2 = \mathrm{TKEL}, \qquad F_\Delta = f\frac{A}{Z}\frac{m}{\mu}\alpha E_0, \tag{4}$$

with $f = 1 + ((A/Z) - 1)\cdot\mathrm{TKEL}/\Delta$.

If it is assumed that at time τ_0, the charge distribution variance reaches the value of the plateau predicted by the one-dimensional oscillator model in the charge asymmetry degree of freedom [9] : $\sigma_Z^2 = \hbar\omega/2K$ (K is the stiffness parameter), the following expression is obtained for the slope:

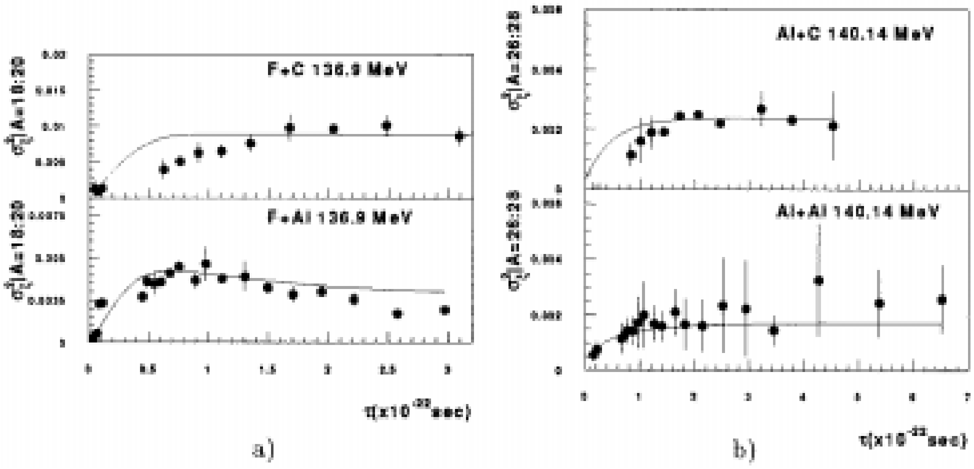

Figure 3. Comparison of experimental data for conditional charge variance with predictions of damped quantum oscillator model for (**a**) fluorine induced reactions Al and (**b**) aluminium induced reactions on C and Al.

$$s = \frac{1}{\frac{m}{\mu}\alpha\frac{E_0}{l_{\mathrm{gr}}}\frac{\hbar\omega}{2K}\left(\frac{A}{Z}\right)^2}. \tag{5}$$

In spite of the very simple hypotheses, the relationship (5) is valid in the limit of a factor 1.5 for all the systems included in the systematics.

In figures 3(a), (b) one can see the comparison between the experimental data for the conditional charge variance and the predictions of the model for the damped quantum oscillator in the charge asymmetry degree of freedom, treated as an open quantum system, with the same parameters used for heavier systems [10].

The elastic scattering data have been analysed within the Frahn formalism and reaction and non-fusion processes cross sections have been estimated.

From the experimental results presented in this work one can conclude that, the deep inelastic reaction mechanism is also present in the interaction of light systems at energies below 10 MeV/nucleon. The presence of the same types of correlations as those established for medium and heavy systems, suggests the existence of similar underlying microscopic mechanisms, which could be a challenge to the new generation of microscopic models.

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