Direct nucleonemission from hot and dense regions described in the hydrodynamical model of relativistic heavy ion collisions

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The collision process is described by hydrodynamical equations. The escape of nucleons which do not take part in the thermal equilibrium is considered by including drain terms in these equations. The energy spectra of the escaped nucleons and of nucleons evaporated after the breakup of the fluid are compared.

[NUCLEAR REACTIONS Relativistic heavy ion reactions, nuclear hydrodynamics, nucleon spectra.]

Numerous theoretical models[1–4] apply the assumptions of thermodynamical and hydrodynamical equilibration. However, the apparent success of cascade[5] and kinetic[6] models has risen doubts about the existence of local equilibrium. One point usually discussed is the length of the mean free path. Although this problem is not totally solved yet, recent experimental studies[7] yielded a value of $\lambda=2.4\pm0.2$ fm for a proton shot into a nucleus with high energy. It follows that for nucleus collisions the mean free path is in the order of 1 fm. Critical fluctuations at the occurrence of phase transitions may decrease the mean free path at high enough energies even more.[8]

In the present work we are studying another problem that was not yet considered from the hydrodynamical point of view although in other models it is widely discussed.[5,6,9] From the hot and dense nuclear matter some nucleons can be emitted after one or a few collisions, and can leave the system before the collective processes are completed. Thus these particles cannot contribute later to the local equilibrium. The important question of whether this is a negligible or important effect, is not trivial to answer. In certain experiments[10] the preequilibrium emission seems to be dominating and these results are explained well[11] in the linear cascade model where only a limited equilibration is possible. However, even in the same kind of experiments with heavier systems the collective processes are already apparent.[12]

A first attempt to estimate this preequilibrium emission in a simple model[13] used only schematic assumptions about the formation of a hot spot,[14] and the nucleon emission was taken into account as a second stage in the collision process. Correspondingly the estimated rate of the preequilibrium emission was based on the assumption that the hot spot embedded in a surrounding cold nuclear matter has a well defined distance[13] $R-R_s$ from the surface, and this distance and the thermal velocity define the emission rate.

Since both the formation of the dense and hot shocked region (hot spot) and the preequilibrium emission are caused by the nucleon-nucleon collisions or interactions, the previous separation is somewhat artificial. In the present paper we study the building up of the hot and dense shocked region in the presence of possible nucleon emission. After each nucleon-nucleon collision the scattered nucleons can leave the system with some probability. The collision number per unit volume and time for such particles where one of the final nucleons has a velocity v_1 is given by[15]

$$R=\int d^3v_2 d\Omega\,|v_1-v_2|\,\sigma(\Omega)\,f(r,v_1',t)\,f(r,v_2',t)\,, \tag{1}$$

where σ is the differential cross section and f is the nucleon distribution function. So the nucleon flux nq' from a fluid element of density n at position r in a direction v_1 through the surface at distance $l(r,v_1,t)$ is

$$nq'(v_1)d^3v_1 = R\exp[-l(r,v_1,t)/\lambda(n(r),v_1)]d^3v_1 , \quad (2)$$

where λ is the mean free path averaged over the path of the escaping nucleon. Consequently the total loss rate per fluid element of unit volume reads as

$$nq(r) = \int d^3v_1 d^3v_2 d\Omega \, |v_1 - v_2| \, \sigma(\Omega) \, f(r,v_1',t) \, f(r,v_2',t) \exp[-l(r,v_1,t)/\lambda(n(r),v_1)] . \quad (3)$$

Only those particles can escape which have a kinetic energy enabling them to surmount the potential barrier at the surface. So, although the exponential factor $e^{-l/\lambda}$ would favor the emission of particles from the surface regions, the higher density and temperature of the central regions lead to higher collision numbers and so to a higher escape probability. In order to give a quantitative estimate of the number of escaping nucleons we included this process as a drain into a one dimensional hydrodynamical model,[16] and used the following simplifying assumptions in Eq. (3):

(i) In agreement with the one fluid hydrodynamical approach the local momentum distribution $f(r,v,t)$ was equal to a thermal equilibrium Maxwell-Boltzmann distribution.

(ii) The average mean free path was chosen to be constant and equal to the mean free path in the normal nuclear matter[15]

$$\lambda = 1/n_0\sigma_{\text{tot}}\sqrt{2} ,$$
$$\sigma_{\text{tot}} = 40 \text{ mb} , \quad (4)$$
$$n_0 = 0.17/\text{fm}^3 .$$

(iii) The average distance was also set to a constant

$$l = \tfrac{3}{4} \sqrt[3]{3A_{\text{tot}}/4\pi} \, r_0 , \quad r_0 = 1.18 \text{ fm} . \quad (5)$$

(iv) Only those nucleons were allowed to escape for which the average internal energy of the fluid cell was positive.

It is important to note that these assumptions might lead to an overestimation of the nucleon escape rates.

The drain terms were then included in the one dimensional relativistic fluid dynamical model[16]

$$[\partial_t + (u\cdot\nabla_r)]N = -N \operatorname{div} u - qN ,$$
$$[\partial_t + (u\cdot\nabla_r)]M = -M \operatorname{div} u - (\nabla\cdot\Gamma) - qM , \quad (6)$$
$$[\partial_t + (u\cdot\nabla_r)]E = -E \operatorname{div} u - \operatorname{div}(u\Gamma) - qE ,$$

where M and E are the T^{oi} and T^{oo} components of the energy-momentum tensor T^{ik}, and

$$N = \gamma n, \quad M = (\rho + \Gamma)u\gamma^2 , \quad E = (\rho + \Gamma u^2)\gamma^2 ,$$
$$\Gamma = \eta\gamma[\partial_t + (u\cdot\nabla_r)]n + p, \quad \gamma = 1/\sqrt{1-u^2} .$$

It is assumed that the escaping particles take with them the part of energy and momentum which is proportional to their ratio to the whole matter. This assumption may be somewhat modified if we take into account that mainly the nucleons having high thermal velocity can escape, and so, if their number is not negligible, an observable cooling may be produced. So in the presence of large nucleon escape rates (30%) the fluid dynamics is influenced considerably and the maximum compression and temperature decrease.

The other details of the hydrodynamical and the subsequent evaporational model were the same as in Ref. 16. The escaped nucleons maintained their collective flow velocity component u, and their random thermal velocity distribution was calculated from the energy taken by them from the system. At the moment where the fluid became sufficiently dilute[17] the fluid cell broke up and a final evaporation model[16] was used for the nucleons which survived in a fluid phase up to this time.

In Fig. 1 the obtained cross sections are shown for a Ca + Ar collision at 800 MeV/nucleon projectile energy. An apparent structure may be observed in the $\theta = 0°$ energy spectra of the emitted nucleons in the form of two peaks which are somewhat closer to each other than the original target and projectile momentum difference. This structure is caused by the fact that the fluid cells heated up just above the escape barrier did lose only a small portion of their target or projectilelike collective velocity. So an observable peak structure may be formed. The nucleons emitted later from the hotter regions already give a smooth contribution to the energy spectrum. The sharpness of the peaks may be somewhat relaxed in three dimensional cases since there the collective flow velocity is not confined into the beam

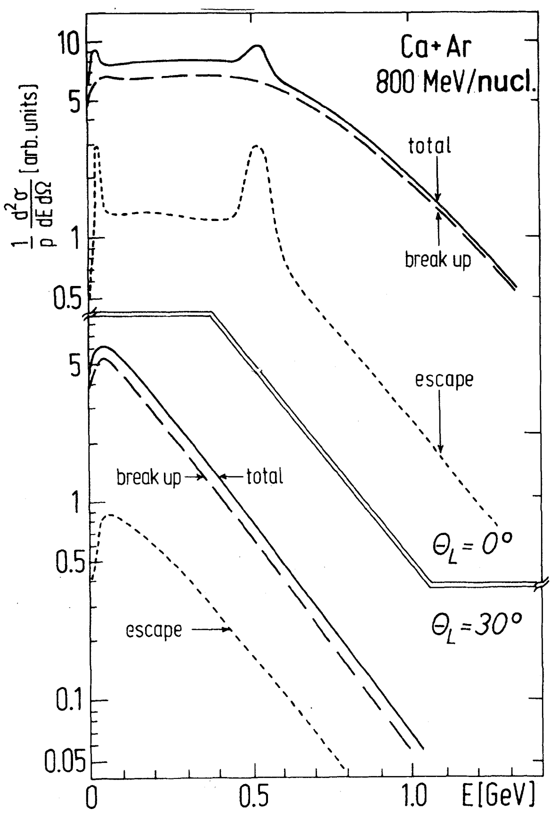

FIG. 1. Invariant double differential nucleon cross section for Ca + Ar reaction at 800 MeV/nucleon projectile energy calculated in the hydrodynamical model with drain at two laboratory angles. Here the large mean free path λ' is used. The dotted lines indicate the contribution of the nucleons that escaped the system before the collective flow was completed and the fluid broke up. The full curves also contain the nucleons from the final breakup evaporation (dashed curves). An observable peak structure is caused by the escaped nucleons.

direction. Another effect which may cause a considerable smearing is that in three dimensions the nucleon fluid has a changing and complicated surface which changes the direction of the escaping nucleons if they do not penetrate it orthogonally. Thus we somewhat overestimate the peak structure in our model. However, to make a full three dimensional calculation with continuous escape in order to evaluate the above mentioned two effects is of high numerical expenditure.

The main point is that we can estimate quantitatively where the collective effects are dominating. The total number of escaped nucleons is listed in Table I. We can see that in small systems the neglect of preequilibrium nucleon emission is not allowed, but, at higher masses the escape rates are

TABLE I. Number of escaped nucleons before the breakup of the nuclear matter (in percents of the total starting baryon number).

Reaction	Projectile energy	$\lambda=1/\sqrt{2}n\sigma$	$\lambda'=1/n\sigma$
Pb + Pb	400 MeV/nucleon	10.6(2.5%)	47.0(11%)
Ca + Ar	400 MeV/nucleon	11.2(14%)	23.1(29%)
Ca + Ar	800 MeV/nucleon	13.3(17%)	26.5(33%)

really small. This strong sensitivity stems from the fact that the ratio of the mean free path and the distance from the surface appears in the exponent. Owing to this fact the escape rates also depend strongly on the estimated form of the mean free path. If we use, instead of Eq. (4), a smaller mean free path (see Table I at $\lambda'=1/n_0\sigma_{tot}$), the escape rates decrease considerably.

Comparing the present results to a previous viscous fluid-dynamical study,[16] which has not considered the direct nucleon escape, we see essential differences in smaller colliding systems ($A=40$). The most important observable difference is the peak in the cross section in forward direction around 500−600 MeV proton energy (Fig. 1), similar to the recently observed "shoulder-arm" behavior[18] of the proton spectra. This peak is caused by the direct nucleon escape in the model. Owing to the energy and momentum carried by these escape nucleons, the temperature and density increase is somewhat less than in the previous model.[16] However, in large systems such as Pb + Pb, the escape process is certainly negligible (Table I), and a noticeable difference cannot be observed between the two approaches. The reabsorption of the particles, which could escape in smaller systems, here contributes to the momentum and energy transfer inside the fluid, i.e., to the viscosity and heat conduction. Thus we can conclude that in heavy systems the viscous and heat conducting fluid-dynamical model has a great accuracy.

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