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EVAPORATION vs TRANSVERSE EXPANSION IN TRANSVERSE MOMENTUM DISTRIBUTION

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Abstract

Evaporation of particles at the surface of thermalized expanding matter is studied and its effects are compared with transverse expansion. If hydrodynamical flow has indeed been established in current high energy nuclear collisions, evaporation helps to get a more consistent picture with data. In any case, it has a sizable effect on the pion transverse mass spectrum so should be included in attempts to develop a complete hydrodynamical description of matter in relativistic heavy ion collisions at future accelerators.

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Introduction

The description of relativistic heavy ion collisions is still in its infancy. There does not exist a picture on which everybody agrees. In fact one can distinguish two radical view points. On one side, there are the dynamical extremists [1] who try to describe nuclear collisions as a superposition of nucleon-nucleon collisions, described phenomelogically. This is still complicated and some approximations must be made (e.g. independent string fragmentation). This allows to describe data such as transverse energy distributions. On the other side, there are the statistical extremists [1]. Those ones do not want to hear about such complicated and poorly known physics as that of proton structure and p-p collisions or nucleus-nucleus collisions. In fact, if thermalization has been attained, such details have been erased and the more sound methods of statistical mechanics can be used. This also permits to reproduce data such as transverse momentum distributions. Of course between these two extremes, there is a range of other view points (e.g. the extremely puzzled).

The basic origin of this ambiguity is that we do not know the thermalization time, or time needed for the particles created early in a collision to evolve from the initial state to a thermal equilibrium state. The often quoted value of 1 fm [2] might be exceeded (cf. e.g. reference [3]) or overestimated (cf. e.g. reference [4]). A reliable estimate of the thermalization time can only be done by a microscopic dynamical description of the reaction, which requires knowledge of interaction cross sections, initial density reached, etc, i.e. quantities that are not well established yet. It is however thought that [5], due to the higher multiplicities and longer dense matter lifetimes available, states of thermal equilibrium should be reached (if they have not been reached yet) at the future accelerators, RHIC and LHC, that will be in use before the end of the decade. In this sense it is important to develop a complete hydrodynamical description of relativistic heavy ion collisions.

There is indeed a lot of activity in this direction. Full three-dimensional hydrodynamical codes (i.e. codes where the relativistic laws of conservation of momentum-energy and baryon number are numerically solved point by point) are becoming available [6,7] and transverse momentum and rapidity distributions are predicted. These took over more simplified solutions [8,9,4]. Finer details are now being studied. The effect of the freeze out criteria and initial conditions are tested using such codes or easier to handle semi-numerical approaches [10-13]. The impact of resonance decays (in particular in connection with the observed low-p_t pion enhancement) is being evaluated both in static thermal models and hydrodynamical models [14-17]. The aim of this paper is to study a new escape criterion of particles produced by thermalized expanding matter. Besides the escape caused, as usual, by the rarefaction of the medium (freeze out), particles may be emitted from the surface (evaporation). In a certain sense, our study is an improvement of the dissociation condition presented in reference [12]. Evaporation has not received much attention yet but has interesting qualitative features and may be quantitatively important in a hydrodynamical description.

Theoretical description of evaporation

The phenomenon that we want to describe is the following. At each instant, the temperature in a dense matter slice perpendicular to the beam axis at various times is as shown below in figure 1.a . There is a constant temperature plateau, followed by a steep decrease of temperature on a small distance (for times $\leq$ 4 fm) and then a diffuse tail. Part of the particles, in the diffuse tail, freeze out and free stream to the detector. For simplicity, we will suppose that the freeze out criteria is $T \leq T_{fo}$. Then, following this diluted materia, particles in a shell of thickness a mean free path also escape towards the detectors (they evaporate), if their momentum is oriented outward. An example of evaporating and freezing out shells is shown in figure 1.b. It is important to include the evaporation contribution to the transverse

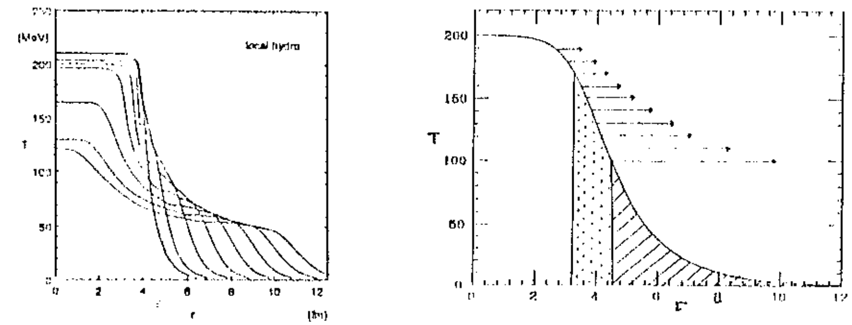

Figure 1: a) Temperature as function of radius for times between 0 and 7 fm, with increment of 1 fm, as calculated with a hydrodynamical code with longitudinal and transverse expansion [18]. The initial profile for energy density was chosen to be of a Fermi type in both transverse and longitudinal directions. b) Contributions to the transverse mass spectrum at a fixed time for $T(r) = 200\,MeV\,[(1+exp(-7))/(1+exp(2r-7))]^(1/3)$. The dashed area corresponds to freezing out particles ($T \leq 100\,MeV$). The dotted area indicates particles that evaporate if their momentum is outward. Arrows indicate length of mean free path $(1/[\sigma_{\pi\pi} n_\pi(T)]$ with $\sigma_{\pi\pi} \sim \sigma_{NN}$=40 mb) at the corresponding temperature.

mass spectrum because of the gradient in temperature near the plateau. We have access to temperatures well above freeze out via evaporation at least initially when there is a steep fall in temperature. Later (at times > 4 fm), the temperature after the plateau falls slowly so outgoing particles would scatter in diluted matter before they go out and escape at a low temperature. When the plateau temperature finally fall below T_{fo}, all the matter left freezes out.

The transverse mass distribution of the final state particles has schematically the form

$$\frac{dN}{dym_\perp dm_\perp} = \frac{dN}{dym_\perp dm_\perp}_{|t_0\, to\, t_{fo}} + \frac{dN}{dym_\perp dm_\perp}_{|T_{fo}} \tag{1}$$

The first term is the integration over time of the various shells of particles evaporating from the surface, from the initial time t_0 to the freeze out time t_{fo}. The second term is the contribution due to the particles that freeze-out.

To actually compute the two terms in equation (1), we use the Cooper-Frye formula [19]

$$E\frac{d^3N}{dp^3} = \frac{dN}{dydp_\perp^2} = \frac{g}{(2\pi)^3}\int \frac{p^\mu.d\sigma_\mu}{exp[p.u-\mu]/T \pm 1} \tag{2}$$

where the integral is over the three-dimensional surface crossed by the particles. This is a hydrodynamical generalization of the formula from statistical mechanics

$$\frac{d^3N}{dp^3} = \frac{g}{(2\pi)^3}\int d^3x \frac{1}{exp[(E-\mu)/T] \pm 1} \tag{3}$$

We need to know the time and space dependence of the temperature, chemical potentials and flow velocity as well as choose the 3-surface to actually calculate quantities with equation (2). To do that, we are going to make a number of simplifying assumptions. What we want to do is calculate order of magnitudes and point out properties of evaporation. If the result looks interesting, then a more careful calculation shoud be done, e.g. by implementing evaporation in numerical hydrodynamical codes.

We suppose, to fix a frame to perform simple calculations, that the longitudinal expansion can be described by the Bjorken solution [2], in particular we neglect baryonic number. Now let us start with the freeze out term in equation (1). It contains the matter that freezes out in the dilute tail at various instants and the matter that freeze out globally at t_{fo}. We expect the latter, a volume term, to dominate the former, surface terms. As a first aprroximation, we will only consider therefore the matter that freezes out globally. The condition $T(t,\vec{x}) = T_{fo}$ fixes a surface $t(z)$ and the vector $d\sigma_\mu$ reads $(d\rho\rho d\phi\tau_{fo}ch\eta d\eta, 0, 0, -d\rho\rho d\phi\tau_{fo}sh\eta d\eta)$. So we get

$$\frac{dN}{dym_\perp dm_\perp} = \frac{g\tau_{fo}}{(2\pi)^3}\int \rho d\rho d\phi d\eta \frac{m_\perp ch(\eta-y)}{exp[m_\perp ch(\eta-y)/T_{fo}] \pm 1} = \frac{gR^2\tau_{fo}}{2\pi} m_\perp \sum (\mp)^n K_1(\frac{nm_\perp}{T_{fo}}) \tag{4}$$

R is the firebarrel radius (at freeze out). This is a standard result and can be found for instance in reference [20].

Now we turn to the evaporation term. We suppose that evaporation occurs at the plateau temperature. To compute this temperature precisely would imply doing hypothesis about transverse flow so we leave this to a later work (possibly numerical). We also suppose that the evaporation surface is at a fixed $\rho = cst$. Since the dependence in radius turns later to be not very big (evaporation and feeze out differ linearly by $\sim R$), we approximate $cst \sim R$. Therefore the vector $d\sigma_\mu$ reads $(0, Rcos\phi\tau d\tau d\eta, Rsin\phi\tau d\tau d\eta, 0)$ and we get

$$\frac{dN}{dym_\perp dm_\perp} = \frac{gR}{(2\pi)^3}\int \tau d\tau d\phi_p d\phi d\eta \frac{p_\perp cos(\phi-\phi_p)}{exp[m_\perp ch(\eta-y)/T_{fo}] \pm 1} = \frac{gR}{\pi^2} p_\perp \int_{\tau_0}^{\tau_{fo}} \tau d\tau \sum (\mp)^n K_0(\frac{nm_\perp}{T_t}) \tag{5}$$

We can estimate the order of magnitude of the evaporation compared to freeze out in the transverse mass spectrum (at various transverse masses) by forming the ratio of equation (5) to (4). We get

$$\frac{"evap."}{f.o.} \simeq v_\perp(y=0)\int_{\tau_0}^{\tau_{fo}} \frac{d\tau}{R}\frac{\tau}{\tau_{fo}}\frac{e^{-m_\perp/T(\tau)}}{e^{-m_\perp/T_{fo}}} \tag{6}$$

Typical values for S+S collisions would be $R = 3.7\,fm$, $\tau_0 = 1\,fm$ and $\tau_{fo} = R/c_{sound} \sim 6\,fm$ so that *the dominant factor is the ratio of exponentials.* Supposing $T_0 = 200\,MeV$ and $T_{fo} = 100\,MeV$ we get for this ratio $\sim 10^2$ if $m_\perp = 1\,GeV$ (then "$evap \gg f.o.$", in particular for heavy mass particles) and ~ 1 for $m_\perp = 0.2\,GeV$ (then "$evap \sim f.o.$" for light transverse mass, e.g. slow pions).

Above we have supposed that the evaporation occurs on a fixed $\rho = cst$ surface, in reality we expect it to take place in the shell of radii between $cst - \lambda$ and cst where λ is the mean free path at proper time τ and location cst. As a consequence evaporation is more difficult at high T (smaller λ) than at low T. To take this roughly into account we can multiply the integrand of the evaporation term in equation (5) by the probability to be in a shell at less than λ from the surface, i.e. $2\lambda/R - (\lambda/R)^2$. This quantity is between 0 and 1 because initially $\lambda \ll R$ and freeze out can be taken to occur when $\lambda \sim R$.

To complete our calculations of equations (4) and (5), we need to know the time dependence of the temperature. The change of the temperature is due to the hydrodynamical expansion and the evaporation. To coupute this, we write the conservation of energy in a thin dense matter slice of radius R, perpendicular to the collision axis, extending from -Δ to +Δ around $z = 0$ (i.e. a slice at rest in the center of mass).

$$\partial_t E = -\int dS_z j^z - \int dS_\perp j^\perp \tag{7}$$

In equation (7), the amount of energy inside the disk (first term) changes with time because due to longitunal expansion, some particles go out along the collision axis Oz (second term) and because close to surface, particles can also escape (third term). We describe matter inside the cylinder as a perfect fluid (with equation of state $p = c_s^2\epsilon$) and evaporating matter as free particles. We get

$$\begin{aligned}
\partial_t E &\overset{z=0}{=} \partial_t \int \epsilon\, \rho d\rho d\phi dz = \partial_t\epsilon \times \pi R^2 2\Delta \\
\int j^z.dS_z &= \int \partial_z T^{0z}_{fl} \overset{z=0}{=} (1+c_s^2)\epsilon/t \times \pi R^2 2\Delta \\
\int j^\perp.dS_\perp &= \frac{3}{(2\pi)^3}\int d^3p \frac{p_\perp}{e^{E/T}-1} cos(\phi-\phi_p)\rho d\rho d\phi dz \delta(\rho - R) = \frac{3}{(2\pi)^3}\int d^3p \frac{p_\perp}{e^{E/T}-1} \times 2R\, 2\Delta
\end{aligned} \tag{8}$$

It is easy to integrate this and get

$$\epsilon(t) = \epsilon_0 (\frac{t_0}{t})^{1+c_s^2} - \frac{3}{(2\pi)^3}\frac{2}{\pi R}\int d^3p \frac{p_\perp}{t^{1+c_s^2}} \int_{t_0}^{t} dt' \frac{t'^{1+c_s^2}}{e^{E/T(t')}-1} \tag{9}$$

The first term in $\epsilon(t)$ is the usual one in the Bjorken solution [2] showing how the energy density decreases due to the longitudinal expansion of the volume occupied by matter. The second term indicates that, due to evaporation, the energy density in fact decreases more quickly.

Neglecting the pion mass, equation (9) gives

$$T(t) \sim T_0 \left(\frac{t_0}{t}\right)^{1/3} e^{(-0.06/R)(t-t_0)} \tag{10}$$

If one wants to multiply the evaporation term in (8) by the probablity to be close (less than a mean free path) to the surface, one gets instead

$$T(t) = T_0 \left(\frac{t_0}{t}\right)^{1/3} [1 - 0.5/(R^2\sigma)\frac{(t-t_0)^2}{T_0^3 t_0}]^{1/3} \tag{11}$$

Again, the first factor in equation (10) or (11) is the Bjorken solution [2] and will dominate for small times. The second factor in (10) is exponential because in that case, evaporation is proportional simply to what is contained in the disk. The second factor in (11) is decreasing fast for very large t but freeze out occurs before (see below).

Note that in the above calculation, we have supposed that when matter evaporates at the surface, the lost of energy is immediatly shared by all the matter inside. In reality, depending on the matter properties, there may be a cooling of the surface due to evaporation (for example, the sun is hotter inside than at its surface, so is a bowl of hot soup) rather than an instantaneous re-equilibration of temperature in a slice undergoing evaporation. If surface cooling is very strong, the temperature at the evaporating slice may even fall below T_{fo}. All particles, whatever the orientation of their momentum, would then leave the shell, by evaporation or freeze out. The next slice not affected by this can evaporate and freeze out at its turn. Evaporation would then look like a peeling of shells each at the expanding fluid temperature which is also what happened approximatively with equations (10) and (11). So this extreme scenario (up to changes in the radius) will still look like the instantantaneous re-equilibration scenario studied before. A detailed calculation of surface cooling would however be useful.

Numerical results

The time behavior of temperature is depicted below. We show explicitly the expansion and evaporation contribution to the cooling. We see that $T(t) \simeq T_{Bjorken}(t)$ at least for values of t below freeze out time. As mentioned above however, surface cooling due to evaporation may induce deviations from this behavior.

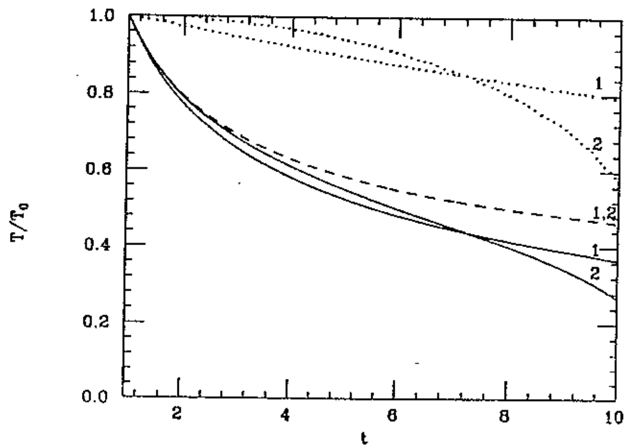

Figure 2: Temperature as a function of time. Label 1 refers to equation (10) and 2 to (11). For both equations, dashed line is the Bjorken part, dotted line is the evaporation contribution and solid line is Bjorken plus evaporation. Equation (11) is evaluated with T_0 =200 MeV and $\sigma \sim 6\ fm^2$ (or equivalently T_{fo} = 100 MeV) so curves labeled with 2 are strictly speaking only valid up to T/T_0 =0.5. (In addition, for both cases, t_0=1 fm and R=3.7 fm.)

We now show the transverse mass distribution for light and heavy particles. For pions, as discussed before, at small $m_\perp$, freeze out and evaporation are comparable and the slope reflects the freeze out temperature. For high transverse mass, evaporation dominates and the slope reflects the initial temperature. This gives rise to a sizable curvature of the spectrum. Note that we have not included resonance decays though in principle, at high temperature (e.g. T_0), there should be a copious number of them decaying into low $p_\perp$ pions. This will tend to increase the curvature.

For nucleons, as discussed above, since the transverse mass is always high, evaporation dominates and the slope reflects the initial temperature all along. Note that this result concerns thermal nucleons and comes from the fact that heavy particles are normally very suppressed when the temperature decreases. To take into account baryon number, a term $exp[\mu(t)/T(t)]$ should be included in the integrand of the evaporation term in equation (5) and a term $exp(\mu_{fo}/T_{fo})$ in the freeze out term in equation (4). If μ/T stays constant, then taking into account baryon number only affects the overall scale of the spectrum. Otherwise, the time evolution of μ/T will affect the precise shape of the spectrum.

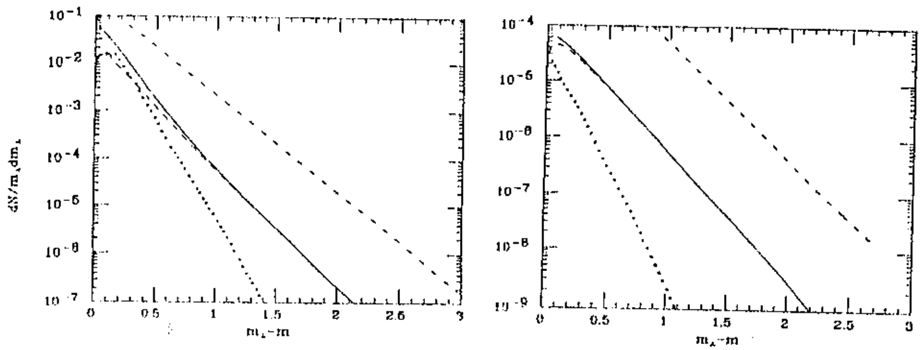

Figure 3: The various contributions to the observed transverse momentum distribution (equations (4) plus (5) a) for pion b) for nucleon. Dashed line is the evaporation contribution, dotted line is the freeze out contribution and solid line is the combination of both. For comparison, a thermal distribution (same formula as for freeze out) is also shown, with temperature T_0, as a dash-dotted line. We took t_0=1 fm, T_0=200 MeV and T_{fo}=100 MeV.

These conclusions can be contrasted with those for dense matter with longitudinal and transverse expansion. There, the high $p_\perp$ part of the transverse mass spectra has a slope that reflects the freeze-out temperature blue-shifted by the fluid transverse expansion speed. In addition, all the particle types that decouple at the same temperature acquire the same expansion speed (in addition to thermal speed) but different momentum. Thus, the transverse mass spectrum of heavier particles extends to higher value of $p_\perp$ giving a higher value of inverse slope. So for increasing particle mass, we expect increasing apparent temperature (at large $p_\perp$), i.e. an ordering of the temperatures [21] (see also [11]). However at really high value of $p_\perp$ ($p_\perp \gg m$) the theoretically predicted curves look parallel whatever the mass.

Comparison with experimental data

Since we have worked with a simplified model, it would be unwise to use it to fit data. Instead we want to see if its qualitative features go in the right direction to reproduce data

and if there are quantitatively sizable.

Data on transverse mass spectra have been obtained by most experiments. At Cern, NA34, NA35, WA80, EMU05 seem to agree to say that the pion spectrum has a curvature [22] and NA35, NA36, WA85 find within error bars similar slopes for heavy particles [23] This is in agreement with what our simple model predicts and below, we superpose its predictions for $T_0 = 200MeV$ and $T_{fo} = 100MeV$ with NA35 S+S data. Taking in account resonance decays would permit a higher value of T_{fo}. Other hydrodynamical models without evaporation are

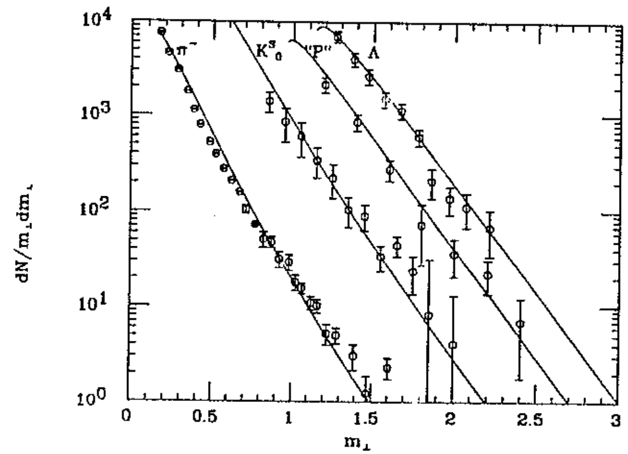

Figure 4: Transverse mass spectra. The points are NA35 data (see reference [23] and curves are from equation (4) plus (5) implemented with (10) and for T_0=200 MeV and T_{fo}=100 MeV. This is not a least square fit.

able to reproduce NA35 data see e.g. Lee et al. [11] for a model with spherical expansion (the authors who are purists noted that the first points in the pion spectrum were not well predicted and suggested that this might be due to resonance decays not included) and Ornik & Weiner [17] for a model with longitudinal and transverse expansion and resonance decays.

There exist however some data where evaporation might be crucial, namely particle ratios such as those obtained at Cern by NA35, NA36 and WA85. Various groups (see e.g. references [24,25] have shown that to reproduce with a non-expanding thermal gas the WA85 ratios $\overline{\Lambda}/\Lambda$, $\overline{\Xi}^-/\Xi^-$, Ξ^-/Λ and $\overline{\Xi}^-/\overline{\Lambda}$ and NA35 ratios $\overline{\Lambda}/\Lambda$ and K^0_S/Λ, temperatures of order 200 MeV are needed. Such temperatures are hard to understand in term of freeze out and transverse expansion that only "mimicks" high temperatures should not help. In our description, since these experimental ratios concern heavy particles, their spectra should be dominated by evaporation i.e. exhibit naturally a high temperature. Ratios involving pions and heavy particles should not correspond simply to a single temperature (pions and heavy particles may be emitted with different temperatures). We have not yet performed more precise calculations because this requires the knowledge of $exp(\mu(t)/T(t))$.

Conclusion

The idea that high $p_\perp$ particles could come from evaporation (at the surface of expanding matter) and low $p_\perp$ ones from a different mechanism (e.g. freeze out) was suggested in '76 by Gorenstein et al. [26], as a possible explaination for the change of curvature in the transverse momentum spectrum of secondaries in p-p collisions at the ISR. As no attempt was made there to compute the possible magnitude of evaporation with regard to the "other" mechanism, it was not clear whether the transverse mass spectrum could indeed be fitted or not. Today it also seems controversial to use hydrodynamics to describe ISR data (particularly at the lowest energies). Evaporation was studied as well, though more as a secondary idea, by Glendening and Karant a few years later [27]. These authors, in an attempt to find signals sensitive to the hadronic spectrum, described high energy (10 GeV/nucleon in the center of mass) nuclear collisions via the formation and disassembly due to evaporation of thermal fireballs. From a numerical simulation of evaporation, they obtained concave transverse mass spectra. It is not obvious how this conclusion would be affected by say, hydrodynamical expansion, initial and final temperatures, etc. Recently Lee et al. [11] commented briefly that (concave) experimental pion spectra could be reproduced by evaporation, but only using irrealistic weights in the time integral of equations analogous to Eq.(5). Basically, evaporation has not drawn much attention.

In fact, evaporation and freeze out are different aspects of the same dynamics of the dense gas. The exact particle emission criterion is that a given particle does not interact anymore. This criterion is not easy to manipulate so approximate ones, corresponding to specific properties of particles, are used. The usual freeze out conditions $T \sim T_{fo}$ or $R \sim 1/(\sigma n(T))$ are independent of the initial energy. A better criterion is $R(t) \sim 1/(\sigma n(T))$ [12] or $1/\sum_j \langle \sigma_{ij} v_{ij} \rho_j \rangle \sim min(R(t)/\langle v_i \rangle, -\rho/\dot{\rho})$ [10,11]. This includes more of the dynamics but still neglects the position of the particle (close or not to the surface) and the direction of its momentum (inward or outward). Here we have tried to assess the importance of surface emission on the transverse mass spectrum.

The model that we used is simplified but our results seem to indicate that it is worth investing more in trying to include surface effects to develop a complete hydrodynamical of matter in view of applications to future relativistic heavy ion collisions (in addition to longitudinal and transverse expansion, resonance decays, reasonable freeze out criteria, etc). Precisely, we have shown that evaporation may have a sizable effect on the pion transverse mass spectrum with reasonable values of T_0 and T_{fo}. In addition, if hydrodynamical flow has indeed been established in high energy nuclear collisions, evaporation leads to a consistent explaination of experimental data (pion curvature, similar slopes for all particle types, perhaps particle ratios). Finally, new effects on the transverse mass spectrum (concavity/convexity according to the freeze out temperature, ordering of slopes) might also occur.

Acknowledgments

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