Confronting Particle Emission Scenarios with Strangeness Data

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We show that a hadron gas model with continuous particle emission instead of freeze-out may solve some of the problems (high values of the freeze-out density and specific net charge) that one encounters in the latter case when studying strange particle ratios such as those from the experiment WA85. This underlines the necessity to understand better particle emission in hydrodynamics to be able to analyze data. It also reopens the possibility of a quark-hadron transition occurring with phase equilibrium instead of explosively. [S0031-9007(97)05187-9]

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An enhancement of strangeness production in relativistic nuclear collisions (compared to, e.g., proton-proton collisions at the same energy) is a possible signature [1] of the much sought-after quark-gluon plasma. It is therefore particularly interesting that current data at AGS (Alternating Gradient Synchroton) and SPS (Super Proton Synchrotron) energies do show an increase in strangeness production (see, e.g., [2]). At SPS energies, this increase seems to imply that something new is happening: In microscopical models, one has to postulate some previously unseen reaction mechanism (color rope formation in the RQMD code [3], multiquark clusters in the VENUS code [4], etc.) while hydrodynamical models have their own problems (be it those with a rapidly hadronizing plasma [5] or those with an equilibrated hadronic phase, preceded or not by a plasma phase). In this paper, we examine the shortcomings of the latter class of hydrodynamical models and suggest that they might be due to a too rough description of particle emission. (The main problem for the former class of hydrodynamical models is the difficulty to yield enough entropy after hadronization.)

To be more precise, let us assume that a hadronic fireball (region filled with a hadron gas, or HG, in local thermal and chemical equilibrium) is formed in heavy ion collisions at SPS energies and that particles are emitted from it at freeze-out (i.e., when they stop interacting due to matter dilution). One then runs into (at least) three kinds of problems when discussing strange particle ratios.

First, the temperature ($T_{\rm f.\,out} \sim 200$ MeV) and baryonic potential ($\mu_{b\rm f.\,out} \sim$ few 100 MeV) needed *at freeze-out* [6–10] to reproduce strangeness data of the WA85 [11] and NA35 [12] experiments actually correspond to *high* particle densities: This is inconsistent with the very notion of freeze-out. (While WA85 and NA35 data for strange particle ratios are comparable and lead to high T's and μ_b's, NA36 data are different and lead to lower T's [Phys. Lett. B **327**, 433 (1994)] for similar targets but a somewhat different kinematic window. However, the rapidity distribution for Λ's [E. G. Judd *et al.*, Nucl. Phys. **A590**, 291c (1995)] as well as $\overline{\Lambda}$'s and K_s^0's [J. Eschke *et al.*, Heavy Ion Phys. **4**, 105 (1996)] for NA36 are quite below that of NA35; NA44 midrapidity data for $K^{\pm}$ agree with that of NA35.)

Second, to reproduce strange particle ratios, it turns out that the strange quark potential μ_s must be small and the strangeness saturation factor γ_s of order 1 (this quantity, with value usually between 0 and 1, measures how far from chemical equilibrium the strange particles are, 1 corresponds to full chemical equilibrium of the strange particles). Both facts are expected in a quark-gluon plasma hadronizing suddenly, not normally in a hadronic fireball [13,14].

Third, using the values at freeze-out of the temperature, baryonic potential, and saturation factor extracted to reproduce WA85 strange particle ratios, one can predict the value of another quantity, the specific net charge (ratio of the net charge multiplicity to the total charge multiplicity). This quantity has been measured not by WA85, but in experimental conditions similar to that of WA85 by EMU05 [15]. It turns out that the predicted value is too high (while it might be smaller if a quark-gluon plasma fireball had been formed) [5,16].

In what follows, we study how problems 1 and 3 are related to the mechanism for particle emission normally used, freeze-out, and suggest that the use of continuous emission instead of freeze-out might shed some light on these questions. (We also rediscuss problem 2.) This underlines the necessity to understand better particle emission in hydrodynamics and reopens perspectives (see conclusion) for scenarios of the quark-hadron transition.

Fluid behavior and particle spectra.—First let us see in more detail what the two particle emission mechanisms just mentioned are. In the usual freeze-out scenario, hadrons are kept in thermal equilibrium until some decoupling criterion has become satisfied (then they free-stream toward the detectors). For example, in the papers mentioned above where experimental strange particle ratios are reproduced, the freeze-out criterion is that a certain temperature and baryonic potential have been reached. The formula for the emitted particle spectra used normally is the Cooper-Frye formula [17]. In the particular case of a gas expanding longitudinally only in a boost invariant way, freezing out at some fixed temperature and chemical potential, the Cooper-Frye formula reads

$$\frac{dN}{dy p_\perp dp_\perp} = \frac{gR^2}{2\pi}\tau_{\text{f. out}} m_\perp \sum_{n=1}^{\infty} (\mp)^{n+1} \exp(n\mu_{\text{f. out}}/T_{\text{f. out}}) \times K_1(nm_\perp/T_{\text{f. out}}) \,. \tag{1}$$

(The plus sign corresponds to bosons, and minus to fermions.) It depends only on the conditions at freeze-out: $T_{\text{f. out}}$ and $\mu_{\text{f. out}} = \mu_{b\text{f. out}} B + \mu_{S\text{f. out}} S$, with B and S the baryon number and strangeness of the hadron species considered, and $\mu_{S\text{f. out}}(\mu_{b\text{f. out}}, T_{\text{f. out}})$ obtained by imposing strangeness neutrality. So the experimental spectra of particles teach us in that case only what the conditions were at freeze-out.

In the continuous emission scenario developed in [18,19], the basic idea is the following: Because of the finite dimensions and lifetime of the fluid, a particle at space-time point x has some chance $\mathcal{P}$ to have already made its last collision. In that case, it will fly freely towards the detector, carrying with it memory of what the conditions were in the fluid at x. Therefore the spectrum of emitted particles contains an integral over all space and time, counting particles where they last interacted. In other words, the experimental spectra will give us in principle information about the whole fluid history, not just the freeze-out conditions. For the case of a fluid expanding longitudinally only in a boost invariant way with continuous particle emission, the formula that parallels (1) is

$$\frac{dN}{dy p_\perp dp_\perp} \sim \frac{2g}{(2\pi)^2} \int_{\mathcal{P}=0.5} d\phi \, d\eta \times \frac{m_\perp \cosh\eta \, \tau_F \rho \, d\rho \, + \, p_\perp \cos\phi \, \rho_F \tau \, d\tau}{\exp[(m_\perp \cosh\eta \, - \, \mu)/T] \pm 1} \,, \tag{2}$$

where $\tau_F(\rho, \phi, \eta; v_\perp)$ $[\rho_F(\tau, \phi, \eta; v_\perp)]$ is the time [radius] where the probability to escape without collision $\mathcal{P} = 0.5$ is reached. $\mathcal{P}$ is given by a Glauber formula, $\exp[-\int \sigma v_{\text{rel}} n(\tau')\, d\tau']$, and depends in particular on location and direction of motion. We are using both (1) and (2) in the following. Clearly, in (2), various T and $\mu = \mu_b B + \mu_S S$ appear [again $\mu_S(\mu_b, T)$ is obtained from strangeness neutrality], reflecting the whole fluid history, not just $T_{\text{f. out}}$ and $\mu_{b\text{f. out}}$.

So to predict particle spectra, in the case of continuous emission, we need to know the fluid history. To get it, we fix some initial conditions $T(\tau_0, \rho) = T_0$ and $\mu_b(\tau_0, \rho) = \mu_{b\,0}$ and solve the equations of conservation of momentum energy and baryon number for a mixture of free and interacting particles, using the equation of state of a resonance gas (including the 207 known lowest mass particles) and imposing strangeness neutrality. As a result we get $T(\tau, \rho)$, $\mu_b(\tau, \rho)$ and we can use these as input in the formula for the particle spectra (2). The procedure is similar to that of a massless pion gas [18,19] but is numerically more involved.

An important result [18,19] for the following is that for heavy particles, the spectrum (2) is dominated by the initial conditions, precisely a formula similar to (1) with freeze-out quantities replaced by initial conditions could be used as an approximation (particularly at high $p_\perp$); for light particles the whole fluid history matters. To understand this fact, one can consider Eq. (2) and compare particles emitted at $T(\tau, \rho) = 200$ and 100 MeV. For particles with mass of 1 GeV, the exponential term gives a thermal suppression above 100 between these two temperatures. The multiplicative factors in front of the exponential are in principle larger at the lower temperature but do not compensate for such a big decrease. This is why heavy particles are abundantly emitted at high temperatures. On the other side for pions, the thermal suppression is only a factor of 2. This is why light particles are emitted significantly in a larger interval of temperatures.

Note that since heavy particle and high $p_\perp$ particle spectra are sensitive mostly to the initial values of T and μ_b, the exact fluid expansion does not matter very much for them; in particular, the assumption of boost invariance should play no part in the forthcoming analysis of strange high $p_\perp$ particle ratios. (Note also that the data considered below are in a small rapidity window, near midrapidty. Were it not for this fact, boost invariance should not be assumed, because the rapidity distributions do not have this symmetry.) It would be, however, interesting to include continuous emission in, e.g., a hydrodynamical code, to obtain the fluid evolution and study pion data and low $p_\perp$ data.

Particle ratios.—Once the spectra have been obtained, they can be integrated to get particle numbers, taking into account eventual experimental cutoffs and correcting for resonance decays. Since we had to specify the initial conditions to solve the conservation equations and use this solution as input into (2), the particle numbers depend on $T_0, \mu_{b\,0}$. In contrast, for the freeze-out case, particle numbers depend on the conditions at freeze-out, $T_{\text{f. out}}$ and $\mu_{b\text{f. out}}$.

We look for regions in the $T_0, \mu_{b\,0}$ space which permit one to reproduce the latest WA85 experimental data on strange baryons [11] for $2.3 < y < 2.8$ and $1.0 < p_\perp < 3.0$ GeV: $\bar{\Lambda}/\Lambda = 0.20 \pm 0.01$, $\overline{\Xi^-}/\Xi^- = 0.41 \pm 0.05$, and $\Xi^-/\Lambda = 0.09 \pm 0.01$ ($\overline{\Xi^-}/\bar{\Lambda} = 0.20 \pm 0.03$ follows). In fact, there is no set of initial conditions which permits one to reproduce all the above ratios. A similar situation occurs with freeze-out, as noted in [20].

In the comparison of our model with WA85 data we have assumed, however, complete chemical equilibrium for strangeness production. As already mentioned in the introduction, this is not expected for a HG. In order to account for incomplete strangeness equilibration, we introduce the additional strangeness saturation parameter γ_s by making the substitution $\exp(\mu_S S) \rightarrow \gamma_s^{|S|} \exp(\mu_S S)$

in the (Boltzmann) distribution functions [21]. In our case, *a priori*, γ_s depends on the space-time location x; however, since as already mentioned, the initial conditions dominate in the shape and normalization of the spectra of heavy particles (particularly at high $m_\perp$), we take

$$\frac{dN}{dyp_\perp dp_\perp} \sim \gamma_s^{|S|}(\tau_0)\,\frac{dN_{\rm eq}}{dyp_\perp dp_\perp}\,, \qquad (3)$$

with $dN_{\rm eq}/dyp_\perp dp_\perp$ given by (2). In Fig. 1(a), we see that for $\gamma_s(\tau_0) = 0.58$, there exists an overlap region in the $T_0, \mu_{b\,0}$ plane where all the above ratios are reproduced. For the freeze-out case, a similar situation occurs as noted in [20], namely, there exists an overlap region for $\gamma_s = 0.7$.

In the freeze-out case, the values of the parameters in the overlap region correspond to high particle densities, and so it is hard to understand how particles have ceased to interact: this is the problem 1 mentioned in the introduction. In the continuous emission case, T_0 and $\mu_{b\,0}$ in the overlap region lead to high initial densities, but this is, of course, quite reasonable since these are values when the HG started its hydrodynamical expansion.

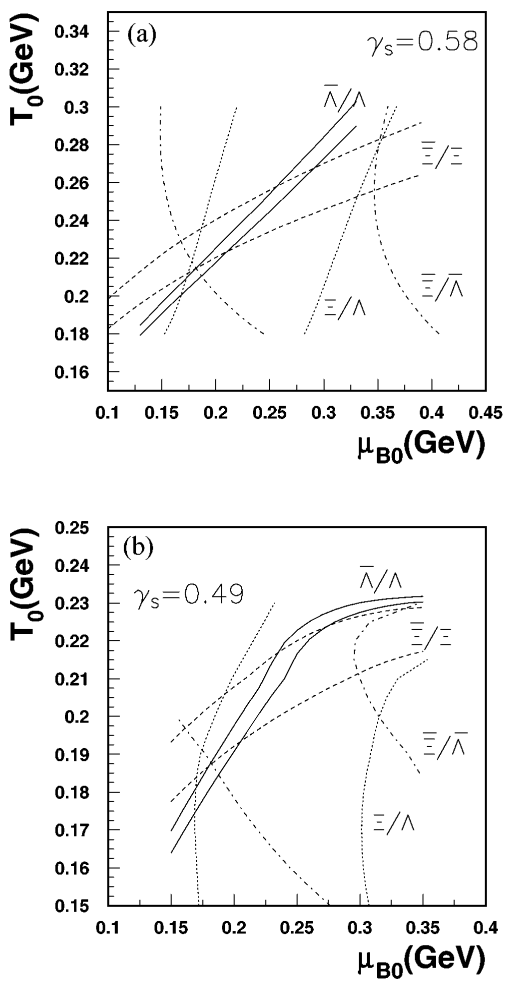

FIG. 1. Overlap region in the T_0-$\mu_{b\,0}$ plane for WA85 data, with $\langle \sigma v_{\rm rel} \rangle = 1\,fm^2$ (a) without (b) with hadronic volume corrections.

The aim of Fig. 1(a) is to allow an easy comparison with freeze-out results such as [20]; however, it is not physically complete: so far we have neglected hadronic volume corrections. For freeze-out, this correction cancels between numerator and denominator in baryon ratios so it can be ignored [10] but for continuous emission, since we are considering the whole fluid history to get particle numbers (and then their ratio), it must be included. There are various ways to do this (e.g., [10,22–24]). Using the more consistent method of [25,26], we get the overlap region shown in Fig. 1(b), which is shifted towards smaller T's and μ_b's but not very different from that of Fig. 1(a). Given that simulations of QCD on a lattice indicate a quark-hadron transition for temperatures around 200 MeV, it seems more reasonable to consider initial conditions $T_0 \sim 190$ MeV and $\mu_{b\,0} \sim 180$ MeV, i.e., the bottom part of the overlap region. The *precise* location of the overlap region (and exact value of γ_s) is sensitive to changes in the equation of state—as we have just seen—as well as in the cross section or cutoff $\mathcal{P} = 0.5$ in Eq. (2). Therefore, problem 1 (whether the overlap region is physically reasonable) is taken care of.

To be complete, we also examined the more recent ratios obtained by WA85 [27] (at midrapidity): $\overline{\Omega^-}/\Omega^-_{m_\perp \geq 2.3\ \rm GeV} = 0.57 \pm 0.41$, $(\Omega^- + \overline{\Omega^-})/(\Xi^- + \overline{\Xi^-})_{m_\perp \geq 2.3\ \rm GeV} = 1.7 \pm 0.9$, $K_s^0/\Lambda_{p_\perp > 1.0\ \rm GeV} = 1.43 \pm 0.10$, $K_s^0/\overline{\Lambda}_{p_\perp > 1.0\ \rm GeV} = 6.45 \pm 0.61$, and $K^+/K^-_{p_\perp > 0.9\ \rm GeV} = 1.67 \pm 0.15$. We looked for a region in the $T_0, \mu_{b\,0}$ plane where $\overline{\Omega^-}/\Omega^-_{m_\perp \geq 2.3\ \rm GeV}$ is reproduced: Because of the large experimental error bars, this does not bring new restrictions to Fig. 1(b). We also calculated our value for $(\Omega^- + \overline{\Omega^-})/(\Xi^- + \overline{\Xi^-})_{m_\perp \geq 2.3\ \rm GeV}$ in the overlapping region and found $\sim$0.7, in marginal agreement with the above experimental values. The three ratios involving kaons depend on more than just initial conditions (kaons are intermediate in mass between pions and lambdas, so part of the fluid thermal history must be reflected in their spectra), in particular $\gamma_s(x) \sim \gamma_s(\tau_0) \sim cst$ may not be a good approximation, and we are still working on this. The above experimental ratios concern SW collisions, data with SS are not so extensive yet but not very different [28] so a similar overlapping region can be found.

The apparent temperature extracted from the experimental $p_\perp$ spectra for Λ, $\overline{\Lambda}$, Ξ^-, and $\overline{\Xi^-}$ is $\sim$230 MeV [11]. Given that we extracted from ratios of these particles, temperatures $T_0 \geq 190$ MeV, we conclude that heavy particles exhibit little transverse flow, which is compatible with the fact that they are emitted early during the hydrodynamical expansion.

Specific net charge.—We now turn to

$$D_q = (N^+ - N^-)/(N^+ + N^-) \qquad (4)$$

using the continuous emission scenario. As mentioned in the introduction, for HG models with freeze-out the predicted D_q is too high, when using values of the freeze-out parameters that fit strangeness data, e.g.,

$T_{\text{f. out}} \sim 200$ MeV, $\mu_{b\text{f. out}} \sim 200$ MeV, and $\gamma_s \sim 0.7$. For continuous emission, due to thermal suppression, particles *heavier than the pion* are approximately emitted at $T_0 \sim 200$ MeV, $\mu_{b\,0} \sim 200$ MeV, and $\gamma_s \sim 0.49$ [Fig. 1(b)], so D_q so far is similar to that of freeze-out. However, there is an additional source of particles that enters the denominator of (4), namely pions are emitted at T_0 *and then on* (since they are not thermally suppressed). So we expect to get a lower value for D_q in the continuous emission case than in the freeze-out case. (We recall that pions are the dominant contribution in $N^+ + N^-$.) This would go into the direction of solving problem 3; it is still under investigation.

Conclusion.—Our present description is simplified. For example, we do not include the transverse expansion of the fluid, use similar interaction cross sections for all types of particles, etc. In addition, we need to look systematically at strangeness data from other collaborations as well as other types of data such as Bose-Einstein correlations. Nevertheless, we have seen that the continuous emission scenario with a HG may shed light on problems 1 and 3 (discussed in the introduction) that a freeze-out model with a HG encounters. Namely, in the overlap region of the parameters needed to reproduce WA85 data, the density of particles is high, and this is consistent with the emission mechanism, since it is the initial density of the thermalized fluid. We also expect D_q to be smaller for continuous emission than freeze-out. But (problem 2) the value of the strangeness saturation parameter may be high for a HG, particularly at the beginning of its hydrodynamical expansion. However, what we really need to get Fig. 1(b), is that $\Xi^-/\Lambda = \gamma_\Xi \Xi^-/\gamma_\Lambda \Lambda_{|\text{eq.}}$ and $\overline{\Xi^-}/\overline{\Lambda} = \gamma_\Xi \overline{\Xi^-}/\gamma_\Lambda \overline{\Lambda}_{|\text{eq}}$ with $\gamma_\Xi/\gamma_\Lambda = 0.49$. We expect indeed that multistrange Ξ^- and $\overline{\Xi^-}$ are more far off chemical equilibrium than singlestrange Λ and $\overline{\Lambda}$ so that $\gamma_\Xi/\gamma_\Lambda < 1$. The result $\gamma_s = 0.49$ arises *if* one makes the *additional hypothesis* that quarks are independent degrees of freedom inside the hadrons so that one has factorizations of the type $\gamma_\Lambda \exp(\mu_\Lambda/T) = \gamma_s \exp 2(\mu_q/T) \exp(\mu_s/T)$, and $\gamma_\Xi \exp(\mu_\Xi/T) = \gamma_s^2 \exp(\mu_q/T) \exp(2\mu_s/T)$. Therefore problem 2 may not be so serious.

The fact that we may cure some of the problems of the HG scenario does not mean that no quark-gluon plasma has been created before the HG, in fact it may open new possibilities for scenarios of the quark-hadron transition (e.g., an equilibrated quark-gluon plasma evolving into an equilibrated HG with continuous emission); in particular, it may not be necessary to assume an explosive transition [5] or a deflagration-detonation scenario [29–31].

But our main conclusion is that the emission mechanism may modify profoundly our interpretation of data. (For example, does the slope in transverse mass spectrum tell something about freeze-out or initial conditions?) In turn this modifies our discussion of what potential problems (such as 1 and 3) are emerging. Therefore we believe it is necessary to devote more work to get a realistic description of particle emission in hydrodynamics, [18,19] being a first step in that direction. We remind the reader that the idea that particles are emitted continuously and not on a sharp freeze-out surface is supported by microscopical simulations at AGS energies [32] and SPS energies [33].

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Note added.—After completing this paper, we learned that G.D. Yen, M.I. Gorenstein, W. Greiner and S.N. Yang suggested [34] another solution to problems 1 and 3 above, in terms of the excluded volume approach of [25], for the preliminary Au + Au (AGS) and Pb + Pb (SPS) data.

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