Hadron production in central heavy-ion collisions

R. Gagnon and M.-A. Simard
Département de Mathématique, Physique, et Informatique, Centre Universitaire de Moncton, Université de Moncton, Moncton, Nouveau-Brunswick, Canada E1A 3E9
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We extend a model developed by Margolis and collaborators to describe inclusive central particle production in p-p scattering at high energy to relativistic ion-ion collisions. We calculate the invariant production rate of any particle of mass m as a function of the temperature. Assuming that a temperature of approximately 130 MeV is reached in Ne-NaF collisions at 2.1 GeV/nucleon, we estimate the ratio $\sigma(\pi)/\sigma(K) \sim 100$, to be compared with the experimental value of 70 ± 46.

One of the most promising places to look for a phase transition from ordinary nuclear matter to a quark-gluon plasma is relativistic ion-ion collisions. Indeed, several estimates[1] indicate that the necessary energy density can almost be reached by present-day accelerators and most certainly will be reached in the near future. It is thus very important to investigate the possible signatures of such a phase transition. Among them is the expectation of a relatively large strange-particle signal.[2,3]

In this note, we present a model of inclusive particle production in relativistic nucleus-nucleus reactions emphasizing the production of strange particles. We consider only head-on or central collisions as those events provide the highest energy density. The model is in fact an extension of a model developed by Margolis and collaborators[4,5] which well describes inclusive particle production in central p-p collisions. The physical picture is the following. The colliding nuclei are assumed to fuse, each one forming a quark-gluon plasma as in the usual scenario.[3,6,7] Thermalization then takes place via multiple collisions.[3,7] Interactions among constituents and in particular $gg \to gg$, which is the dominant subprocess in the appropriate subenergy range, leads to the formation of a fireball which next decays statistically into the detected particle plus a residual fireball.

Thus, taking into account only the dominant contribution, the cross section for the inclusive production of a particle of mass m in a plasma is written as[4,8]

$$\sigma(m,T) = (16)^2 \frac{V_p^2}{(2\pi)^6} \int_{M_0^2}^{\infty} dM^2 \int d^3k_1 d^3k_2 f_g(k_1) f_g(k_2) \delta(M^2-(k_1+k_2)^2)\sigma_0(M) \int_{M_0'}^{M-m} dM' B(M \to M'+m), \quad (1)$$

where the factor 16 accounts for the gluon spin and color degrees of freedom and V_p is the volume of the plasma. The lower limits of integration are chosen so as to grossly account for quantum-number conservation. According to our assumptions and motivated by the fact that, as suggested by lattice calculations,[9] the quark-gluon plasma is almost ideal immediately above the transition, the gluon momentum distribution is simply a Bose distribution, i.e.,

$$f_g(k) = (e^{K/T} - 1)^{-1}, \quad (2)$$

with T the temperature of the plasma. σ_0 is the $gg \to gg$ cross section:[5,10]

$$\sigma_0(M^2) = 9\pi\alpha_s^2(M^2) \left[\frac{17}{12(M^2+\mu^2)} + \frac{1}{\mu^2} - \frac{1}{(M^2+\mu^2)} \ln\left[\frac{M^2+\mu^2}{\mu^2}\right]\right], \quad (3)$$

where μ is a cutoff and α_s the running coupling constant:

$$\alpha_s = \frac{12\pi}{25\ln(M^2/\Lambda^2)}. \quad (4)$$

$B(M \to M'+m)$ is the branching ratio for the decay of the initial fireball (M) into a hadron (m) and the residual fireball (M'). It is given by the density of the observed states in the final system divided by the density of all available states. In the spirit of the statistical bootstrap model,[11] one has

$$B(M \to M'+m) = \frac{\rho(M')}{\rho(M)} \frac{V}{16\pi^2} \lambda^{1/2}(M^2,M'^2,m^2) \times \frac{[M^4-(M'^2-m^2)^2]}{M^4}, \quad (5)$$

where V is the volume of the fireball and

$$\lambda(x,y,z) \equiv x^2+y^2+z^2-2xy-2xz-2yz. \quad (6)$$

The density of states $\rho(M)$ is taken to be[5]

$$\rho(M) \propto \frac{e^{aM^{6/7}}}{(M+m_0)^{4/7}}, \quad (7)$$

corresponding to the density of states of massless constituents in a confining linear potential. However, the parameters a and m_0 (cutoff to prevent the divergence at the origin) are left arbitrary.

In this model, the production and decay mechanisms of the fireball are exactly the same as in proton-proton collisions of Ref. 5. We thus take the same parameters which are known to fit the data, namely, $\Lambda = 127$ MeV, $\mu = 0.54$ GeV, $V = 5.575$ fm^3, $m_0 = 0.3$ GeV, $a = 6.0$ GeV$^{-6/7}$. Therefore, our results are normalized to actual data and thus it is possible to make absolute predictions of physical quantities. For instance, using[12]

$$\frac{1}{V_p^2} \frac{k_1^\mu \cdot k_{2\mu}}{|k_1|\,|k_2|} \frac{d\sigma(m,T)}{dM^2} = \frac{dA(m,T)}{dM^2}, \quad (8)$$

where $k_1^\mu \cdot k_{2\mu}/|k_1|\,|k_2|$ is the relative velocity of massless particles, we obtain the invariant production rate of particles of mass m.

Results for strange-particle production are presented in Fig. 1. The lower solid curve is obtained when all strange particles are summed over while the dashed curve is the kaon contribution only. The latter accounts for more than 90% of the total rate in the temperature range that we considered. A comparison with a calculation of total strangeness production via $q\bar{q} \rightarrow s\bar{s}$ and $gg \rightarrow s\bar{s}$ by Rafelski and Müller[8] shows that our results are smaller by a factor varying from two to one orders of magnitude with increasing temperature. We emphasize that our results are normalized to actual data and that no extra parameters have been introduced. This was not the case in Ref. 8 where uncertainties on the coupling constant and on the strange-quark mass were large. Also shown in Fig. 1 is the pion production rate predicted by our model (upper solid curve). The π/K ratio varies from approximately 200 to 10 over our temperature range.

In Fig. 2, we present the invariant production rate of nonstrange particles versus their mass m at fixed temperature. We notice a rapid, almost exponential, falloff. A modest increase in the temperature leads to significantly larger and less steep rates. The $\times$'s indicate the corresponding kaon and $K^*(892)$ rates, showing the effect of quantum-number conservation through M_0' and M_0 in Eq. (1). As expected, this effect decreases with increasing temperature.

On the other hand, it is often more convenient to know cross sections rather than rates, as these are the quantities generally delivered by experimentalists. We thus also calculated the inclusive particle production cross section. The results for pion and kaon production are displayed in Fig. 3. The general shapes are the same as for the rates.

It is clear that for the time being, any comparison with actual data of theoretical predictions based on a phase transition of nuclear matter to a quark-gluon plasma is risky. Indeed, so far, experiments have been performed at relatively low energies. Therefore, a scenario relying on three rather well separated regions, i.e., two fragmentation regions and a central region, is not yet applicable. A more appropriate picture would rather be that of single piece of highly excited matter formed by the fusion of the two colliding nuclei.[13] But then the question of whether the resulting energy density is sufficient to cause a phase transition remains. The possibility to almost "sit" on the critical region is great, as recent works[14] suggest a much smoother transition when quarks are taken into account than it was expected from lattice studies of pure Yang-Mills theories. If this is the case, the state of equilibrium in the plasma will be more difficult to reach. Clearly, the low-energy regime of heavy-ion collisions is extremely complicated and, quite likely, one should apply neither the thermodynamics of a pure gluon gas nor that of a quasi-ideal quark-gluon plasma.

One of the rare pieces of data comes from an experiment studying Ne-NaF collisions at 2.1 GeV/nucleon. The ratio $\sigma(\pi)/\sigma(K)$ was found to be 70 ± 46.[15,16] To gain some insight, let us assume that in spite of all the above restrictions, our model is applicable in this low-energy range, i.e., let us assume that a transition to a quark-gluon plasma has occurred and that a suitable state of equilibrium has been established. In this experiment, a temperature of 125

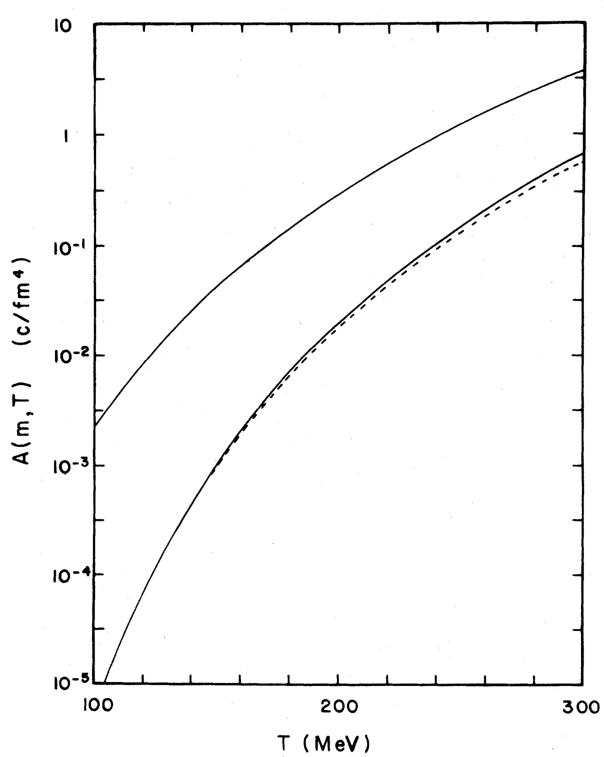

FIG. 1. Invariant rate per unit time and volume of inclusive pion (upper solid curve), strange-particle (lower solid curve), and kaon production (dashed curve) vs temperature.

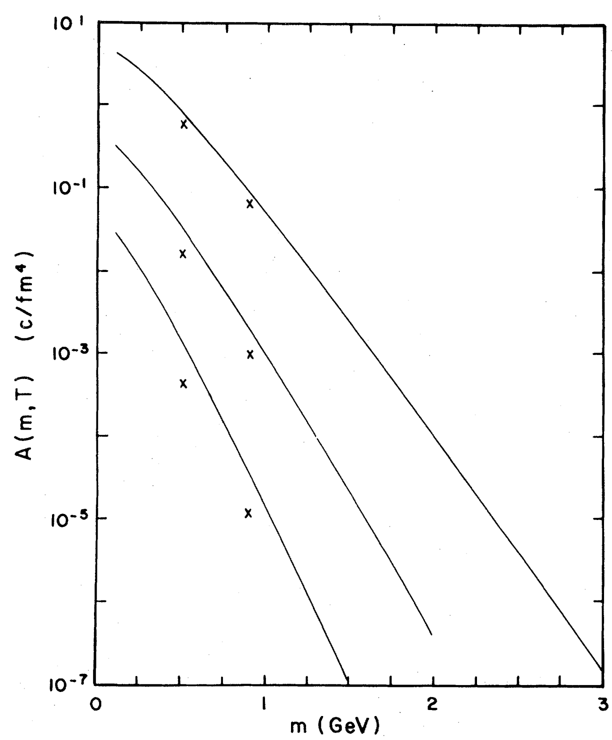

FIG. 2. Invariant rate per unit time and volume of inclusive particle production vs mass at $T = 140$ MeV (lower curve), $T = 200$ MeV (middle curve), and $T = 300$ MeV (upper curve). The $\times$'s indicate the kaon and $K^*(892)$ rates.

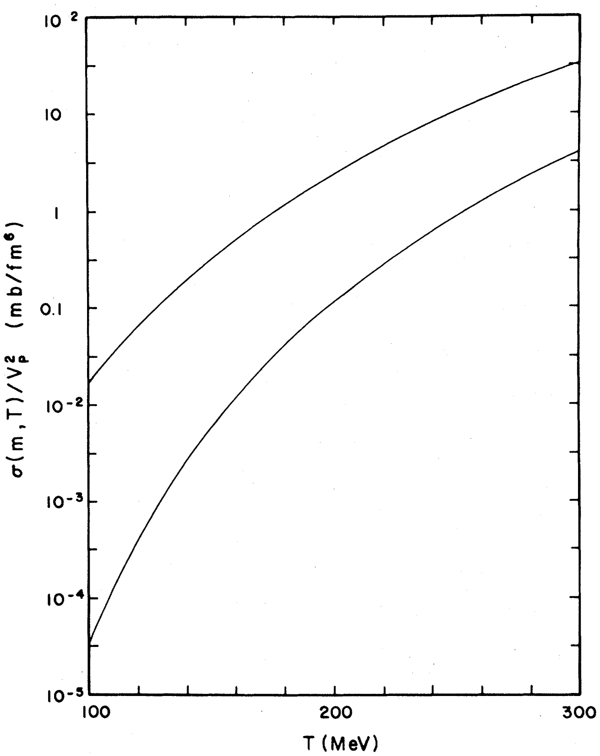

FIG. 3. Inclusive pion (upper curve) and kaon (lower curve) production cross sections per unit of square volume vs temperature.

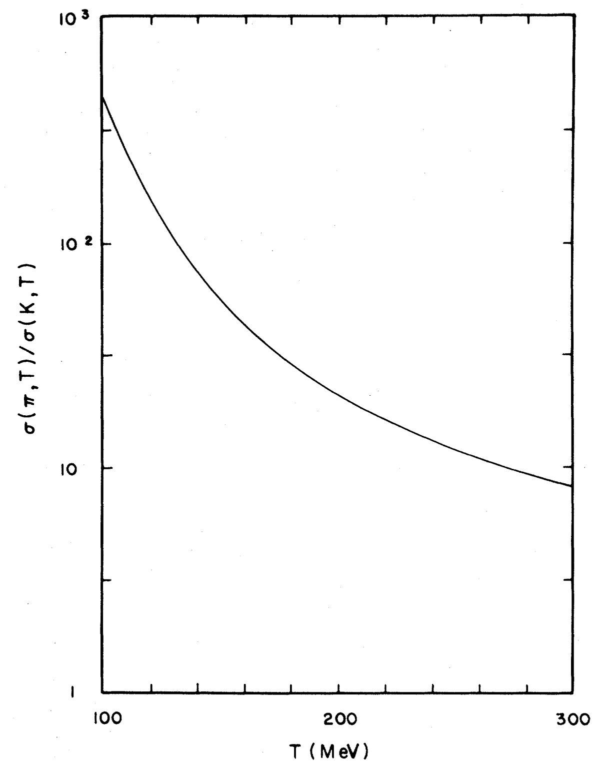

FIG. 4. Ratio of inclusive pion to kaon production cross sections vs temperature.

MeV was estimated from the kaon distribution.[17,18] Since kaons decouple earlier from the rest of the system than say pions[17] and are therefore more reminiscent of the early stage of the reaction, we will consider 125 MeV as close to the initial temperature reached in the plasma. Of course, the actual value depends directly on the incident kinetic energy, but at this low energy, it is not expected to be much higher.

Under these assumptions, our model predicts a value of 137, which is higher than the data but of the right order of magnitude. However, as can be seen from Fig. 4, this region is sensitive to the initial temperature. For instance, a temperature of 130 MeV would lead to a ratio of approximately 100, while at $T=150$ MeV, one rather has a value of 50. One thus sees the importance of devising an accurate thermometer derived either from final-products measurements[7] or from a model relating the temperature of the plasma to the incident kinetic energy. As it is, the relatively good agreement with experiment is somewhat surprising since one does not really believe in the formation of a quark-gluon plasma at this energy. This and the fact that our model predicts production rates substantially lower than in Ref. 8 suggest that the strange-particle signal is not such a clear signature of a phase transition. More work on the problem is certainly needed.

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