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Strangeness Production in Ultrarelativistic Nucleus–Nucleus Collisions *

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Based on the relaxation equations describing the chemical equilibration of gluons, quarks and s quarks at finite baryon density derived from the Jüttner distribution of partons, with the help of a rapid phase transition scenario from quark phase to hadron phase, we calculate strangeness production in the quark phase and hadron phase. It is found that the K^-/π^- ratio is enhanced to be larger than that in pp collisions by about a factor 3.

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In order to explore the existence of the quark–gluon plasma (QGP), many experiments have been designed. For example, the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory is hoping to produce a deconfined QGP. Because of the very short lifetime (several fm) of QGP, a direct detection of this state of matter is impossible. Thus various indirect signatures have to be used for its detection, such as J/ψ suppression,[1] strangeness enhancement,[2] and dilepton spectra.[3] A tentative probe of Δ-scaling has also been proposed in ultrarelativistic nucleus–nucleus collisions.[4] At super proton synchrotron energies, an enhanced production of strangeness, considered as one of the more robust signatures of the quark–hadron phase transition, has been observed.[5,6] One naturally wonders how strangeness is produced, evolves and depends on finite baryon density in a chemically equilibrating QGP system created at RHIC energies. In order to answer these questions, we should study strangeness of a chemically equilibrating QGP at finite baryon density by the Jüttner distribution of partons, and consider chemical reactions $gg \rightleftharpoons ggg$, $gg \rightleftharpoons q\bar{q}$, $gg \rightleftharpoons s\bar{s}$ and $q\bar{q} \rightleftharpoons s\bar{s}$ in the system. In this work, with the help of a rapid phase transition from QCD phase into hadrons, we first obtain the initial values of the hadron phase, then solve the relaxation equation to study strangeness production in the hadron phase. It is worth emphasizing here the difference between our treatment and that of Ref. [7]. The authors of Ref. [7] have taken the distribution function of partons as $f_j(E_j,\lambda_j)=\lambda_j f_j^{eq}(E_j)$, where $f_j^{eq}(E_j)$ is the thermodynamic equilibrium Bose–Einstein (Fermi–Dirac) distribution for gluons (quarks), and have not considered the effect of the quark chemical potential on strangeness production. By the way, it is emphasized that in a thermodynamic equilibrium QGP system, strangeness production has also been studied on the basis of the relativistic hydrodynamic model.[8]

Expanding densities of quarks (anti-quarks) over quark chemical potential μ_q, we obtain the baryon density of the system[9,10]

$$n_{b,q}=\frac{g_q}{6\pi^2}\Big[T^3(Q_1^2\lambda_q-\bar{Q}_1^2\lambda_{\bar{q}})+2\mu_qT^2(Q_1^1\lambda_q+\bar{Q}_1^1\lambda_{\bar{q}}) + T\mu_q^2(Q_1^0\lambda_q-\bar{Q}_1^0\lambda_{\bar{q}})+\frac{1}{3}\mu_q^3\Big(\frac{\lambda_q}{\lambda_q+1} + \frac{\lambda_{\bar{q}}}{\lambda_{\bar{q}}+1}\Big)\Big], \quad (1)$$

and the corresponding energy density including contribution from s quarks

$$\varepsilon_{qgp}=\frac{g_q}{2\pi^2}\Big[T^4\Big(Q_1^3\lambda_q+\bar{Q}_1^3\lambda_{\bar{q}}+\frac{g_g}{g_q}G_1^3\lambda_g+2\frac{g_s}{g_q}S_1^3\lambda_s\Big) + 3\mu_qT^3(Q_1^2\lambda_q-\bar{Q}_1^2\lambda_{\bar{q}})+3\mu_q^2T^2(Q_1^1\lambda_q + \bar{Q}_1^1\lambda_{\bar{q}})+T\mu_q^3(Q_1^0\lambda_q-\bar{Q}_1^0\lambda_{\bar{q}}) + \frac{1}{3}\mu_q^4\Big(\frac{\lambda_q}{\lambda_q+1}+\frac{\lambda_{\bar{q}}}{\lambda_{\bar{q}}+1}\Big)+\frac{2\pi B_0}{g_q}\Big], \quad (2)$$

where $\lambda_{q(\bar{q})}$, λ_g and λ_s are the fugacities of quarks (anti-quarks), gluons and s quarks; $g_{q(\bar{q})}$, g_g and g_s are the degeneracy factors of quarks (anti-quarks), gluons and s quarks, respectively. We can easily numerically calculate the integral factors appearing in the above expansion,

$$G_m^n=\int\frac{Z^ndZ}{(e^Z-\lambda_q)^m}, \quad Q_m^n(\bar{Q}_m^n)=\int\frac{Z^ndZ}{(\lambda_{q(\bar{q})}+e^Z)^m},$$
$$S_m^n=\int\frac{Z^ndZ}{(\lambda_s+e^{Z_s})^m}, \quad (3)$$

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with $Z = p/T$ and $Z_s = [Z^2 + (m_s/T)^2]^{1/2}$, where m_s is the mass of the s quark.

To study strangeness production, we consider the reactions leading to chemical equilibrium not only $gg \rightleftharpoons ggg$ and $gg \rightleftharpoons q\bar{q}$ but also $gg \rightleftharpoons s\bar{s}$ and $q\bar{q} \rightleftharpoons s\bar{s}$. Provided that elastic parton scatterings are sufficiently rapid to maintain at the local thermal equilibrium, the evolutions of gluon, quark and s quark density can be given by the master equations. Since the number of s quarks is very small as compared to gluons and light quarks, we can neglect the back reactions $s\bar{s} \to gg,\ q\bar{q}$. We note that taking $\lambda_q = \lambda_{\bar{q}}$ does not change the qualitative property of the evolution of the system because the calculated initial quark chemical potential for Au^{197}+Au^{197} collisions at RHIC energies is relatively small. Combining these master equations with equations of baryon number and energy–momentum conservation for the longitudinal scaling expansion of the system, we can obtain a set of relaxation equations which describes the evolutions of temperature T, quark chemical potential μ_q and fugacities for quarks, gluons and s quarks on the basis of the thermodynamic relations of the system with finite baryon density, as obtained above:

$$\begin{aligned}
&\Big(\frac{1}{\lambda_g} + \frac{G_2^2}{G_1^2}\Big)\dot{\lambda}_g + 3\frac{\dot{T}}{T} + \frac{1}{\tau} = R_3\Big[1 - \frac{G_1^2}{2\xi(3)}\lambda_g\Big] \\
&\quad - 2R_2^{g-q}\Big[1 - \Big(\frac{2\xi(3)}{G_1^2}\Big)^2 \frac{n_q n_{\bar{q}}}{\bar{n}_q \bar{n}_{\bar{q}}}\frac{1}{\lambda_g^2}\Big] \\
&\quad - 2R_2^{g-s}\Big[1 - \Big(\frac{2\xi(3)}{G_1^2}\Big)^2 \frac{n_s n_{\bar{s}}}{\bar{n}_s \bar{n}_{\bar{s}}}\frac{1}{\lambda_g^2}\Big], \qquad (4)
\end{aligned}$$

$$\begin{aligned}
&\dot{\lambda}_q\Big[T^3(Q_1^2 - \lambda_q Q_2^2) + 2\mu_q T^2(Q_1^1 - \lambda_q Q_2^1) + T\mu_q^2(Q_1^0 \\
&\quad - \lambda_q Q_2^0) + \frac{1}{3}\mu_q^3 \frac{1}{(\lambda_q+1)^2}\Big] + \dot{T}\lambda_q[3T^2Q_1^2 \\
&\quad + 4\mu_q T Q_1^1 + \mu_q^2 Q_1^0] + \dot{\mu_q}\lambda_q\Big[2T^2Q_1^1 + 2\mu_q T Q_1^0 \\
&\quad + \mu_q^2 \frac{1}{(\lambda_q+1)}\Big] + \frac{n_q^0}{\tau} \\
&= n_g^0 R_2^{g-q}\Big[1 - \Big(\frac{2\xi(3)}{G_1^2}\Big)^2 \frac{n_q n_{\bar{q}}}{\bar{n}_q \bar{n}_{\bar{q}}}\frac{1}{\lambda_g^2}\Big] \\
&\quad - 2R_2^{q-s}\Big[1 - \Big(\frac{\bar{n}_q}{n_q}\Big)^2 \frac{n_s n_{\bar{s}}}{\bar{n}_s \bar{n}_{\bar{s}}}\Big], \qquad (5)
\end{aligned}$$

$$\begin{aligned}
&\dot{\lambda}_s T^3(S_1^2 - \lambda_s S_2^2) + \dot{T}\lambda_s(3T^2 S_1^2 + m_s^2 D_2^2) + \frac{n_s^0}{\tau} \\
&= n_g^0 R_2^{g-s}\Big[1 - \Big(\frac{2\xi(3)}{G_1^2}\Big)^2 \frac{n_s n_{\bar{s}}}{\bar{n}_s \bar{n}_{\bar{s}}}\frac{1}{\lambda_g^2}\Big] \\
&\quad + n_q^0 R_2^{q-s}\Big[1 - \Big(\frac{\bar{n}_q}{n_q}\Big)^2 \frac{n_s n_{\bar{s}}}{\bar{n}_s \bar{n}_{\bar{s}}}\Big], \qquad (6)
\end{aligned}$$

$$\begin{aligned}
&\dot{\lambda}_q\Big[4\mu_q T^2(Q_1^1 - \lambda_q Q_1^1) + \frac{2}{3}\mu_q^3 \frac{1}{(\lambda_q+1)^2}\Big] \\
&\quad + \dot{T}8\mu_q T Q_1^1 \lambda_q + \dot{\mu_q}\lambda_q\Big[4T^2 Q_1^1 + 2\mu_q^2 \frac{1}{(\lambda_q+1)}\Big] \\
&= -\frac{1}{\tau}\lambda_q\Big[4\mu_q T^2 Q_1^1 + \frac{2}{3}\mu_q^3 \frac{1}{\lambda_q+1}\Big], \qquad (7)
\end{aligned}$$

$$\begin{aligned}
&\dot{\lambda}_g \frac{g_g}{g_q} T^4(G_1^3 + \lambda_g G_2^3) + \dot{\lambda}_q\Big[2T^4(Q_1^3 - \lambda_q Q_2^3) \\
&\quad + 6T^2\mu_q^2(Q_1^1 - \lambda_q Q_2^1) + \frac{2}{4}\mu_q^4 \frac{1}{(\lambda_q+1)^2}\Big] \\
&\quad + \dot{\lambda}_s \frac{2g_s}{g_q} T^4(S_1^3 - \lambda_s S_2^3) + \dot{T}\Big[8T^3 Q_1^3 \lambda_q \\
&\quad + 12\mu_q^2 T Q_1^1 \lambda_q + 4\frac{g_g}{g_q} T^3 \lambda_g \cdot G_1^3 + \frac{2g_s}{g_q} T\lambda_s(4T^2 S_1^3 \\
&\quad + m_s^2 D_2^3)\Big] + \dot{\mu_q}\lambda_q\Big[12\mu_q T^2 Q_1^1 + 2\mu_q^3 \frac{1}{\lambda_q+1}\Big] \\
&= -\frac{1}{\tau}\Big[2T^4 Q_1^3 \lambda_q + 6\mu_q^2 T^2 Q_1^1 \lambda_q \Big(\frac{\lambda_q}{\lambda_q+1}\Big) \\
&\quad + \frac{g_g}{g_q} T^4 \lambda_g G_1^3 + \frac{g_s}{g_q} T^4 \lambda_s S_2^3\Big], \qquad (8)
\end{aligned}$$

where $\bar{n}_{q(\bar{q})}$ is the value of $n_{q(\bar{q})}$ at $\lambda_{q(\bar{q})} = 1$, $n_q^0 = n_q/(g_q/2\pi^2)$, $n_g^0 = n_g/(g_g/2\pi^2)$, $\xi(3) = 1.20206$, and the integral factor $D_m^n = \int dZ e^{Z_s} Z^n / [(\lambda_s + e^{Z_s})^m Z_s]$. Since the chemical potential of s quarks is zero, in baryon number conservation equation (8) the influence from s quarks cannot be seen directly. Adopting factorizations as done in Ref. [11], we have production rates for processes $gg \to ggg$, $gg \to q\bar{q}$ and $gg \to \bar{s}s$:

$$\frac{R_3}{T} = \frac{32}{3a_1}\frac{\alpha_s}{\lambda_g}\Big[\frac{(M_D^2 + s/4)M_D^2}{9g^2T^4/2}\Big]^2 I(\lambda_g, \lambda_q, T, \mu_q), \qquad (9)$$

$$\frac{R_2^{g-q}}{T} = \frac{g_g}{24\pi}\frac{{G_1^1}^2}{G_1^2} N_f \alpha_s^2 \lambda_g \ln(1.65/\alpha_s L), \qquad (10)$$

$$\frac{R_2^{g-s}}{T} = \frac{g_g}{24\pi}\frac{{G_1^1}^2}{G_1^2} N_f \alpha_s^2 \lambda_g \ln(1.65/\alpha_s l), \qquad (11)$$

$$M_D^2 = \frac{3g^2T^2}{\pi^2}\Big[2G_1^1\lambda_g + 2N_f Q_1^1 \lambda_q + \Big(\frac{\mu_q}{T}\Big)^2\Big(\frac{\lambda_q}{\lambda_q+1}\Big)\Big], \qquad (12)$$

with

$$L = \lambda_g + \frac{1}{G_1^1}\Big[Q_1^1\lambda_q + \Big(\frac{\mu_q}{T}\Big)^2\Big(\frac{\lambda_q}{\lambda_q+1}\Big)\Big], \qquad (13)$$

$$l = \lambda_g + \frac{1}{G_1^1} S_1^1 \lambda_s, \qquad (14)$$

and the QCD running coupling constant α_s is given by

$$\alpha_s(T) = \frac{6\pi}{27\ln[T/(50\,\mathrm{MeV})]}, \qquad (15)$$

where M_D^2 is the Debye screening mass, $a_1 = 2\pi^2 g_g G_1^2$, $I(\lambda_g, \lambda_q, T, \mu_q)$ is as the functions of λ_g, λ_q, T, μ_q,[12] and N_f is the quark flavour. Similarly, the production rate R_2^{q-s}/T for process $q\bar{q} \to s\bar{s}$ is calculated by taking cross section $\sigma(q\bar{q} \to s\bar{s})$ from Ref. [13].

Now, we study the strangeness production in the hadron phase. In this work, both the quark chemical potential and the temperature of the system are functions of time, the value (μ_q, T) of the system reaches a certain point of the phase boundary to make the phase transition. Our results show that at the point of the phase transition, the quark chemical potential becomes so small that it can be neglected as compared with the temperature (see curve b in Fig. 1). Thus, in the hadron phase, we can neglect the quark chemical potential and obtain the initial temperature $T_h(\tau_c)$ of the hadron phase from $\varepsilon_{qgp}(\tau_c) = \varepsilon_h(\tau_c)$, where the energy density of hadron phase $\varepsilon_h = \frac{\pi^2}{10}T_h^4$, while τ_c is the time at which the sudden phase transition occurs.

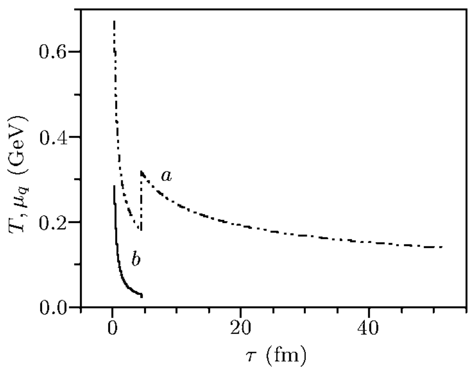

Fig. 1. Calculated temperature T and quark chemical potential μ_q of the system for initial values $\tau_0 = 0.25$ fm, $T_0 = 0.67$ GeV, $\lambda_{g0} = 0.34$, $\lambda_{q0} = 0.068$ and $\lambda_{s0} = 0.034$. Curves a and b denote, respectively, the temperature and the chemical potential.

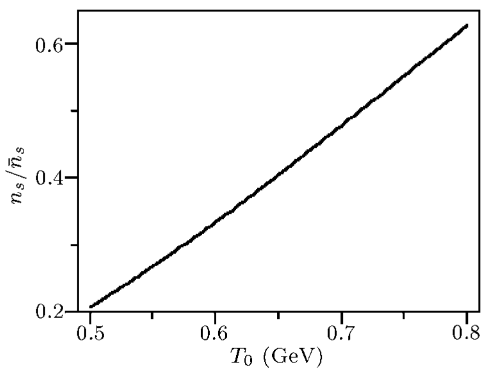

Fig. 2. Calculated strangeness $n_s/\bar{n}_s$ at the phase boundary as a function of the initial temperature T_0 under the same initial conditions as given in Fig. 1.

Strangeness evolves in the hadron phase according to

$$\frac{dn_{K^-}}{d\tau} = R_h\Big[1 - \Big[\frac{n_{K^-}}{\bar{n}_{K^-}}\Big]^2\Big] - \frac{n_{K^-}}{\tau}, \qquad (16)$$

where R_h is the production rate,[14] which can be expressed by

$$R_h = \frac{AT^6}{8\pi^4}z_0^3K_3(z_0) + \frac{BT^6}{64\pi^3}z_0(3 + 3z_0 + z_0^2)e^{-z_0}, \qquad (17)$$

$z_0 = 2m_K/T$, $A = 17$ mb, $B = 16$ mb. The initial condition is $n_{K^-}(\tau_c) = n_s(\tau_c)/2$, where half of the strange quarks are bound in K^- and the half in $\bar{K}^0$ mesons. We take the time development of the temperature in the hadron phase as $T(\tau) = (\tau_c/\tau)^{1/3}T_h(\tau_c)$. Then we solve Eq. (16) to obtain the strangeness evolution in the hadron phase.

Adopting the Jüttner distribution, we can obtain the s quark number density

$$n_s = \frac{g_sT^3}{2\pi^2}\int\frac{\lambda_sZ^2dZ}{e^{[Z^2+(m_s/T)^2]^{1/2}} + \lambda_s}. \qquad (18)$$

The K^- equilibrium number density in the hadron phase reads

$$n_{K^-} = \int\frac{d^3k}{(2\pi)^3}\frac{1}{\exp[(k^2 + m_K^2)^{1/2}/T] - 1}, \qquad (19)$$

where m_K is the kaon mass again.

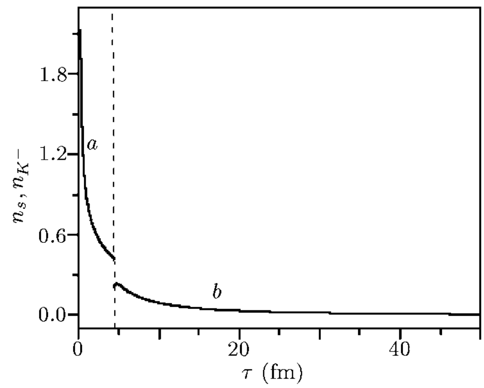

Fig. 3. Calculated strangeness n_s, n_{K^-} under the same initial conditions as given in Fig. 1. Curve a is the strangeness n_s in the QGP phase, and curve b is the strangeness n_{K^-} in the hadron phase.

At present, we take the initial values from the self-screened parton cascade (SSPC) model:[15] $\tau_0 = 0.25$ fm, $T_0 = 0.67$ GeV, $\lambda_{g0} = 0.34$, $\lambda_{q0} = 0.068$ and $\lambda_{s0} = 0.034$. We have solved the set of relaxation equations (4)–(8) for initial quark chemical potentials $\mu_{q0} = 0.284$ GeV, and obtained the evolutions of the temperature and quark chemical potential in the QGP phase. The calculated temperature T and quark chemical potential μ_q of the system have been shown in Fig. 1. Curves a and b denote, respectively, the temperature T and the quark chemical potential μ_q. We can clearly see from Fig. 1 that the temperature T and the quark chemical potential μ_q of the system decrease rapidly with evolution time in the QGP phase. At evolution time τ_c, the sudden phase transition occurs. Because of the huge latent heat of the phase transition, the temperature of the system rises suddenly. After the phase transition occurs, in the hadron phase the temperature T of the system decreases more slowly than that in the QGP phase. Obviously, at τ_c, the quark chemical potential μ_q becomes very small, about $\mu_q(\tau_c) = 0.03\,\text{GeV}$. Thus, the effect of the quark chemical potential can be neglected in the hadron phase.

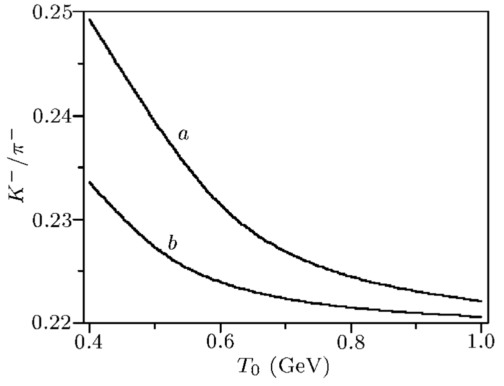

Fig. 4. Calculated K^-/π^- ratio at the freezing point $T_f = 140\,\text{MeV}$ as a function of the initial temperature T_0. Curves a and b are, respectively, obtained from initial values $\tau_0 = 0.70\,\text{fm}$, $\lambda_{g0} = 0.09$, $\lambda_{q0} = 0.02$, and $\lambda_{s0} = 0.01$ (given by the Hijing model calculation), and from the same initial values as given in Fig. 1.

We have calculated strangeness $n_s/\bar{n}_s$ according to the relation given by Eq. (18) from the calculated s quark equilibration rate λ_s, temperature T as well as s quark mass m_s, where $\bar{n}_s$ is the value of n_s at $\lambda_s = 1$, and $Z = p/T$ again. The calculated strangeness $n_s/\bar{n}_s$ at the phase boundary as a function of the initial temperature T_0 under the same initial conditions as given in Fig. 1 has been shown in Fig. 2. One can see that the curve rises approximately linearly with the initial temperature T_0 in the region from the temperature (about 0.50 GeV) of the RHIC to the one (about 0.80 GeV) of the LHC.[12] This implies that the relation between the strange particle production and the initial temperature remains simple if the phase transition is fast, which leads to an immediate hadronization and break-up without a hadronic after-burner stage, as is suggested by several hadronization models based on quark-coalescence.[16,17] We also give the calculated strangeness n_s and n_{K^-} as shown in Fig. 3. Curves a and b represent the strangeness n_s in the QGP phase and the strangeness n_{K^-} in the hadron phase, respectively. From Fig. 3, we can see that the strangeness decreases with evolution time. In the QGP phase it decreases rapidly, while in the hadron phase it decreases slowly. It shows that the system is approaching the equilibrium. A proposed signal for the formation of QGP is the relative abundance of kaons to pions.[18] We give the calculated K^-/π^- ratio at the freeze out point $T_f = 140\,\text{MeV}$ as a function of the initial temperature T_0 in Fig. 4. Curves a and b are, respectively, obtained from the initial values $\tau_0 = 0.70\,\text{fm}$, $T_0 = 0.57\,\text{GeV}$, $\lambda_{g0} = 0.09$, $\lambda_{q0} = 0.02$, and $\lambda_{s0} = 0.01$ (given by the Hijing model), and from the same initial values as given in Fig. 1. In our scenario there is little sensitivity of the K^-/π^- ratio at the freeze out point to the initial temperature T_0. The ratio is almost always in the range 0.22–0.24, which is an enhancement of about three over $p\bar{p}$ collisions. This enhancement of strangeness is mainly attributed to fact that the QGP phase lifetime increases with the increasing initial quark chemical potential, at a larger initial temperature of the system.[9] Furthermore, from Fig. 4 we can see that strangeness production is very sensitive to the initial conditions.

In summary, we have included the dominant reactions leading to chemical equilibrium $gg \rightleftharpoons ggg$, $gg \rightleftharpoons q\bar{q}$, $gg \rightleftharpoons s\bar{s}$ and $q\bar{q} \rightleftharpoons s\bar{s}$ in the system so as to study strangeness production. We can see that K^-/π^- ratio is enhanced to be larger than that in $p\bar{p}$ collisions by about a factor 3. It is emphasized that the strangeness equilibrium ratio $n_s/\bar{n}_s$ decreases with the increasing initial quark chemical potential since factor T^3 is cancelled in n_s and $\bar{n}_s$. Obviously in order to understand the relation between the strangeness production and the other physical factors, it is useful to consider the produced strangeness density n_s, instead of the ratio $n_s/\bar{n}_s$. In addition, we find that the ratio $n_s/\bar{n}_s$ at the phase boundary approximately linearly depends on the initial temperature. This implies that the relation between the strange particle production and the initial temperature remains to be simple provided that the phase transition is fast, which leads to an immediate hadronization and break-up without a hadronic after-burner stage, as is suggested by several hadronization models based on quark-coalescence.[14] Obviously, our result may be helpful to clarify important issues related to the understanding of the hadronization processes, and therefore it is interesting.

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