Hadron spectra and quark-gluon plasma hadronization in Au+Au collisions at relativistic energies

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The transverse mass spectra of Ω hyperons and ϕ mesons measured recently by STAR Collaboration in Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV are described within a hydrodynamic model of the quark-gluon plasma expansion and hadronization. The flow parameters at the plasma hadronization extracted by fitting these data are used to predict the transverse mass spectra of J/ψ and ψ' mesons.

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The hadron chemical freeze-out in nucleus-nucleus ($A+A$) collisions at the Super Proton Synchrotron (SPS) and relativistic heavy ion collider (RHIC) energies seems to take place near the boundary between the quark-gluon and hadron phases. The values of the temperature parameter extracted from the data are similar for both energies, $T_H=170\pm10$ MeV. On the other hand, the data analysis at the SPS [1,2] and a numerical modeling of the hadron cascade stage at the SPS and RHIC [3,4] indicate that the kinetic (i.e., particle spectra) freeze-out of the most abundant hadrons takes place at temperatures significantly lower than T_H. Nevertheless, one expects that the kinetic freeze-out of Ω hyperons and ϕ, J/ψ, and ψ' mesons may occur directly at the quark-gluon plasma (QGP) hadronization stage or close to it since these particles have small hadronic cross sections. Thus for these hadrons the chemical and kinetic freeze-outs are expected to coincide and to be determined by the features of the QGP hadronization. For J/ψ and ψ' mesons, this is our suggestion [5–7], which is a straightforward consequence of the recently proposed statistical mechanism of charmonia production at the QGP hadronization [8–11]. The transverse mass spectra of Ω hyperons [12] and ϕ mesons [13] produced in central Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV were recently measured by the STAR Collaboration. These data allow us to extract parameters of the QGP hadronization at RHIC energies, and consequently predict the spectra of J/ψ and ψ' mesons.

Within a hydrodynamical approach of the QGP hadronization, the transverse mass spectrum of ith hadron in the central rapidity region can be written [14] as

$$\left.\frac{dN_i}{m_T dm_T dy}\right|_{y=0}=\frac{d_i\lambda_i\gamma_i^{n_i}}{\pi}\tau_H R_H^2\int_0^1 \xi d\xi K_1\left(\frac{m_T\cosh y_T}{T_H}\right)\times I_0\left(\frac{p_T\sinh y_T}{T_H}\right), \qquad (1)$$

where y is the particle longitudinal rapidity and $y_T(\xi)=\tanh^{-1}v_T$ is the fluid transverse rapidity. R_H and τ_H are, respectively, the transverse system size and proper time at the hadronization (i.e., at the boundary between the mixed phase and hadron matter), and $\xi=r/R_H$ is a relative transverse coordinate. The particle degeneracy and fugacity are denoted as d_i and λ_i, respectively, $m_T=\sqrt{p_T^2+m_i^2}$ is the hadron transverse mass, and K_1 and I_0 are the modified Bessel functions. The parameter γ_i in Eq. (1) (γ_S [15] for $i=\phi,\Omega$ and γ_C [9,10] for $i=J/\psi,\ \psi'$) describes a possible deviation of strange and charm hadrons from complete chemical equilibrium ($n_i=2$ for $\phi,J/\psi,\psi'$ and $n_i=3$ for Ω).

Note that spectrum (1) is obtained under the assumption that the hydrodynamic expansion is longitudinally boost invariant, and that the freeze-out occurs at constant longitudinal proper time. In order to complete Eq. (1), the functional form of the transverse rapidity distribution of hadronizing matter $y_T(\xi)$ has to be given. A linear flow profile, $y_T(\xi)=y_T^{max}\xi$, used in our model is justified by the numerical calculations of Ref. [4].

Thus, in our model, the QGP hadronization is described by the following parameters: temperature T_H, volume parameter $\tau_H R_H^2$, maximum flow rapidity y_T^{max}, fugacities λ_i, and saturation factors γ_i. Note that the $\phi,J/\psi,\psi'$ have no conserved charges and $\lambda_i=1$ for these particles. We use the fixed values of the parameters $T_H=170$ MeV, $\gamma_S=1.0$, and $\lambda_{\Omega^-}=1/\lambda_{\Omega^+}=1.09$ (note that $\lambda_{\Omega^-}\equiv\exp[(\mu_B-3\mu_S)/T]$, where μ_B and μ_S are, respectively, baryon and strange chemical potentials). These (average) values of the *chemical freeze-out* parameters have been found in the hadron gas analysis [16] of the full set of the midrapidity particle number ratios measured in central Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV. The fit to the m_T spectra of $\Omega^\pm$ hyperons [12] and ϕ mesons [13] measured in central (14% for $\Omega^\pm$ and 11% for ϕ) Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV is shown in Fig. 1. The fit results are: $y_T^{max}=0.74\pm0.09$, $\tau_H R_H^2=275\pm70$ fm$^3/c$, and $\chi^2/ndf\cong0.46$. In the calculation of errors of the two free parameters of the model the uncertainties of T_H (±5 MeV), γ_S (±0.05), and λ_{Ω^-} (±0.06) were taken into account. The normalization factors of Ω and ϕ spectra are simultaneously treated in terms of the same volume parameter $\tau_H R_H^2$.

A simple exponential approximation of the spectra is usually utilized to parametrize the experimental data:

$$\left.\frac{dN}{m_T dm_T dy}\right|_{y=0}=C\exp\left(-\frac{m_T}{T^*}\right). \qquad (2)$$

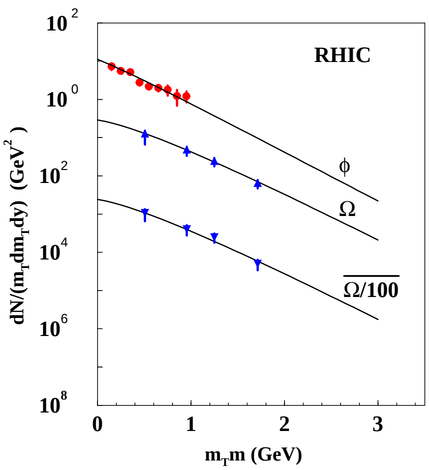

FIG. 1. The hadron transverse mass spectra in Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV are shown. The points indicate experimental data for the Ω [12] and ϕ [13] measured by the STAR Collaboration. The model results are shown by full lines.

The m_T spectrum (1) may, however, deviate significantly from a purely exponential one, and its shape depends on the magnitude of the transverse flow and the mass of the particle. The normalization factors C and the inverse slope parameters T^* in different intervals of m_T-m can be found from the ϕ, Ω, J/ψ, and ψ' spectra given by Eq. (1) using the maximum likelihood method. The average values of T^* for the m_T domains of "low-p_T" ($m_T-m<0.6$ GeV) and "high-p_T" (0.6 GeV$<m_T-m<1.6$ GeV), discussed in Refs. [4,7], are shown in Fig. 2. The values of T^* obtained by fitting the $\Omega^{\pm}$, J/ψ, and ψ data in Pb+Pb collisions at 158A GeV (see Ref. [6]) are also shown for comparison. The observed increase of T^* with increase of the hadron mass is much stronger at the RHIC than at SPS energies. It is caused by larger transverse flow velocity of hadronizing QGP at RHIC ($\overline{v_T}\cong 0.44$) than at SPS ($\overline{v_T}\cong 0.19$). The increase of T^* is much more pronounced in low-p_T region than in high-p_T one (see Fig. 2). In our model the m_T-spectra of charmonia are extraordinarily affected by the strong transverse flow at the RHIC due to enormous masses of these hadrons.

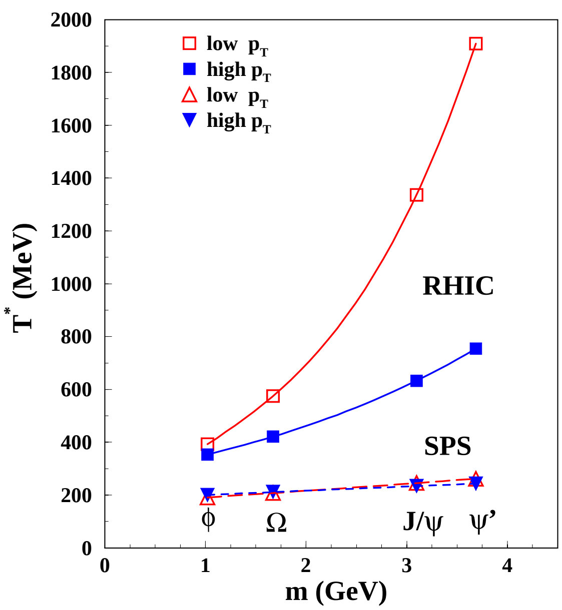

FIG. 2. The values of the inverse slope parameters T^* for two different m_T domains—low p_T and high p_T—in Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV are presented. For comparison, the values of T^* extracted from fitting the data in Pb+Pb collisions at the SPS are also shown.

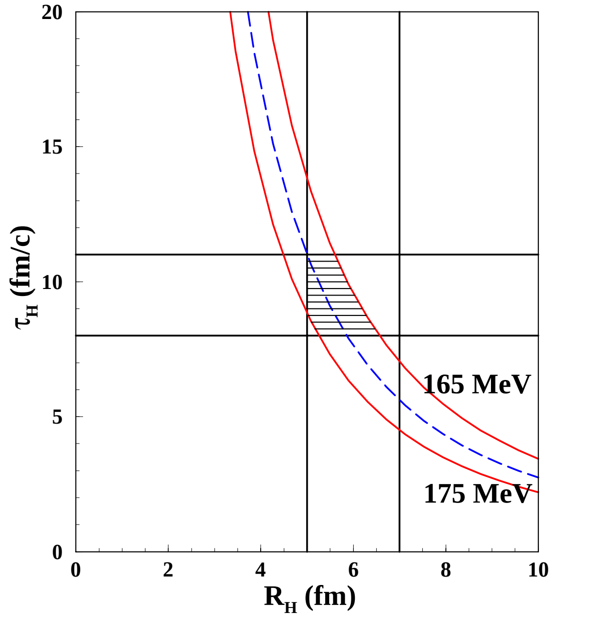

FIG. 3. The lines $\tau_H=A(T_H)R_H^{-2}$ of constant "volume parameter" $A(T_H)$ are shown: $T_H=170$ MeV corresponds to the dashed line, $T_H=165$ MeV and $T_H=175$ MeV correspond to the lower and upper solid lines, respectively. The dashed area is the intersection with the region of $R_H=5-7$ fm and $\tau_H=8-11$ fm/c estimated from Ref. [4].

The hadronization volume parameter $\tau_H R_H^2$ obtained in our present analysis can be compared with that calculated in the "hydro QGP + hadron cascade" model. This parameter $\tau_H R_H^2 \equiv A(T_H)$ extracted from the fit to the Ω and ϕ spectra defines the line $\tau_H=A(T_H)R_H^{-2}$ in the R_H-τ_H plane. The allowed region in the R_H-τ_H plane can be estimated by varying the temperature parameter within its limits, $T_H=165$ MeV and $T_H=175$ MeV. The resulting lines are shown in Fig. 3. The transverse radius $R_H=5-7$ fm and the proper time $\tau_H=8-11$ fm/c at the QGP hadronization can be estimated from the hydrodynamical calculations of Ref. [4] for central Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV (see Fig. 3 in Ref. [4]). These model boundaries and their intersection with the R_H-τ_H region found in our analysis are shown in Fig. 3. Therefore, our results do not contradict the estimates of Ref. [4]. This fact supports the basic assumptions of our model, and it demonstrates their physical consistency.

Within our approach the m_T spectra of ϕ, Ω, J/ψ, ψ' are assumed to be frozen at the space-time hypersurface where the hadron phase starts. This assumption is justified by the

TABLE I. The values of inverse slope parameters T^* for (anti)protons and (anti-)Λ's in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV are presented (the difference in the results for particle and its antiparticle is small).

	$T^*_{low\text{-}p_T}$ (MeV)	$T^*_{high\text{-}p_T}$ (MeV)	Refs.
DATA $p,\bar{p}$	455±105	290±40	[19,21]
Hydro+RQMD	480	300	[4]
Single freeze-out	315	310	[17,18]
DATA $\Lambda,\bar{\Lambda}$	505±60	320±30	[20,22]
Hydro+RQMD	440	310	[4]
Single freeze-out	360	330	[18]

small hadronic cross sections and large masses of these particles (in addition, the m_T spectra of these hadrons are almost not affected by the resonance feeding). However, the m_T spectra of many other hadrons are expected to be significantly modified by hadronic rescattering. Contrary to this expectation, it was recently postulated [17,18] that the simultaneous chemical and kinetic freeze-out in Au+Au collisions at the RHIC occurs for all hadrons (a single freeze-out model). Do experimental data allow us to distinguish between these two approaches?

The "hydro QGP + hadron cascade" approach [4] predicts for central Au+Au collisions at $\sqrt{s_{NN}}$=130 GeV that the hadron cascade stage modifies the m_T spectra of nucleons and Λ hyperons substantially. In particular, a large increase of the inverse slope parameter in the low-p_T region is expected for these hadrons as a result of hadronic rescattering and resonance decay effects. Thus measurements of (anti)proton and (anti-)Λ m_T spectra should allow us to distinguish between the single freeze-out model and models which assume different kinetic freeze-out conditions for different hadrons.

Therefore, we performed the T^* analysis of the present RHIC data from the STAR [19,20] and PHENIX Collaboration [21,22]. The resulting T^* values are summarized in Table I together with the predictions of the single freeze-out model [17,18] and QGP hydro + hadron cascade model [4]. The m_T spectra of Λ and $\bar{\Lambda}$ are also shown in Fig. 4. There are significant systematic differences between T^* parameters obtained from the STAR and PHENIX data. In view of this fact, the values quoted in Table I are calculated as an arithmetic average of both results, whereas the (systematic) error was estimated to be a half of the difference between them.

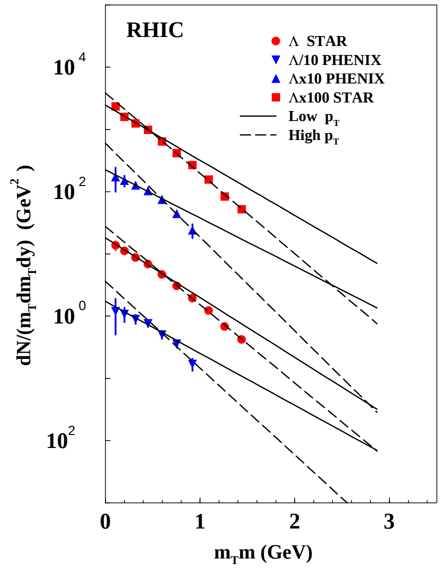

FIG. 4. The points indicate the experimental m_T spectra of Λ and $\bar{\Lambda}$ in central Au+Au collisions at $\sqrt{s_{NN}}$=130 GeV measured by the STAR [20] and PHENIX [22] Collaborations. The "straight lines" are the exponential approximations of the spectra with Eq. (2) in the low-p_T (solid lines) and high-p_T (dashed lines) regions.

Despite the large uncertainties, the data seem to favor the QGP hydro + hadron cascade model over the single freeze-out model. Additional data in the low-p_T region and their theoretical analysis would be helpful to clarify presence of the hadron cascade stage and its influence on $T^*_{low\text{-}p_T}$ of (anti)protons and (anti-)Λ's.

Assuming a statistical approach to the charmonia production at the QGP hadronization in high energy nuclear collisions, we predict a strong (a few times) increase of the inverse slope parameter T^* of the charmonia m_T spectra at RHIC in comparison with those found at the SPS. The higher the energy, the larger the inverse slope expected due to increasing transverse flow of hadronizing QGP. Thus, at $\sqrt{s_{NN}}$=200 GeV, the increase of T^* should become even more pronounced than at $\sqrt{s_{NN}}$=130 GeV. Due to strong sensitivity of the charmonia spectra to the hadronization temperature and transverse flow velocity, their analysis would significantly improve our estimate of these parameters.

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