# Hadron Spectra and QGP Hadronization in Au+Au Collisions at RHIC

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The transverse mass spectra of $\Omega$ hyperons and $\phi$ 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 $J/\psi$ and $\psi'$ mesons.

Recent measurements [1] of the energy dependence of pion and kaon production in central collisions of heavy nuclei (A+A) indicate [2] that the transient state of deconfined matter is created at the early stage of these collisions for energies higher than about 40 A·GeV, i.e. at high SPS and RHIC energies. Analysis of the hadron multiplicities measured in these collisions within statistical models at the SPS [3] and RHIC [4] energies shows that the chemical freeze–out takes 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, $T_H = 170 \pm 10$ MeV, and they are close to the value of the deconfinement transition temperature at zero baryonic density estimated in the lattice QCD (see e.g. Ref. [5]).

The analysis of the experimental data at the SPS [6,7] and a numerical modeling of the hadron cascade stage in A+A collisions at SPS and RHIC energies [8,9] 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 some heavy and weakly interacting hadrons (e.g. $\Omega$ hyperons and $\phi$, $J/\psi$, $\psi'$ mesons) may occur directly at the quark–gluon plasma (QGP) hadronization stage or close to it. Thus for these hadrons the chemical and kinetic freeze–outs coincide and are determined by the features of the QGP hadronization. For $\Omega$ hyperons and $\phi$ mesons this expectation is based on the results of "hydro QGP + hadron cascade" approach [8,9]. For $J/\psi$ and $\psi'$ mesons this is our suggestion [10–12], which is a straightforward consequence of the recently proposed statistical mechanism of charmonia production at the QGP hadronization [13–16]. Within this approach the transverse mass spectra of the $\Omega$, $J/\psi$ and $\psi'$ measured in Pb+Pb collisions at the SPS have been described successfully [11]. The transverse mass spectra of $\Omega$ hyperons [17] and $\phi$ mesons [18] produced in central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV were recently measured by the STAR Collaboration. These data allow to test our model in the new energy regime. They also give a unique opportunity to extract parameters of the QGP hadronization at RHIC energies and consequently predict spectra of $J/\psi$ and $\psi'$ mesons.

Within a hydrodynamical approach of the QGP hadronization the transverse mass spectrum of $i$-th hadron in the central rapidity region can be written as (see, e.g., Ref. [19]):

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

where $y$ is the particle longitudinal rapidity and $y_T(\xi) = \tanh^{-1} v_T$ is the fluid transverse rapidity. $R_H$ and $\tau_H$ are, respectively, the transverse system size and proper time at the hadronization (i.e., at the boundary between the mixed phase and hadron matter), $\xi = r/R_H$ is a relative transverse coordinate. The particle degeneracy and fugacity are denoted as $d_i$ and $\lambda_i$, respectively, $m_T = \sqrt{p_T^2 + m_i^2}$ is the hadron transverse mass, $K_1$ and $I_0$ are the modified Bessel functions. Parameter $\gamma_i$ in Eq. (1) ($\gamma_S$ [20] for $i = \phi, \Omega$ and $\gamma_C$ [14,15] 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 $\Omega$).

The 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 $\tau = \sqrt{t^2 - z^2}$ ($t$ is the time and $z$ is the longitudinal coordinate), i.e. the freeze–out time $t$ is independent of the transverse coordinate $r$. 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, $y_T(\xi) = y_T^{max} \cdot \xi$, used in our model is justified by the numerical calculations of Ref. [9].

Thus, in our model, the QGP hadronization is described by the following parameters: temperature $T_H$, "volume" $\tau_H R_H^2$, maximum flow rapidity $y_T^{max}$, fugacities $\lambda_i$, and saturation factors $\gamma_i$. 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, $\gamma_S = 1.0$, $\lambda_{\Omega^-} = 1/\lambda_{\Omega^+} = 1.09$ (note that $\lambda_{\Omega^-} \equiv \exp[(\mu_B - 3\mu_S)/T]$, where $\mu_B$ and $\mu_S$ are, respectively, baryon and strange chemical potentials). These (average) values of the *chemical freeze-out* parameters have been found in the hadron gas analysis [4] 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 [17] and $\phi$ mesons [18] measured in central (14% for $\Omega^{\pm}$ and 11% for $\phi$) Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV is shown in Fig. 1. The fit results are: $y_T^{max} = 0.74 \pm 0.09$, $\tau_H R_H^2 = 275 \pm 70$ fm$^3$/c and $\chi^2/ndf \cong 0.46$. In the calculation of errors of the two free parameters of the model the uncertainties of $T_H$ ($\pm 5$ MeV), $\gamma_S$ ($\pm 0.05$) and $\lambda_{\Omega^-}$ ($\pm 0.06$) were taken into account.

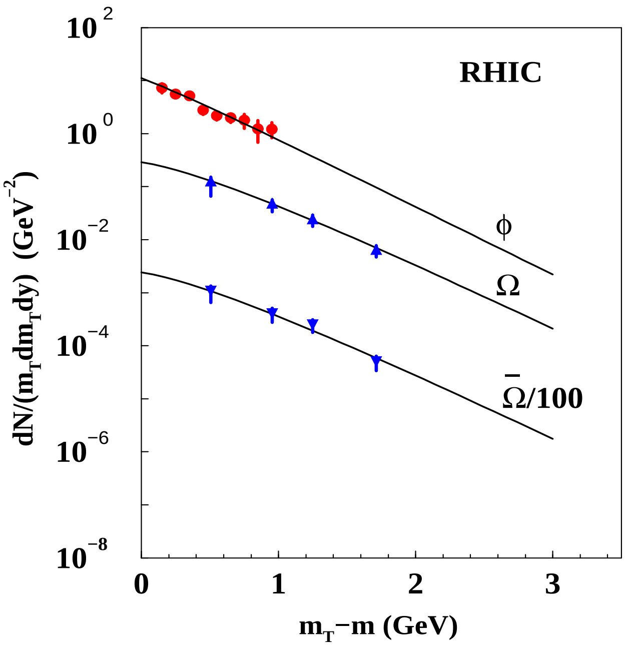


FIG. 1. The hadron transverse mass spectra in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV are shown. The points indicate experimental data for the $\Omega$ [17] and $\phi$ [18] measured by STAR. The model results are shown by full lines.

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

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

Note that in Refs. [10–12] an additional factor $m_T^{1/2}$ was present in the r.h.s. of Eq. (2). It led to smaller values of $T^*$ when fitting the same spectrum. 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 $\phi$, $\Omega$, $J/\psi$ and $\psi'$ 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. [9,12], are shown in Fig. 2. The values of $T^*$ obtained by fitting the $\Omega^{\pm}$, $J/\psi$ and $\psi'$ data in Pb+Pb collisions at 158 A·GeV (see Ref. [11]) are also shown for comparison. The observed increase of $T^*$ with increase of the hadron mass is much stronger at 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. In our model the $m_T$-spectra of charmonia are extraordinary affected by the stronger transverse flow at RHIC due to enormous masses of these hadrons. Thus, the data on $J/\psi$ and $\psi'$ production in Au+Au collisions, soon to be obtained at RHIC, should allow to test the hypothesis of their formation at the QGP hadronization.

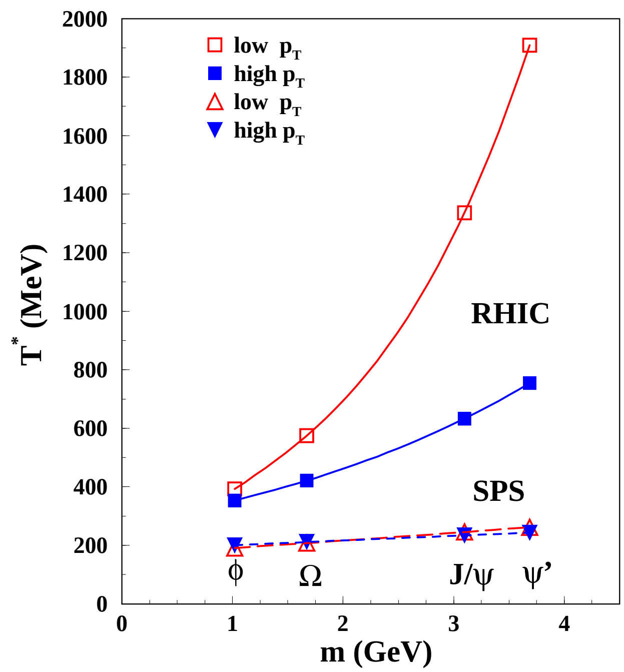


FIG. 2. The values of the inverse slope parameters $T^*$ for two different $m_T$ domains – "low-$p_T$" ($m_T - m < 0.6$ GeV) and "high-$p_T$" (0.6 GeV$< m_T - m < 1.6$ GeV) – in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV are presented. They are found using Eq. (1) with $T_H$ = 170 MeV and $y_T^{max}$ = 0.74. For comparison, the values of $T^*$ extracted from fitting the data in Pb+Pb collisions at the SPS (Eq. (1) with $T_H$ = 170 MeV, $y_T^{max}$ = 0.28, see Ref. [11]) are also shown.

We note here that at present there exists an uncertainty in the estimates of the $\gamma_C$ factor, therefore, the predictions concerning charmonia multiplicities in Au+Au collisions at RHIC within statistical approaches significantly vary and their discussion goes beyond the scope of this letter.

The "volume parameter" $\tau_H R_H^2 \equiv A(T_H)$ extracted from the fit to the $\Omega$ and $\phi$ spectra defines the line $\tau_H = A(T_H) \cdot R_H^{-2}$ in the $R_H$–$\tau_H$ plane. The allowed region in the $R_H$–$\tau_H$ 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 $R_H = 5 \div 7$ fm and the proper time $\tau_H = 8 \div 11$ fm/c at the QGP hadronization can be estimated from the hydrodynamical calculations of [9] for central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV (see Fig. 3 in Ref. [9]). These model boundaries and their intersection with the $R_H$–$\tau_H$ region found in our analysis are shown in Fig. 3.

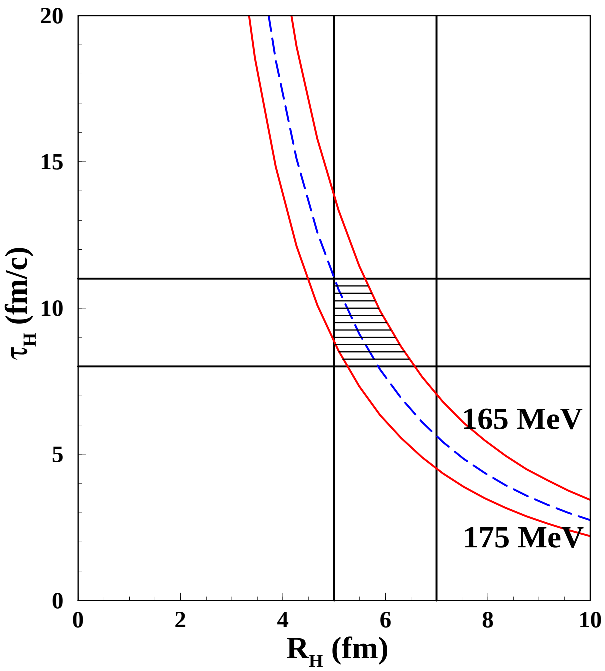


FIG. 3. The lines $\tau_H = A(T_H) \cdot R_H^{-2}$ of constant "volume parameter" $A(T_H)$ are shown: $T_H = 170$ MeV corresponds to the dashed line, $T_H = 165$ MeV and $T_H = 175$ MeV correspond to the lower and upper solid lines, respectively. The dashed area is the intersection of the $R_H$–$\tau_H$ region between the $T_H = 165$ MeV and $T_H = 175$ MeV lines with the region of $R_H = 5 \div 7$ fm and $\tau_H = 8 \div 11$ fm/c estimated from Ref. [9].

| | $T^*_{low-p_T}$ (MeV) | $T^*_{high-p_T}$ (MeV) | Refs. |
|---|---|---|---|
| **DATA** $p, \bar{p}$ | $455 \pm 105$ | $290 \pm 40$ | [23,25] |
| Hydro+RQMD | 480 | 300 | [9] |
| Single freeze-out | 315 | 310 | [21,22] |
| **DATA** $\Lambda, \bar{\Lambda}$ | $505 \pm 60$ | $320 \pm 30$ | [24,26] |
| Hydro+RQMD | 440 | 310 | [9] |
| Single freeze-out | 360 | 330 | [22] |

Table I. The values of inverse slope parameters $T^*$ for (anti)protons and (anti)lambdas in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV are presented. The experimental values are taken as the average ones over the STAR and PHENIX results (a difference in the results for particle and its antiparticle is small).

Within our approach the $m_T$-spectra of $\phi$, $\Omega$, $J/\psi, \psi'$ are assumed to be frozen at the space-time hyper-surface where the hadron phase starts. This assumption is justified by the 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 [21,22] that the simultaneous chemical and kinetic freeze-out in Au+Au collisions at RHIC occurs for all hadrons (a single freeze-out model). Do experimental data allow us to distinguish between these two approaches?

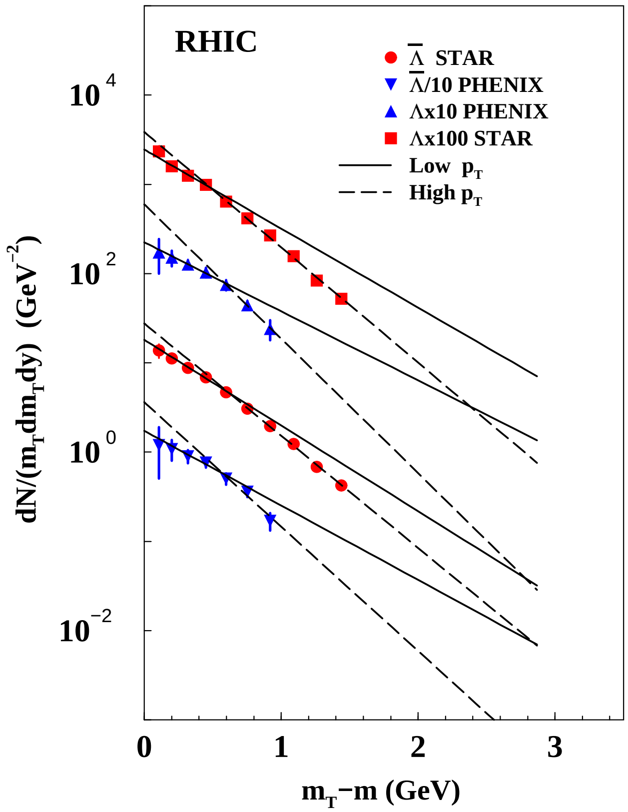


FIG. 4. The points indicate the experimental $m_T$-spectra of the $\Lambda$ and $\bar{\Lambda}$ in central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV measured by the STAR [24] and PHENIX [26] Collaborations. The "straight lines" are the exponential approximations of the spectra with Eq. (2) in the low-$p_T$ (solid lines) and high-$p_T$ (dashed lines) regions.

The "hydro QGP + hadron cascade" approach [9] 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 $\Lambda$ 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)lambda $m_T$-spectra should allow to distinguish between the single freeze-out model and models which assume different kinetic freeze-out conditions for different hadrons. We performed the $T^*$ analysis of the present RHIC data from STAR [23,24] and PHENIX [25,26]. The resulting $T^*$ values are summarized in Table I together with the predictions of the single freeze–out model [21,22] and "QGP hydro + hadron cascade" model [9]. The $m_T$-spectra of the $\Lambda$ 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 the 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.

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 $T^*_{low-p_T}$ of (anti)protons and (anti)lambdas.

The results on $m_T$–spectra of charmonia in central Au+Au collisions at the RHIC energies are expected to be available soon. They should allow to test a statistical approach to the charmonia production at the QGP hadronization in high energy nuclear collisions. In particular, within this approach, 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 that at SPS. The higher is the energy the larger inverse slope is 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 should significantly improve our estimate of these parameters.

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