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ϕ, Ω, and ρ production from deconfined matter in relativistic heavy ion collisions

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We investigate the production of the ϕ meson and the Ω baryon which interact relatively weakly with hot hadronic matter, their spectra thus reflecting the early stage of the heavy ion collisions. Our analysis shows that the hadronization temperature, $T_{\rm had}$, and the transverse flow, v_T^0, of the initial deconfined phase are strongly correlated: $T_{\rm had}+a\cdot(v_T^0)^2=0.25$ GeV, where $a=0.37$ GeV in the Pb+Pb collision at 158A GeV/c. When choosing appropriate initial values of $T_{\rm had}$ and v_T^0 from the temperature region $T_{\rm had}=175\pm15$ MeV, the measured ρ meson spectra was reproduced surprisingly well by the MICOR model. We have found weak influence of final state hadronic interactions on the transverse hadron spectra at $m_T-m_i>0.3$ GeV.

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Recent analysis by the NA50 Collaboration [1] on ϕ and ρ/ω meson transverse momentum spectra in Pb+Pb collision at the CERN Super Proton Synchrotron (SPS), yielded remarkably small values for the inverse slopes of these particles, namely $T_{\rm eff}^{\rm exp}(\phi)=222\pm6$ MeV and $T_{\rm eff}^{\rm exp}(\rho/\omega)=219\pm5$ MeV. Furthermore, analysis by the WA97 Collaboration [2] reveals a slightly larger value for the inverse slope of the $\Omega^-+\overline{\Omega}^+$ particle spectra, $T_{\rm eff}^{\rm exp}(\Omega)=238\pm17$ MeV.

These inverse slopes do not fit the suggested straight line of $T_{{\rm eff},i}=T_{\rm fo}+m_i\langle v_T\rangle^2$ [3,4], which may indicate a mutual hadronic transverse flow and which holds for $\pi^\pm$, $K^\pm$, p, $\overline{p}$, ϕ, Λ, $\overline{\Lambda}$, and d data of NA44 [4] and NA49 [5–7] with freeze-out temperature $T_{\rm fo}=175$ MeV and average transverse flow $\langle v_T\rangle=0.35c$. On the other hand, the measured slopes of the Ξ^- and $\overline{\Xi}^+$ did not follow this linear dependence on hadron masses m_i [2]. This phenomena was explained by the early freeze-out of the Ξ and the Ω in an analysis based on the RQMD model [8], where final state interactions were considered to reproduce the measured hadronic transverse slopes. Since the interaction of the ϕ meson with nonstrange baryon-rich matter is also small [9], the measured value of $T_{\rm eff}^{\rm exp}(\phi)$ from NA50 agrees with this picture.

However, accepting that the momentum spectra of the ϕ and Ω reflect the early stage of the heavy ion collisions, we can ask if this early stage could have been a deconfined matter, or simply resonance matter as indicated by RQMD [8].

In this paper we investigate the direct production of the Ω, ϕ, and ρ from thermalized massive quark matter. We use the MIcroscopical COalescence Rehadronization (MICOR) model [10,11], which is the successor of the ALCOR [12,13] and the Transchemistry models [14]. The ALCOR and Transchemistry models were constructed to determine the total number of hadrons produced from quark matter. The MICOR model is able to determine the full momentum spectra of final state hadrons. For the investigation of the production of ϕ and Ω we use a part of the full MICOR model; this part will be summarized here. A full scale description of the MICOR model and the detailed investigation of all particle spectra will be published elsewhere [15].

One description of the deconfined phase consists of massive quarks, antiquarks, and gluons in the temperature region $1\leq T/T_c\leq 3$ [16]. In the MICOR model, which is based on this description, the massive gluons (whose number is suppressed relative to the quarks and antiquarks) become responsible for an attractive effective potential between the colorful quarks and antiquarks and this effective strong interaction drives the hadronization via the coalescence of quarks. The obtained quark-antiquark plasma is assumed to be a fully thermalized state, and in the hadronization stage it is characterized by a hadronization temperature $T_{\rm had}$, a transverse flow v_T^0 and a Bjorken-scaled longitudinal flow. In spite of the thermal initial conditions, the coalescence of the massive quarks and antiquarks produces a hadron resonance gas which is out of equilibrium. Furthermore, the decays of the resonances do not lead to equilibrium. While the final state hadronic spectra can be fitted by inverse slopes familiar from equilibrium descriptions, this does not mean that we obtain equilibrated hadronic final states.

During hadronization mesonlike objects are formed in one step via quark-antiquark coalescence. Baryonlike objects are formed in two steps: the formation of diquarks from quarks are followed by the coalescence of diquarks and quarks into baryons. The presence of strongly correlated hadronlike objects in the deconfined phase is supported by lattice-QCD results [17]. We use the name ''prehadron'' for such a correlator. The values of prehadron masses, $m_{\rm preh}$, are not sharply determined. In the static case one may determine the spectral function of the correlator, extracting some ''mass'' and ''width.'' However, in our case the two-body coalescence process dynamically creates an off-shell prehadron with $\sigma_{\rm coal}$ cross section (see Ref. [12] for the coalescence cross section).

We assume that during the hadronization period these color-neutral prehadrons can escape the deconfined state without disintegration and they will become the species of the produced excited hadronic gas. Large constituent quark masses imply a further assumption that the production of the excited $J=1$ vector mesons (ρ,K^*,ϕ) and $J=3/2$ baryons

(Δ, Σ^*, Ξ^*, Ω) are favored during the hadronization. The $J=0$ pseudoscalar mesons (pions and kaons) cannot be formed by quark coalescence, but appear together with the $J=1/2$ baryons as products of the decay of the heavier excited hadrons. The expected minor difference between the prehadron masses and the excited hadron masses will be corrected in a last step: when the prehadron escapes from the deconfined region, it becomes on shell by conserving its velocity.

In general, the coalescence-type hadron production, $q_1+q_2\rightarrow h$, can be described by a relativistic rate equation based on the densities [18]:

$$\partial_\mu(n_h u^\mu)=\sum_{q_1,q_2}\langle\sigma^h_{q_1q_2}v_{12}\rangle n_{q_1}n_{q_2}. \tag{1}$$

Here n_{q_1} and n_{q_2} are the local quark densities, n_h is the prehadron density, u^μ is the four-velocity of the matter, v_{12} is the relative velocity of the two quarks, $\sigma^h_{q_1q_2}$ is the quark coalescence cross section, and $\langle\sigma^h_{q_1q_2}v_{12}\rangle$ is the momentum space average of their product:

$$\langle\sigma^h_{q_1q_2}v_{12}\rangle=\frac{\int d^3p_1d^3p_2f_1f_2\sigma^h_{q_1q_2}v_{12}}{\int d^3p_1d^3p_2f_1f_2}. \tag{2}$$

For the invariant quark distributions, $f_i(p_i,x_i)$, thermalized Jüttner functions are used. However, in general, other momentum distributions could also be used. We neglect the melting of the prehadrons back into the deconfined phase. This equation assumes the escape of color-neutral prehadrons from the deconfined phase.

In the MICOR model we determine the momentum spectra of the produced prehadrons generalizing a momentum dependent version of the rate equation found in Eq. (1). We introduce an extended averaging on the $\tau=\tau_h$ hadronization hypersurface:

$$\langle\langle\sigma v_{12}\rangle\rangle=\frac{\hat{I}[f_1f_2\sigma v_{12}]}{\hat{I}[f_1f_2]}, \tag{3}$$

where

$$\hat{I}[\ldots]=\int dV_1d^3p_1dV_2d^3p_2[\ldots] \tag{4}$$

$$=4\int\prod_{i=1}^{2}dV_id^4p_i\Theta(E_i)E_i\delta(p_i^2-m_i^2)[\ldots] \tag{5}$$

is the 12-dimensional phase space integration operator. Assuming two-particle coalescence, the momentum of the outgoing particle is the sum of the incoming momenta: $p=p_1+p_2$. Since we are interested in the momentum spectra of the outgoing particle, it is more useful to represent $\hat{I}$ in Eq. (5) as an integral of the relative four-momentum $q=(p_1-p_2)/2$ and the outgoing four-momentum p with $s=p^2$:

$$\hat{I}[\ldots]=\int d^4p\hat{I}_p[\ldots], \tag{6}$$

$$\hat{I}_p[\ldots]=\int_{\tau=\tau_h}dV_1dV_2\sum_{\mathrm{sgn}q^0=\pm1}\int_{q^2=(m_1^2+m_2^2/2)-s/4}\frac{d^3q}{|q^0|}\times E_1E_2\,\delta\left(pq-\frac{m_1^2-m_2^2}{2}\right)\Theta\left(\frac{E}{2}-|q^0|\right)[\ldots]. \tag{7}$$

Using the parametrization

$$p^\mu=(m_T'\,\mathrm{ch}\,y,p_T'\cos\varphi,p_T'\sin\varphi,m_T'\,\mathrm{sh}\,y), \tag{8}$$

after some tedious algebra [15] we obtain a simplified expression for the phase space integral and we can derive the differential form of the averaging in Eq. (3):

$$\frac{d\langle\langle\sigma v_{12}\rangle\rangle}{d^4p}=\frac{\hat{I}_p[f_1f_2\sigma v_{12}]}{\hat{I}[f_1f_2]}. \tag{9}$$

Equation (9) leads to the momentum dependent rate equations for the produced prehadrons and diquarks.

In Eq. (9) the prehadron is created off shell, $s=p^2=m^2_{\mathrm{preh}}$. When the prehadron leaves the deconfined region, it assumes an on-shell resonance by emitting or absorbing energy. For simplicity, we assume that its velocity distribution remains unchanged during this process. One can parametrize the transverse velocity as

$$v_T=p_T'/m_T'=\mathrm{th}\mu, \tag{10}$$

where $m_T'=\sqrt{p_T'^2+s}$. With this parametrization the differential momenta element is

$$d^4p=\frac{1}{2}s\,ds\,\mathrm{ch}\,\mu\,d\mathrm{ch}\,\mu\,dy\,d\varphi, \tag{11}$$

and thus the four-velocity distribution is

$$\frac{dI}{\mathrm{ch}\,\mu\,d\,\mathrm{ch}\,\mu\,dy\,d\varphi}=\int ds\,s\frac{d\langle\langle\sigma v_{12}\rangle\rangle}{d^4p}. \tag{12}$$

If we substitute $\mathrm{ch}\mu=m_T/m_h$ into Eq. (12) and convert the velocity distribution into a four-momentum distribution, we obtain the on-shell momentum distribution for hadrons with mass m_h and transverse mass $m_T=\sqrt{p_T^2+m_h^2}$:

$$\frac{dI}{m_Tdm_Tdy\,d\varphi}=\frac{1}{m_h^2}\int ds\,s\frac{d\langle\langle\sigma v_{12}\rangle\rangle}{d^4p}. \tag{13}$$

This formula gives the momentum distribution of the primarily produced excited hadrons. From the expression in Eq. (13) one can determine in one step the transverse momentum slope of the ϕ and in two steps the Ω (included the formation of an ss diquark). These results can be compared directly with the experimental data. For the description of all final state hadrons we would need to follow the time evolu-

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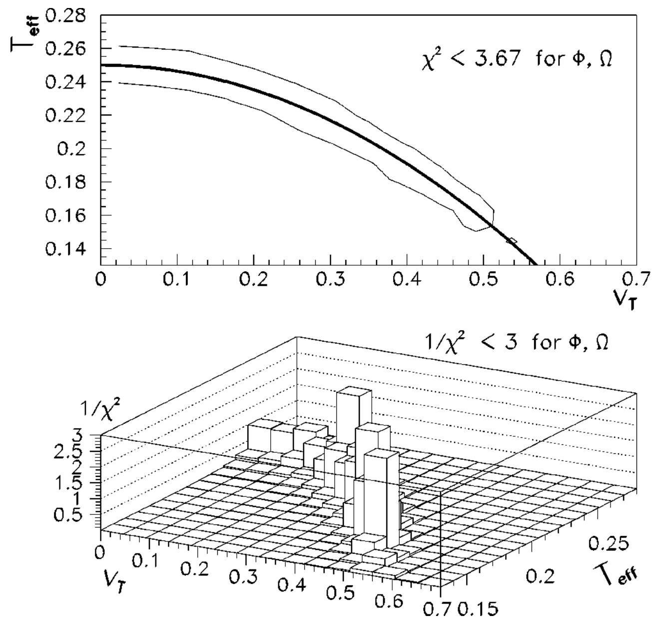

FIG. 1. The χ^2 fit of the calculated $T_{\rm eff}$ slopes for the ϕ meson and the Ω baryon. The area inside the solid contour line indicates $\chi^2<3.67$. The solid dark line shows the fit $T_{\rm had}+a\cdot(v_T^0)^2=0.25$ GeV, where $a=0.37$ GeV. In the bottom figure we show our fit, displaying the values of $1/\chi^2<3$ on a Lego plot.

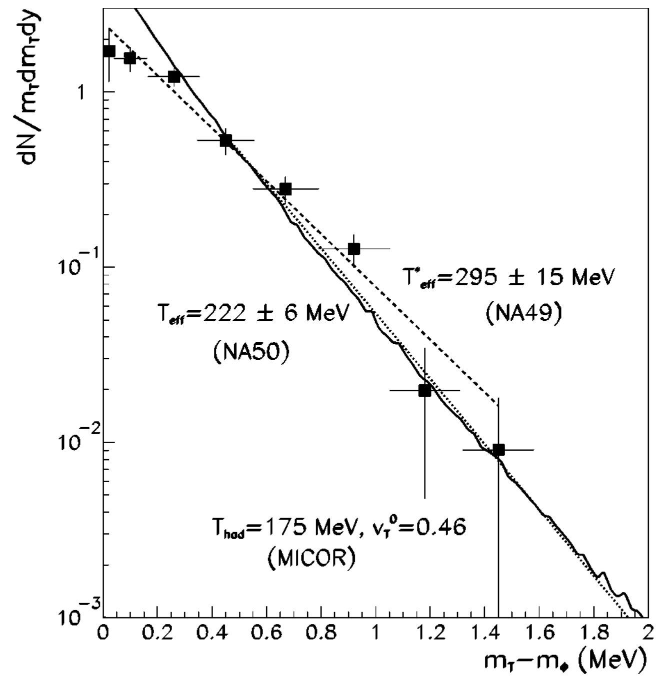

FIG. 2. The transverse momentum spectra of the ϕ meson measured by the NA49 Collaboration in Pb+Pb collision at 158A GeV (full squares), the dashed line indicates the effective slope $T^*_{\rm eff}=295\pm15$ MeV [5]. The dotted line indicates the measured slope of the NA50 Collaboration [1] in the transverse momentum region $0.5<m_T-m_\phi<2.2$. The solid curve with fluctuations is the MICOR result.

tion of the multicomponent hadronization and the decay of excited hadrons. This is beyond the scope of this paper and those calculations will be published in a forthcoming paper [15].

The deconfined matter is characterized by the hadronization temperature, $T_{\rm had}$, and an initial transverse flow, v_T^0. We consider a large enough longitudinal extension for the deconfined matter: $\eta_0=\pm2.2$, where η_0 is the space-time rapidity. This parameter will not influence the transverse momentum spectra at $y=0$. The constituent quark masses are chosen to be $m_Q=300$ MeV and $m_S=450$ MeV.

We vary the hadronization temperature in the region $T_{\rm had}=130-260$ MeV and the initial transverse flow $v_T^0=0-0.7$. The obtained transverse spectra for the ϕ and the Ω are fitted in the measured transverse momentum region $0.5<m_T-m_\phi<2.2$ GeV for ϕ and $0.3<m_T-m_\Omega<1.5$ GeV for Ω, following the procedures of the NA50 and WA97 Collaborations, respectively. We compare the theoretical slopes to the experimental data. Figure 1 displays the values of χ^2 obtained from the measured and the calculated slopes of the ϕ and the Ω spectra. The area inside the solid contour line indicates $\chi^2<3.67$.

One can see a very strong correlation between the hadronization temperature and the initial transverse flow, which can be characterized by the expression

$$T_{\rm had}+a\cdot(v_T^0)^2=0.25\ \ {\rm GeV}, \tag{14}$$

where $a=0.37$ GeV. This correlation is indicated by the solid dark line in Fig. 1. Considering only the $\chi^2<3.67$ values, a large temperature region is allowed, namely $T_{\rm had}=160-230$ MeV (paired with the appropriate initial transverse flow v_T^0), for an initial condition for the hadronization. In the bottom part of Fig. 1 we show the details of our fit, displaying the values of $1/\chi^2<3$ on a Lego plot. Here an ''excellent'' agreement can be seen between the result of the MICOR model and the experimental data in the region $T_{\rm had}=175\pm15$ MeV and $v_T^0=0.46\pm0.05$.

To avoid later confusion between the theoretical result of this paper and the experimental data of the NA50 [1] and NA49 Collaborations [5,6], Fig. 2 displays our recent information on the transverse momentum spectra of the ϕ meson. In the MICOR model, according to Eq. (14) we use $T_{\rm had}=175$ MeV and $v_T^0=0.46$ to calculate the theoretical transverse momentum spectra of the ϕ meson.

The full squares show the NA49 data as reconstructed from Ref. [5]. The dashed line indicates the $T^*_{\rm eff}=295\pm15$ MeV slope with the parametrization

$$dN/m_T dm_T \propto \exp(-m_T/T^*_{\rm eff}) \tag{15}$$

in the momentum region $0.02<m_T-m_\phi<1.5$ GeV.

The dotted line indicates the results of the NA50 Collaboration [1], namely the $T_{\rm eff}^{\rm exp}(\phi)=222\pm6$ MeV slope with the parametrization

$$dN/m_T dm_T = C\cdot m_T\cdot K_1(m_T/T_{\rm eff}) \tag{16}$$

in the momentum region $0.5<m_T-m_\phi<2.2$ GeV. Applying the expansion of the Bessel function in Eq. (16) one obtains

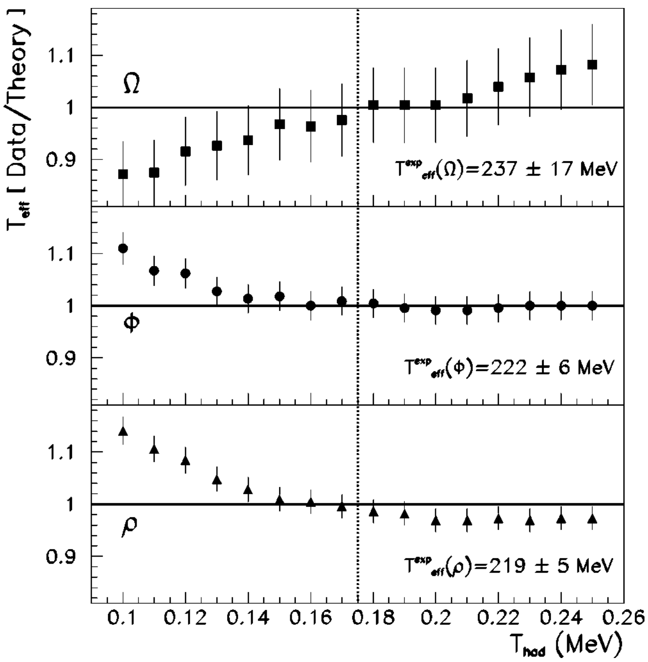

FIG. 3. The ‘‘Data/Theory’’ values for recalculated $T_{\mathrm{eff}}(\Omega)$ and $T_{\mathrm{eff}}(\phi)$ as a function of hadronization temperature T_{had} with transverse flow v_T^0 satisfying Eq. (14). We display the same ratio for the ρ particle calculated in the MICOR model (bottom part). The vertical dotted line indicates $T_{\mathrm{had}}=175$ MeV.

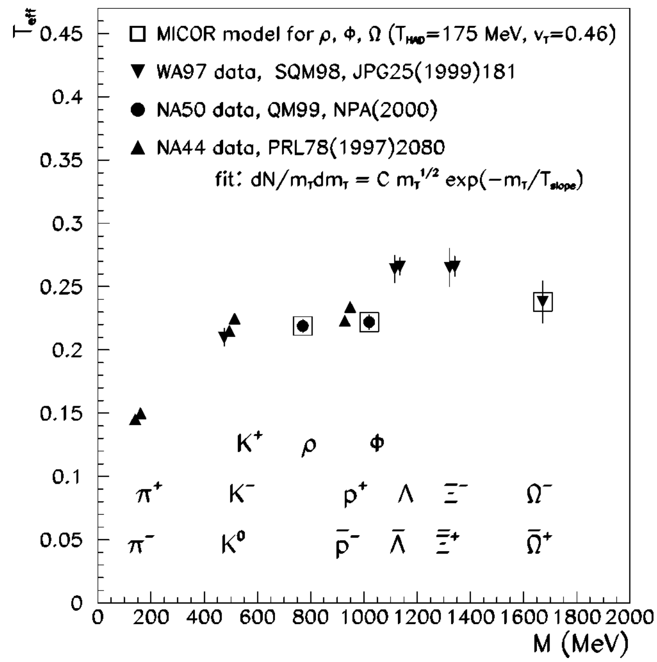

FIG. 4. Experimental results on the effective hadronic slopes of the transverse momentum spectra (T_{eff}) in the Pb+Pb collision at 158A GeV energy from the WA97 [2] (inverted triangles), NA50 [1] (dots) and NA44 Collaborations [4] (triangles). The results of WA97 and NA50 were fitted originally by Eq. (17) and we fit the NA44 data on $\pi^{\pm}$, $K^{\pm}$, p^+, and $\overline{p^-}$ [21] in the same way in the momentum region $m_T - m_i > 0.3$ GeV. Open squares indicate the theoretical results from the MICOR model on the ρ, ϕ, and Ω particles.

$$dN/m_T dm_T = \tilde{C}\cdot m_T^{1/2}\exp(-m_T/T_{\mathrm{eff}}), \tag{17}$$

where $\tilde{C}=C\cdot\sqrt{T_{\mathrm{eff}}\pi/2}$. In the above momentum region the difference between the parametrizations in Eq. (16) and Eq. (17) is negligible. Thus the results of NA50 can be compared directly to the results of WA97 [2], who used the parametrization of Eq. (17). In the following we will use the parametrization of Eq. (17).

Figure 2 shows that the slopes of the NA49 Collaboration are valid for the transverse momentum region $m_T - m_\phi < 1$ GeV and the slope of the NA50 Collaboration is valid for $m_T - m_\phi > 0.3$ GeV. The MICOR result was chosen to agree with the NA50 measurement, and it agrees with the experimental results of the NA49 Collaboration in the region $m_T - m_\phi > 0.3$ GeV. In parallel, Fig. 2 demonstrates that the coalescence process creates a nonthermal momentum distribution, and the obtained momentum distribution for the ϕ can mimic a thermalized final state in large momentum region. (The fluctuations on the MICOR results are coming from the applied Monte-Carlo evaluation of the phase-space integral.) Figure 2 shows that the MICOR model fails to reproduce the NA49 data in the momentum region $m_T - m_\phi < 0.3$ GeV, which requires further improvements at small p_T. However this disagreement will not influence our analysis and discussion at larger p_T.

We apply the obtained correlation between the hadronization temperature and early transverse flow from Eq. (14) and recalculate the slopes of the transverse momentum spectra for Ω and ϕ. Figure 3 shows our results, displaying the ‘‘Data/Theory’’ ratios for the different T_{eff} values (including the experimental error bars) as a function of hadronization temperature, T_{had}. This figure confirms the validity of the function used in Eq. (14).

We also calculate the ρ/ω spectra. In the MICOR model the ρ/ω particle is formed in one step from the coalescence of a quark and an antiquark. The theoretical value of this slope parameter was fit in the measured transverse momentum region $1.5 < m_T < 3.2$ and compared to the experimental value $T_{\mathrm{eff}}^{\mathrm{exp}}(\rho)=219\pm5$ MeV. The bottom part of Fig. 3 shows that the pairs of T_{had} and v_T^0 parameters which satisfy Eq. (14) by reproducing the slope of ϕ and Ω, also reproduce the measured slope of ρ. This occurs especially in the region $T_{\mathrm{had}}=175\pm15$ MeV.

This result is very surprising. We could expect that the weakly interacting ϕ and Ω will conserve their transverse momentum distribution from the initial hot phase (according to our assumption this is a strongly coupled deconfined phase). But the ρ particle is very strongly coupled to nucleons and pions [19], thus final state interactions should modify their spectra with an extra transverse boost. It was hardly expected that the ρ meson could conserve any of its early transverse momentum distribution.

With this surprising result, we collect the available data on the T_{eff} extracted by the parametrization of Eq. (17), similarly to ρ, ϕ, and Ω. We show these experimental data in Fig. 4. The data on K_S^0, Λ, $\overline{\Lambda}$, Ξ^-, $\overline{\Xi}^+$, and Ω can be found in Ref. [2]. The data on ρ and ϕ are from Ref. [1]. For π^+,

π^-, K^+, K^-, p^+, and $\overline{p}^-$ we considered the NA44 data [20,21] and using Eq. (17) fit these data in the momentum region $m_T - m_i > 0.3$ GeV. We obtained $T_{\rm eff}^{\rm exp}(\pi^+) = 150$ MeV, $T_{\rm eff}^{\rm exp}(\pi^-) = 145$ MeV, $T_{\rm eff}^{\rm exp}(K^+) = 225$ MeV, $T_{\rm eff}^{\rm exp}(K^-) = 216$ MeV, $T_{\rm eff}^{\rm exp}(p^+) = 234$ MeV, $T_{\rm eff}^{\rm exp}(\overline{p}^-) = 223$ MeV. These data followed the tendency that the value of the $T_{\rm eff}$ decreases with 25–30 MeV when using Eq. (17) as opposed to Eq. (15), see, e.g., Ref. [2].

Figure 4 helps to estimate the efficiency of the final state interactions in the transverse momentum region $m_T - m_i > 0.3$ GeV. It reveals that the separation of the p^+, $\overline{p}^-$, Λ, $\overline{\Lambda}$, Ξ^-, and $\overline{\Xi}^+$ from the weakly interacting ϕ and Ω is much smaller than indicated in Refs. [6,7]. Even more, according to our fit, the slope of p^+ and $\overline{p}^-$ is very close to that of the weakly interacting ϕ meson. Thus the slope of the ρ meson and its restoration in the MICOR model is not surprising anymore. Figure 4 indicates that in the transverse momentum region $m_T - m_i > 0.3$ GeV the hadronic spectra may not suffer large modifications because of secondary collisions. Pions could be exempt, since their separation from the other particles may indicate extra-long hadronic evolution, or their appearance from resonance decays. These results demand further investigation into the properties of the hadronic spectra at $m_T - m_i < 0.3$ GeV.

In this paper, we analyzed the recent experimental results on the production of the ϕ meson and the Ω baryon, using the MICOR model. We have found a strong correlation between the hadronization temperature and the transverse flow of the early deconfined state, where the ϕ and Ω were created from quark-antiquark plasma. We have found that $T_{\rm had} = 175 \pm 15$ MeV and $v_T^0 = 0.46 \pm 0.05$ is favored by the data. In this temperature region the MICOR model also reproduced the measured ρ/ω slope. This result indicates that final state interactions modify very weakly the transverse momentum spectra of the ρ/ω meson in the transverse momentum region $1.5 < m_T < 3.2$ GeV. In the large m_T region the final state interactions may not modify the transverse slopes created in an early state. Further calculations [15] are in progress to investigate if all hadronic spectra can be reproduced by the MICOR model assuming the formation of massive quark-antiquark plasma and its hadronization throughout quark coalescence.

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