EXPLANATION OF THE RHIC $p_\perp$-SPECTRA IN A SINGLE-FREEZE-OUT MODEL* **

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The $p_\perp$-spectra of hadrons measured at RHIC are very well described in a model which assumes that the chemical and thermal freeze-outs occur simultaneously. The model calculation includes all hadronic resonances and uses a simple parametrization of the freeze-out hypersurface.

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In this talk we present a simple model describing the $p_\perp$-spectra of various hadrons measured recently at RHIC. Our approach combines the thermal model, used frequently in the studies of the relative hadron yields [1–10], with a model of the hydrodynamic expansion of matter at freeze-out. The main assumptions of the model are as follows [11–13]: First of all, we assume that the chemical freeze-out and the thermal freeze-out occur at the same time. This means that we neglect elastic rescattering after the chemical freeze-out. Secondly, we include all hadronic resonances in both the calculation of the hadron multiplicities and the spectra. In particular, all cascade decays are taken into account exactly in a semi-analytic fashion. Finally, we assume a simple form of the freeze-out hypersurface, which is a generalization of the Bjorken model [14] (see also [15–20])

$$\tau = \sqrt{t^2 - x^2 - y^2 - z^2} = \text{const.} \tag{1}$$

The hydrodynamic flow on the freeze-out hypersurface (1) is taken in the form resembling the Hubble law

$$u^\mu = \frac{x^\mu}{\tau} = \frac{t}{\tau}\left(1, \frac{x}{t}, \frac{y}{t}, \frac{z}{t}\right). \tag{2}$$

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Recently, several arguments have been accumulated in favor of our first assumption. The measurements of the transverse HBT radii at RHIC show that the hadronic system does not evolve for a long time. The ratio $R_{\rm out}/R_{\rm side}$ is close to unity in the whole range of the measured transverse momentum (for a compilation of the recent HBT measurements see, *e.g.*, Ref. [22]), indicating that the pion emission time is short in comparison with a typical transverse size of the system. The assumption about the single freeze-out solves also the antibaryon puzzle [23]. Since the annihilation cross section for $p\bar{p}$ pairs is much larger than the elastic cross section, most of the protons would annihilate with antiprotons during the long way from the chemical to the thermal freeze-out. Such effect is not seen. In addition, let us mention that a rapid transverse expansion of the firecylinder, as found at RHIC also in our model, suppresses the collision rate and makes the potential gap between the two freeze-outs smaller.

Our model has two thermodynamic and two geometric (expansion) parameters. The two thermodynamic parameters are obtained from the analysis of the ratios of the hadron multiplicities measured at RHIC. The fit to 9 independent ratios yields the values of the temperature and the baryon chemical potential: $T = 165$ MeV, $\mu_B = 41$ MeV [10]. Since the particle ratios depend weakly on the centrality of the collision [24], the thermodynamic parameters may be regarded as the universal parameters (independent of centrality). The two geometric parameters are τ and $\rho_{\rm max}$. The parameter $\rho_{\rm max}$ determines the transverse size of the firecylinder at the freeze-out,

$$\rho = \sqrt{x^2 + y^2} \leq \rho_{\rm max}. \tag{3}$$

Clearly, the values of τ and $\rho_{\rm max}$ depend on the considered centrality class of events. For the minimum-bias data, which average over centralities, we find: $\tau = 5.55$ fm and $\rho_{\rm max} = 4.50$ fm, whereas for the most central collisions we find: $\tau = 7.66$ fm and $\rho_{\rm max} = 6.69$ fm [11]. The calculation of the spectra (and determination of the geometric parameters) is based on the standard Cooper–Frye formalism. The details of our method, especially of the technical problems concerning the treatment of the resonances, are given in the Appendix of Ref. [12].

In Fig. 1 we compare the model predictions for the $p_\perp$-spectra of pions, kaons and (anti)protons with the PHENIX minimum bias preliminary data [21] (the official data released recently [25] agree with those shown on the plot). The quality of the fit is very good. The model curves cross practically all the data points within error bars. Even the high-$p_\perp$ data are reproduced. Also, the convex shape of the pion spectra is provided by the model. We have checked that this is a consequence of the radial flow [11]. The main effect coming from the resonance decays is an effective cooling of the spectrum by 30–40 MeV — the inverse slope of the spectrum becomes smaller as discussed in more detail in Ref. [10]. The effect of the cooling of the spectrum by the decays of the resonances explains a difference between the high temperature of the chemical freeze-out (in different approaches it turns out to be very similar and close to 170 MeV) and a smaller "apparent" temperature (inverse slope) inferred from the analysis of the spectra, which is typically not more than 130 MeV.

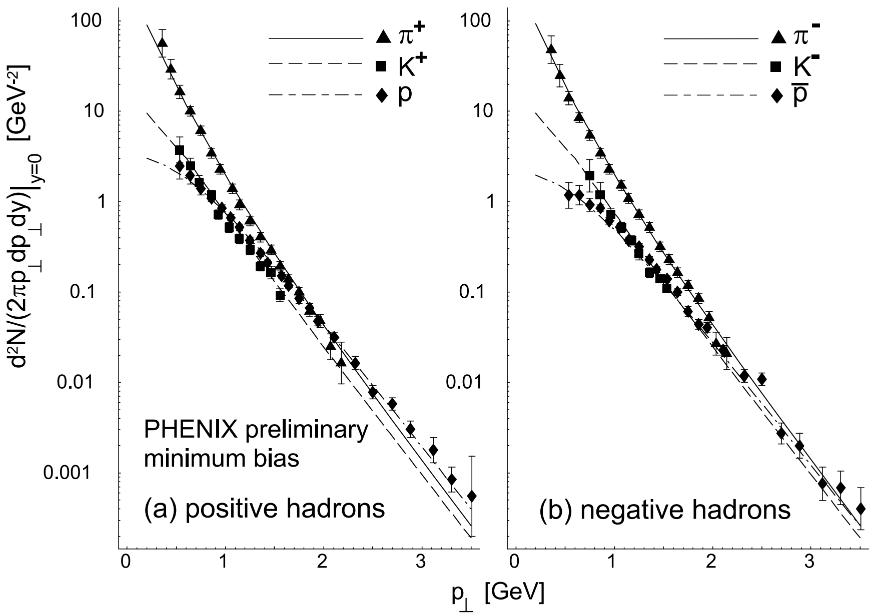

Fig. 1. The $p_\perp$-spectra at midrapidity of pions (solid line), kaons (dashed line) and protons or antiprotons (dashed–dotted line). The model calculation is compared to the PHENIX preliminary minimum-bias data [21], Au + Au collisions at $\sqrt{s} = 130$ GeV A.

In Fig. 2 we show our results for the most central collisions. In the left part we show the spectra of pions, kaons, antiprotons, and of the ϕ mesons. The parameters were fitted already in Ref. [11] with the help of the spectra of pions, kaons and antiprotons only. The good agreement of the measured ϕ meson spectrum [27] with the model calculation supports our approach, since the interaction of the ϕ meson with the hadronic environment is negligible, and ϕ may be regarded as a good thermometer of the hadronic system. The right part of Fig. 2 shows the prediction of our model for the spectra of hyperons. The data for $\bar{\Lambda}$ come from [28]. Since these data are not normalized, we have adjusted their normalization arbitrarily[1].

[1] The newly-released normalized data on $\bar{\Lambda}$ production [29] are consistent with our norm.

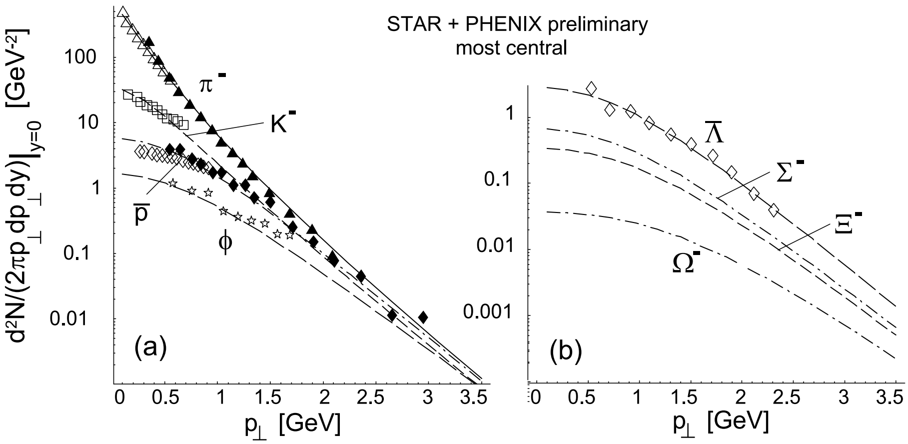

Fig. 2. The $p_\perp$-spectra of various hadrons measured in the most central collisions at RHIC ($\sqrt{s}=130$ GeV A). The filled symbols are the data from PHENIX [21], the open symbols are the STAR data [26–28]. The curves represent the spectra obtained in the single-freeze-out model.

Let us now make a few comments about the size of our geometric parameters. For the most central events, the fitted value of $\rho_{\rm max} \sim 6$ fm is very close to the radius of the colliding gold nuclei, and is similar in magnitude with the measured HBT transverse radius R_s. The latter describes, however, an average (r.m.s.) transverse size, which is smaller than the true geometric size of the system. This means that our values of the geometric parameters are too low. This problem can be circumvented by the inclusion of the excluded-volume corrections in the thermodynamic description of the hadron gas [1, 5]. Such corrections make the system more dilute, which can be compensated by an increase of τ and $\rho_{\rm max}$ [13]. If we rescale τ and $\rho_{\rm max}$ by the same factor, the spectra remain unchanged and the agreement with the measured transverse radius can be achieved. On the other hand, the time-extension of our system is much smaller than the space-extension, so we expect that the experimental result $R_{\rm out}/R_{\rm side} \approx 1$ will naturally appear in our model. The calculation of the HBT radii in our model with the full treatment of the hadronic resonances is in progress.

In conclusion, we emphasize that our approach explains in a very economic way (4 parameters) both the relative hadron yields and the $p_\perp$-spectra of all up-to-now measured hadrons ($\pi^+, \pi^-, K^+, K^-, p, \bar{p}, \bar{\Lambda}, \phi$). The model includes in a transparent way the decays of the resonances, and the longitudinal and transverse flow. Further extensions of the application of the model should include the elliptic-flow effects and the rapidity dependence.

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