Transverse spectra of hadrons at RHIC

K. J. Eskola\textsuperscript{a}, H. Niemi\textsuperscript{a}, P. V. Ruuskanen\textsuperscript{a}, S. S. Räsanen\textsuperscript{a}

\textsuperscript{a}Department of Physics, University of Jyväskylä, P.O. Box 35, FIN-40014 University of Jyväskylä, Finland

We present results on spectra of pions, kaons and (anti)protons from a study of heavy ion collisions using the perturbative QCD + saturation model to calculate the production of initial (transverse) energy and baryon number followed by a hydrodynamic description of the expansion of produced matter. In particular, we study how the hadron spectra and multiplicities depend on the decoupling temperature $T_{\text{dec}}$ when the low temperature phase contains all hadrons and hadron resonances with mass below 2 GeV. We show that the spectra and multiplicities of pions, kaons and (anti)protons measured at RHIC in central Au+Au collisions with $\sqrt{s} = 130$ GeV can be obtained with a single decoupling temperature $150 \ldots 160$ MeV, common for both the chemical and the kinetic freeze-out.

1. INTRODUCTION

The average transverse momentum of primary particles in heavy ion collisions is expected to be larger than the experimentally observed one. Two ways out of this problem have been discussed: In one case the number of produced particles is small and the final multiplicity is achieved after fragmentation which reduces also the average transverse momenta of final, observed particles \cite{1}. On the other hand, results from the calculation can be used as initial conditions in a hydrodynamical approach \cite{2}. In this case the extra transverse energy is transferred into the longitudinal motion through the work by pressure in the expansion. The transfer from transverse to longitudinal degrees of freedom takes place because the matter is produced in a strong longitudinal expansion.

When time passes, also a transverse flow builds up and leads, e.g., to a clear mass dependence of final hadron spectra. The shape of spectra depend both on the transverse flow and the decoupling temperature $T_{\text{dec}}$ but the ratios of particle multiplicities on the $T_{\text{dec}}$ and on the baryon chemical potential $\mu_{B,\text{dec}}$. Strangeness chemical potential is fixed by demanding that the net strangeness density is zero.

Modelling the heavy ion collisions at collider energies in terms of perturbative QCD calculation of minijet production at saturation \cite{2} and of hydrodynamic expansion of produced matter, has lead to a successful description of multiplicities and transverse energy at mid-rapidities \cite{3}. This talk summarizes the predictions for particle spectra in central Au+Au collisions at $\sqrt{s} = 130$ GeV from the pQCD+saturation+hydrodynamics model \cite{4}.

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2. THE MODEL FOR CALCULATING THE TRANSVERSE SPECTRA

In a high energy $AA$ collision parton production can be calculated from the nuclear parton distribution functions and the perturbative parton-parton cross sections, provided that the momentum transfer in the partonic collision $p_T \gg \Lambda_{QCD}$. Assuming independent partonic collisions, the dominant part of the initial production is obtained by extending the (LO) calculation of partonic jets down to $p_0 = 1...2 \text{ GeV} \gg \Lambda_{QCD}$ [5].

The basic quantities for characterizing the parton production in nuclear collisions are the number and the total transverse energy of minijets per unit rapidity. These are obtained as a function of $p_0$ from the transverse energy distribution of minijets in the central rapidity unit as the normalization $\sigma_{jet}(p_0)$ and the first moment $\sigma\langle E_T \rangle$ [5]. Combining these with the nuclear overlap function $T_{AA}$ (or the product of thickness functions of colliding nuclei) gives the average total number and transverse energy of partons with $p_T > p_0$. The net baryon number can be obtained as a difference of the quark and anti-quark numbers [6]. Finally, to close the model, a cut-off momentum must be fixed and here we assume that it originates from the saturation of partons [7]. We express this in terms of final, produced partons as a simple geometrical condition: each parton is given a transverse size $\pi/p_T^2$, and when the partons overlap, extra independent primary collisions with smaller $p_T$ are suppressed. The lower cut-off $p_0 = p_{sat}$ is thus fixed from the saturation condition [2]

$N(p_0, \Delta y) \cdot \pi/p_0^2 = \pi R_A^2$.

From the minijets at saturation we can calculate the energy density and the net baryon number density after introducing a correlation between the longitudinal momentum and the longitudinal space-time formation point of the minijet. We assume that rapidity of the minijet equals the space-time rapidity of the formation point, $y = \eta = 0.5 \ln[(t+z)/(t-z)]$. The formation time, defined as $1/p_{sat}$ is taken as the initial time for the hydrodynamic evolution. The details of the determination of the initial state can be found in [4, 3].

It can be argued that $\tau_0 = 1/p_{sat}$ (~0.2 fm/c for Au+Au at RHIC) is too short to achieve thermalization. However, from the point of view of the average energy per particle, the system does look thermal [2]. Also, one should expect collisions to take place and the build-up of collective behaviour to start already during the thermalization process. From this point of view, the use of hydrodynamics at early times should be considered to approximate the effects of momentum transfer in the collisions during equilibration.

To solve the hydrodynamic equations, an equation of state (EoS) is needed. We assume an ideal QGP high temperature phase with a first order phase transition to a hadron resonance gas at $T_c = 165 \text{ MeV}$. All hadrons and hadron resonances with $M < 2 \text{ GeV}$ are included and a repulsive mean field is assumed in order to ensure a consistent temperature behaviour of the pressure [8]. The final spectra are obtained using the Cooper–Frye freeze-out procedure and the two- and three-body decays of all resonances are included.

3. RESULTS

In Figure 1 the $T_{dec}$ dependence of spectra of negative pions, kaons and antiprotons is shown together with the data measured by the PHENIX Collaboration [9]. The slopes of the spectra are seen to change considerably with $T_{dec}$. For $p_T > 1.5 \text{ GeV}$, the decrease of $T_{dec}$ from 150 MeV to 120 MeV changes the inverse slope $T_{fit}$ from 265 MeV to 305 MeV for pions, from 275 MeV to 330 MeV for kaons and from 295 MeV to 375 MeV for protons.
For the $\langle p_T \rangle$ the changes are from 0.46, 0.65 and 0.86 GeV to 0.53, 0.78 and 1.08 GeV for pions, kaons and protons, respectively. The change of the decoupling temperature affects also the normalization of spectra, that is the multiplicity. In fact the multiplicity of pions increases slightly whereas that of kaons decreases 21 % and of protons 52 %. As has been observed earlier [10], to reproduce in thermal models the multiplicities of heavier particles and pions simultaneously, a freeze-out temperature for chemical reactions must be of the order of 150 to 160 MeV. In our calculation not only the multiplicities but also the observed shapes of the spectra are obtained if the kinetic freeze-out and the chemical freeze-out are assumed to take place at the (approximately) same temperature of order 150…160 MeV.

In Figure 2 the spectra of positive pions, kaons and protons are depicted using $T_{\text{dec}} = 150$ MeV in the calculation. Within the accuracy of the data the normalizations of pions and kaons agree but the calculated proton spectrum is slightly below the measured one. This is to be expected since the feed-down from hyperons is included among the measured but not the calculated protons. PHENIX has also reported $p$ and $\bar{p}$ yields corrected for hyperon feed-down, $dN/dy = 19.3 \pm 0.6$ and $13.7 \pm 0.7$ [11]. Our results for $T_{\text{dec}} = 150$ MeV are 20.2 and 13.1 in excellent agreement with the measurement. Also the ratio $\bar{\Lambda}/\Lambda = 0.70$ is consistent with the PHENIX result $0.75 \pm 0.09$ [11].

Note that the deviation of $\bar{p}/p$ and $\bar{\Lambda}/\Lambda$ from unity is due to the net baryon number content of the initial matter at saturation. In the pQCD + saturation calculation the net baryon number cannot be changed independently of the total multiplicity. The relative production of quarks and antiquarks (and gluons) is completely fixed by the parton distributions and the perturbative parton level cross sections. In addition to the net baryon number, the number of baryons relative to that of antibaryons depends strongly
on decoupling temperature and again in our calculation agreement is obtained only for $T_{\text{dec}} \approx 150 \ldots 160$ MeV.

4. DISCUSSION

Using the pQCD + saturation model [2] to calculate the initial particle production in central Au+Au collisions at $\sqrt{s} = 130$ GeV and hydrodynamics to describe the expansion of the matter we obtain a good agreement between the calculated and measured quantities. We find it remarkable that in order to reproduce either the multiplicities, the slopes or the antibaryon-to-baryon ratios we come up in each case with the same decoupling temperature of order $150 \ldots 160$ MeV. Similar conclusion was also obtained in [12].

It has been argued that $\tau_0 = 1/p_{\text{sat}} \sim 0.2$ fm/c is too short a time for achieving full thermalization. This might well be so but it is not plausible to assume that there are no collisions with momentum transfers among the constituents at times before a possible later thermalization time. Collective motion, the flow, is a result of the collisions among the particles of the matter which lead to a net momentum transfer from denser to less dense parts in the matter. From this point of view it is difficult to justify the starting of a hydrodynamical calculation at a later time assuming no initial transversal velocity. In any case, we have checked the effect of the initial time on the shapes of the spectra. Taking $\tau_0 = 0.6$ fm/c, needed to explain the formation of elliptic flow [13], while keeping the total entropy fixed, changes the slopes only slightly. Even $\tau_0 = 1.0$ fm/c is not enough to compensate for the change from the decrease of $T_{\text{dec}}$ from 150 to 120 MeV.

Finally, we want to emphasize that our model scheme is very tight. Uncertainties in the pQCD + saturation calculation are essentially fixed from a single global quantity, like the total multiplicity. In the hydrodynamical part a large number of hadrons and hadron resonances must be included but after fixing the EoS, the only real freedom left is the decoupling temperature $T_{\text{dec}}$.

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