LETTER TO THE EDITOR

Transverse momentum distribution of net baryon number at RHIC

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Submitted to: J. Phys. G: Nucl. Phys.

PACS numbers: 25.75.-q,12.38.Mh

Abstract. We calculate the transverse momentum distribution of net quarks (quarks minus antiquarks) in Au+Au collisions at the Relativistic Heavy Ion Collider in the framework of the parton cascade model at two different rapidities. Parton re-scattering and fragmentation is seen to lead to a substantial difference in the slopes of these distributions between mid- and forward-rapidities, in qualitative agreement with the corresponding data for the net baryon distribution.
Collisions of heavy nuclei at relativistic energies are expected to lead to the formation of a deconfined phase of strongly interacting nuclear matter, often referred to as a Quark-Gluon-Plasma (QGP). Evidences for several of the signatures for the formation of this novel state of matter have recently been reported by experiments conducted at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory [1]. Many aspects of the experimental data indicate that an equilibrated state of hot and dense matter is formed in the collisions of Au nuclei at RHIC. One of the open theoretical problems is how quickly this thermalized state is formed and which mechanisms are responsible for the rapid equilibration.

It is thus of particular interest to identify processes that can give information about the pre-equilibrium dynamics in these collisions. One possible example of such probes of “early phase” physics is the distribution of net baryon number. Baryon number is a locally conserved quantity, and thus its distribution is not easily influenced by final state interactions. The net baryon number in nucleons is carried by the valence quarks. Indeed, the valence quark distribution in the nucleon is defined as the difference between the quark and antiquark, or net quark, distribution.

Flavour conservation in strong interactions dictates that quarks and antiquarks are produced in equal numbers in interactions involving sea quarks and gluons, and thus pair production processes do not change the net quark distribution. During their passage through dense matter, valence quarks collide with other partons and radiate gluons, thereby losing some of their longitudinal momentum. In a recent publication [4] we have shown how the valence quark distribution in the nucleon, combined with these multiple scattering effects, can explain the net baryon excess observed in Au+Au collisions at RHIC in the central rapidity region.

In this letter we shall demonstrate that the net quark distributions (and thus the measurable net baryon distribution) measured in the final state of a heavy ion collision exhibit a strong sensitivity to the dynamics of parton transport processes in these collisions. We find that the transverse momentum distributions of net quarks vary significantly with rapidity, and their broadening at central rapidities is a direct measure of the amount of rescattering experienced by the valence quarks. Preliminary data reported by the BRAHMS collaboration [2] show that the slopes of the net baryon transverse momentum distributions at central and forward rapidities differ significantly and thus support our findings.

The parton cascade model [3] (PCM) provides a suitable framework for the study of the formation of a hot and dense partonic phase, starting from clouds of valence quarks, sea quarks, and gluons which populate the nuclei. The PCM was devised as a description of the early, pre-equilibrium phase of a nucleus-nucleus collision at high energy. The current implementation [5] does not include a description of the hadronization of the partonic matter and of the subsequent scattering among hadrons. These late-stage processes, however, are not expected to significantly alter the distribution of net baryon number with respect to rapidity, since the net baryon number is locally conserved and baryon diffusion in a hadronic gas can be shown to be slow [6]. No such investigation
has been made for the transverse momentum distribution of the net baryons, but obviously the same arguments apply. Also, we have recently found extensive evidence that the transverse momentum distributions of hadrons at RHIC reflect the momentum distribution of the partons from which they form [7].

Let us briefly recall the fundamental assumptions underlying the PCM. We assume that the state of the dense partonic system can be characterized by a set of one-body distribution functions $F_i(x^\mu, p^\alpha)$, where $i$ denotes the flavor index ($i = g, u, \bar{u}, d, \bar{d}, \ldots$) and $x^\mu, p^\alpha$ are coordinates in the eight-dimensional phase space. The partons are assumed to be on their mass shell, except before their first interaction. In our numerical implementation, the GRV-HO parametrization [8] is used, and the parton distribution functions are sampled at an initialization scale $Q_0^2$ to create a discrete set of particles. Partons generally propagate on-shell and along straight-line trajectories between interactions. Before their first collision, all partons move with the beam (target) rapidity and do not have an “intrinsic” transverse momentum.

The time-evolution of the parton distribution is governed by a relativistic Boltzmann equation:

$$p^\mu \frac{\partial}{\partial x^\mu} F_i(x, \vec{p}) = C_i[F]$$

where the collision term $C_i$ is a nonlinear functional of the phase-space distribution function. The calculations discussed below include all lowest-order QCD scattering processes between massless quarks and gluons. A low momentum transfer cut-off $p_T^{min}$ is needed to regularize the infrared divergence of the perturbative parton-parton cross sections. Additionally, we include the branchings $q \rightarrow qg$, $q \rightarrow q\gamma$, $g \rightarrow gg$ and $g \rightarrow q\bar{q}$ [10]. The soft and collinear singularities in the showers are avoided by terminating the branchings when the virtuality of the time-like partons drops below $\mu_0 = 1$ GeV. The results to be discussed below have been obtained using the VNI/BMS [5] implementation of the PCM.

We shall start our investigation by exploring the transverse momentum distribution of the net quarks as a function of rapidity. The left frame of Fig. 1 shows the net quark rapidity distribution for a Au+Au collision at $\sqrt{s_{NN}} = 130$ GeV, using the initialization scale and low momentum cut-off scales of the pQCD cross sections, $Q_0^2 = (p_T^{min})^2 = 0.50$ GeV$^2$. The calculations included multiple scatterings among the partons as well as their fragmentation by time-like branchings. We have already shown [4] that the corresponding value for the net baryons is in good agreement with the results obtained by PHENIX and STAR experiments [11].

We now focus on the transverse momentum distribution of the net quarks (right panel). We see that the spectral slopes are essentially identical for $y_{CM} = 0$ and $y_{CM} = 1$ but significantly steeper for $y_{CM} = 3$. We also find that for $p_T > p_T^{min}$ the spectra are well represented by exponentials, with the “temperature” at mid-rapidity being about 20% larger than at more forward rapidity. The corresponding results for $\sqrt{s_{NN}} = 200$ GeV are given in Fig. 2 and confirm our findings for $\sqrt{s_{NN}} = 130$ GeV. If the slopes of the momentum distributions of hadrons remain proportional to the slopes for the partons
Figure 1. Net baryon number rapidity distributions (left) and $p_T$ distributions at different rapidities (right) for Au+Au reactions at $\sqrt{s_{NN}} = 130$ GeV in the parton cascade model VNI/BMS. The estimated slopes for the $p_T$ spectra are shown. Multiple collisions among partons as well as parton multiplication due to time-like branchings are included. The curves show the estimated slopes.

Figure 2. Same as Figure 1 for $\sqrt{s_{NN}} = 200$ GeV.

as predicted by the recombination model [7], the differences in the slopes of net baryons at $y_{CM} = 0$ and $y_{CM} = 3$ will reflect this difference in agreement with the preliminary experimental findings.

The rapidity dependence of the transverse momentum slopes may be caused by a combination of two effects:

(i) Initial state rapidity–$p_T$ correlations: as we have shown in a previous publication [4], initial (primary-primary) parton scattering “releases” valence quarks at a rapidity corresponding to the Bjorken-x they carry according to the parton distribution function of their mother hadron. This predetermined rapidity (and thus longitudinal momentum and energy) may cause the associated transverse momentum distribution in the primary-primary scattering to become a function of rapidity as well.
(ii) Parton-parton rescattering: the rapidity dependence of the slopes may be due to partons rescattering more often around mid-rapidity than at forward rapidities.

In order to distinguish between these two mechanisms (or to determine their relative importance) we perform two analyses. First, we perform a PCM calculation for a Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV, in which we restrict the interactions among the partons to primary-primary collisions, i.e. allowing each parton to scatter only once. The results are shown in the left-hand frame of Fig. 3. The spectra at $y_{CM} = 0$ and $y_{CM} = 3$ have nearly identical shapes and both exhibit a power-law behaviour, as expected from pQCD. From this calculation we may conclude that the observed rapidity-dependence of the transverse momentum slopes is not caused by rapidity–$p_T$ correlations in the initial state.

On the other hand, when we plot the average number of collisions suffered by partons as a function of their rapidity (right frame of Fig. 3), we find that the partons ending up at the central rapidities suffer on an average many more collisions than those which end up at larger rapidities. This result provides a strong indication that the rapidity dependence of the spectral slopes is directly related to the amount of rescattering experienced by the partons, and that an exponential shape of the parton transverse momentum distribution has its origin in the multiple interactions included in the PCM. In addition, we find that the shape of the $n_{coll}$ vs. $y$ distribution strongly resembles the shape of the rapidity distribution of direct photons produced in parton-parton scatterings, which we have previously shown to be proportional to the number of parton interactions occurring during the evolution of the heavy-ion collision [12].

The PCM allows us to study the full space-time evolution of the parton distributions. We therefore are able to trace the evolution of the net quark momentum
Figure 4. Rapidity distributions (top) and $p_T$ distribution at $y_{CM} = 0$ (middle) and $y_{CM} = 3$ (bottom) for net-quarks at $t=-0.2$ fm/c, 0.0 fm/c, and 0.2 fm/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, as predicted by VNI/BMS.

Distributions at different rapidities from their initial release via primary-primary scattering to their final shape. Figure 4 shows the net quark rapidity distribution (top frame) as well as the net quark transverse momentum distributions at $y_{CM} = 0$ (middle frame) and $y_{CM} = 3$ (bottom frame) at times $t=-0.2$ fm/c, 0.0 fm/c, and 0.2 fm/c, where
$t = 0 \text{ fm}/c$ corresponds to the time of maximal overlap of the two colliding nuclei. Note that the longitudinal spread of the partons according to $\Delta z \sim 1/p_z$ around the centre of the nucleus, incorporated in the PCM, permits collisions between them even when the nuclei have not yet obtained full overlap, provided the collisions are permitted by the cut-offs implemented in the PCM.

Several interesting observations emerge from this analysis: The momentum distribution of the net quarks at larger rapidities gets frozen fairly early during the collision, while the corresponding distributions at central rapidities continue to evolve. This is true for both the rapidity distributions as well as the transverse momentum distributions.

This observation suggests that the net quark (or the net baryon) distribution at different rapidities can serve as a useful tool to explore the interactions among partons (quarks) during the early phase of the heavy-ion collision. For example, the study of matter emitted at larger rapidities will offer insight into the very early stage of a relativistic heavy-ion reaction at which the initial parton distributions decohere (and at which saturation phenomena [13] may be of importance), whereas the mid-rapidity domain will provide information about a system of strongly and multiply interacting partons with all its associated phenomena, ranging from parton equilibration to jet energy-loss.

In brief, we have studied the rapidity dependence of the net quark distribution in relativistic heavy ion collisions using the parton cascade model. We find that the inverse slopes of the transverse momentum distributions at $y_{CM} = 0$ and $y_{CM} = 3$ in Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV differ by about 20%, in agreement with recently reported measurements by BRAHMS [2]. Our analysis shows that this difference arises due to the different amount of multiple scatterings suffered by partons at central and forward rapidities.

Acknowledgments

This work was supported in part by RIKEN, the Brookhaven National Laboratory, and DOE grants DE-FG02-96ER40945 and DE-AC02-98CH10886.

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