A Multi-Phase Transport model for nuclear collisions at RHIC

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Abstract

To study heavy ion collisions at energies available from the Relativistic Heavy Ion Collider, we have developed a multi-phase transport model that includes both initial partonic and final hadronic interactions. Specifically, the parton cascade model ZPC, which uses as input the parton distribution from the HIJING model, is extended to include the quark-gluon to hadronic matter transition and also final-state hadronic interactions based on the ART model. Predictions of the model for central Au on Au collisions at RHIC are reported.

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The beginning of experiments at the Relativistic Heavy Ion Collider (RHIC) this year will start an exciting new era in nuclear and particle physics. The estimated high energy density in central heavy ion collisions at RHIC is expected to lead to the formation of a large region of deconfined matter of quarks and gluons, the Quark Gluon Plasma (QGP). This gives us an opportunity to study the properties of QGP and its transition to the hadronic matter, which would then shed light on the underlying fundamental theory of strong interactions, the Quantum Chromodynamics (QCD).

Because of the complexity of heavy ion collision dynamics, Monte Carlo event generators are needed to relate the experimental observations to the underlying theory. This has already been shown to be the case in heavy ion collisions at existing accelerators such as the SIS, AGS, and SPS [1–6]. As minijet production is expected to play an important role at RHIC energies [7], models for partonic transport have already been developed [8,9]. Furthermore, transport models that include both partonic and hadronic degrees of freedom are being developed [10,11]. We have recently also developed such a multi-phase transport (AMPT) model. It starts from initial conditions that are motivated by the perturbative QCD and incorporates the subsequent partonic and hadronic space-time evolution. In particular, we have used the HIJING model [7] to generate the initial phase space distribution of partons and the ZPC model [9] to follow their rescatterings. A modified HIJING fragmentation scheme is then introduced for treating the hadronization of the partonic matter. Evolution of the resulting hadron system is treated in the framework of the ART transport model [2]. In this paper, we shall describe this new multi-phase transport model and show its predictions for central Au on Au collisions at RHIC.

In the AMPT model, the initial parton momentum distribution is generated from the HIJING model, which is a Monte-Carlo event generator for hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. The HIJING model treats a nucleus-nucleus collision as a superposition of many binary nucleon-nucleon collisions. For each pair of nucleons, the impact parameter is determined using nucleon transverse positions generated from a Wood-Saxon nuclear density distribution. The eikonal formalism is then used to determine the probability for a collision to occur. For a given collision, one further determines if it is an elastic or inelastic collision, a soft or hard inelastic interaction, and the number of jets produced in a hard interaction. To take into account nuclear effects in hard interactions, an impact parameter-dependent parton distribution function based on the Mueller-Qiu parameterization [12] of the nuclear shadowing is used. Afterwards, PYTHIA routines [13] are called to describe hard interactions, while soft interactions are treated according to the Lund model [14].

In HIJING model, minijets from produced partons are quenched by losing energy to the wounded nucleons close to their straight-line trajectories. In the AMPT model, we replace the parton quenching by their rescatterings. To generate the initial phase space distribution for the parton cascade, the formation time for each parton is determined according to a Lorentzian distribution with a half width $t_f = E/m_T^2$ [15], where E and m_T are the parton energy and transverse mass, respectively. Positions of formed partons are calculated from those of their parent nucleons using straight-line trajectories. Since partons are considered to be part of the coherent cloud of parent nucleons during the time of formation, they thus do not suffer rescatterings.

The parton cascade in the AMPT model is carried out using the ZPC model [9]. At present, this model includes only gluon-gluon elastic scatterings with cross sections taken to be the leading divergent cross section regulated by a medium generated screening mass. The latter is related to the phase space density of produced partons [16]. In the present study, a constant screening mass of $\mu = 3\,\mathrm{fm}^{-1}$ is used.

Once partons stop interacting, they are converted into hadrons using the HIJING fragmentation scheme after an additional proper time of approximate 1.2 fm. In the default HIJING model, a diquark is treated as a single entity, and this leads to an average rapidity shift of about one unit in the net baryon distribution. We modify this fragmentation scheme to allow the formation of diquark-antidiquark pairs. In addition, the $BM\bar{B}$ formation probability is taken to be 80% for the produced diquark-antidiquark pairs, while the rest are $B\bar{B}$'s. This gives a reasonable description of the measured net baryon rapidity distribution in Pb+Pb collisions at 158 GeV/nucleon [17].

For the evolution of hadrons, we use the ART model, which is a successful hadronic transport model for heavy ion collisions at AGS energies. To extend the model to heavy ion collisions at RHIC, we have further included nucleon-antinucleon annihilation channels, the inelastic interactions of kaons and antikaons, and neutral kaon production. In the ART model, multiparticle production is modeled through the formation of resonances. Since the inverse double resonance channels have smaller cross sections than those calculated directly from the detailed balance, we thus adjust the double resonance absorption cross sections to fit the NA49 data [17].

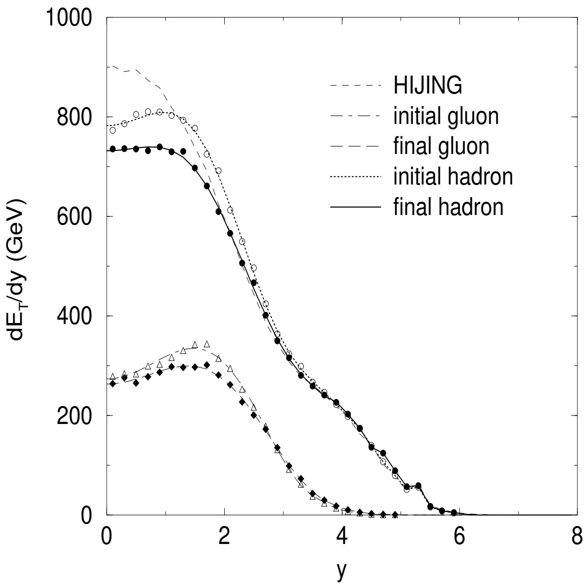

FIG. 1. Transverse energy rapidity distribution for central (b=0) Au+Au collisions at RHIC.

In Fig. 1, we show the rapidity distribution of transverse energy in Au+Au central ($b = 0$) collisions at RHIC. In the default HIJING model, the dE_T/dy at central rapidity is about 900 GeV. Using the modified HIJING framentation scheme leads to a decrease of about 100 GeV in dE_T/dy. After the parton cascade, dE_T/dy is reduced by about 15 GeV as shown by the difference in the initial and final gluon dE_T/dy distributions. We note that the perturbatively produced gluons account for a significant fraction (about 1/3) of the produced dE_T/dy. Including hadronic evolution further reduces dE_T/dy by about 50 GeV. As the transverse energy rapidity distribution is a sensitive probe of longitudinal expansion [18] and is related to the pdV work, these results indicate that both the partonic and hadronic evolution contribute appreciably to longitudinal collective flow.

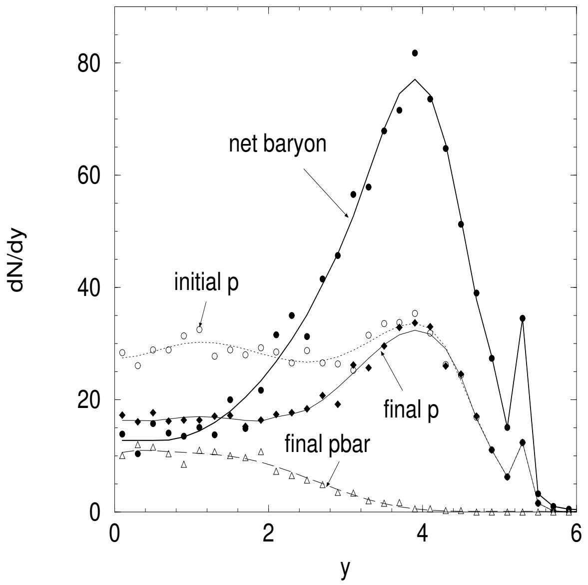

FIG. 2. Baryon rapidity distributions for RHIC Au+Au central (b=0) collisions.

Fig. 2 shows the baryon rapidity distributions. It is seen that the net baryon distribution from the AMPT model has a peak value of 80 at $y \sim 3.9$ while that from the default HIJING model has a peak value of 85 at $y \sim 4.5$. The larger rapidity shift in AMPT is due to the modified fragmentation of diquarks. At central rapidity, AMPT predicts a net baryon number of about 12, which is similar to that from the default HIJING model. Many antiprotons (about 50%) are seen to survive the absorption in hadronic matter, leading to a value of about 10 at central rapidities. The $\bar{p}/p$ ratio at central rapidity is about 60%, which is much larger than the 10% seen in Pb+Pb collisions at 158 GeV/nucleon from SPS [19].

The final meson rapidity distribution is shown in Fig.3. The prediction from the AMPT model has a distinctive plateau structure around central rapidities. Results using the default HIJING model show instead a peak at central rapidity with a higher rapidity density. Also shown in the figure is the distribution of kaons produced from both string fragmentation and hadronic interaction. The latter is seen to enhance significantly the kaon yield.

In Fig. 4, the AMPT results are compared with those from other models without final-state rescatterings such as the Fritiof1.7 and the Venus4.02 [20]. Although both AMPT and Fritiof show similar peaks at $y \sim 3.9$ in the net baryon rapidity distributions, the height of the peak is about 80 in AMPT but is about 100 in Fritiof. On the other hand, the net baryon distribution peaks at a smaller rapidity of $y \sim 2.8$ in Venus. At central rapidities, the net baryon number from AMPT is about 15 and is similar to that from Venus but is much larger than that from Fritiof, which is almost zero at the central rapidity. For mesons, both AMPT and Fritiof have final π^+ rapidity distributions that peak at the central rapidity with

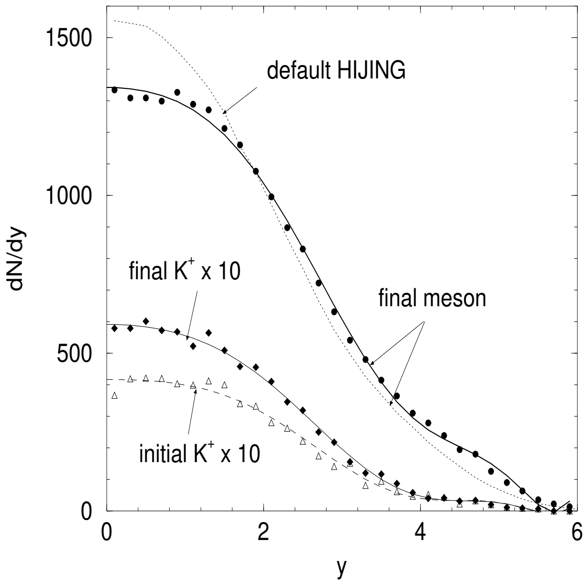

FIG. 3. Meson rapidity distributions for RHIC Au+Au central (b=0) collisions.

a height of about 350 while Venus gives a much larger height of about 1300 at the central rapidity. The forthcoming RHIC data will allow us to test the different predictions from these models and thus to obtain a better understanding of the collision dynamics.

In conclusion, we have developed for heavy ion collisions at the Relativistic Heavy Ion Collider a multi-phase transport model that includes both partonic and hadronic evolution. The model shows that both partons and hadrons contribute to the longitudinal collective work. Because of the production of diquark-antidiquark pairs, there is a relatively large rapidity shift of net baryons compared to the default HIJING fragmentation scheme. Many anti-protons survive final-state interactions and are expected to be observed at RHIC. Also, our model gives a wider meson rapidity plateau at central rapidities than the prediction from the default HIJING model. Furthermore, kaon production is appreciably enhanced due to production from hadronic interactions. For future studies, we shall compare these predictions with the experimental data soon to be available from RHIC. Also, we shall study if inclusion of parton inelastic scatterings and using different hadronization schemes would affect the results obtained here.

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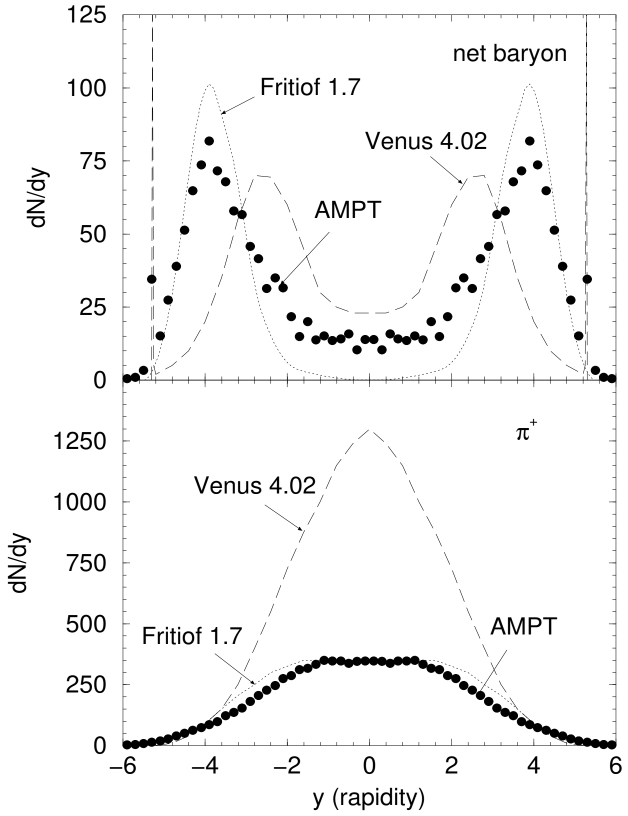

FIG. 4. Comparisons of AMPT, Fritiof1.7, and Venus4.02 predictions for RHIC Au+Au central (b=0) collisions.

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