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Re-hardening of hadron transverse mass spectra in relativistic heavy-ion collisions

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Abstract. We analyze the spectra of pions and protons in heavy-ion collisions at relativistic energies from 2 A GeV to 65+65 A GeV by using a jet-implemented hadron-string cascade model. In this energy region, hadron transverse mass spectra first show softening until SPS energies, and re-hardening may emerge at RHIC energies. Since hadronic matter is expected to show only softening at higher energy densities, this re-hardening of spectra can be interpreted as a good signature of the quark-gluon plasma formation.

Keywords. Relativistic heavy-ion collisions, hadron spectra.

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1. Introduction

The main goal of the high-energy heavy-ion collisions is to explore hot and/or dense hadronic matter far from stable nuclei. Especially, the formation of the quark-gluon plasma (QGP) is of primary interest. In order to achieve this, sincere efforts have been made in this decade, starting from Bevalac at LBL, followed by GSI-SIS, BNL-AGS, CERN-SPS, and BNL-RHIC, by increasing incident energies [1,2]. The QGP is expected to be formed at SPS energies, but we have not yet verified this clearly, although there are some promising signals. The anomalous charmonium suppression [3], enhanced production of strange hadrons [4], and enhanced low-mass di-lepton production [5], suggest the formation of anomalous hadronic matter in which the chiral symmetry is partially restored and non-negligible color-flux is stored. However, we have not seen any evidence which clearly suggests the bulk formation of QGP.

The most important feature of the QGP formation is the sudden release of a large number of degrees of freedom (DOFs), and the consequent softening at around the critical temperature, but this softening can be mimicked by hadronic (resonance and string) DOFs. Practically, the softening of matter is observed and recognized already at SIS-AGS-SPS energies, where the inverse slope parameters of hadron spectra seem to be saturated, and radial and directed flows are decreasing [6]. For example, the directed flow exhibits a maximum at SIS energies, and goes down at higher energies. Since QGP formation is not expected at SIS energies, this softening should be caused by hadronic origin. Sahu *et al* [7] have shown that the incident energy dependence of directed and elliptic flows as well as transverse mass spectrum of protons are well reproduced within a hadron-string picture, by taking into account the reduction of repulsive nuclear interaction and the appropriate increase of resonance-string DOFs. Hagedorn discussed the role of the latter in 1965 [8], suggesting that a limiting temperature around the pion mass would appear if the hadronic level density grows exponentially as a function of mass. In this case, a large part of energy is exhausted by the mass energies of heavy hadrons, then the kinetic energy per hadron cannot be larger than some particular value. This also implies that the pressure would not grow as rapidly as the energy density, and as a result the softening of hadronic matter occurs. Thus the above softening can be considered as a partial realization of Hagedorn gas, where large hadronic DOFs are activated. In a more dynamical context, many of the hadronic cascade models [9–13] which explain the data at these energy regions incorporate large hadronic DOFs, including various resonances and strings, then they naturally describe the above softening. Although there are several models [14,15] which contain smaller hadronic DOFs and which explain the data, they usually incorporate multi-particle production with a finite formation time, which plays a role in generating effective large DOFs [16].

The above discussion tells us that it is very difficult to verify the QGP formation only from the softening of matter, since we cannot distinguish the effects of QGP from those due to the increase of hadronic DOFs. On the other hand, if a re-hardening is observed at higher energy densities, it is very difficult to explain it in a hadronic scenario. The data obtained from recent RHIC energy seem to exhibit this signature [17,18]. The estimated radial flow velocity at $\sqrt{s}$ =130 A GeV is much larger than that at SPS energies. Since the radial flow velocity grows until around AGS energies and stays constant or decreases (depending on the momentum range to estimate the inverse slope parameter) between AGS and SPS for heavy systems, the above increase suggests that the system becomes hard again at RHIC.

The idea of hardening after reaching QGP is not very new. For example, a steep increase of the average transverse momentum was observed at around an energy density of 1.5 GeV/fm^3 in the high energy cosmic ray nuclear interactions on emulsion chambers by JACEE Collaboration [19]. From the theoretical side, Bass and Dumitru [20] have recently shown that a similar tendency is expected at RHIC and LHC energies by applying a hydrodynamical model with UrQMD after burner. The origin of this increase of transverse momentum is nothing but the steep increase of the pressure in QGP. However, in this model, the role of initial parton dynamics such as mini-jet production is not taken into account, and the local equilibrium is assumed *a priori* in the first stage of heavy-ion collisions.

Thus at present, it is very interesting and urgently desired to examine the behavior of radial flow by using models having both hadronic and partonic aspects.

In this report, we show the transverse mass spectra of hadrons from SIS to RHIC energies, by using JAM, a jet-implemented hadron-string cascade model [13].

2. Model

In JAM, various hadronic resonances as well as strings are explicitly propagated. At high energies ($\sqrt{s}$ >10 GeV), we also include multiple mini-jet production in which jet cross-section and the jet number are calculated using an eikonal formalism for perturbative QCD and hard parton–parton scattering with initial and final state radiation are simulated using the Lund model (PYTHIA 6.1) [21]. In this framework, we can simulate parton and gluon DOFs belonging to one parton–parton hard scattering. In addition, it has already been demonstrated that JAM explains the hadron spectra very well from p+^{9}Be to ^{197}Au+^{197}Au reactions at AGS energies [13], and those in ^{208}Pb+^{208}Pb reactions at SPS energies [22]. At collider energies, JAM can be considered as a space–time version of HIJING [23,24]. Therefore, it is an appropriate framework to systematically describe the bulk behavior of hadron spectra in a wide energy range.

3. Results

We have made simulation calculations of ^{197}Au+^{197}Au reactions at SIS (2 A GeV), AGS (10.6 A GeV), JHF (25 A GeV) and RHIC ($\sqrt{s} = 56$ and 130 A GeV) energies, and ^{208}Pb+^{208}Pb reactions at SPS (158 A GeV) energy. In these calculations, JAM has been used with default parameters [24a]. In all these reactions, the impact parameter range is limited to $0 < b < 3.3$ fm, which corresponds to central 350 mb collisions. In each incident energy, we have generated more than 1000 events.

In figure 1, we show the rapidity distributions of hadrons at AGS, SPS and RHIC energies. Although the baryon stopping power is overestimated a little at AGS and SPS energies, the overall general trend of the data is well-reproduced. At RHIC energy ($\sqrt{s} = 130$ A GeV), there are three sets of data from PHENIX Collaboration [25], BRAHMS Collaboration [26], and PHOBOS Collaboration [27], for the charged particle pseudorapidity distributions at mid-rapidity region. All of them give the value around $\mathrm{d}N/\mathrm{d}\eta|_{\eta=0} \simeq 570$ for central collisions, which is well-reproduced, as well. In addition, the calculated ratio of pseudorapidity density of $\bar{p}$ to p at $\eta = 0$ is 0.63 which agrees well with the experimental data of 0.61±0.06(stat.)±0.4(syst.) from the BRAHMS Collaboration [26]. Therefore, we can expect that the description of the bulk dynamics from AGS to RHIC energies within JAM is reliable.

Next we show the transverse mass spectra of hadrons at mid-rapidity in figure 2. At AGS and SPS energies, the pion and negative hadron spectra are reproduced very well, including the deviation from a single exponential behavior at low energies, coming from the decay of low-lying baryon resonances. For protons, the higher energy behavior is satisfactory, but the lower energy part is overestimated. Since the yield of this part is known to be very sensitive to the nuclear mean field [7], this overestimation would be a natural consequence of cascade model results without mean field.

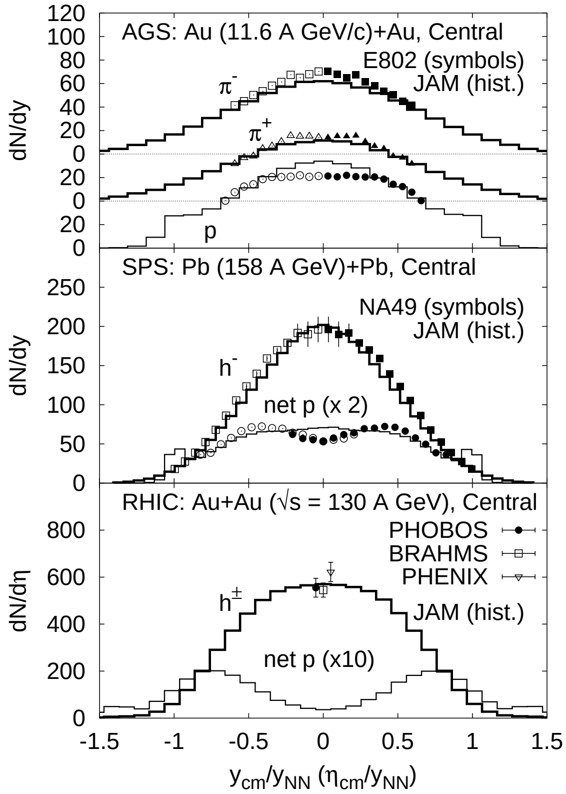

Figure 1. Rapidity distribution ($\mathrm{d}N/\mathrm{d}y$) at the AGS and SPS energies, and pseudorapidity distribution ($\mathrm{d}N/\mathrm{d}\eta$) at the RHIC energy. Calculated results are compared with the E802 [28], NA49 [29], PHENIX [25], BRAHMS [26], and PHOBOS [27] data. Collisions with impact parameter $b < 3.3$ fm has been taken in the calculations. For experiments, $\sigma_{\mathrm{trig}} = 350$mb for the E802 experiment, 5% for NA49 and PHENIX, and 6% for BRAHMS and PHOBOS.

In this figure, we find an interesting behavior of proton spectra. The inverse slope parameters of protons at AGS and SPS energies are almost the same, but grows rapidly at RHIC energy. On the other hand, pion spectra become stiffer gradually as the incident energy increases.

In order to realize this point more quantitatively, we fit the transverse mass spectra of pions and protons with a single exponential. As described above, the low energy part of the spectra is affected by a mechanism other than the emission from an expanding fire ball, and therefore we chose the energy region, $\Delta_{\mathrm{min}} < m_{\mathrm{T}} - m_0 < \Delta_{\mathrm{max}}$. For the choice of Δ, we have tried several cases, as shown in table 1. The results of fitting are shown in the upper panel of figure 3. In all the cases, the inverse slope parameter of proton stays almost constant between AGS and RHIC energies at $\sqrt{s} = 56$ A GeV, and rapidly grows at RHIC energy of $\sqrt{s} = 130$ A GeV. When we separate the inverse slope parameter (T') into the temperature (T) and radial flow (β_t) by using the non-relativistic relation, $T' = T + m\beta_t^2/2$, the meaning of

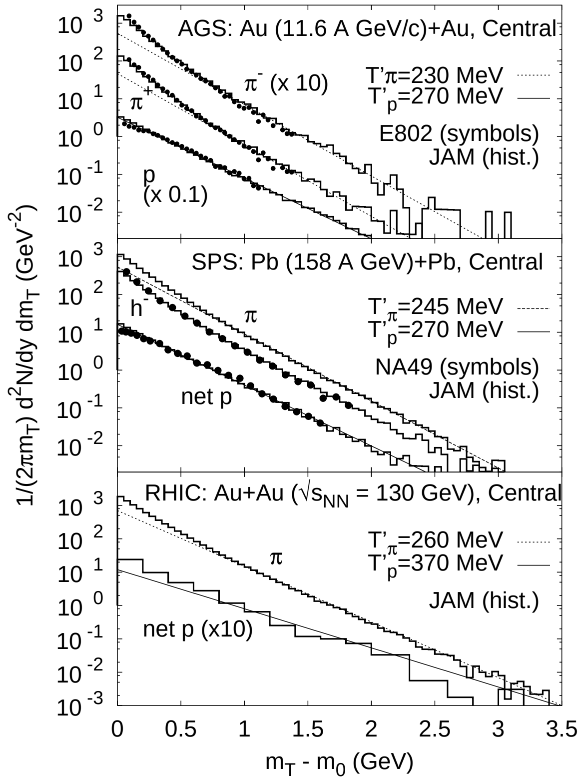

Figure 2. Transverse mass spectra of hadrons at the AGS, SPS and RHIC energies. Calculated results are compared with the E802 [28] and NA49 [29] data. Collisions with impact parameter $b < 3.3$ fm has been taken in the calculations. For experiments, σ_{trig}=350 mb for the E802 experiment, and 5% for NA49. The exponential lines with the slope parameters T' are shown to guide eyes.

the above behavior becomes clearer. As shown in the middle and the lower panels of figure 3, while the hadronic temperature slowly grows as a function of incident energy, the flow velocity first grows at low energies, subsequently saturates, then decreases between AGS and SPS energies, and increases *again* at RHIC energies.

This behavior – re-hardening after softening – can be most naturally interpreted with a phase transition scenario from hadronic matter at the Hagedorn regime to QGP. Hadronic matter becomes softer according to the large level density of hadronic objects, but at some energy density, hadrons cannot exist as they are in vacuum to dissolve into quarks and gluons. Then the pressure grows linearly again as a function of the energy density, $\mathrm{d}P/\mathrm{d}\epsilon \simeq 1/3$. On the other hand, it would be very difficult to interpret the above behavior in purely hadronic scenarios. We have to assume a very strong repulsive interaction at very high energy density, or we have to assume a rapid decrease of hadronic level density at some mass. As for the former, it is already shown that the reduction of repulsive interaction at high

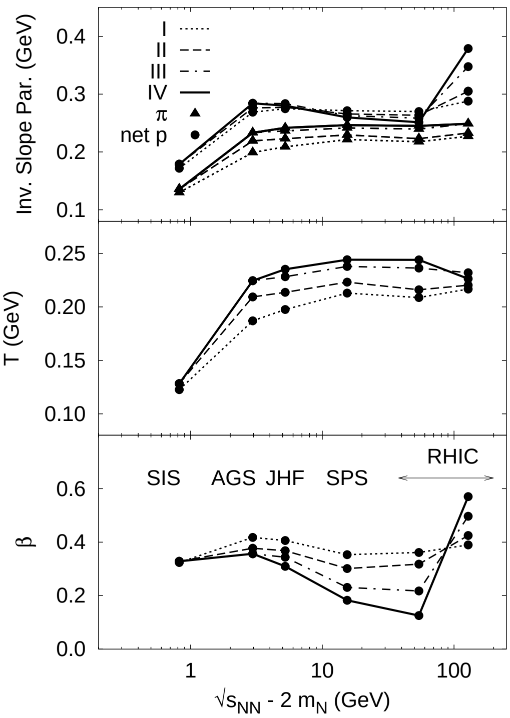

Figure 3. Calculated inverse slope parameters (top), the extracted temperature (middle) and radial flow parameters (bottom) from SIS to RHIC energies with four fit range sets of I (dotted), II (dashed), III (dot–dashed) and IV (solid). See table 1 for fit ranges I, II, III and IV.

momenta or density is necessary in the analysis of directed and elliptic flows at SIS to AGS energies [7], then it is unnatural to incorporate very strong repulsive interaction again at RHIC energies. The latter is also an unnatural assumption, because of the complex particle nature of hadrons.

As shown, the behavior of temperature and radial flow depends on the selection of the fitting range. The lower part of the transverse spectra is dominated by resonance decay at later stage of collisions, while mini-jet production affects the higher part. It means that transverse mass spectra are involved in various stages of collisions. So a more detailed study on the relation between the fitting range and collision history is needed.

4. Discussions and conclusion

In this paper, we have demonstrated that the re-hardening of hadron spectra would emerge at RHIC energies. The most natural interpretation for this re-hardening is achieved by assuming the QGP formation, and this behavior is already seen in the preliminary data at RHIC [18]. Further studies are necessary to conclude it convincingly.

Table 1. Minimum and maximum kinetic energies in fitting the transverse mass spectra with a single exponential. We have tried four sets of parameters, I, II, III and IV. Each value is in GeV.

	I		II		III		IV	
	$\Delta_{\min}$	$\Delta_{\max}$	$\Delta_{\min}$	$\Delta_{\max}$	$\Delta_{\min}$	$\Delta_{\max}$	$\Delta_{\min}$	$\Delta_{\max}$
SIS	0.0	3.0	0.5	2.0	0.5	2.0	0.5	2.0
AGS-RHIC	0.0	3.0	0.5	2.0	0.8	2.0	1.0	2.0

The above interpretation is based on a hydrodynamical picture of heavy-ion collisions, and this is supported by the recent RHIC data, which suggest that equilibrium is reached to a certain rate. The hadronic transverse mass spectra shows exponential behavior rather than a power-law behavior, and the inverse slope parameter behaves approximately linearly as a function of mass [30]. These facts are consistent with a hydrodynamical picture of the expanding fireball. Equilibration processes largely affect the hadron spectra in the present calculation, too. For example, if we ignore meson–baryon and meson–meson collisions in JAM, hadron spectra at RHIC become much softer at low momenta and strongly deviate from the exponential behavior at large momenta. Therefore, the hadron interactions in the later stage are very important, and the hadron gas is well-equilibrated. On the other hand, the partonic equilibration among different mini-jets (parton cascade) is not included in the present model treatment. However, since the bulk part of hadrons is strongly kicked by initial mini-jets, the space–time volume where partons are propagating is considered to be large. Then it is natural to expect that equilibration among mini-jets to QGP proceeds easily, once the parton cascade processes are incorporated. These parton cascade processes would modify the present results in a better constructive direction. For example, the preliminary RHIC data show stiffer hadron transverse mass spectra and a larger baryon stopping power $(\mathrm{d}N(\mathrm{net}\,p)/\mathrm{d}y \geq 10)$ than the calculated results shown here.

We have also demonstrated that the recently developed jet-implemented hadron-string cascade model, JAM, is capable of describing the bulk dynamics of high-energy heavy-ion collisions from AGS to RHIC energies. Within this model with default parameters, the local minimum of the radial flow is calculated to appear between SPS and lower RHIC energies, and the local maximum of radial flow in the hadronic regime between AGS and JHF energies. Therefore, the excitation function between SPS and RHIC energies should be useful to get the signature of the quark-gluon plasma formation.

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