Acta Phys. Hung. A 24/1–4 (2005) 181–188

HEAVY ION PHYSICS

Transverse Pressure in Relativistic Nuclear Collisions: Evidence for Partonic Interactions?

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Received 8 July 2004

Abstract. Transverse hadron spectra from proton–proton, proton–nucleus and nucleus–nucleus collisions from 2 A·GeV to 21.3 A·TeV are investigated within two independent transport approaches (HSD and UrQMD). For central Au+Au (Pb+Pb) collisions at energies above $E_{\rm lab} \sim 5$ A·GeV, the measured $K^{\pm}$ transverse mass spectra have a larger inverse slope parameter than expected from the default calculations. The additional pressure — as supported by lattice QCD calculations at finite quark chemical potential μ_q and temperature T — might be generated by strong interactions in the early pre-hadronic/partonic phase of central Au+Au (Pb+Pb) collisions [1].

Keywords: heavy ion collision, flow, excitation function
PACS: 25.75.-q, 25.75.Dw, 25.75.Ld, 13.60.Le

Recent lattice QCD (lQCD) calculations at vanishing quark chemical potential and finite temperature indicate critical energy densities for the formation of a quark–gluon plasma (QGP) of ∼0.6–1 GeV/fm^3 [2]. Such energy densities might already be achieved at Alternating Gradient Synchrotron (AGS) energies of ∼10 A·GeV for central Au+Au collisions [3–5]. According to lQCD calculations at finite quark chemical potential μ_q [6] a rapid increase of the thermodynamic pressure P with temperature above the critical temperature T_c for a cross over (or phase transition) to the QGP is expected.

1219-7580/ $ 20.00

Indeed, a *hardening* of the measured transverse mass (m_t) spectra in central Au+Au collisions relative to pp interactions [7,8] from AGS energies on is observed. This increase of the inverse slope parameter T is commonly attributed to strong collective flow, which is absent in the respective pp or pA collisions. It has been proposed [9] to interpret the high and approximately constant $K^{\pm}$ slopes above $\sim$30 A·GeV — the 'step' — as an indication of the phase transition.

In this contribution we explore whether the pressure needed to generate a large collective flow to explain the hard slopes of the $K^{\pm}$ spectra with a 'plateau' at SPS energies is produced in the present transport models by interactions of hadrons or whether additional partonic contributions in the equation of state are needed to explain these effects. To understand whether a failure of the present models indeed hints a QGP onset, we explore two distinct effects that might result in a substantial increase of the transverse pressure: I) initial state Cronin enhancement and II) heavy resonance formation.

In our studies we use two independent relativistic transport models that employ hadronic and string degrees of freedom: UrQMD [10, 11] and HSD [12, 13]. They take into account the formation and multiple rescattering of hadrons and thus dynamically describe the generation of pressure in the hadronic expansion phase. This involves also interactions of leading pre-hadrons that contain a valence quark (antiquark) from a primary 'hard' collision (cf. Refs. [14, 15]). Note that, in these models, only hadrons, valence quarks and valence diquarks and their interactions are treated explicitly. Gluonic degrees of freedom are not treated explicitly, but are present implicitly in strings. This simplified treatment is generally accepted to describe proton–proton and proton–nucleus interactions. Here we test whether this description is still valid for the more complicated nucleus–nucleus collisions, where large energy densities can be reached over extended volumes.

Let us start by "benchmarking" the model calculations with pA data. Figure 1 shows the results for the inverse slope parameters T for various reactions — see figure caption for details. It can be seen that the models reproduce the transverse slope parameters of different particles produced in pA interactions with targets from Be to Pb reasonably well.

We continue with nucleus–nucleus collisions, where Fig. 2 summarises our results: the dependence of the inverse slope parameter T on $\sqrt{s}$ is shown and compared to experimental data (partly preliminary) from [7, 16–20] for central Au+Au (Pb+Pb) collisions (l.h.s.) and [18, 21, 22] for pp collisions (r.h.s.). The upper and lower solid lines (with open circles) on the l.h.s. in Fig. 2 correspond to results from HSD calculations, where the upper and lower limits are due to fitting the slope T, an uncertainty in the repulsive $K^{\pm}$–pion potential or the possible effect of string overlaps. The solid lines with stars correspond to HSD calculations with the Cronin effect. The dashed lines with open triangles represent slope parameters from UrQMD 1.3, the dot-dashed lines with open inverted triangles correspond to UrQMD 2.0 results, which are well within the limits obtained from the different HSD calculations without the Cronin enhancement. The dotted lines with crosses show the UrQMD 2.1 results that incorporate the high mass resonance states.

The slope parameters from pp collisions (r.h.s. in Fig. 2) are seen to increase smoothly with energy both in the experiment (full symbols) and in the HSD calculations (full lines with open circles). The UrQMD 1.3 results are shown as open triangles connected by a solid line and systematically lower than the slopes from HSD at all energies. When including jet production and fragmentation via PYTHIA in UrQMD 2.0 (dot-dashed lines with open inverted triangles) the results become similar to HSD above $\sqrt{s}$ = 10 GeV demonstrating the importance of jets in pp reactions at high energy.

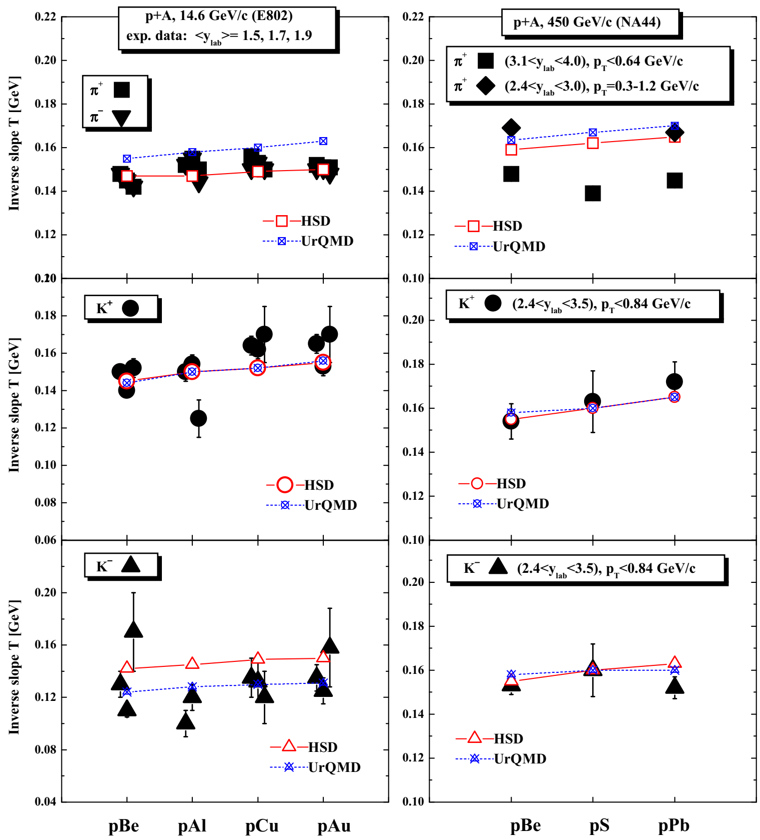

Fig. 1. Inverse slope parameters T for $\pi^{\pm}$, K^+ and K^- at midrapidity from pA reactions at 14.6 GeV/c (A = Be, Al, Cu, Au) — left part and at 450 GeV/c (A = Be, S, Pb) — right part, from HSD (open symbols) and UrQMD 2.0 (closed symbols). The full symbols in the left part correspond to the midrapidity data ($\langle y_{\rm lab}\rangle$ = 1.5, 1.7, 1.9) from the E802 Collaboration [23], in the right part to the NA44 data [24] at $2.4 \leq y_{\rm lab} \leq 3.5$, $p_T \leq 0.84$ GeV/c for K^+, K^- and at $2.4 \leq y_{\rm lab} \leq 3.0$, $p_T = 0.3 \div 1.2$ GeV/c (full diamonds) and $3.1 \leq y_{\rm lab} \leq 4.0$, $p_T \leq 0.64$ GeV/c (full squares) for π^+

Coming back to the slope parameters of K$^{\pm}$ mesons for central Au+Au/Pb+Pb collisions (l.h.s. of Fig. 2) we find that the Cronin initial state enhancement indeed improves the description of the data at RHIC energies, however, does not give any sizeable enhancement at AGS energies. Here UrQMD 2.1 (dashed lines with crosses) with the high mass resonance states performs better: including high mass resonances we end up with reasonable results for K^{+} mesons, however, fail by 10 to 15% for pions as well as anti-Kaons. In this context it is interesting to note that the experimental results on C+C and Si+Si at 158 A·GeV show small slopes [21] and are therefore in agreement with the models [25].

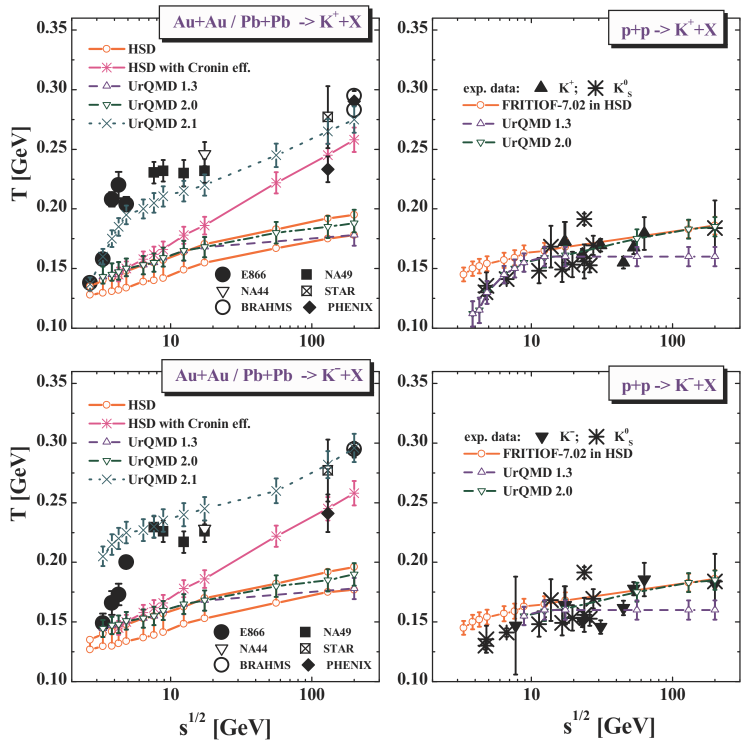

Fig. 2. Comparison of the inverse slope parameters T for K^{+} and K^{-} mesons from central Au+Au (Pb+Pb) collisions (l.h.s.) and pp reactions (r.h.s.) at midrapidity as a function of the invariant energy $\sqrt{s}$ from HSD (upper and lower solid lines with open circles), UrQMD 1.3 (dashed lines with open triangles), UrQMD 2.0 (dot-dashed lines with open inverted triangles), UrQMD 2.1 (dotted lines with crosses) with the data from Refs. [7, 16–20] for AA and [18, 21, 22] for pp collisions. The upper and lower solid lines in the left diagrams result from different limits of the HSD calculations as discussed in the text while the solid lines with stars correspond to HSD calculations with the Cronin initial state enhancement

What is the origin of the rapid increase of the $K^{\pm}$ slopes with invariant energy for central Au+Au collisions at AGS energies and the constant slope at SPS energies (the 'step'), which is missed in all transport approaches presently employed?

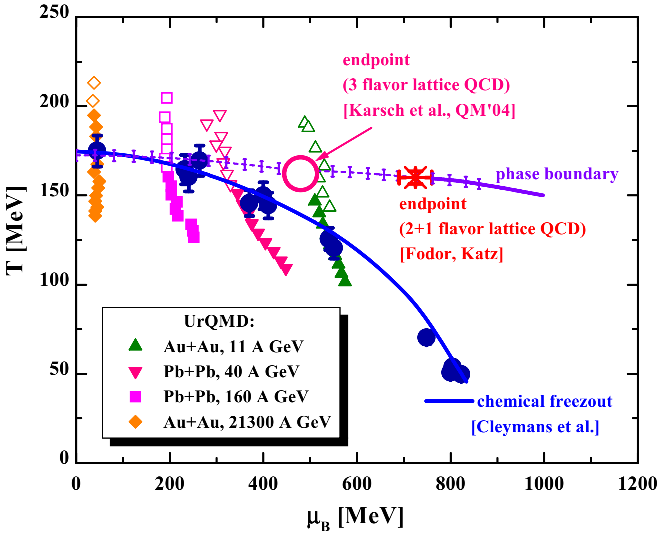

Fig. 3. Schematic phase diagram in the T–μ_B plane. The solid line characterises the universal chemical freeze-out line from Cleymans et al. [27] and the full dots (with error bars) denote the 'experimental' chemical freeze-out parameters from Ref. [27]. The various symbols represent temperatures T and chemical potentials μ_B extracted from UrQMD 1.3 transport calculations in central Au+Au (Pb+Pb) collisions at 21.3 A·TeV, 160, 40 and 11 A·GeV [26] (see text). The large open circle and the star indicate the tri-critical endpoints and phase boundary from lattice QCD calculations by Karsch et al. [28] and Fodor and Katz [6], respectively. The horizontal line with error bars is the phase boundary from [6]

Following the previous study [25] we speculate that partonic degrees of freedom might be responsible for this effect already at $\sim$5 A·GeV. Our arguments here are based on a comparison of the thermodynamic parameters T and μ_B extracted from the transport models in the central overlap regime of Au+Au collisions [26] with the experimental systematics on chemical freeze-out configurations [27] in the T, μ_B plane. The solid line in Fig. 3 characterises the universal chemical freeze-out line from Cleymans et al. [27] and the full dots with error bars denote the 'experimental' chemical freeze-out parameters — determined from the thermal model fits to the experimental particle ratios [27]. The various smaller symbols (in vertical sequence) represent temperatures T and chemical potentials μ_B extracted from UrQMD 1.3 transport calculations in central Au+Au (Pb+Pb) collisions at $\sqrt{s} = 200$ A·GeV, 160, 40 and 11 A·GeV [26] as a function of the reaction time in the center-of-mass (from top to bottom).

During the non-equilibrium phase (open symbols) the transport calculations show much higher temperatures (or energy densities) than the 'experimental' chemical freeze-out configurations at all bombarding energies (≥11 A·GeV). These numbers are also higher than the tri-critical endpoints and phase boundary extracted from lattice QCD calculations by Karsch et al. [28] (large open circle) and Fodor and Katz [6] (star with horizontal error bar). Though the QCD lattice calculations differ substantially in the value of μ_B for the critical endpoint, the critical temperature T_c is closer to 160 MeV in both calculations, while the energy density is of the order of 1 GeV/fm^3 or even below. This diagram shows that at RHIC energies one encounters more likely a cross-over between the different phases when stepping down in temperature during the expansion phase of the hot fireball.

Thus, the system spends a considerable amount of time in the QGP phase with an equation of state (EoS) of $p_{\mathrm{QGP}} \sim 1/3\varepsilon$, much harder than the employed hadron gas EoS of $p_{\mathrm{HG}} \sim 1/8\varepsilon$. This argument is well in line with the studies on elliptic flow at RHIC energies, which is underestimated by ∼30% at midrapidity in HSD [29] and by a factor of ∼2 in UrQMD 1.3 [30]. It is our opinion that strong pre-hadronic/partonic interactions might cure this problem.

As shown in Ref. [31], in order to describe the elliptic flow seen experimentally at RHIC in a parton cascade model, one has to employ parton cross sections up to 45 mb. However, strong interactions are incompatible with perturbative QCD, which gives cross sections that are lower by more than an order of magnitude [31]. We speculate that such strong non-perturbative interactions on the partonic level are responsible for the large pressure generation in the very early phase of intermediate energy nucleus–nucleus collisions.

In conclusion, we have found that the inverse slope parameters T for K$^\pm$ mesons from the HSD and UrQMD 2.0 transport models are practically independent of system size from pp up to central Pb+Pb collisions and show only a slight increase with collision energy. The calculated transverse mass spectra are in reasonable agreement with the experimental results for pp reactions at all bombarding energies investigated as well as central collisions of light nuclei (C+C and Si+Si) (cf. Ref. [25]). The rapid increase of the inverse slope parameters of Kaons for central collisions of heavy nuclei (Au+Au or Pb+Pb) found experimentally in the AGS energy range, however, is not reproduced by both models in their default version (see Fig. 2).

We have furthermore discussed scenarios to improve the description of the experimental data. However, no fully convincing results could be obtained for all observables and bombarding energies simultaneously.

From comparison to lattice QCD calculations at finite temperature and baryon chemical potential μ_B from Refs. [6] and [28] as well as the experimental systematics in the chemical freeze-out parameters (cf. Fig. 3), we infer that the missing pressure might be generated in the early phase of the collision by non-perturbative partonic interactions.

Acknowledgements

E.L.B. is supported by Deutsche Forschungsgemeinschaft (DFG) and GSI. S.A.B. acknowledges support by RIKEN, Brookhaven National Laboratory and DOE grants DE-FG02-96ER40945 and DE-AC02-98CH10886 as well as an Outstanding Junior Investigator Award (DOE grant DE-FG02-03ER41239). M.B. and M.R. are supported by GSI. M.B. and D.B. are supported by DAAD (Germany) and DST (India). M.B. thanks the Saha Institute of Nuclear Physics for kind hospitality while working on this article.

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