

Evidence for Nonhadronic Degrees of Freedom in the Transverse Mass Spectra of Kaons from Relativistic Nucleus-Nucleus Collisions?

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We investigate transverse hadron spectra from relativistic nucleus-nucleus collisions within two independent transport approaches that are based on quark, diquark, string, and hadronic degrees of freedom. Both transport models show their reliability for elementary pp as well as light-ion (C + C, Si + Si) reactions. However, for central Au + Au (Pb + Pb) collisions above $\sim 5A$ GeV the measured K^\pm transverse mass spectra have a larger inverse slope parameter than expected from the calculation. Thus, the pressure generated by hadronic interactions in the transport models above $\sim 5A$ GeV is lower than observed in the experimental data. This finding shows that the additional pressure—as expected from lattice QCD calculations at finite quark chemical potential and temperature—is generated by strong partonic interactions in the early phase of central Au + Au (Pb + Pb) collisions.

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The phase transition from partonic degrees of freedom (quarks and gluons) to interacting hadrons is a central topic of modern high-energy physics. In order to understand the dynamics and relevant scales of this transition, laboratory experiments under controlled conditions are presently performed with ultrarelativistic nucleus-nucleus collisions. Hadronic spectra and relative hadron abundances from these experiments reflect important aspects of the dynamics in the hot and dense zone formed in the early phase of the reaction. Furthermore, as has been proposed early by Rafelski and Müller [1] the strangeness degree of freedom might play an important role in distinguishing hadronic and partonic dynamics.

Estimates based on the Bjorken formula [2] for the energy density achieved in central Au + Au collisions suggest that the critical energy density for the formation of a quark-gluon plasma (QGP) is by far exceeded during a few fm/c in the initial phase of the collision at the BNL Relativistic Heavy-Ion Collider (RHIC) energies [3], but sufficient energy densities ($\sim 0.7\text{--}1$ GeV/fm³ [4]) might already be achieved at the BNL Alternating Gradient Synchrotron (AGS) energies of $\sim 10A$ GeV [5,6]. More recently, lattice QCD calculations at finite temperature and quark chemical potential μ_q [7] show a rapid increase of the thermodynamic pressure P with temperature above the critical temperature T_c for a phase transition to the QGP. The crucial question is, however, at what bombarding energies the conditions for the phase transition are fulfilled.

Presently, transverse mass (or momentum) spectra of hadrons are in the center of interest: the measured transverse mass m_T spectra of kaons

$$\frac{1}{m_T} \frac{dN}{dm_T} \sim \exp\left(-\frac{m_T}{T}\right) \quad (1)$$

at AGS and SPS (from 30A GeV to 160A GeV at the CERN Super Proton Synchrotron) energies show a substantial *flattening* or *hardening* of the spectra in central Au + Au collisions relative to pp interactions (cf. [8,9]). This hardening of the spectra [or increase of the inverse slope parameter T in (1)] is commonly attributed to strong collective flow which is absent in the respective pp data. We demonstrate in this Letter that the pressure needed to generate such a large collective flow cannot be produced by the interactions of hadrons in the expansion phase of the hadronic fireball.

Two independent transport models that employ hadronic and string degrees of freedom, i.e., UrQMD [10,11] and HSD [12,13], are used for our study. They take into account the formation and multiple rescattering of hadrons and thus dynamically describe the generation of pressure in the hadronic expansion phase. The UrQMD transport approach [10,11] includes all baryonic resonances up to masses of 2 GeV as well as mesonic resonances up to 1.9 GeV as tabulated by the Particle Data Group [14]. For hadronic continuum excitations a string model is used with hadron formation times in the order of 1–2 fm/c depending on the momentum and energy of the created hadron. The transport approach is matched to reproduce the nucleon-nucleon, meson-nucleon and meson-meson cross section data in a wide kinematic range [10,11]. In the HSD approach nucleons, Δ 's, $N^*(1440)$, $N^*(1535)$, Λ , Σ , and Σ^* hyperons, Ξ 's, Ξ^* 's,

and Ω 's as well as their antiparticles are included on the baryonic side, whereas the 0^- and 1^- octet states are included in the mesonic sector. High-energy inelastic hadron-hadron collisions in HSD are described by the FRITIOF string model [15], whereas low energy hadron-hadron collisions are modeled based on experimental cross sections. We point out the important fact that no parton-parton scattering processes are included in the studies below contrary to the multiphase transport model [16], which is currently employed from upper SPS to RHIC energies.

Whereas the underlying concepts of the two transport theoretical models are very similar, the actual realizations differ considerably. Indeed, a systematic analysis of results from both models and experimental data for central nucleus-nucleus collisions from 2A GeV to 160A GeV has shown that the ‘‘longitudinal’’ rapidity distributions of protons, pions, kaons, antikaons, and hyperons are quite similar in both models and in reasonable agreement with available data. The exceptions are the pion rapidity spectra at the highest AGS energy and lower SPS energies, which are overestimated by both models [17]. For a comparison of HSD calculations with experimental data at RHIC energies, we refer the reader to Ref. [18].

We focus on transverse mass spectra of pions and kaons or antikaons from central Au + Au (Pb + Pb) collisions from 2A GeV to 21.3A TeV and compare them to recent data. We start with results on m_T spectra for central C + C and Si + Si collisions at 160A GeV. In Fig. 1 the experimental m_T spectra for π^- , K^+ , and K^- for C + C reactions (17.5% centrality, upper part) and Si + Si (12.5% centrality, lower part) [19] are compared to HSD (solid lines) and UrQMD (dashed lines) calculations. The m_T spectra are calculated in a rapidity interval ($3.0 \leq y_{\text{lab}} \leq 3.23$) close to midrapidity. The agreement between the transport calculations and the data is quite satisfactory; no obvious traces of ‘‘new’’ physics are visible. The situation, however, changes for central Au + Au (or Pb + Pb) collisions as demonstrated in Fig. 2, where we display the calculated spectra from UrQMD (dashed lines) and HSD (solid lines) for 5% (or 7%) central Au + Au (or Pb + Pb) collisions at 4A GeV, 30A GeV, and 160A GeV in comparison to midrapidity data from Refs. [8,20] (note Ref. [21]). Whereas at the lowest energy of 4A GeV the agreement between the transport approaches and the data is still acceptable, severe deviations are visible in the K^\pm spectra at SPS energies of 30A GeV and 160A GeV. Note that the π^\pm spectra are reasonably described at all energies while the inverse slope T of the K^\pm transverse mass spectra is underestimated severely by about the same amount in both transport approaches (within statistics). The increase of the inverse K^\pm slopes in heavy-ion collisions with respect to pp collisions, which is generated by rescatterings of produced hadrons in the transport models, is small only because the elastic meson-baryon scat-

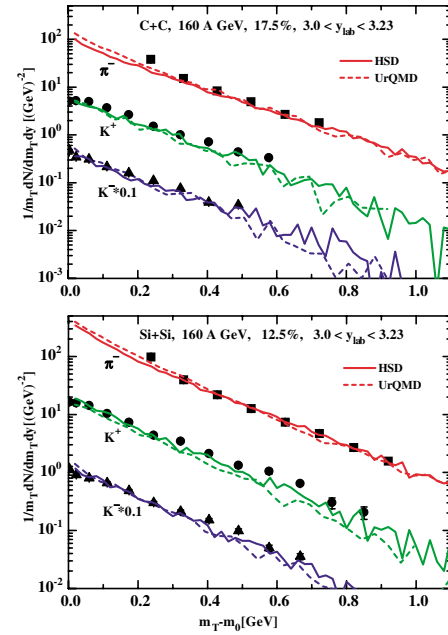


FIG. 1 (color online). Comparison of transverse mass spectra from HSD (solid lines) and UrQMD (dashed lines) for π^- , K^+ , and $K^- (\times 0.1)$ from 17.5% central C + C (upper part) and 12.5% central Si + Si (lower part) reactions at 160A GeV close to midrapidity with data from Ref. [19] (full symbols).

tering is strongly forward peaked and therefore gives little additional transverse momentum at midrapidity.

The question remains whether the discrepancies shown in Fig. 2 might be due to conventional hadronic medium effects. In fact, the m_T slopes of kaons and antikaons at SIS energies (1.5A GeV to 2A GeV) were found to differ significantly [22]. As argued in [13] the different slopes could be traced back to repulsive potentials of kaons with nucleons, which lead to a hardening of the K^+ spectra, and attractive antikaon-nucleon potentials, which lead to a softening of the K^- spectra. However, the effect of such potentials was calculated within HSD and was found to be of minor importance at AGS and SPS energies [13] since the meson densities are comparable to or even larger than the baryon densities at AGS energies and above.

Additional self-energy contributions stem from K^\pm interactions with mesons; however, s -wave kaon-pion interactions are weak due to chiral symmetry arguments, and p -wave interactions such as $\pi + K \leftrightarrow K^*$ transitions are suppressed substantially by the approximately ‘‘thermal’’ pion spectrum. A recent study on the kaon potentials in hot pion matter gives kaon mass shifts of about -52 MeV and vector potentials of $\sim +49$ MeV [23] for a pion gas at temperature $T = 170$ MeV. We have employed even slightly larger K^\pm potentials in dynamical HSD calculations and achieved a hardening of the K^\pm spectra of less than 10%.

Furthermore, we have pursued the idea of Refs. [24,25] that the K^\pm spectra could be hardened by string-string

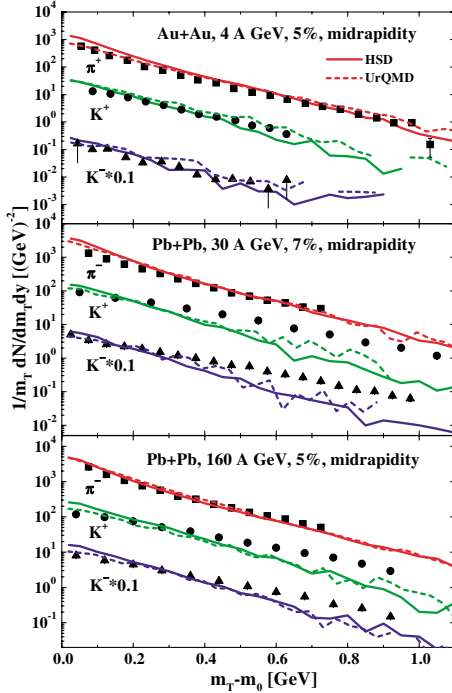


FIG. 2 (color online). Comparison of transverse mass spectra from HSD (solid lines) and UrQMD (dashed lines) for π^\pm , K^+ , and $K^-(\times 0.1)$ from central Au + Au (Pb + Pb) reactions at 4A GeV, 30A GeV, and 160A GeV at midrapidity with the data from Refs. [8,20] (full symbols).

interactions, which increase the effective string tension σ and thus the probability to produce mesons at high m_T [16,25]. In order to estimate the largest possible effect of string-string interactions, we have assumed that for two overlapping strings the string tension σ is increased by a factor of 2, for three overlapping strings by a factor of 3, etc. Here the overlap of strings is defined geometrically assuming a transverse string radius R_s , which according to the studies in Ref. [26] should be $R_s \leq 0.25$ fm. Based on these assumptions (and $R_s = 0.25$ fm), we find only a small increase of the inverse slope parameters at AGS energies, where the string densities are low. At 160A GeV, the model gives a significant hardening of the spectra by about 15%, which, however, is still much less than in the data in Fig. 2.

Our findings are summarized in Fig. 3 where the dependence of the inverse slope parameter T [see Eq. (1)] on \sqrt{s} is shown and compared to experimental data [8,19] for central Au + Au (Pb + Pb) collisions [left-hand side (lhs)] and pp reactions [right-hand side (rhs)]. The upper and lower solid lines (with open circles) on the lhs in Fig. 3 correspond to results from HSD calculations, where the upper and lower limits are due to fitting the slope T itself, an uncertainty in the repulsive K^\pm -pion potential or the possible effect of string overlaps. The open triangles represent slope parameters from default UrQMD calculations (version 1.3) which are well within the limits obtained from the different HSD calculations.

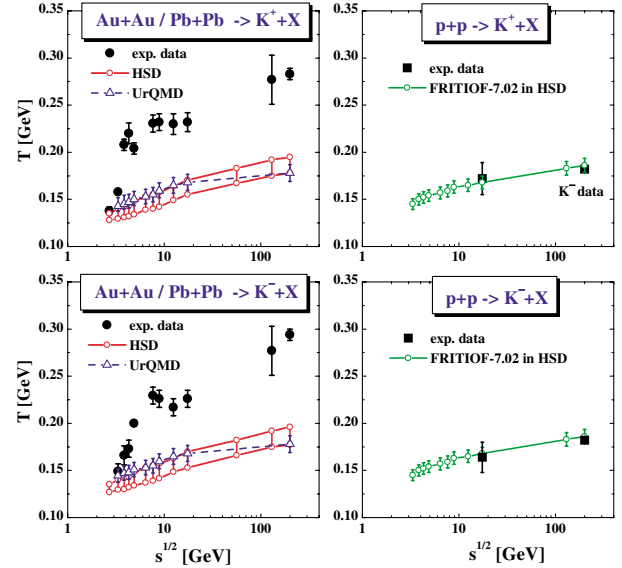


FIG. 3 (color online). Comparison of the inverse slope parameters for K^+ and K^- mesons from central Au + Au (Pb + Pb) collisions (lhs) and pp reactions (rhs) as a function of the invariant energy \sqrt{s} from HSD (upper and lower solid lines) and UrQMD (open triangles) with data from Refs. [8,19]. The upper and lower solid lines result from different limits of the HSD calculations as discussed in the text.

The slope parameters from pp collisions (rhs in Fig. 3) are seen to increase smoothly with energy both in the experiment (full squares) and in the HSD calculations (full lines with open circles). The error bars related to our calculations are due to an uncertainty in extracting the slope parameter when considering different m_T intervals.

We mention that the relativistic quantum molecular dynamics model (RQMD) [24] gives higher inverse slope parameters for kaons at AGS and SPS energies than HSD and UrQMD, which essentially can be traced back to the implementation of resonances with masses above 2 GeV as well as “color ropes” that decay isotropically in their rest frame [27]. However, we consider the implementation of such “heavy resonances” with unknown properties as a phenomenological fit to experimental data.

This still leaves us with the question of the origin of the rapid increase of the K^\pm slopes with invariant energy for central Au + Au collisions, which is missed in both transport approaches. We recall that higher transverse particle momenta arise either from repulsive self-energies—in mean-field dynamics—or from collisions, which reduce longitudinal momenta in favor of transverse momenta. As shown in Fig. 3 conventional hadron self-energy effects and hadronic binary collisions are insufficient to describe the dramatic increase of the K^\pm slopes as a function of \sqrt{s} . We conclude that this points towards a different mechanism for the generation of the pressure observed experimentally and propose that partonic degrees of freedom should be responsible for this effect already at $\sim 5A$ GeV.

Our arguments are based on a comparison of the transverse pressure from the transport models with recent lattice QCD calculations [7]: The transverse pressure ($P_{xx} \approx P_{yy}$)—in the central overlap volume of Au + Au collisions—within UrQMD is about 0.07 GeV/fm³ at 10.7A GeV, 0.1 GeV/fm³ at 40A GeV, and 0.15 GeV/fm³ at 160A GeV (cf. Ref. [28]). These numbers should be compared to lattice QCD calculations. Adopting the results from Ref. [7] and using $T_c \approx 172$ MeV (following Ref. [29]) we end up with a pressure (in thermal and chemical equilibrium) of 0.15 GeV/fm³ at vanishing baryon density ($\mu_B = 0$), 0.17 GeV/fm³ ($\mu_B = 0.21$ GeV), 0.2 GeV/fm³ ($\mu_B = 0.33$ GeV), 0.22 GeV/fm³ ($\mu_B = 0.42$ GeV), and 0.26 GeV/fm³ ($\mu_B = 0.53$ GeV) at a temperature $T = 1.1T_c$ (~ 190 MeV). These values are higher than those from the transport calculations, but correspond to a temperature significantly above T_c . The important finding from the lattice QCD calculations [7] is that the pressure drops by an order of magnitude when the temperature decreases to T_c , which leads to ~ 0.02 – 0.03 GeV/fm³ at T_c . These numbers now are lower than the transport results for bombarding energies $\geq 10.7A$ GeV. Consequently, the phase transition should be reached even at a lower bombarding energy in line with our findings in Fig. 3.

To summarize this study, we conclude that according to two independent string-hadron transport models, HSD and UrQMD, the inverse slope parameters T for K^\pm mesons are practically independent of system size from pp up to central Pb + Pb collisions and show a slight increase with collision energy. The calculated transverse mass spectra are in reasonable agreement with the experimental results for pp collisions and central collisions of light nuclei (C + C and Si + Si). The rapid increase of the inverse slope parameters of kaons for collisions of heavy nuclei (Au + Au) found experimentally in the AGS energy range, however, is not reproduced by both models (see Fig. 3). Since the pion transverse mass spectra are described sufficiently well at all bombarding energies, the failure has to be attributed to a lack of pressure especially for the strange K^\pm mesons. We have argued—based on lattice QCD calculations for the pressure at finite temperature and baryon chemical potential μ_B from Ref. [7]—that this additional pressure must be generated in the early phase of the collision because the strong hadronic interactions in the later stages do not produce it.

The interesting finding of our analysis is that nonhadronic degrees of freedom seem to play a substantial role in central Au + Au collisions already at AGS energies above $\sim 5A$ GeV. Further indications for a low energy onset of a phase transition are the missed K^+/π^+ ratios in

the AGS and lower SPS regimes [17]. Additionally, the excitation function of the elliptic flow v_2 indicates a softening of the equation of state at $\sim 5A$ GeV in Au + Au collisions [30,31], which signals a change of the pressure, too. In spite of the latter observations—all showing a significant change at $\sim 5A$ GeV Au + Au collisions—data for weakly interacting (on the hadronic level) ϕ mesons will be necessary to clarify further the question raised in the title from the experimental side.

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