

Transverse Activity of Kaons and the Deconfinement Phase Transition in Nucleus–Nucleus Collisions

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Abstract

We found that the experimental results on transverse mass spectra of kaons produced in central Pb+Pb (Au+Au) interactions show an anomalous dependence on the collision energy. The inverse slopes of the spectra increase with energy in the low (AGS) and high (RHIC) energy domains, whereas they are constant in the intermediate (SPS) energy range. We argue that this anomaly is probably caused by a modification of the equation of state in the transition region between confined and deconfined matter. This observation may be considered as a new signal, in addition to the previously reported anomalies in the pion and strangeness production, of the onset of deconfinement located in the low SPS energy domain.

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The statistical model of the early stage, SMES, of nucleus-nucleus (A+A) collisions suggests [1] that the onset of the deconfinement phase transition at the early stage of the collisions may be signaled by the anomalous energy dependence of several hadronic observables. In particular, following earlier suggestions [2], the behavior of strangeness and pion yields in the transition region was studied in detail. Recent measurements [3] of pion and kaon production in central Pb+Pb collisions at the CERN SPS indeed indicate that the transient state of deconfined matter is created in these collisions for energies larger than about 40 A·GeV. The present data show a maximum of the strangeness to pion ratio at this energy. An exact position and the detailed structure of this maximum will be clarified by the soon expected new results from the 2002 Pb run at 20 and 30 A·GeV.

In the present letter we discuss another well known observable, which may be sensitive to the onset of deconfinement, the transverse momentum, p_T , spectra of produced hadrons. It was suggested by Van Hove [4] more than 20 years ago to identify the deconfinement phase transition in high energy proton-antiproton interactions by an anomalous behavior (a plateau-like structure) of the average transverse momentum as a function of hadron multiplicity. Let us briefly recall Van Hove's arguments. According to the general concepts of the hydrodynamical approach the hadron multiplicity reflects the entropy, whereas the transverse hadron activity reflects the combined effects of temperature and collective transverse expansion. The entropy is assumed to be created at the early stage of the collision and is approximately constant during the hydrodynamic expansion. The multiplicity is proportional to the entropy, $S = s \cdot V$, where s is the entropy density and V is the effective volume occupied by particles. During the hydrodynamic expansion, s decreases and V increases with $s \cdot V$, being approximately constant. The large multiplicity at high energies means a large entropy density at the beginning of the expansion (and consequently a larger volume at the end). A large value of s at the early stage of the collisions means normally high temperature T_0 at this stage. This, in turn, leads to an increase of transverse hadron activity, a flattening of the transverse momentum spectra. Therefore, with increasing collision energy ¹ one expects to observe an increase of both the hadron multiplicity and average transverse momentum per hadron. However, the presence of the deconfinement phase transition would change this correlation. In the phase transition region the initial entropy density (and hence the final hadron multiplicity) increases with collision energy, but temperature $T_0 = T_C$ and pressure $p_0 = p_C$ remain constant. The equation of state presented in the form $p(\varepsilon)/\varepsilon$ versus energy density ε shows a minimum (the 'softest point' [5, 6]) at the boundary of the (*generalized* [6]) mixed phase and the quark gluon plasma. Consequently the shape of the p_T spectrum is approximately independent of the multiplicity or collision energy. The transverse expansion effect may even decrease when crossing the transition region [4]. Thus one expects an anomaly in the energy dependence of transverse hadron activity: the average transverse momentum increases with collision energy when the early stage matter is either in pure confined or in pure deconfined phases, and it remains approximately constant when the matter is in the mixed phase.

¹In the original Van Hove suggestion the correlation between average transverse momentum and hadron multiplicity was discussed for proton-antiproton collisions at fixed energy. Today we have the possibility to study A+A collisions at different energies.

A simplified picture with $T = T_C = \text{const}$ inside the mixed phase is changed if the created early stage matter has a non-zero baryonic density. It was however demonstrated [7] that the main qualitative features ($T \cong \text{const}$, $p \cong \text{const}$, and a minimum of the function $p(\varepsilon)/\varepsilon$ vs ε) are present also in this case. In the SMES model [1], which correctly predicted the energy dependence of pion and strangeness yields, the modification of the equation of state due to the deconfinement phase transition is located between 30 and about 200 A·GeV. Thus the anomaly in energy dependence of transverse hadron activity may be expected in this energy range. Do we see this anomaly in the experimental data?

The experimental data on transverse mass ($m_T = \sqrt{m^2 + p_T^2}$, where m is a particle mass) spectra are usually parameterized by a simple exponential dependence:

$$\frac{dN}{m_T dm_T} = C \exp\left(-\frac{m_T}{T^*}\right), \quad (1)$$

where the inverse slope parameter T^* is sensitive to both the thermal and collective motion in the transverse direction. In the parameterization (1) the shape of the m_T spectrum is fully determined by a single parameter, the inverse slope T^* . In particular, the average transverse mass, $\langle m_T \rangle$, can be expressed as:

$$\langle m_T \rangle = T^* + m + \frac{(T^*)^2}{m + T^*}. \quad (2)$$

The energy dependence of the inverse slope parameter fitted to the K^+ and K^- spectra for central Pb+Pb (Au+Au) collisions is shown in Figs. 1 and 2. The results obtained at AGS [8], SPS [3] and RHIC [9] energies are compiled. The striking features of the data can be summarized and interpreted as follows.

- The T^* parameter increases strongly with collision energy up to the lowest (40 A·GeV) SPS energy point. This is an energy region where the creation of confined matter at the early stage of the collisions is expected. Increasing collision energy leads to an increase of the early stage temperature and pressure. Consequently the transverse activity of produced hadrons, measured by the inverse slope parameter, increases with increasing energy.
- The T^* parameter is approximately independent of the collision energy in the SPS energy range. In this energy region the transition between confined and deconfined matter is expected to be located. The resulting modification of the equation of state “suppresses” the hydrodynamical transverse expansion and leads to the observed plateau structure in the energy dependence of the T^* parameter.
- At higher energies (RHIC data) the T^* again increases with collision energy. The equation of state at the early stage becomes again stiff, the early stage temperature and pressure increase with collision energy. This results in increase of T^* with energy.

The anomalous energy dependence of the m_T spectra is a characteristic feature of the kaon data. Why is this the case? How do the m_T spectra of other hadrons look like? The

answer is rather surprising: among the measured hadron species the kaons are the best and unique particles for observing the effect of the modification of the equation of state due to the onset of deconfinement. The arguments are as follows.

- The kaon m_T -spectra are only weakly affected by the hadron re-scattering and resonance decays during the post-hydrodynamic hadron cascade [10, 11].
- A simple one parameter exponential fit (1) is quite accurate up to $m_T - m \cong 1$ GeV for K^+ and K^- mesons in A+A collisions at all energies. This means that the energy dependence of the average transverse mass $\langle m_T \rangle$ and average transverse momentum $\langle p_T \rangle$ for kaons is qualitatively the same as that for the parameter T^* . This simplifies the analysis of the experimental data.
- The high quality data on m_T spectra of K^+ and K^- mesons in central Pb+Pb (Au+Au) collisions are available in the full range of relevant energies.

The “hydro QGP + hadron cascade” approach [10, 11] predicts a strong modification of the m_T -spectra of protons and lambdas during the hadron cascade stage in A+A collisions at both the SPS and RHIC. As the hadron gas expands, the pions excite Δ and Σ^* resonances and transform some part of their transverse energy in the nucleon and hyperon sectors. Therefore, the hadron re-scattering and resonance decays lead to significant increase (about 40% [11]) of the inverse slope parameters T^* for (anti)nucleons and (anti)lambdas at the expense of the pion transverse energy (also see discussion in Ref. [12]). These changes of the slopes T^* are not directly related to the equation of state of the matter at the early stage. It is rather difficult to separate these hadron-cascade effects and in any case, this separation will be strongly model dependent. Note also that a simple exponential fit (1) neither works for π -mesons ($T_{low-p_T}^* > T_{high-p_T}^*$) [13] nor for protons and lambdas ($T_{low-p_T}^* < T_{high-p_T}^*$). This means that the average transverse masses, $\langle m_T \rangle$, and their energy dependence are not connected to the behaviour of the slope parameters in the simple way described by Eq. (2): one should separately consider both $T_{low-p_T}^*$ and $T_{high-p_T}^*$ slopes for these hadrons (see Ref. [11] for details).

The transverse activity of Ω hyperons and ϕ mesons should, as in the case of kaons, be sensitive to the matter equation of state at the early stage of the collisions. These particles seem to decouple just after the hydrodynamic expansion stops, they do not participate in the hadron cascade stage [10, 11, 12, 14]. Unfortunately the spectra of Ω hyperons are measured only at top SPS and RHIC energies [15]. More data exist for ϕ meson production [16]. However, the large uncertainties in the experimental results do not allow to draw a definite conclusion on the possible anomaly in the energy dependence of m_T spectra.

In conclusion, we observe an anomalous energy dependence of transverse mass spectra of K^+ and K^- mesons produced in central Pb+Pb (Au+Au) collisions. The inverse slopes of the m_T -spectra increase with energy in the AGS and RHIC energy domains, whereas they remain constant in the intermediate SPS energy range. We argue that this anomaly is caused by a modification of the equation of state in the transition region between confined and deconfined matter. This observation may be considered as a new signal, in addition

to the previously reported anomalies in energy dependence of the pion and strangeness production, of the onset of deconfinement located at the low SPS energies.

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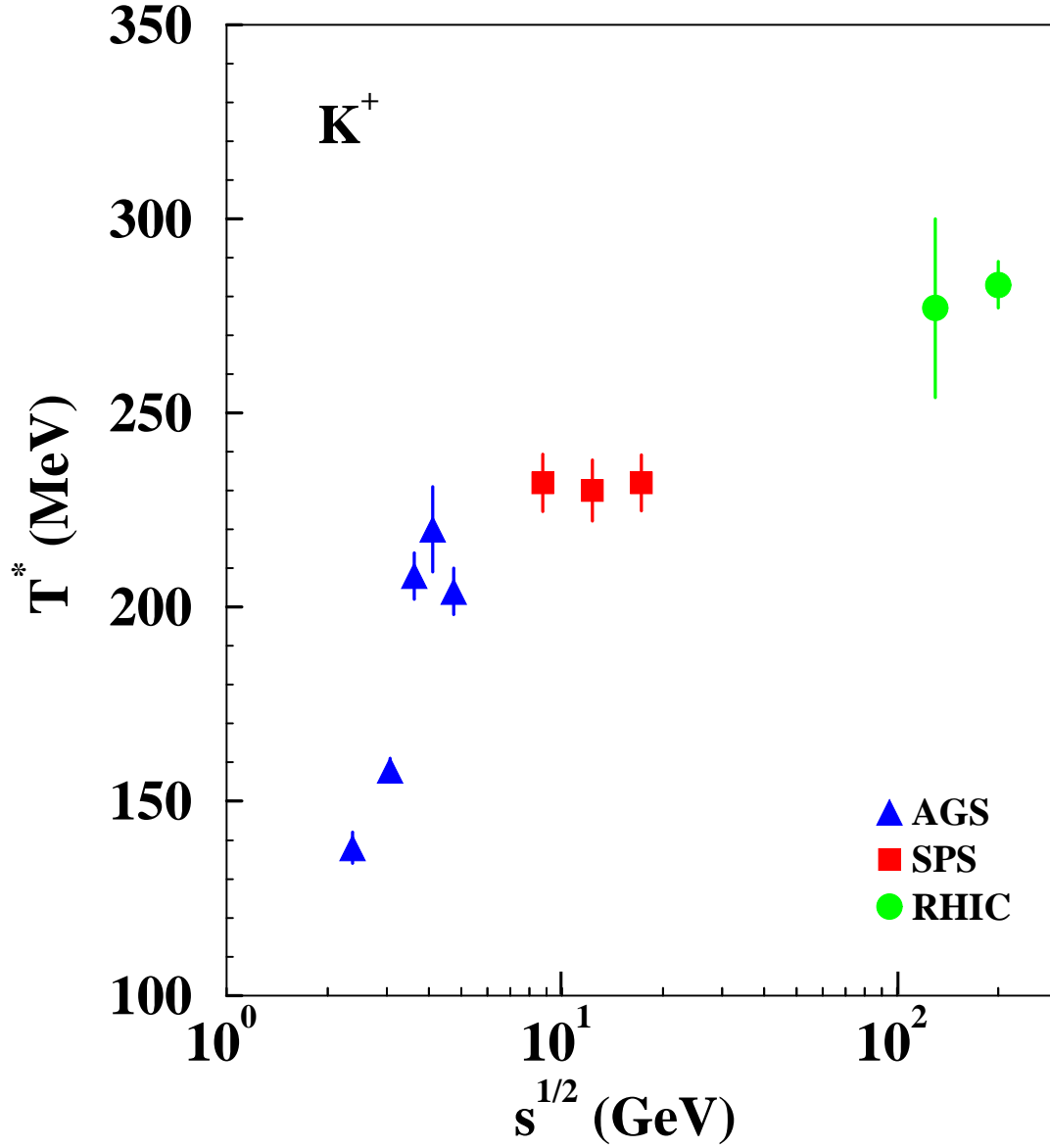


Figure 1: The energy dependence of the inverse slope parameter T^* for K^+ mesons produced at mid-rapidity in central Pb+Pb (Au+Au) collisions at AGS [8] (triangles), SPS [3] (squares) and RHIC [9] (circles) energies.

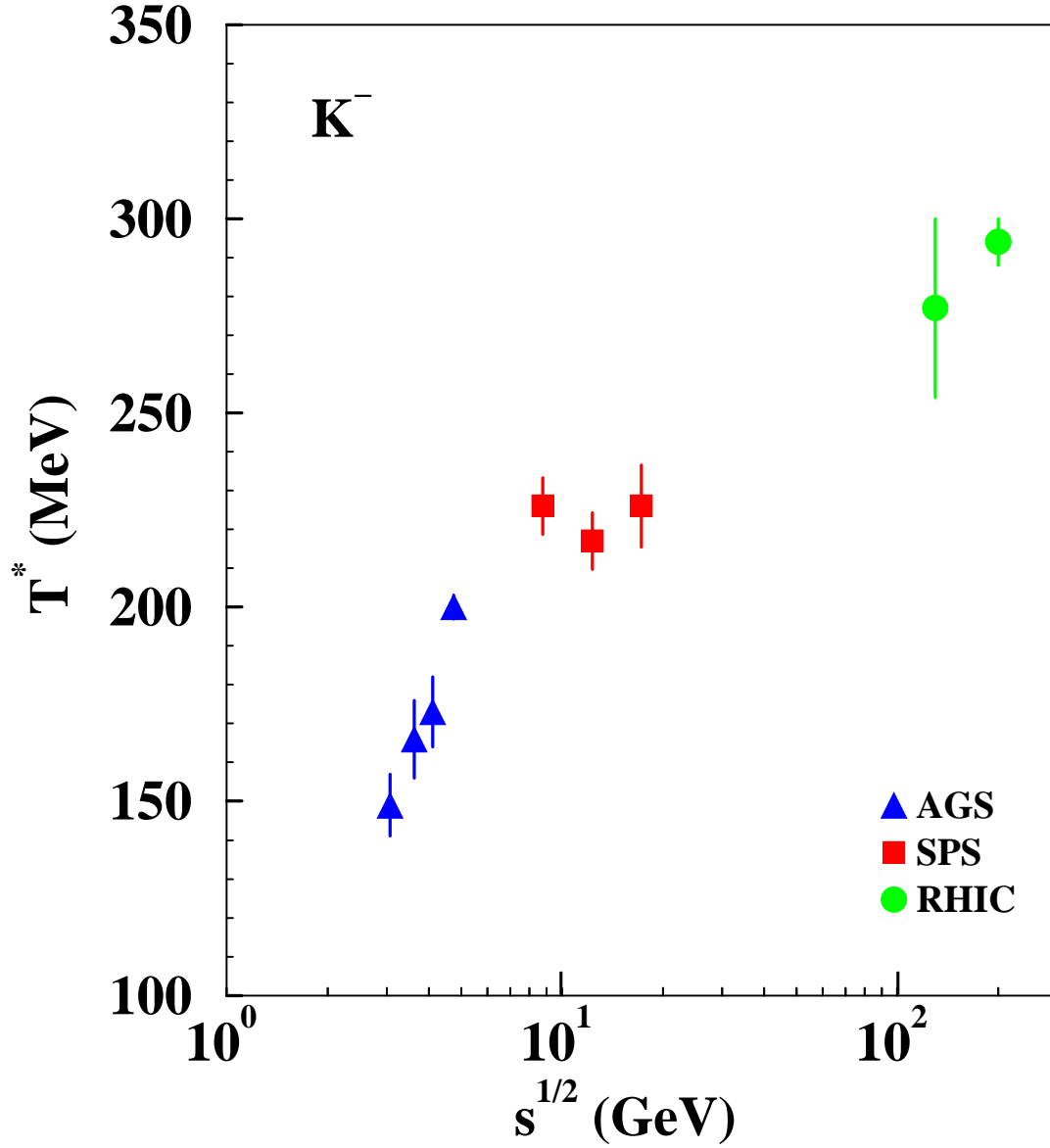


Figure 2: The energy dependence of the inverse slope parameter T^* for K^- mesons produced at mid-rapidity in central Pb+Pb (Au+Au) collisions at AGS [8] (triangles), SPS [3] (squares) and RHIC [9] (circles) energies.