Available online at www.sciencedirect.com
SCIENCE DIRECT

PHYSICS LETTERS B

Physics Letters B 567 (2003) 175–178

www.elsevier.com/locate/npe

Transverse activity of kaons and deconfinement phase transition in nucleus–nucleus collisions

M.I. Gorenstein [a,b], M. Gaździcki [c,d], K.A. Bugaev [a,e]

[a] *Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine*
[b] *Institut für Theoretische Physik, Universität Frankfurt, Germany*
[c] *Institut für Kernphysik, Universität Frankfurt, Germany*
[d] *Świętokrzyska Academy, Kielce, Poland*
[e] *Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany*

Received 16 June 2003; accepted 24 June 2003

Editor: L. Montanet

Abstract

We found that the experimental results on transverse mass spectrum of kaons produced in central Pb+Pb (Au+Au) collisions show an anomalous dependence on the colliding energy. The inverse slope of the spectrum increases with the energy in the low (AGS) and high (RHIC) energy domains, whereas it remains constant in the intermediate (SPS) energy range. We argue that this anomaly is probably caused by the 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.

The statistical model of the early stage, SMES, of nucleus–nucleus ($A + A$) collisions suggests [1] that the onset of 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 [3,4] of pion and kaon production in central Pb + Pb collisions at CERN SPS indeed indicate that the transient state of deconfined matter is created in these collisions for energies larger than about 30 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 expected soon new results on Pb + Pb collisions at 20 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 [5] more than 20 years ago to identify the deconfinement phase transition in high energy proton–antiproton interactions with an anomalous behavior (a plateau-like structure) of the average transverse momentum as a function of hadron multiplicity. Let us briefly recall the Van Hove's arguments. According to

E-mail address: marek.gazdzicki@cern.ch (M. Gaździcki).

0370-2693
doi:10.1016/j.physletb.2003.06.043

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). The 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 spectrum. Therefore, with increasing collision energy[1] one expects to observe an increase of both the hadron multiplicity and average transverse momentum per hadron. However, a 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 a form $p(\varepsilon)/\varepsilon$ versus ε shows a minimum (the 'softest point' [6,7]) at the boundary of the (*generalized* [7]) mixed phase and the QGP. 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 [5]. 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.

A simplified picture with $T = T_C = \text{const}$ inside the mixed phase is changed if the created early stage matter has a nonzero baryonic density. It was however demonstrated [8] 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 energy dependence of pion and strangeness yields, the modification of the equation of state due to 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:

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

where C is the normalization constant, and the inverse slope parameter T^* is sensitive to both the thermal and collective motion in the transverse direction. At small p_T the T^* parameter can be expressed within the hydrodynamical approach as

$$T^* = T_f + \frac{1}{2} m \bar{v}_T^2, \tag{2}$$

where T_f is the kinetic freeze-out temperature and $\bar{v}_T$ is the mean transverse flow velocity. 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

$$\langle m_T \rangle = T^* + m + \frac{(T^*)^2}{m + T^*}. \tag{3}$$

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 [9], SPS [3,4] and RHIC [10] energies are compiled. The striking features of the data can be summarized and *interpreted* as following.

- The T^* parameter increases strongly with collision energy up to the point at the lowest (30 A GeV) SPS energy. This is an energy region where the creation of confined matter at the

[1] In the original Van Hove suggestion the correlation between average transverse momentum and hadron multiplicity were discussed for proton–antiproton collisions at fixed energy. Today we have an advantage to use $A + A$ collisions at different energies.

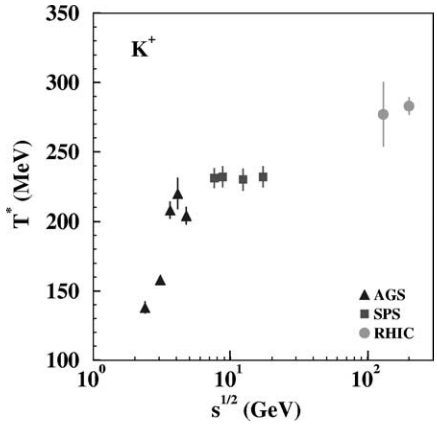

Fig. 1. The energy dependence ($s^{1/2}$ is c.m. energy per nucleon–nucleon pair) of the inverse slope parameter T^* for K^+ mesons produced at midrapidity in central Pb + Pb (Au + Au) collisions at AGS [9] (triangles), SPS [3,4] (squares) and RHIC [10] (circles) energies.

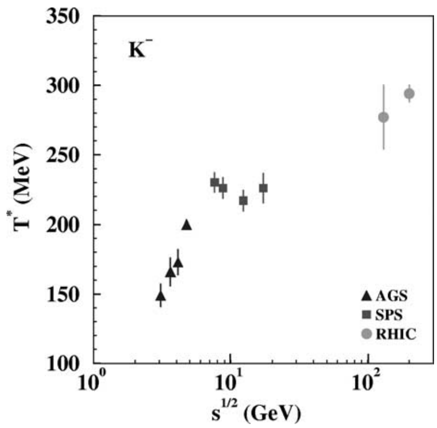

Fig. 2. The energy dependence ($s^{1/2}$ is c.m. energy per nucleon–nucleon pair) of the inverse slope parameter T^* for K^- mesons produced at midrapidity in central Pb + Pb (Au + Au) collisions at AGS [9] (triangles), SPS [3,4] (squares) and RHIC [10] (circles) energies.

early stage of the collisions is expected. Increasing collision energy leads to an increase of the early stage temperature and pressure. This results in larger final values of both T_f and $\bar{v}_T$ in Eq. (2). 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, 30–158 A GeV. 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" an increase of both T_f and $\bar{v}_T$, and this leads to the observed plateau structure in the energy dependence of the T^* parameter.
- At RHIC (the c.m. energies per nucleon–nucleon pair $\sqrt{s} = 130$ GeV and 200 GeV) the T^* is significantly larger than at SPS energies. In the RHIC energy domain 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 the transverse flow $\bar{v}_T$ and, consequently, in increase of T^* (2) between SPS and RHIC energies.

The anomalous energy dependence of the m_T spectra is a characteristic feature of the kaon data. Why is it the case? How do the m_T spectra of other hadrons look like? The answer is rather surprising: among measured hadron species the kaons are the best and unique particles for observing in their transverse momentum spectra the effect of the modification of equation of state due to the onset of deconfinement. The arguments are as following.

- 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 $\langle m_T \rangle$ (3) and average transverse momentum $\langle p_T \rangle$ for kaons is qualitatively the same as that for the parameter T^*. This simplifies analysis of the experimental data.
- The shape of kaons m_T spectra is only weakly affected by the hadron rescattering and resonance decays during the post-hydrodynamic hadron cascade [11,12].
- 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.

In contrast to kaons m_T spectra, a simple exponential fit (1) does not work accurately in a wide p_T-region for other hadrons: $T^*_{\text{low-}p_T} > T^*_{\text{high-}p_T}$ for 'light' pions, and $T^*_{\text{low-}p_T} < T^*_{\text{high-}p_T}$ for protons, lambdas and other 'heavy' hadrons (for the SPS and RHIC energies see discussion of hydrodynamic results in Ref. [13] and the data in Ref. [14]). This means that the average transverse masses, $\langle m_T \rangle$, and their energy dependence are not connected to the behavior of the slope parameters in a simple way (3): one should separately consider both $T^*_{\text{low-}p_T}$ and $T^*_{\text{high-}p_T}$ for each of hadron species.

The "hydro QGP + hadron cascade" approach Refs. [11,12] 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 transfer a fraction of their transverse energy to the nucleon and hyperon sectors. Therefore, the hadron rescattering and resonance decays lead to an essential increase (about 40% [12]) 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. [15]). 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.

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 [11–13,15]. Unfortunately, the spectra of Ω hyperons are measured only at top SPS and RHIC energies [16]. More data exist for ϕ meson production [17]. However, the large uncertainties in the experimental results do not allow for precise enough study of energy dependence.

In conclusion, we observe the anomalous energy dependence of transverse mass spectra of K^+ and K^- mesons produced in central Pb + Pb (Au + Au) collisions. The inverse slope of the m_T spectrum increases with the energy in the AGS and RHIC energy domains, whereas it is constant in the intermediate SPS energy range. We argue that this anomaly is caused by the 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 in the low SPS energy domain.

Acknowledgements

We thank W. Greiner for discussions and comments. Partial support by Bundesministerium für Bildung und Forschung and by Polish Committee of Scientific Research under grant 2P03B04123 (M.G.) is acknowledged.

References

[1] M. Gaździcki, M.I. Gorenstein, Acta Phys. Pol. B 30 (1999) 2705, and references therein.
[2] M. Gaździcki, D. Röhrich, Z. Phys. C 65 (1995) 215;
M. Gaździcki, D. Röhrich, Z. Phys. C 71 (1996) 55.
[3] NA49 Collaboration, S.V. Afanasiev, et al., Phys. Rev. C 66 (2002) 054902.
[4] NA49 Collaboration, V. Friese, et al., nucl-ex/0305017.
[5] L. Van Hove, Phys. Lett. B 118 (1982) 138.
[6] E.V. Shuryak, O.V. Zhirov, Phys. Lett. B 89 (1979) 253.
[7] C.M. Hung, E.V. Shuryak, Phys. Rev. Lett. 75 (1995) 4003.
[8] C.M. Hung, E.V. Shuryak, Phys. Rev. C 57 (1998) 1891.
[9] E866, E917 Collaborations, L. Ahle, et al., Phys. Lett. B 490 (2000) 53.
[10] BRAHMS Collaboration, D. Ouerdane, et al., nucl-ex/0212001;
STAR Collaboration, C. Adler, et al., nucl-ex/0206008.
[11] S. Bass, A. Dumitru, Phys. Rev. C 61 (2000) 064909.
[12] D. Teaney, J. Lauret, E.V. Shuryak, Phys. Rev. Lett. 86 (2001) 4783, nucl-th/0110037.
[13] M.I. Gorenstein, K.A. Bugaev, M. Gaździcki, Phys. Rev. Lett. 88 (2002) 132301.
[14] NA49 Collaboration, S. Afanasiev, et al., Nucl. Phys. A 715 (2003) 453c;
STAR Collaboration, C. Adler, et al., Phys. Rev. Lett. 87 (2001) 262301;
STAR Collaboration, C. Adler, et al., Phys. Rev. Lett. 89 (2002) 092301;
PHENIX Collaboration, K. Adcox, et al., Phys. Rev Lett. 88 (2002) 242301;
PHENIX Collaboration, K. Adcox, et al., Phys. Rev. Lett 89 (2002) 092302.
[15] K.A. Bugaev, M. Gaździcki, M.I. Gorenstein, hep-ph/0211337, Phys. Rev. C, in press.
[16] NA49 Collaboration, S. Afanasiev, et al., Nucl. Phys. A 715 (2003) 161c;
WA97 Collaboration, F. Antinori, et al., J. Phys. G 27 (2001) 375;
STAR Collaboration, G. van Buren, et al., Nucl. Phys. A 715 (2003) 129c.
[17] NA49 Collaboration, S. Afanasiev, et al., Phys. Lett. B 491 (2000) 59;
NA50 Collaboration, B. Alessandro, et al., Phys. Lett. B 555 (2003) 147;
STAR Collaboration, F. Laue, et al., J. Phys. G 28 (2002) 2051;
E917 Collaboration, R.K. Seto, et al., Nucl. Phys. A 661 (1999) 506c.