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Indication of a coexisting phase of quarks and hadrons in nucleus-nucleus collisions

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The variation of average transverse mass of identified hadrons with charge multiplicity has been studied for AGS, SPS, and RHIC energies. The observation of a plateau in the average transverse mass for multiplicities corresponding to SPS energies is attributed to the formation of a coexistence phase of quark gluon plasma and hadrons. A subsequent rise for RHIC energies may indicate a deconfined phase in the initial state. Several possibilities which can affect the average transverse mass are discussed. Constraints on the initial temperature and thermalization time have been put from the various experimental data available at SPS energies.

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Results based on QCD (quantum chromodynamics) renormalization group approach predict that strongly interacting systems at high temperatures and/or densities are composed of weakly interacting quarks and gluons [1,2] due to asymptotic freedom and the Debye screening of color charge. Nucleus-nucleus (A-A) collisions at very high energies may create situations conducive for the formation of a thermodynamic state where the properties of the system are governed by quarks and gluonic degrees of freedom. Such a state is called quark gluon plasma (QGP). QCD lattice gauge theory suggests that the critical temperature T_c for such a transition is ~170 MeV [3]. This has led to intense theoretical and experimental activities in this field of research [4].

Experimental detection of the QGP in A-A collisions is a nontrivial task because of the small space-time volume of the system. Among many signals of the QGP formation [5], one of the earliest is based on the relation of the thermodynamical variables, temperature, and entropy to the average transverse momentum and multiplicity, respectively. This was originally proposed by Van Hove in the context of proton-proton collisions [6]. It was argued that a plateau in the transverse momentum beyond a certain value of multiplicity will indicate the onset of the formation of mixed phase of QGP and hadrons; analogous to the plateau observed in the variation of temperature with entropy in a first-order phase transition scenario. One hence looks for the variation of average transverse momentum $\langle p_T \rangle$ or transverse mass $\langle m_T \rangle$ ($m_T = \sqrt{p_T^2 + m^2}$, m being the rest mass of the particle) with respect to the total number of particles produced per unit rapidity (dN/dY) in A-A collisions at high energies. An increase in energy density should increase $\langle m_T \rangle$ till it reaches a critical density for phase transition to occur, where it should then show a plateau due to formation of mixed phase. Further increase of energy density should again increase $\langle m_T \rangle$ of produced particles.

Several attempts have been made so far to look for such signals. While the data from cosmic ray experiments [7] are inconclusive, the data from A-A collisions in the laboratory for fixed center of mass energies ($\sqrt{s}$) with different centralities (impact parameters) [8–10] have so far not shown this kind of behavior. This implies that a mere change in the centrality of the collisions does not change the energy density of the system formed after the collisions required to create any change of phase. So it is imperative to study the variation of $\langle m_T \rangle$ with dN_{ch}/dY for a broad range of beam energies for fixed centrality.

In this paper, the variation of $\langle m_T \rangle$ with dN_{ch}/dY is examined for AGS, SPS, and RHIC energies spanning $\sqrt{s}$ from $2A$ GeV to $200A$ GeV. We then carry out explicit theoretical calculations to understand the observed behavior in terms of the properties of the matter produced in the initial stages.

In Fig. 1, the variation of $\langle m_T \rangle$ with charge multiplicity is depicted for pions, kaons, and protons at AGS, SPS, and RHIC energies around midrapidity. The data shown here correspond to central events for different colliding systems, particle types (produced), and center of mass energies (see Table I). The experimental data on transverse mass spectra can be parametrized as

$$\frac{dN}{m_T dm_T} \sim C \exp\left(-\frac{m_T}{T_{eff}}\right), \tag{1}$$

where the inverse slope parameter T_{eff} is the effective temperature (effective because it includes the contribution from both the thermal and collective motion in the transverse direction). The variation of T_{eff} with $\sqrt{s}$ for kaons has recently

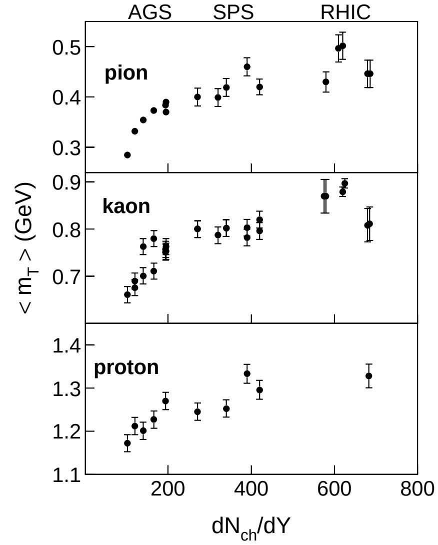

FIG. 1. Variation of $\langle m_T \rangle$ with produced charged particles per unit rapidity at midrapidity for central collisions corresponding to different $\sqrt{s}$ spanning from from AGS to RHIC. The error bars reflect both the systematic and statistical errors in obtaining T_{eff}.

TABLE I. The details of the experimental data used in the analysis along with the references.

$\sqrt{s}$ (GeV)	Type	Centrality (%)	m_T-m	Ref.
2.3 (Au+Au)	π^+,K^+	5	0.1–1.0, 0.05–0.7	[12]
2.3 (Au+Au)	p	5	0.0–1.0	[13]
3.0 (Au+Au)	$\pi^+,K^\pm$	5	0.1–1.0, 0.05–0.7	[12]
3.0 (Au+Au)	p	5	0.0–1.0	[13]
3.6 (Au+Au)	$\pi^+,K^\pm$	5	0.1–0.9, 0.05–0.7	[12]
3.6 (Au+Au)	p	5	0.0–1.0	[13]
4.1 (Au+Au)	$\pi^+,K^\pm$	5	0.1–1.0, 0.05–0.7	[12]
4.1 (Au+Au)	p	5	0.0–1.0	[13]
4.7 (Au+Au)	$\pi^+,K^\pm$	5	0.1–0.8, 0.05–0.7	[12]
4.86 (Au+Au)	$\pi^\pm,K^\pm$	10	0.1–1.5, 0.05–0.8	[14]
4.86 (Au+Au)	p	7	0.05–1.0	[14]
8.76 (Pb+Pb)	$\pi^-,K^\pm$	7.2	0.2–0.7, 0.05–0.9	[15]
8.76 (Pb+Pb)	p	7.2	0.0–1.0	[15]
12.3 (Pb+Pb)	$\pi^-,K^\pm$	7.2	0.2–0.7, 0.05–0.9	[15]
12.3 (Pb+Pb)	p	7.2	0.0–1.0	[15]
17.3 (Pb+Pb)	$\pi^-,K^\pm$	5	0.2–0.7, 0.05–0.9	[15]
17.3 (Pb+Pb)	p	5	0.0–1.0	[15]
17.3 (Pb+Pb)	π^-,K^-	10	0.1–1.2, 0.05–1.0	[16]
17.3 (Pb+Pb)	$\pi^-,K^\pm$	3.7	0.28–1.2, 0.05–0.84	[17]
130 (Au+Au)	$\pi^\pm,K^\pm$	5	0.1–1.0, 0.1–1.2	[18]
130 (Au+Au)	p	5	0.05–2.0	[18]
130 (Au+Au)	$\pi^-,K^\pm$	5,6	0.02–0.6, 0.05–1.2	[9,10]
200 (Au+Au)	$\pi^\pm,K^\pm$	10	0.28–1.4, 0.1–1.2	[19]

been shown in Ref [11]. The average transverse mass of the particles obtained from Eq. (1) is

$$\langle m_T\rangle = T_{eff} + m + \frac{(T_{eff})^2}{m+T_{eff}}. \tag{2}$$

From the results shown in Fig. 1, one observes an increase in $\langle m_T\rangle$ with dN_{ch}/dy for AGS energies followed by a plateau for charge multiplicities corresponding to SPS energies for all the particle types, pions, kaons, and protons. This may hint at the possible coexistence of the quark and hadron phases. For charge multiplicities corresponding to RHIC energies, $\langle m_T\rangle$ shows an increasing trend indicating the possibility of a pure QGP formation.

It is essential now to investigate whether the above experimental variation of $\langle m_T\rangle$ can arise from various physical effects other than due to QGP formation. We will address this issue by trying to answer the following questions:

(a) How does (3+1)-dimensional hydrodynamical evolution of the system, with and without QCD phase transition, formed in heavy ion collisions affect $\langle m_T\rangle$ at freeze-out?

(b) Does the analysis of experimental data on hadrons, photons, and dileptons indicates similar values of the initial temperature (T_i)? How does the value of T_i compare with T_c predicted by lattice QCD [3]?

(c) How does $\langle m_T\rangle$ get affected by the gain in transverse momentum by hadrons through their successive collisions (Cronin effect [20]) with the particles in the system?

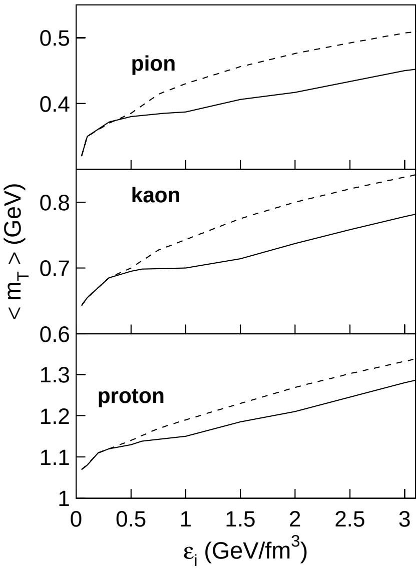

FIG. 2. Variation of $\langle m_T\rangle$ with initial energy density ϵ_i for a QGP scenario (solid line) and hadronic scenario (dashed line) obtained from (3+1)-dimensional hydrodynamics.

(d) How does $\langle m_T\rangle$ of produced particles vary with $\sqrt{s}$ in a standard event generator based on the principle that nucleus-nucleus collision is a superposition of nucleon-nucleon collisions?

The answers to the above questions are as follows.

(a) To understand the variation of $\langle m_T\rangle$ with dN_{ch}/dY for a system undergoing a (3+1)-dimensional expansion, we solve the hydrodynamical equations for various initial energy densities ϵ_i [21]. The initial radial velocity is taken as zero. The momentum distribution of particles originating from a system undergoing transverse expansion [21] with boost invariance along the longitudinal direction [22] contains the effect of thermal motion as well as transverse flow. Hence it is imperative to examine how the value of the inverse slope or average transverse mass is affected by transverse motion. To achieve this we proceed as follows. We evaluate the m_T spectra for various hadrons at the freeze-out point as a function of ϵ_i for two different kinds of space-time evolution scenarios.

First, we consider a hadronic gas at various values of ϵ_i from $\sim$0.05–4 GeV/fm^3 without introducing a QCD phase transition. For all these initial energy densities, the (3+1)-dimensional hydrodynamic equations are solved to obtain the freeze-out surface at a temperature of 120 MeV. This is used as an input to evaluate the transverse mass spectra of hadrons. The hadronic equation of state (EOS) [23] contains hadronic degrees of freedom up to strange sector [24]. From the m_T spectra of hadrons (pions, kaons, and protons) corresponding to each ϵ_i, we evaluate $\langle m_T\rangle$. This is plotted in Fig. 2 (dashed line).

In the second scenario, we introduce the QGP (composed of up, down, strange quarks, and gluons) at an energy density above $\epsilon_Q\sim 1.7$ GeV/fm^3 corresponding to critical temperature $T_c = 170$ MeV which converts to the hadronic phase at an energy density, $\epsilon_H\sim 0.56$ GeV/fm^3 at the same temperature. The effective degeneracy g_{eff} at T_c for the hadronic phase is ~16 obtained from the study of hadronic EOS in Ref. [23]. So in this scenario we have a mixed phase within the energy range $0.56<\epsilon\,(\mathrm{GeV/fm}^3)<1.7$. For $\epsilon>1.7$ GeV/fm^3, a QGP bag model EOS has been used. The variation of m_T as a function of ϵ_i for this scenario is shown in Fig. 2 (solid line). It is clear that $\langle m_T\rangle$ varies at a much slower rate for the second scenario. Although a complete plateau structure is not observed, it can be argued that the formation of a mixed phase slows down the rate of increase of $\langle m_T\rangle$ with multiplicity. In fact, the slope of the curve in the case of pions for the first scenario is larger than the second by a factor of 2.5 at $\epsilon_i=1$ GeV/fm^3. $\langle m_T\rangle$ for pions is about 400 MeV for values of ϵ_i corresponding to mixed phase, which is similar to those obtained experimentally.

(b) The lower bound on T_i realized at SPS energies can be obtained from the measured $\langle m_T\rangle$ provided we can estimate the effects of the flow. The inverse slope of the m_T spectra contains the effect of flow and can be parametrized as [25]

$$T_{eff}=T\sqrt{\frac{1+\langle v_r\rangle}{1-\langle v_r\rangle}}, \tag{3}$$

where $\langle v_r\rangle$ is the average velocity and $T=T_F$ is the "true" freeze-out temperature. We start by noting that $\langle m_T\rangle$ is actually the average energy $\langle E\rangle$ of the particle at zero rapidity ($E=m_T\cosh y$) and in a thermal system the average energy is proportional to temperature. Therefore, for a system which has zero transverse velocity but nonzero longitudinal velocity, one must have

$$\langle m_T\rangle_i>\langle m_T\rangle_f \tag{4}$$

because of the loss of thermal energy due to work done in longitudinal expansion. Here the subscript i (f) refers to initial (freeze-out) state. Assuming $\langle m_T\rangle_f=\langle m_T\rangle_{expt}$ (i.e., all the hadrons are emitted from the freeze-out surface) and using Eqs. (2) and (4), we get

$$T_i>\langle m_T\rangle_{expt}/2. \tag{5}$$

A value of $\langle v_r\rangle\sim0.4$ reproduces the slope of the m_T distribution of pions at SPS energies reasonably well. For this value of $\langle v_r\rangle$ we get $T_F\sim120$ MeV from Eq. (3), indicating $\langle m_T\rangle=m+T_F+T_F^2/(m+T_F)\sim315$ MeV. It should be noted here that the effects of the transverse flow are "subtracted" out from $\langle m_T\rangle$ now. Using Eq. (5) we obtain $T_i>158$ MeV.

Photons and dileptons emitted from the strongly interacting matter constitute one of the most efficient probes to measure the initial temperature of the system [5]. It was shown earlier [26] that direct photons (measured by WA98 collaboration [27]) having transverse momentum in the range $1<p_T(\mathrm{GeV})<2.5$ are expected to originate from a thermal source. The inverse slope of this spectra is ~275 MeV. For $\langle v_r\rangle\sim0.4$, we obtain an average temperature $T_{av}\sim178$ MeV by using Eq. (3). A similar value of T_{av} is obtained from the p_T distribution of e^+e^- [28]. Since photons and dileptons are emitted from all the stages of space-time evolution, T_{av} satisfies the condition $T_i>T_{av}>T_F$. All these indicate that a value $T_i\geqslant170$ MeV may have been realized at SPS energies.

The total multiplicity of hadrons is related to the initial temperature T_i and thermalization time τ_i as

$$\frac{dN}{dY}\sim4\frac{\pi^2}{90}g_{eff}\,\pi R^2\,T_i^3\,\tau_i/3.6, \tag{6}$$

where R is the radius of the colliding nuclei and g_{eff} is the effective statistical degeneracy. Taking $dN/dY\sim700$ corresponding to the highest SPS energies and using Eq. (5), we get $\tau_i\leqslant1.2$ fm/c $\sim1/\Lambda_{QCD}$, where Λ_{QCD} is the QCD scale parameter.

(c) Recently, there have been some attempts to explain the transverse mass spectra of produced particles without introducing a transverse expansion. The hadrons gain transverse momentum through successive collisions with the particles in the system. This can be treated as a random walk of the hadrons [29] in the medium. The m_T spectra of pions at SPS energies can be reproduced by this model, but it fails to reproduce the slope of kaon and proton distribution at the same colliding energies.

(d) As a last consideration, we investigate how $\langle m_T\rangle$ of produced particles vary with $\sqrt{s}$ of A-A systems in a standard event generator based on the principle that the A-A collision is a superposition of nucleon-nucleon collisions. This is done by using the event generator HIJING [30] which contains the effect of minijets. The results of this calculation do not show the variation of $\langle m_T\rangle$ with $\sqrt{s}$ as has been observed experimentally.

In summary, a detailed analysis of the experimental data of the transverse mass spectra of identified hadrons, at AGS, SPS, and RHIC energies, shows a characteristic behavior of $\langle m_T\rangle$ as a function of multiplicity similar to that proposed by Van Hove. The plateau in $\langle m_T\rangle$ corresponding to the multiplicity at SPS energies may hint at the formation of a mixed phase of QGP and hadrons in the initial stages. The average temperature obtained from the analysis of photons and dileptons lends support to this. We have shown by solving the hydrodynamical equations that the presence of a mixed phase really slows down the growth of $\langle m_T\rangle$ with dN/dY substantially. In the present work, all the hadronic degrees of freedom up to mass 2.5 GeV have been included in the EOS; a fewer hadronic degrees of freedom will slow down this growth even more. Since a lower bound of the initial temperature is obtained here, the formation of QGP at a higher temperature cannot be ruled out. However, even if QGP phase is created at SPS, its space-time volume could be too small to affect the dynamics of the system and hence our conclusions. The upward trend in the slope of $\langle m_T\rangle$ at RHIC energies is indicative of a deconfined phase in the initial state.

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