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PION AND STRANGENESS PRODUCTION AS SIGNALS OF QCD PHASE TRANSTION

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Abstract

It is shown that data on pion and strangeness production in central nucleus–nucleus collisions are consistent with the hypothesis of a Quark Gluon Plasma formation between 15 A·GeV/c (BNL AGS) and 160 A·GeV/c (CERN SPS) collision energies. The experimental results interpreted in the framework of a statistical approach indicate that the effective number of degrees of freedom increases by a factor of about 3 in the course of the phase transition and that the plasma created at CERN SPS energy may have a temperature of about 280 MeV (energy density $\approx$ 10 GeV/fm^3). Experimental studies of central Pb+Pb collisions in the energy range 20–160 A·GeV/c are urgently needed in order to localize the threshold energy, and study the properties of the QCD phase transition.

1 Introduction

In this paper we review the recent status of our search for a QCD transition to the Quark Gluon Plasma [1] by a systematic analysis of entropy and strangeness production in nuclear collisions. There are important reasons to select entropy [2] and strangeness [3] as basic observables. Both are defined in any form of strongly interacting matter. Their equilibrium values are directly sensitive to matter properties: effective number of degrees of freedom and their effective masses. Entropy and strangeness production are also believed to freeze–out at the early stage of evolution of a system created in nuclear collisions.

Our strategy of data[2] analysis [4] reviewed here can be summarized as follows:

1. We study the dependence of the properly normalized entropy (mainly determined by pion multiplicity) and strangeness (mainly determined by kaon

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[2] Data obtained by about 100 different experiments are used. The references to the original experimental works can be found in the compilation papers [4].

and hyperon yields) production on the volume of the colliding nuclear matter at a fixed collision energy. We demonstrate that a fast saturation occurs. The simplest qualitative interpretation is, that equilibration of entropy and strangeness takes place (Section 2).
2. We study the dependence of the saturation levels on the collision energy. We demonstrate that the saturation levels for both entropy and strangeness show an unusual change between AGS (≈15 A·GeV/c) and SPS (≈160 A·GeV/c) energies. The simplest qualitative interpretation is, that the threshold energy for QGP creation is located in the above energy range (Section 3).
3. Finally, we formulate a simple statistical model for entropy and strangeness production in nuclear collisions and demonstrate that the experimental results at SPS energy can be quantitatively described assuming creation of QGP (Section 4).

2 Volume Dependence

Experimental data on pion[3] and strangeness production in central nucleus–nucleus (A+A) and all inelastic nucleon–nucleon (N+N) collisions are shown in Fig. 1 as a function of the number of participant nucleons, $\langle N_P \rangle$, for various collision energies. In order to eliminate a trivial volume dependence, the normalized multiplicities are studied: $\langle \pi \rangle / \langle N_P \rangle$ and $E_S \equiv (\langle \Lambda \rangle + \langle K + \overline{K} \rangle)/\langle \pi \rangle$, where $\langle \pi \rangle$, $\langle \Lambda \rangle$, and $\langle K + \overline{K} \rangle$ are mean multiplicities of pions, Λ/Σ^0 hyperons, and kaons and antikaons, respectively. For all energies a similar behaviour is observed: a rapid change between results for N+N interactions and intermediate mass nuclei ($\langle N_P \rangle \approx 50$) is followed by a well defined region in which the normalized pion and strangeness production is almost constant. We interpret the observed saturation as a result of an equilibration of entropy and strangeness yields.

3 Energy Dependence

The collision energy dependence of the normalized entropy and strangeness production is shown in Fig. 2. The energy dependence is studied using the Fermi energy variable [5, 6] $F \equiv (\sqrt{s}_{NN} - 2m_N)^{3/4}/\sqrt{s}_{NN}^{1/4}$, where $\sqrt{s}_{NN}$ is the c.m. energy for a nucleon–nucleon pair and m_N is the nucleon mass. There are several advantages in using F as an energy variable. The measured mean pion multiplicity in N+N interactions is approximately proportional to F [4, 7].

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[3] Here we use pion multiplicity instead of entropy in order to start analysis from 'raw' experimental data. An improved estimate of entropy is given in the next section.

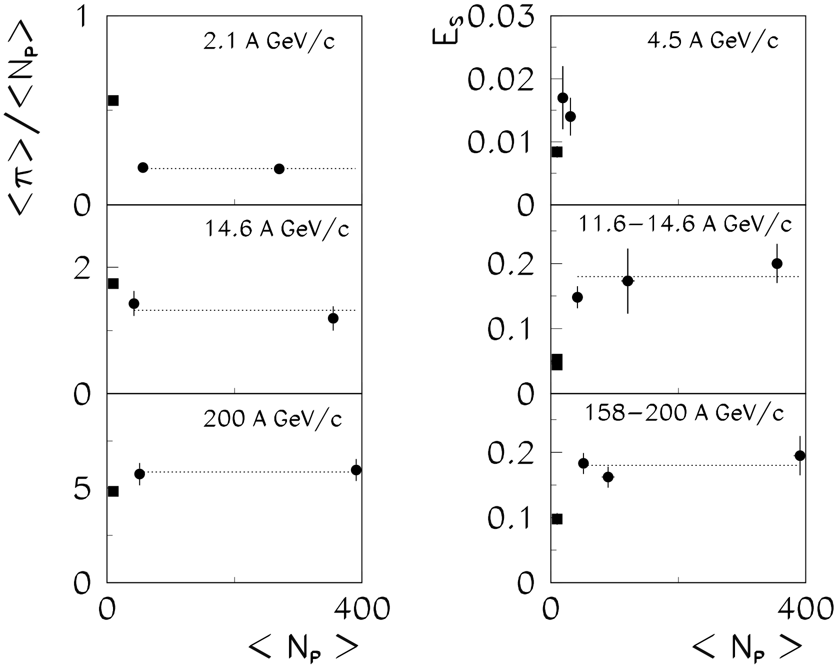

Figure 1: (left) The dependence of the ratio $\langle\pi\rangle/\langle N_P\rangle$ on $\langle N_P\rangle$ at three different collision energies. (right) The dependence of the E_S ratio on $\langle N_P\rangle$ at three different collision energies. The data for central A+A collisions are indicated by circles and the data for N+N interactions by squares.

In the Landau model [6] both the entropy and the initial temperature of the matter (for $\sqrt{s}_{NN} \gg 2m_N$) are also proportional to F.

The 'entropy' presented in Fig. 2 is calculated as: $S \equiv \langle\pi\rangle + \kappa\langle K + \overline{K}\rangle + \alpha\langle N_P\rangle$, where two last components take into account kaon production and pion absorption [4]. Thus S can be treated as the inelastic entropy measured in the pion entropy units.

The normalized 'entropy' for central A+A collisions at low energies (AGS and below) follows the dependence established by N+N data. The normalized 'entropy' for A+A collisions at SPS energy (the data of NA35 and NA49 Collab.) is about 30% higher than the corresponding value for N+N interactions.

The energy dependence of the E_S ratio is also shown in Fig. 2. The results for N+N interactions are scaled to fit A+A data at AGS. A monotonic increase of E_S between Dubna energy (p_{LAB} = 4.5 A·GeV/c) and SPS energy

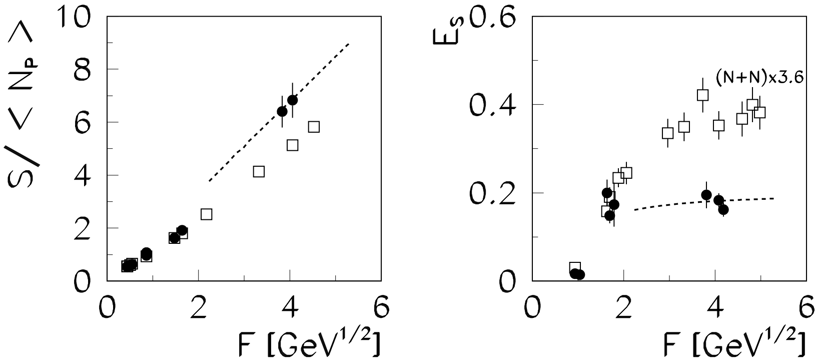

Figure 2: The dependence of $S/\langle N_P\rangle$ (left) and E_S (right) on the collision energy measured by the Fermi variable F. The data for central A+A collisions are indicated by circles and the data for N+N interactions by squares (the E_S values for N+N interactions are scaled by a factor of 3.6). The dashed lines show results obtained within the generalized Landau model assuming QGP creation.

is observed. In the range from AGS to SPS the E_S ratio for N+N interactions is enhanced by a factor of about 2. A qualitatively different dependence is seen for central A+A collisions. The rapid increase of E_S between Dubna and AGS energies is followed by a weak change of E_S between AGS and SPS collision energies.

Let us now try to understand the observed energy dependence on a qualitative level. In the generalized Landau model [4] the inelastic entropy is proportional to $g^{1/4}\langle N_P\rangle F$, where g is the effective number of degrees of freedom. Thus the observed deviation of the data for A+A collisions from the Landau scaling, $S/\langle N_P\rangle \sim F$, can be interpreted as due to an increase of the effective number of degrees of freedom when crossing the transition collision energy. The magnitude of this increase can be estimated, within the model, as the fourth power of the ratio of slopes of straight lines describing low and high energy A+A data: $1.33^4 \approx 3$ [4].

The second dominant effect of the transition to QGP is the reduction of the effective masses of degrees of freedom. Basic thermodynamics tells us that for massless particles the ratio *particle number/entropy* is independent of the temperature. For massive particles the ratio increases with T at low temperature and approaches the saturation level (equal to the corresponding ratio for massless particles) at high temperatures, $T \gg m$. This property can be used to study the magnitude of the effective mass of strangeness carriers in strongly interacting matter. The E_S ratio is approximately proportional to the ratio *number of strangeness carriers/entropy (strangeness/entropy)* and therefore its temperature (collision energy, F) dependence should be sensitive to the effective mass of strangeness carriers. Reducing the mass of strangeness carriers should cause a weaker dependence of the E_S ratio on the collision energy. The rapid increase of the E_S ratio in the energy range of $F < 2$ GeV$^{1/2}$ can be interpreted as due to the large effective mass of strangeness carriers (kaons or constituent strange quarks, $m_S \approx 500$ MeV/c^2) in comparison to the temperature of matter, $T < T_C \approx 150$ MeV. At temperatures above T_C, the matter is in the form of QGP and the mass of strangeness carriers is equal to the mass of current strange quarks, $m_S \approx 150$ MeV/c^2, consequently $m_S \leq T$. Thus a much weaker dependence of the E_S ratio on F is expected in the high energy region where the creation of QGP takes place. The equilibrium value of the *strangeness/entropy* ratio is higher in hadronic matter (HM) than in QGP at very high temperatures [8]. This is due to the fact that it is proportional to the ratio of the effective number of strangeness degrees of freedom to the number of all degrees of freedom. This ratio is lower in QGP than in HM. At low temperature, however, the *strangeness/entropy* ratio is lower in HM than in QGP. This is caused, as previously discussed, by the high mass of strangeness carriers in HM. Thus, in general, a transition to QGP may lead to an increase or a decrease of the *strangeness/entropy* ratio depending at which temperatures of QGP and HM the comparison is made.

The presented data suggest that the transition is associated with a decrease of the *strangeness/entropy* ratio.

4 Model of QGP in A+A

Encouraged by the qualitative agreement of the data with the hypothesis of the equilibrium QGP creation in the early stage of A+A collision at SPS, we attempt to make a quantative comparison using the generalized Landau model. We assume that inelastic energy is deposited in a volume equal to the Lorentz contracted volume of a nucleus (we consider collisions of two identical nuclei only). In this volume an equilibrated QGP is formed. For simplicity, we assume that the created QGP is baryon free[4]. Furthermore, we assume that inelastic entropy and strangeness are not changed during the system evolution. The inelastic energy at SPS was measured to be (67±7)% of the available energy

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[4] Introduction of baryon rich QGP significantly complicates a model. We checked, however, that it seems to have only small influence on the final results.

[9], the same for S+S and Pb+Pb collisions. It is also weakly dependent on the collision energy between AGS and SPS [10]. The effective radius of the nucleus was taken to be $r_0 A^{1/3}$ with $r_0 = 1.30 \pm 0.03$ fm given by the fit to the inelastic cross section data [11]. The QGP is assumed to consist of gluons, u, d, and s quarks, and the corresponding antiquarks. The strange quark mass was taken to be 175±25 MeV/c^2 [12]. This mass is determined at an energy scale of 1 GeV. The conversion factor between the calculated entropy and the 'entropy' evaluated from the experimental data is taken to be 4 (entropy per pion at T $\approx$ 150 MeV). The conversion factor between total strangeness and strangeness measured by the sum of Λ and $K + \overline{K}$ yields is taken to be 1.36 according to the N+N data and a procedure developed in [13]. It should be stressed that the model formulated in the above way has no free parameters.

The resulting production of entropy and strangeness in the energy range 30–500 A·GeV is represented by dashed lines in Fig. 2. The agreement with the data is surprisingly good. The analysis suggests that plasma created at the SPS has an energy density of about 10 GeV/fm^3 and a temperature of about 280 MeV.

5 Summary and Conclusions

The experimenal data on pion and strangeness production indicate:
– saturation of pion and strangeness production with the number of participant nucleons,
– change in the collision energy dependence taking place between 15 A·GeV/c and 160 A·GeV/c.
Within a statistical approach the observed behaviour can be qualitatively understood as due to:
– equilibration of entropy and strangeness in collisions of heavy nuclei,
– transition to QGP occuring between AGS and SPS energies associated with the increase of the effective number of degrees of freedom by a factor of about 3.
These observations hold already for the central S+S collisions, they are not unique to central Pb+Pb collisions.

The results at SPS energy are in surprisingly good agreement with the calculations done within the generalized Landau model. The analysis suggests that plasma created at SPS has a temperature of about 280 MeV (energy density of about 10 GeV/fm^3).

Experimental studies of central Pb+Pb collisions in the energy range 20–160 A·GeV are **urgently** needed in order to localize the threshold energy more precisely and study the properties of QCD phase transition.

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