QUARK GLUON PLASMA IN A+A COLLISIONS AT CERN SPS

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1. Introduction

At the final state of high energy nuclear collisions many new particles appear. They are massive and extended objects: hadrons and hadronic resonances. What is the nature of particle creation in strong interactions? How does matter look like in a state of very high energy density which is created during the collision of two nuclei? These questions motivate a broad experimental programme in which properties of high energy nuclear collisions are investigated [1].

Due to a lack of a calculable theory of strong interaction the interpretation of the experimental results has to rely on phenomenological approaches. The first proposed models of high energy collision process were statistical models of the early stage [2, 3], the stage in which the excitation of the incoming matter takes place. In their original formulations the models failed to reproduce experimental results. However, when a broad set of the data became available [4, 5], it was realized [6, 7] that after necessary generalization a statistical approach to the early stage gives surprising agreement with the results. It could be therefore used as a tool to identify the properties of the state created at the early stage and answer the question whether this state is in the form of Quark Gluon Plasma (QGP) – a quasi ideal gas of deconfined quarks and gluons.

A special role in this study is played by the entropy [8] (at high collision energy carried mainly by final state pions) and heavy flavours (strangeness,

charm) production [9, 10, 11]. It can be argued that they are insensitive to the late stages of the collision and therefore they carry information on the early stage.

In the first part of this contribution we briefly review a history of data collection and interpretation of the results on which further presented picture of the early stage of A+A collisions is based. In the second part of the contribution basic assumptions and results of a statistical model of the early stage of the A+A collisions are presented. Conclusions close the paper.

2. History

1988: *Strangeness enhancement in central S+S collisions at 200 A·GeV.*
The NA35 Collaboration presented first results on strangeness production in central S+S collisions at 200 A GeV [12]. It was demonstrated that the production of strange and antistrange hadrons relative to nonstrange hadrons is increased by a factor of about 2 in S+S collisions in comaprison to nucleon–nucleon (N+N) interactions at the same energy per nucleon. This conclusion can be reached due to large acceptance of the NA35 streamer chamber and the measurement of the main carriers of strangeness produced in the collision process: (anti)kaons and Λ hyperons. The observation of strangeness enhancement rules out models of A+A collisions based on a independent superposition of N+N interactions [12].

1992: *Absence of strangeness enhancement in p+A interactions at 200 GeV.*
The compilation of data on strange and nonstrange hadron production in p+A interactions at 200 GeV leads to the conclusion that the strangeness enhancement effect is not present in these reactions [13]. This suggests that the effect observed in central S+S collisions is not due to secondary hadronic processes. During the last 10 years there were numerous attempts to reproduce strangeness enhancement effect in A+A collisions at SPS within string–hadronic models including hadronic rescattering [14]. No satisfactory description of the data is reached. This supports preliminary conclusion based on p+A results.

1994: *Pion suppression in central A+A collisions at low energies.*
The first results on pion production in Au+Au collisions at 11 A·GeV (AGS BNL) are shown [15]. The compilation of results on pion production in N+N interactions and central A+A collisions at AGS and lower energies leads to the conclusion [4] that the number of produced pions per nucleon participating in the collision is significantly lower in A+A collisions than in N+N interactions at the same energy per nucleon. The observed scaling properties and the magnitude of the pion suppression effect suggest that it can be caused by the pion and Δ absorption [16] which takes place during

the expansion of hadronic matter.

1994: *Pion enhancement in central S+S collisions at 200 A·GeV.*
The pion suppression effect is not present in central S+S collisions at 200 A·GeV. In contrary, the number of pions per participant is larger than in the N+N interactions at the same collision energy [4]. It is also observed [6] that the energy dependence of pion (entropy) production in N+N interactions is consistent with that predicted by the statistical model of the early stage formulated about 50 years ago by Fermi and Landau [2, 3]. Finally it is pointed out that the transition from the pion suppression at low energy A+A collisions to pion enhancement observed at SPS energy can be due to transition to deconfined matter which takes place between AGS and SPS energies. A first version of the statistical model of the early stage is formulated. The experimental results on pion production analyzed within this approach indicate that the transition leads to the increase of the effective number of degrees of freedom by a factor of about 3 [6].

1995: *Pion saturation in central A+A collisions at SPS.*
The NA49 experiment presents first results on pion production in central Pb+Pb collisions at 158 A·GeV [17]. It is observed that the pion to participant ratio is similar in central S+S and Pb+Pb collisions. This result agrees with the prediction of statistical model of the early stage used for the interpretation of the S+S results [6].

1995: *Energy dependence of strangeness production in A+A collisions.*
The data on strangeness production in Au+Au collisions at AGS are obtained [18]. These results together with other compiled data on strangeness production in A+A collisions and N+N interactions lead to the following observations [5]. The strangeness to pion ratio increases by a factor of about 2 between AGS and SPS energies for N+N interactions. The corresponding ratio for central A+A collisions is similar for AGS and SPS energies. These experimental findings are interpreted as a result of the transition to QGP taking place between AGS and SPS energies. This interpretation, again based on the statistical model, is consistent with the interpretation of the pion data.

1996: *Strangeness saturation in central A+A collisions at SPS.*
The NA49 experimant presents first results on strangeness production in central Pb+Pb collisions at 158 A·GeV [19]. It is observed that the strangeness to pion ratio for central S+S collisions and Pb+Pb collisions is similar. This saturation of strangeness production is expected in the statistical approach [5].

1997: *Quantitative agreement: QGP and A+A results at SPS.*
It is shown that the pion and strangeness yields measured for A+A collisions

at SPS are in quantitative agreement with the calculations made under
assumption that a QGP is created in the early stage of collisions [7].

1996–1998: J/Ψ saturation in Pb+Pb collisions at 158 A·GeV.
The NA50 experiment presents results on J/Ψ production in Pb+Pb col-
lisions at 158 A·GeV as a function of transverse energy [20]. It is shown
[21] that the J/Ψ to pion ratio seems to be independent of the collision
centrality. Thus the dependence of J/Ψ multiplicity on the volume of the
colliding matter (i.e. $\langle J/\Psi \rangle \sim V$) is the same as dependence of pion and
strangeness yields. This suggests to consider charm production in A+A col-
lisions in the statistical model. It is argued that this dependence is expected
in the statistical model [21] when the charm production is assumed to be
governed by the phase space, in full analogy to the entropy and strangeness
treatment.

3. A Model of the Early Stage of A+A Collisions

Based on the experimental results and interpretation ideas sketched in the
previous section a statistical model of the early stage of A+A collisions was
formulated [21]. In the following we briefly present its main assumptions
and results.

3.1. FORMULATION OF THE MODEL

– The basic assumption of our model is that the production of new particles
(e.g. quarks and gluons) in the early stage of nucleus–nucleus collisions is
a statistical process. Thus formation of all microscopic states allowed by
conservation laws is equally probable. This means that the probability to
produce a given macroscopic state is proportional to the total number of
its microscopic realizations, i.e. a macroscopic state probability P is

$$P \sim e^S, \tag{1}$$

where S is the entropy of the macroscopic state.

– As the particle creation process does not produce net baryonic, flavour
and electric charges only states with the total baryon, flavour and electric
numbers equal to zero should be considered. Thus the properties of the
created state are entirely defined by the volume in which production takes
place, the available energy and a partition function. In the case of collisions
of large nuclei the thermodynamical approximation can be used and the
dependence on the volume and the energy reduces to the dependence on
the energy density. The state properties can be given in the form of a
equation of state.

– We assume that the early stage entropy creation takes place in the volume equal to the volume of the Lorentz contracted nucleus:

$$V = \frac{V_0}{\gamma}, \tag{2}$$

where $V_0 = 4/3\pi r_0^3 A$ and $\gamma = \sqrt{s}_{NN}/(2m_N)$. The r_0 parameter is taken to be 1.30 fm in order to fit the mean baryon density in the nucleus, $\rho_0 = 0.11$ fm^{-3}.

– Only a fraction of the total energy in A+A collision is transformed into the energy of created particles. This is because a part of the energy is carried net baryon number which is conserved during the collision. This available energy can be expressed as:

$$E = \eta(\sqrt{s}_{NN} - m_N) \; A. \tag{3}$$

The parameter η is assumed to be independent of the collision energy and the system size as suggested by the experimental data. This experimental observation is usually justified by a model of a quark–gluon structure of the nucleon [22]. The value of η used for the numerical calculations is 0.67 [23].

– In order to predict a probability of creation of a given macroscopic state all possible degrees of freedom and interaction between them should be given in the form of the partition function. In the case of large enough volume the grand canonical approximation can be used and the state properties can be given in the form of an equation of state. The question of how one can use this equation of state to calculate the space–time evolution (hydrodynamics) of the created system requires a special separate study.

– The most elementary particles of strong interaction are quarks and gluons. In the following we consider u, d, s and c quarks and the corresponding antiquarks with the internal number of degrees of freedom equal to 6 (3 colour states × 2 spin states). In the entropy evaluation the contribution of c, b and t quarks can be neglected due to their large masses. The internal number of degrees of freedom for gluons is 16 (8 colour states × 2 spin states). The masses of gluons and nonstrange (anti)quarks are taken to be 0, the strange and charm (anti)quark masses are taken to be 175 MeV [24] and 1.5 GeV, respectively.

– In the case of creation of colour quarks and gluons the equation of state is assumed to be the ideal gas equation of state modified by the bag constant B in order to account for a strong interaction between quarks and gluons and the surrounding QCD vaccum (see e.g. [25]):

$$p = p^{id} - B \; , \quad \varepsilon = \varepsilon^{id} + B, \tag{4}$$

where p and ε denote pressure and energy density, respectively, and B is the bag constant selected to be 600 MeV/fm^3. The equilibrium state defined above is called Quark Gluon Plasma or Q–state.

8. At the final freeze–out stage of the collision the degrees of freedom are hadrons – extended and massive objects composed of (anti)quarks and gluons. Due to their finite proper volume hadrons can exist in their well defined asymptotic states only at rather low energy density. Estimates $\epsilon < 0.1 \div 0.4$ GeV/fm^3 for the hadron gas with van der Waals excluded volume have been found in Ref. [26]. In the early stage of A+A collisions such a low energy density states could be created only at very low collision energies of a few GeV per nucleon. Asymptotic hadronic states can be questioned as a possible degrees of freedom in the early stage also on the base of our current understanding of $e^+ + e^-$ anihilation process, where the initial degrees of freedom are found to be colourless $q\bar{q}$ pairs [27].

Guided by this considerations we assume that at collision energies lower than the energy needed for a QGP creation the early stage effective degrees of freedom can be approximated by point–like colourless bosons. This state is called W–state (White state). The nonstrange degrees of freedom which dominate the entropy production are taken to be massless, as seems to be suggested by the original analysis of the entropy production in N+N and A+A collisions [6]. Their internal number of degrees of freedom was fitted to the same data [6, 7] to be about 3 times lower than the internal number of effective degrees of freedom for the QGP $(16 + (7/8) \cdot 36 \cong 48)$. Thus it is taken to be $48/3 = 16$. The mass of strange degrees of freedom is assumed to be 500 MeV, equal to the kaon mass. The internal number of strange degrees of freedom is estimated to be 14 as extracted from the fit to the strangeness data at AGS. The phenomenological reduction factor 3 is used in our numerical calculations between the total number of degrees of freedom for Q–state and nonstrange W–state because of the different magnitude of strangeness suppression due to different masses of strangeness carriers in both cases. The ideal gas equation of state is selected.

– We assume that the only process which changes the entropy content of the produced matter during the expansion, hadronization and freeze–out is an equilibration with the baryonic subsystem. It was argued that it leads to entropy transfer to baryons which corresponds to the effective absorption of about 0.35 π–mesons per baryon [6, 16]. This interaction causes also that the produced hadrons in the final state do not obey symmetries of the early stage production process, i.e. there are non-zero baryonic number and electric charge in the final hadron state.

– It is assumed that the total number of s and $\bar{s}$ quarks is conserved during the expansion, hadronization and freeze–out.

3.2. MAIN RESULTS

– For large enough volume of the system the grand canonical approximation is applicable. In the case of the formulated above model this approximation can be safely used already for central Si+Al collisions at AGS energy when entropy and strangeness are considered. It is shown that this approximation is also valid starting from central S+S collisions at SPS when charm production is calculated. Thus the first consequence of the model is that entropy, strangeness and charm yields per volume of the state created in the early stage (or equivalently per participating nucleon) should be independent of the size of the colliding nuclei at SPS energy. This agrees with the experimental data as shown in Fig. 1.

   – The model predicts that at low collision energies a pure W–state is created whereas at high energy a pure Q–state is produced. There is an intermidiate energy region in which W– and Q–states coexist. For the selected parameters of the model the mixed state starts at $p_{LAB} = 30$ A·GeV and ends at $p_{LAB} = 65$ A·GeV. Thus at SPS energies (158–200 A·GeV) a pure QGP is predicted to be created in the early stage. A quantitative agreement of the model with the results on entropy and strangeness in central A+A collisions at SPS is observed (see solid lines in Fig. 1).

   – The model predicts that the transition from W–state to Q–state should be associated with the rapid increase of the pion multiplicity and an nonmonotonic energy dependence of the strangeness to pion ratio. The corresponding model results are shown in Fig. 2 together with the experimental data.

4. CONCLUSIONS

We conclude that a broad set of experimental data is in agreement with the hypothesis that QGP is created in central A+A (S+S and Pb+Pb) collisions at the SPS. Carefull experimental investigation of the A+A collisions in the energy region between top AGS and SPS energies is needed.

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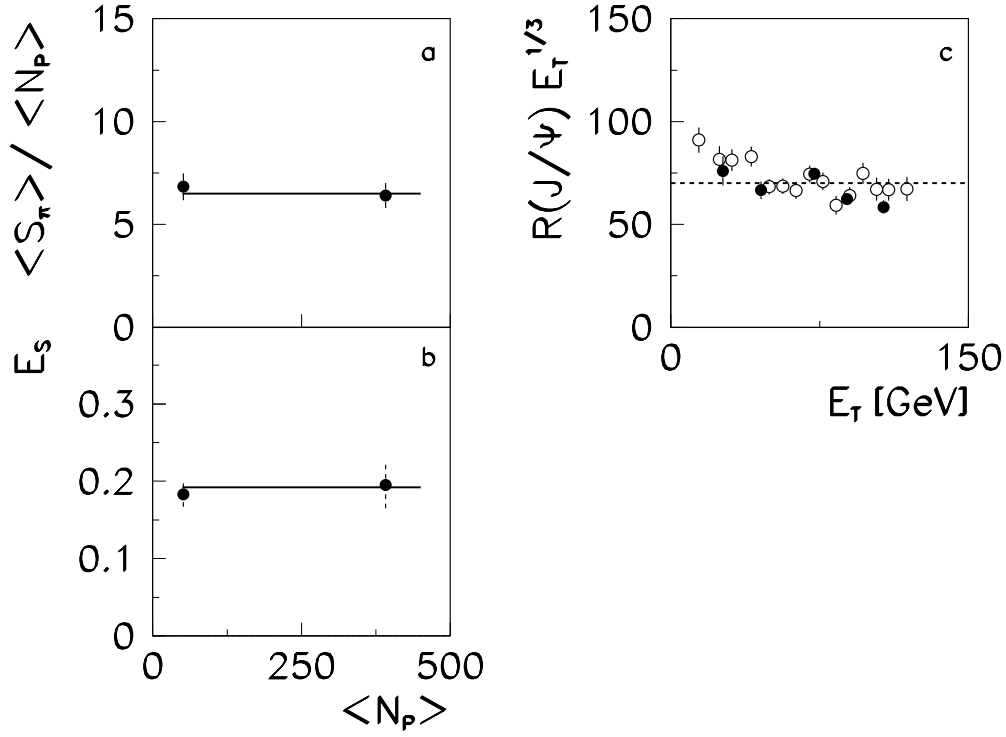
Figure 1. The experimental measures of (quantities proportional to) entropy to participant (a), strangeness to pion (b) and J/Ψ to pion (c) ratios as a function of the volume of the colliding matter for A+A collisions at SPS. The most right points on the plots correspond to central Pb+Pb collisions. The solid lines on Figs. 1a and 1b show results of calculations made within the statistical model of the early stage. The resulting magnitude is defined by the properties of the QGP. The model predicts also indepedence of the charm to pion ratio of the volume of the colliding matter for large enough systems. This prediction seems to be in qualitative agreement with the results for J/Ψ to pion ratio (Fig. 1c). A quantitative comparison requires an additional model of J/Ψ formation from the hadronizing QGP.
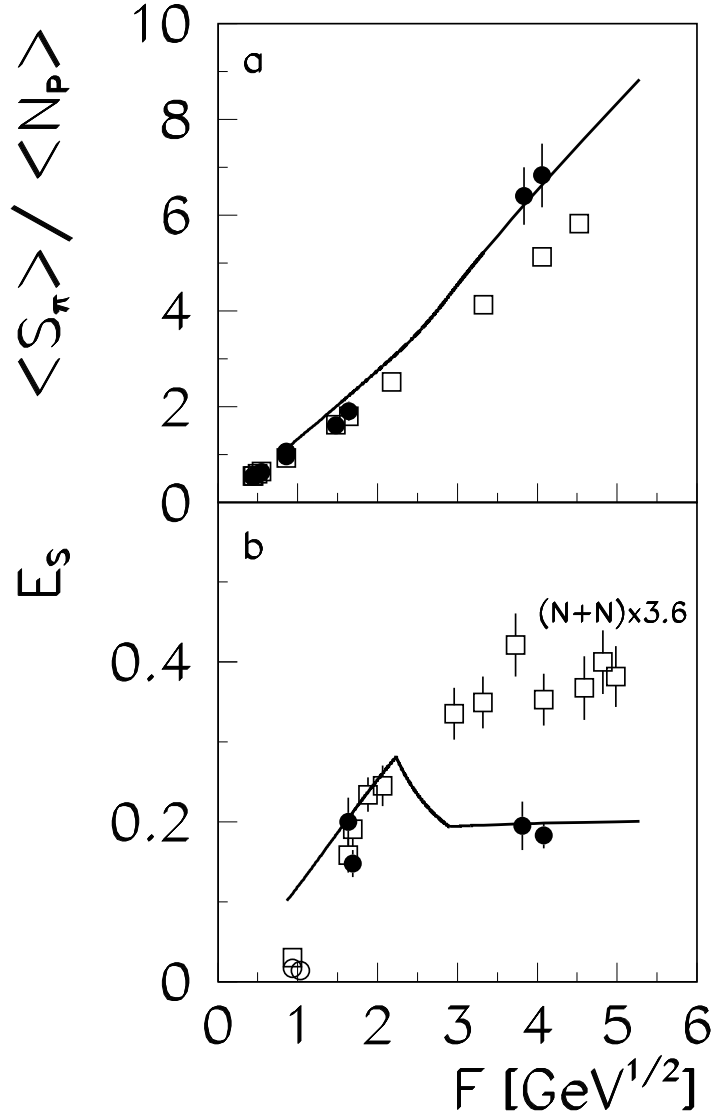
Figure 2.   Dependence of the measures of entropy to participant (a) and strangeness to pion (b) ratios on the collision energy ($F = (\sqrt{s}_{NN} - 2m_N)^{3/4}/(\sqrt{s}_{NN})^{1/4}$) calculated within the statistical model of the early stage (solid lines). The compiled data on central A+A collisions are indicated by close points; the most right points correspond to the collisions at SPS. The results for N+N interactions are shown by open squares for a comparison.