Study of the quark-gluon matter by the PHOBOS experiment

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The PHOBOS experiment at the Relativistic Heavy Ion Collider (RHIC) has collected a large dataset of Au+Au, Cu+Cu, d+Au and p+p collisions in the center of mass energy range spanning from 19 GeV/nucleon to 200 GeV/nucleon. The almost full angular coverage of the PHOBOS detector allows the study of particle production over 10 units pseudorapidity. The unique design of the spectrometer enables reconstruction and identification of charged particles down to very low transverse momenta.

In this paper properties of the strongly interacting Quark-Gluon Plasma (sQGP) created in the nucleus-nucleus collisions at the highest energy available in laboratory are discussed. Results from the PHOBOS experiment on jet suppression, very low p_T particles production and elliptic flow are shown. In more details are presented the most recent studies of the correlations of charged particles with respect to a high-p_T trigger particle, elliptic flow fluctuations and two particle correlations.

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1 Introduction

The fundamental interactions of quarks and gluons, especially these with large momentum transfer, studied in lepton-hadron and hadron-hadron collisions, are successfully described by Quantum Chromodynamics (QCD). A challenge for this theory is the description of larger and more complex systems, necessary for understanding the properties of the matter created in the early stage of the Big Bang.

Conditions similar to that in the early stage of the Universe are created in the collisions of heavy nuclei in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. In this accelerator the beams of heavy ions, up to Au, can be accelerated to the momentum 100 GeV/c per nucleon and collide with the highest energy available currently in the laboratory ($\sqrt{s_{NN}}$ = 200 GeV). The system created in the collision of two Au nuclei reaches, after approximate equilibration at $\tau \sim 2$ fm/c, the energy density of at least 3 GeV/fm^3. This energy density is about 6 times larger than that of the proton under normal conditions [1]. QCD based calculations using numerical techniques of lattice gauge theory suggest that under such conditions a different type of matter, Quark-Gluon Plasma (QGP), should appear.

In the following sections the properties and the evolution of the system created in the heavy nuclei collisions are described. The dependence on the centrality of the collision (i.e. the geometrical overlap between nuclei in the plane transverse to their direction of flight) represented by the number of binary collisions between nucleons, N_{coll}, and the number of nucleons participating in the collision, N_{part}, is extensively studied.

2 Strongly interacting Quark-Gluon Plasma

The early prediction for the hot and dense nuclear matter suggested weak interactions between partons and creation of a gas of quarks and gluons, but experimental results did not confirm these expectations [2]. The first evidence of strong interactions between partons came from the observation of high-p_T particles, which originate from jets created in relatively rare hard collisions of quarks or gluons. A proper measure of the relative yields of such particles is the nuclear modification factor:

$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$

which normalizes production in $A+A$ collisions by elementary $p+p$ yields and accounts for increased probability of hard processes by dividing by N_{coll}.

In the absence of any nuclear effects R_{AA}=1, and this value is obtained for large p_T

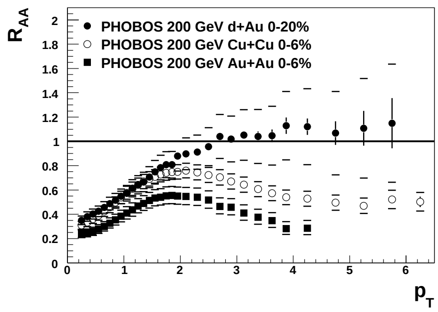

Figure 1: Yields of charged particles in the central nucleus-nucleus collisions, scaled to the elementary interactions, as a function of transverse momentum [3, 4, 5].

in $d + Au$ collisions [3], where no such effects are expected. In the most central $Au + Au$ collisions R_{AA} drops below 0.4 for $p_T > 3$ GeV/c (Fig. 1). This effect is explained by strong interactions in the medium causing that only partons produced near the surface and emitted in the outside direction do not lose their momentum and can fragment into high-p_T particle(s). For smaller systems like $Cu+Cu$ or for less central $Au+Au$ collisions the suppression is also present, but its magnitude is smaller [4, 5].

Large acceptance of the PHOBOS detector allows to study the effects of parton absorption in the sQGP. Recently, we have measured in $Au+Au$ collisions the correlation between a high-p_T trigger particle ($p_T > 2.5$ GeV/c) with the remaining particles [6]. It is known that in the elementary $p + p$ interactions such high-p_T particle is accompanied by close partners, but correlated particles are also present at opposite azimuthal angles. In the case of $Au + Au$ collisions production of correlated particles is enhanced (Fig. 2). In contrast to the elementary interactions the correlation in the "near side" is present also at large distances in pseudorapidity, $|\Delta\eta| > 2$, which may be related to the longitudinal expansion of the system.

Equally interesting is the study of very low-p_T particles production. Theory predicted strong increase of their yields in the case of quark-gluon gas creation. The PHOBOS experiment is capable to register and identify charged particles with very low momenta, starting from p_T= 30 MeV/c. Measured yields (Fig. 3) do not show any significant enhancement, they agree with the extrapolations of the fits (performed in the higher p_T range) of the models assuming expansion of the system, for more details see [8].

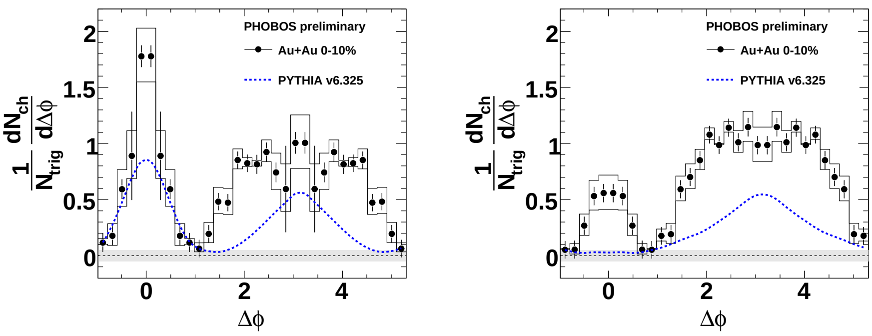

Figure 2: Per-trigger correlated yield as a function of $\Delta\phi$ for the most central (0-10%) Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV in the short range ($|\Delta\eta| < 1$, left) or long range (-4 $< |\Delta\eta| <$ -2, right) compared to p+p interactions from Pythia generator (dashed line). Systematic uncertainty from elliptic flow v_2 estimate is represented by boxes.

3 Evolution of the system

As it was already shown before, the system created in the $A + A$ collision is expanding. More detailed information on the system evolution is obtained in the study of the collective elliptic flow. The elongated shape of the overlap area of the nuclei is reflected in the anisotropy in azimuth of the particle momenta distribution and measured as the second coefficient, v_2, in the Fourier expansion of ϕ distribution (relative to the reaction plane, which is defined by the direction of the beam and the impact parameter vector) [9, 10]. As expected, largest flow is observed in peripheral collisions and decreases with centrality (Fig. 4). For comparison of the flow with collision geometry the eccentricity, $\epsilon_{std} = (\sigma_y^2 - \sigma_x^2)/(\sigma_y^2 + \sigma_x^2)$, of the interaction area was used. The PHOBOS experiment has proposed to introduce participant eccentricity [11], $\epsilon_{part} = \sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}/(\sigma_y^2 + \sigma_x^2)$, basing on positions of nucleons taking part in the collision (as obtained from Glauber Monte Carlo simulations). This definition accounts for the fact that the axis of the interaction area defined by the nucleons usually is rotated with respect to the reaction plane. Dividing of v_2 for $Au + Au$ and $Cu + Cu$ collisions by eccentricity allows to obtain a universal dependence on N_{part} only if ϵ_{part} is used (Fig. 5).

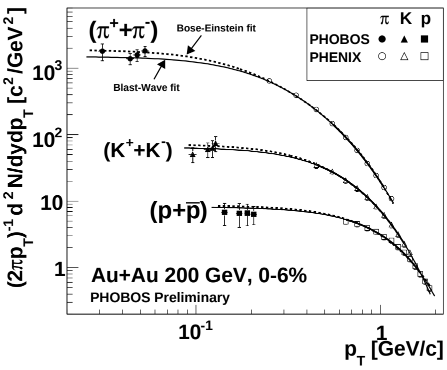

Figure 3: Identified particle spectra near mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The Blast-Wave (solid lines) and Bose-Einstein (dotted lines) parameterizations were fitted to the PHENIX experiment data [7] at larger p_T and extrapolated to the lowest p_T points measured by the PHOBOS experiment [8].

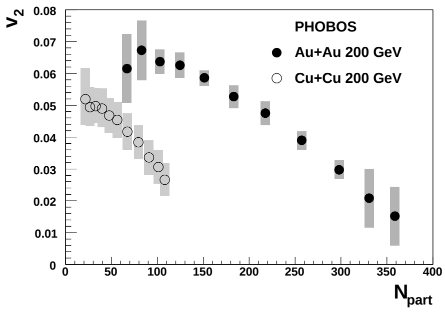

Figure 4: Elliptic flow, v_2, as a function of the number of nucleons taking part in Au+Au [9] and Cu+Cu [10] collisions at $\sqrt{s_{NN}}$=200 GeV.

One step further goes the analysis of the elliptic flow fluctuations [12]. The relative v_2 fluctuations measured by PHOBOS are large, they exceed 30%. The comparison with the fluctuations of participant eccentricity presented in Fig. 6 shows that the fluctuations present at the very beginning of collisions are not significantly modified during the expansion of the system.

Details of the expansion of the system and it's hadronization determine also two-particle correlations, which are measured by PHOBOS in the full azimuthal angle and a wide pseudorapidity range, $|\Delta\eta| < 3$. Earlier study of forward-backward multiplicity correlations has already shown strong short-range correlations, not explained by the models of $A + A$ collisions [14]. They can be interpreted and parameterized by a cluster model [15], which assumes that the particles are produced in two steps: first some unstable objects, clusters, are produced, later they decay into observed particles. Using the correlation functions obtained from the experimental data two basic parameters of the clusters can be extracted [16, 17]: K_{eff} - the effective number of particles forming

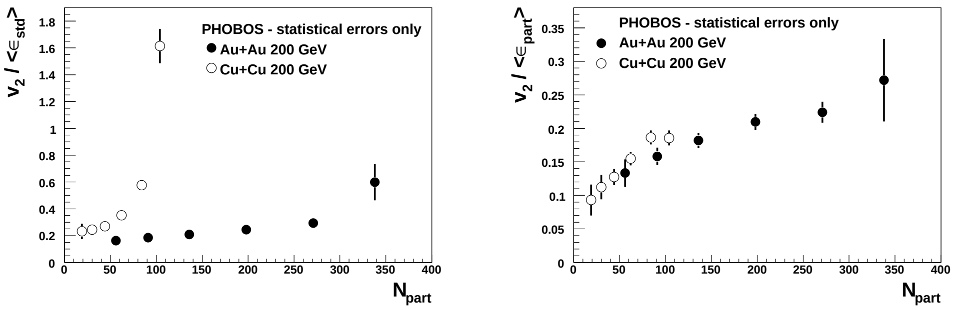

Figure 5: Elliptic flow, v_2, divided by eccentricity: standard, ϵ_{std} (left), and participant, ϵ_{part} (right) for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$=200 GeV [10].

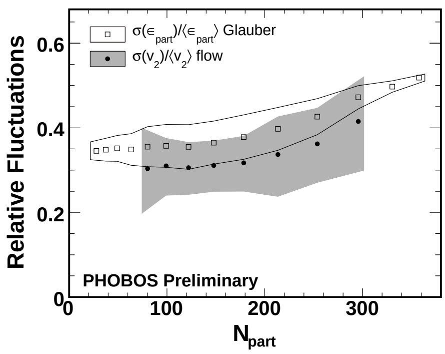

Figure 6: Relative fluctuations of elliptic flow, $\sigma(v_2)/ < v_2 >$, and relative fluctuations of eccentricity, $\sigma(\epsilon_{part})/\epsilon_{part}$ calculated in a Glauber Monte Carlo model, for Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV [12].

a cluster and δ - the width of the 2-particle correlation in η which is directly connected with the cluster width. The values of these parameters obtained for $p+p$, $Cu+Cu$ and $Au+Au$ collisions are presented in Fig. 7. Width of the clusters in the $A+A$ collisions seems to be larger than for $p+p$. The cluster size, K_{eff}, decreases with centrality of $A+A$ collision. The values of K_{eff} are large, especially as they were not corrected for acceptance effects (which would increase them) and that the neutral particles, which are not detected, belonging to the clusters are not counted. Interestingly, the centrality dependence for $Au+Au$ and $Cu+Cu$ becomes almost identical if events with similar shapes of nuclei overlap area are compared [17].

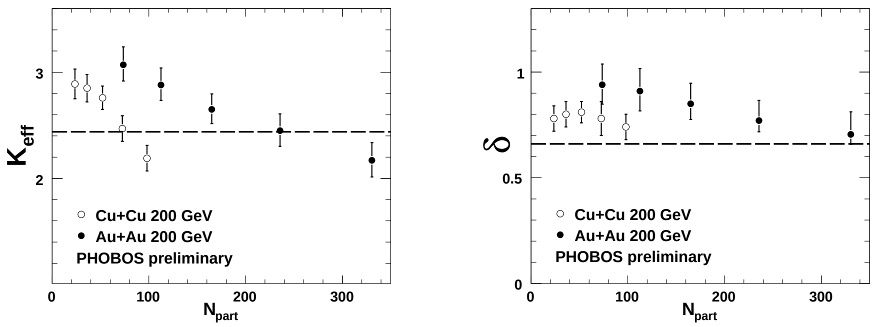

Figure 7: Effective cluster size, K_{eff} (left), and width parameter, δ (right), as the functions of the number of nucleons taking part in the Au+Au and Cu+Cu collisions [17]. The dashed lines represent values of these parameters for p+p collisions [16]. The values were obtained for $|\eta| < 3$ and were not corrected for acceptance effects.

4 Conclusions

In the collisions of heavy nuclei at very high energies extremely high energy density is reached and a new phase of matter, sQGP, is created [2]. Strong interactions in the quark-gluon matter are visible as the suppression of high-p_T particles, the lack of enhancement in low-p_T particles production and the presence of collective effects leading to elliptic flow. The yields of low-p_T particles and the elliptic flow are consistent with the assumption of expansion of the system, as predicted by hydrodynamic model for an almost perfect fluid. Global observables in the collisions of nuclei, not discussed in this paper, reveal unexpected simple relations: scaling of multiplicity with N_{part} and extended longitudinal scaling of $dN/d\eta$ and v_2 [1].

In the recent studies the PHOBOS experiment measured correlations of associated particles with a high-p_T trigger particle, which extend at least 4 units in pseudorapidity. Such long range correlations may be a sign of longitudinal expansion of the system. New results on the yields of low-p_T particles support the hypothesis of a radial component of such expansion. The shape of the interaction area, characterized by eccentricity ϵ_{part}, determines the value of elliptic flow, v_2. Fluctuations of elliptic flow are of the same size as the fluctuations of eccentricity at the very beginning of the collision. Strong short range correlations are observed in the A+A collisions, large size of clusters can not be explained by low mass resonances.

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