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RECENT RESULTS FORM THE BRAHMS EXPERIMENT AT RHIC *

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We present the results obtained by the BRAHMS experiment at the Relativistic Heavy Ion Collider (RHIC) for three colliding systems, namely: Au + Au, d + Au and p + p at $\sqrt{s_{NN}} = 200$ GeV. The main focus is here to give an overview of the main results on the reaction dynamics and on the properties of hot and high energy density matter produced in utra-relativistic heavy ion collisions. Measurement of particle production, particle spectra over boar rapidity interval as well as high pt measurements related to nuclear modification in Au + Au and d + Au collision are discussed. The observed number of charged particles produced per unit of rapidity at the central rapidity region indicates the high energy density (> 5 GeV/fm^3) system is created at the initial stage of the Au + Au reaction. From the particle spectra we deduced significant radial expansion ($\beta \approx 0.75$) which is consistent with the large initial energy density. For Au + Au at $\eta = 0$ we observe the suppression of the high p_T particles as compared to the elementary collisions, whereas for d + Au reaction the Cronin type enhancement is observed. We also discuss to what extent these results can be taken as evidence for the quark gluon plasma

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(QGP). Finally, we present the nuclear modification effects in d + Au reaction as a function of rapidity and consider whether the observed suppression at forward rapidities constitute the sufficient evidence for the possible precursor state to the QGP, i.e. the Color Glass Condensate (CGC).

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1. Introduction

Reactions between heavy nuclei provides a unique opportunity to produce and study nuclear (hadronic) matter far form it's ground state, at extremely high densities and temperatures. From the onset of formulation of the quark model and the first understanding of the nature of the binding and confining potential between quarks about 30 years ago it has been realized that at very high density and temperature the hadronic matter may undergo transition to the more primordial form of matter characterized by a strongly reduced interaction between its constituents, quarks and gluons, such that the partons would exist in the nearly free state. This proposed state of matter has been designated the quark gluon plasma (QGP).

Experimental attempts to create the QGP in the laboratory by colliding heavy nuclei have been carried out for more than 20 years. During that period, center of mass energies per pair of colliding nucleons have risen steadily from the $\sqrt{s_{NN}} = 1$ GeV domain of the Bevalac at LBNL, to energies of $\sqrt{s_{NN}} = 5$ GeV at the AGS at BNL, and to $\sqrt{s_{NN}} = 17$ GeV at the SPS at CERN. Although a number of signals suggesting the formulation of a very dense state of matter, no strong evidence for QGP formation was found at these energies.

In mid-August 2001 a systematic data collecting by the four RHIC experiments, namely BRAHMS, PHENIX, PHOBOS and STAR, began at the energy of $\sqrt{s_{NN}} = 200$ GeV. The RHIC operational started a new era of systematic studies of strongly interacting matter created in ultra-relativistic nucleus-nucleus collision. BRAHMS (Broad RAnge Hadron Magnetic Spectrometers) [1], consists of set of detectors designed to measure global features of the collision like overall charge particle multiplicity and the flux of spectator neutrons, and of two spectrometer arms that provide the measurement of the full particle four-momentum vector. By rotating the arms within the small (from 2 to 30 degree) and large particle emission angles (from 30 to 90 degree) BRAHMS can map the phase space over the large rapidity and transverse momentum range.

In the next section we will discuss the general features of system created in the high energy heavy ion reactions in the 'soft' (low p_T) regime like: particle production and related energy density, nuclear stopping, anti-particle to particle ratios and particle transverse spectra in the wide rapidity range. Thereafter we will concentrate on high p_T results, namely on the nuclear modification factors in Au + Au and d + Au collisions, measured by BRAHMS at central rapidity region. Furthermore will show the nuclear modification effects in d + Au reactions as a function of rapidity and discuss the possible theoretical explanations of the observed suppression at forward rapidities.

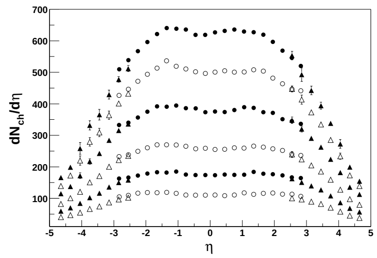

Fig. 1. Distributions of $dN_{ch}/d\eta$ measure by BRAHMS for Au + Au at $\sqrt{s_{NN}} = 200$ GeV GeV. The centrality bins are indicated on the plot.

Fig. 2. Multiplicity density of charged particles, at $\eta = 0$, normalised with the number participant pair as a function of energy. Systematics for nucleus - nucleus and p + p collisions are shown.

2. Overall bulk characteristics

Multiplicity distribution of emitted particles is a fundamental observable in ultra-relativistic collisions. It is sensitive to all stages of the reaction and can address issues like the role of hard scatterings between partons and the interaction of these partons in the high-density medium [2,3,4]. Figure 1 shows the measured pseudo-rapidity density of charged hadrons, dN_{ch}/dη over the wide range of η for different centralities indicated on the plot. For the most central collisions (0-5%) we observed about 4500 of charged particle within the rapidity range covered and the dN_{ch}/dη $|_{\eta=0} = 625$ *pm* 56. Figure 2 shows the energy systematic dN_{ch}/dη scaled with the number of participating nucleon pairs. It is seen that the production of charged particle in the central Au + Au collisions exceeds the particle production observed in elementary p + $\bar{p}$ collisions at the same energy by 40-50%. This means that nucleus-nucleus collisions at the considered energies are far from being the simple superposition of elementary collisions.

This simple measurement of charged particle density $dN_{ch}/d\eta$ can be used to

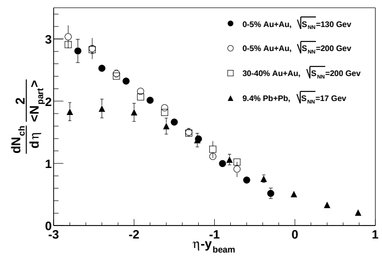

Fig. 3. Charged-particle multiplicities normalized to the number of participant nucleon pairs for indicated species, energies and centrality classes. Data at different beam energies are plotted as a function of the pseudo-rapidity shifted by the relevant beam rapidity.

estimate the so called Bjorken energy density, ε [5]. The formula

$$\varepsilon = \frac{3}{2} \times \frac{\langle E_t \rangle}{\pi R^2 \tau_o} \times \frac{dN_{ch}}{d\eta} \tag{1}$$

provides the value of ≈ 4 GeV/fm^3. In (1) we assumed that $\tau_o = 1$ fm/c, $\langle E_t \rangle = 0.5$ GeV and R = 6 fm. Factor 3/2 is due to the assumption that the charged particles carried out of the reaction zone only a fraction (2/3) of the total available energy. The more fine results obtained from the identified particle spectra calls for larger value of 5 GeV/fm^3 [8]. This value exceeds by factor of 30 the density of normal nuclear matter by factor of 5 the density of baryons and by factor of 5 the predicted energy density for the boundary between hadronic and partonic phases [7].

In Figure 3 we plot particles densities normalized to the number of participating pairs for SPS data, RHIC data at $\sqrt{s_{NN}}$ = 130 GeV, and RHIC data at $\sqrt{s_{NN}}$ = 200 GeV for two selected centrality cuts. Data at different beam energies are plotted as a function of the pseudo-rapidity shifted by the respective beam rapidity. It is seen that the particle production stays constant for different collisions geometries and different energies (from SPS to RHIC) at rapidity 0.5-1.5 units below the beam rapidity (fragmentation region). This behavior is consistent with the Limiting Fragmentation Picture in which the energy available for the particle production in the fragmentation region saturates already below top SPS energy. At mid-rapidity, however, there is a significant increase of the particle production with the increasing projectile kinetic energy - the dissipated energy is transported into the central rapidity region .

The rapidity density of net-proton measured by BRAHMS for central collision in the broad rapidity range is shown in Fig. 4 [9]. For comparison we plotted our results with the same measurement from AGS [10,11,12] and SPS [13]. The dashed vertical lines indicate the corresponding beam rapidities. As one can see, with the increasing energy (from AGS to RHIC) the nucleus-nucleus collisions are more and more transparent which is seen as a depletion of the net-proton density at central rapidities. At AGS we have about 60 net-protons per unit of rapidity whereas in BRAHMS we observe about 15 net-baryons. Our rapidity coverage for protons is

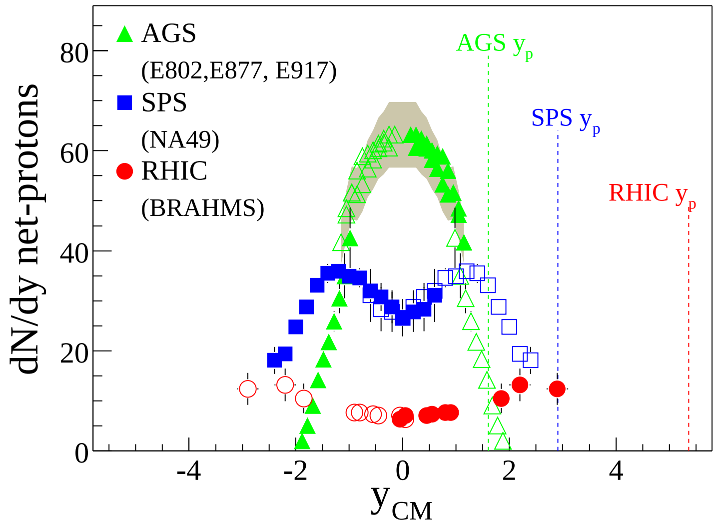

Fig. 4. Rapidity densities of net-protons measured at AGS, SPS and RHIC (BRAHMS).

limited to about 3, however, fits with two different parameterizations, with the integral fixed to N_{part}, give a very similar results on the average rapidity shift which is 2.0 ± 0.4 (see [9] for details). This value is significantly lower than predicted by the empirical linear scaling from lower AGS and SPS energies, so this scaling is broken at RHIC energies [14,15]. It should be noted that the rapidity loss is still significant and that, since the overall beam energy (rapidity) is larger at RHIC that at SPS, the absolute energy loss increases appreciably form SPS to RHIC. From the net-baryon density extrapolated to the full rapidity range we can calculate the energy carried by net-baryon after the collision and, from this, calculate the average energy loss which is 72 GeV per participant. This energy is available for the particle production.

BRAHMS measured also the anti-particle to particle rations for pions ($N(\pi^-)/N(\pi^+)$), kaons ($N(K^-)/N(K^+)$) and protons ($N(\bar{\mathrm{p}})/N(\mathrm{p})$) over the large rapidity interval. Whereas $N(\pi^-)/N(\pi^+)$ stays constant and is equal 1 in the whole covered rapidity range ($0 < \mathrm{y} < 3.2$) the $N(K^-)/N(K^+)$ and $N(\bar{\mathrm{p}})/N(\mathrm{p})$ equal respectively 0.95 and 0.76 at mid-rapidity decrease with increasing rapidity to reach values of 0.6 for $N(K^-)/N(K^+)$ and 0.3 for $N(\bar{\mathrm{p}})/N(\mathrm{p})$ around rapidity 3. Figure 5 shows the $N(K^-)/N(K^+)$ as a function of corresponding $N(\bar{\mathrm{p}})/N(\mathrm{p})$ for various rapidities. The data are for central collisions. AGS and SPS rasults for the same ratios are plotted for comparison. The solid line refers to the fit with statistical model assuming that the temperature at the chemical freeze-out is 170 MeV [?,17]. It is seen that the data are well described by the statistical model over the broad rapidity range with baryonic chemical potential changing from 27 MeV at mid-rapidity to 140 MeV at the most forward rapidities.

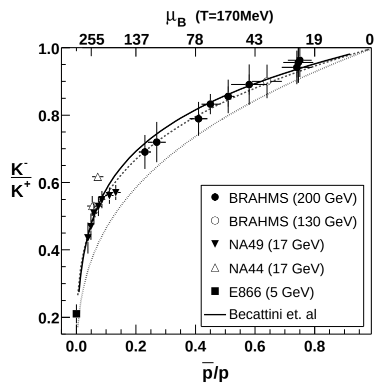

Fig. 5. Correlation between the ratio of charged kaons and ratio of anti-protons to protons. The solid curve refers to statistical model calculation with a chemical freeze-out temperature of 170MeV

Fig. 6. Preliminary temperature and transverse flow velocity at mid-rapidity as a function of centrality for Au + Au collisions.

The properties of matter in the latest stage of the collision when the interactions between particles cease (kinetic freeze-out) can be studied from the shape of spectra of the emitted particles. This shape depends in general on the temperature of the emitting source and on the collective flow. For central collisions where one should not expect any azimuthal depencendy only so called transverse (radial) flow is important [18,19]. In the so-called bast-wave approach the spectrum is parametrized by a function depending on the temperature and on the transverse expansion velocity. Figure 6 shows results from analysis of the particle spectra from the BRAHMS experiment using the blast-wave model fit, simultaneously to π^+, π^-, K^+,K^-, protons and anti-protons.

The obtained result indicates that the kinetic freeze-out temperature is in the range 120 - 140 MeV and that the maximum flow velocity is about 0.7 - 0.75c (see Fig. 6). The first quantity is lower than the temperature of the chemical freeze-out indicating that, as expected, the freeze-out of particle ratios occurs earlier than the kinetic freeze-out. The transverse flow velocity is larger than that observed at SPS energies. This is consistent with a large initial density of the system created at the RHIC.

3. High p_T suppression

Particles with high p_T (above 2 GeV/c) are primarily produced in hard scattering processes early in the collision. In high energy nucleon-nucleon reactions hard scattered partons fragment into jets of hadrons. However, in nucleus-nucleus collision hard scattered partons travel in the medium. If the medium is QGP the partons will lose a large fraction of their energy by induced gluon radiation, effectively leading to suppression of jet production. Experimentally this phenomenon, known as a Jet Quenching, will be observed as a depletion of high p_T region in hadron spectra.

The measure commonly used to study the medium effects is called the nuclear modification factor, R_{AA}. It is defined as a ratio of the particle yield produced in nucleus-nucleus collision, scaled with the number of hard collisions, and the particle yield produced in elementary nucleon-nucleon collision:

$$R_{AA} = \frac{Yield(AA)}{N_{coll} \times Yield(NN)} \tag{2}$$

As mentioned above, at the high p_T the particle production is dominated by the hard scattering, so in the absence of nuclear effects (when the nucleus-nucleus collision reduces to the superposition of elementary collisions) we expect R_{AA} to be 1. At low p_T , where the production rate scales rather with N_{part} R_{AA} should converge to N_{part}/N_{coll} which is roughly 1/3 for Au + Au at RHIC energies. $R_{AA} < 1$ at high p_T 's will indicate the suppression which, as has been discussed, is the indication for the Jet Quenching. At SPS there is no suppression, in fact it is well known that there is enhancement for $p_T > 2$ GeV/c and this so called Cronin effect is attributed to initial multiple scattering of reacting partons. The nuclear modification factors constructed from the hadron spectra measured by BRAHMS are presented in Figure 7. The elementary collision reference spectrum is from $p + \bar{p}$ reactions measured by UA1 experiment at CERN [21] At mid-rapidity for central collisions we see a clear suppression in the high p_T region. For peripheral collisions there is no suppression as expected and we see the nice scaling consistent with number of hard scattering. At rapidity 2.2 we observe the same trend however because of large systematic uncertainty from the reference spectra the systematic errors (shaded areas) are large. To limit these errors we defined the R_{CP} which is a scaled particle yield at central collisions to the scaled yield at the peripheral collisions. R_{CP} shows suppression at both studied rapidities [20].

However, it has been conjectured that the observed suppression might be the result of the entrance channel effect like the initial state parton saturation, which is also called the Color Glass Condensate (CGC). As a test of these ideas we determined the nuclear modification (R_{dAu}) for d + Au reaction at the same energy in the nucleon-nucleon frame. It is obvious that the quenching in the medium cannot

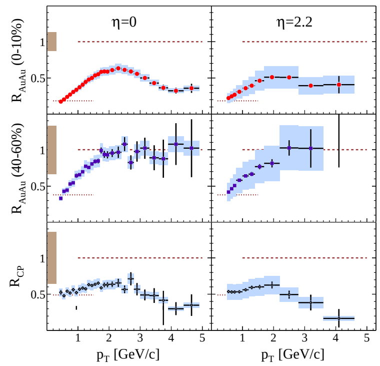

Fig. 7. Nuclear modification factors R_{AuAu} for central and semi-peripheral Au + Au collisions at mid-rapidity (left column) and $\eta = 2.2$ (right column). The bottom row shows the factor R_{CP} which has the property of being independent on the p + p reference spectrum [20].

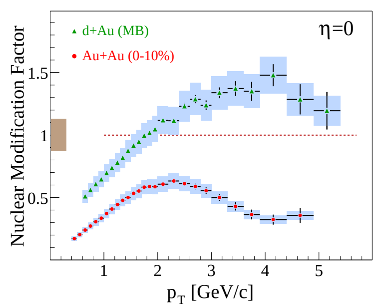

Fig. 8. Nuclear modification factor measured for minimum bias d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV GeV compared to central Au + Au collisions. The gray band at $p_T = 0$ is the uncertainty on the scale of R_{AuAu}.

be present in d + Au reactions, so the measurement of R_{dAu} could be a good test whether the CGC scenario can account for the observed suppression in central Au + Au collisions. The measured minimum bias R_{dAu} at η=0 is shown in Figure 8. For comparison we plotted also R_{AuAu} for central collision. It is seen from the figure that R_{dAu} exhibits no suppression, in contrary we see the Cronin type enhancement. Thus we conclude that the lack of suppression in d + Au at mid-rapidity excludes alternative interpretation in term of initial state parton saturation (CGC) effects and supports the Jet Quenching scenario for central Au + Au collisions. Let us add that the STAR collaboration supplemented this check out by proving that the high p_T particles observed in nucleus-nucleus reaction at RHIC reflect the azimuthal topology expected for Jets [22].

Let us supplement this qualitative discussion by more quantitative considerations. Hirano and Nara modelled the final state parton interaction in very simple and intuitive way. They applied hydro-dynamical model to describe the evolution of soft part of created matter and the perturbative QCD (pQCD) base model to

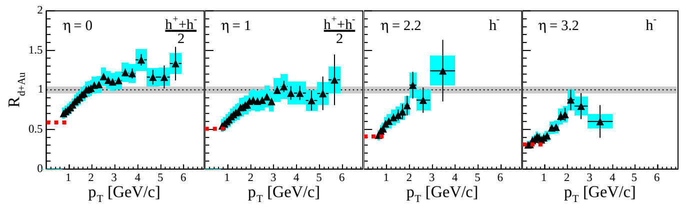

Fig. 9. Nuclear modification factor for charged hadrons measured in central d + Au collisions at pseudo-rapidities η = 0, 1, 2.2, 3.2 [24]. (Need to update this plots for eta=3.2)

generate high p_T probes inside the evolving medium. The results of this calculation provide a good quantitative description of the measured R_{AuAu} both for η=0 and η=2.2 [23].

4. Rapidity evolution of R_{dAu}

BRAHMS also investigated the evolution of R_{dAu} with rapidity. The result is presented in Figure 9. It turn out that mentioned absence of suppression at central rapidity is not the case at forward rapidities, namely we observe the increasing suppression with increasing rapidity on the deuteron side and at $\eta = 3.2$, R_{dAu} is well below the binary scaling [24]. This forward rapidity data triggered a noticeable activity of theorists. Accardi and Gyulassy tried to describe the suppression within the pQCD approach imposing a large geometrical shadowing, but even with opacity 3 times the opacity form the fit to data at mid-rapidity, the proposed model significantly overpredicts the measured R_{dAu} [25]. More recently Kharzeev et al. made a calculation assuming that the forward production can be described in terms of the quark-dipole scattered on the nucleus which can be described as a CGC. These calculations give the overall good description of data also with the reasonable description of the centrality dependence [26]. The CGC model also describes successfully the overall charge particle production in d + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV GeV measured by BRAHMS [27,28]. We should also note the approach presented at this workshop by E. G. Ferreiro. It was shown that the difference in R_{dAu} between $\eta = 0$ and $\eta = 3.2$ measured by BRAHMS can be explained in the string model such as Dual Parton Model with the addition of dynamical shadowing correction (to readers: I have no idea whether they can describe also the centrality dependence what this is crucial) [29].

5. Summary

The results from the first round of BRAHMS and other RHIC experiments clearly show that studies of high energy nucleus - nucleus collision have moved to a qualitatively new physics domain characterized by a high degree of reaction transparency leading to the formation of a near baryon free central region with approximate balance between matter and antimatter. From the study of nuclear stopping we learnt that there is appreciable energy loss of the colliding nuclei providing the conditions for the formation of a very high energy density zone around mid-rapidity. The lower limit for this energy at $\tau_o = 1$fm/c determined from the particle multiplicities and spectra is 5 GeV/fm^3, therefore the condition necessary for the formation of a deconfined system appear to be fulfilled. Analysis within the statistical model of the relative abundances of π^-, π^+, p and $\bar{p}$ suggests the equilibrium at chemical freeze-out at temperature of 170 MeV. The particle spectra suggest large transverse expansion (with expansion velocity above 0.7c) which is consistent with the high initial energy density.

The remarkably large high p$_T$ suppression is observed in central Au + Au collisions. This effect appears readily explainable by radiation losses due to the interaction of high p$_T$ partons with the deconfined medium. The theoretical investigations indicate that scenarios based on interactions between hadronic objects cannot reproduce the magnitude of the observed effect as well as they exclude the effect of shadowing near the central rapidity zone. Additionally, the absence of suppression in d + Au reactions at $\eta = 0$ excludes alternative interpretation of suppression for Au + Au in terms of initial effects like CGC. The last effect, however, might be responsible for the suppression of R$_{dAu}$ at the forward rapidities seen from the BRAHMS data (PHOBOS and PHENIX confirmed the same trend but in the much smaller rapidity interval). Nevertheless, more efforts, both on experiment and theory side, are required to verify the origin of the forward rapidity suppression in nucleon - nucleus collisions.

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