Quark Gluon Plasma and Color Glass Condensate formed at RHIC? A perspective from the BRAHMS experiment.

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We review the main results obtained by the BRAHMS collaboration on the properties of hot and dense nuclear matter produced in ultrarelativistic heavy ion collisions at RHIC. A particular focus of this article, (or white paper), is to discuss to what extent the results collected so far by BRAHMS and by the other three experiments operating at RHIC can be taken as evidence for the formation of a state of deconfined partonic matter, the so called quark-gluon-plasma (QGP). We also discuss possible precursor mechanisms to QGP formation, eg. the proposed Colar Glass Condensate.

1. Introduction

From the onset of the 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 conjectured that a state of matter characterized by a large density of quarks and gluons (together called partons) might be created for a fleeting moment in violent nuclear collisions (refs 4,5, of GandMcL). This dense state would be characterized by a strongly reduced interaction between its constituents, the partons, such that the partons would exist in a nearly free state. Aptly, this proposed state of matter has been designated the quark gluon plasma (QGP). It now generally thought that the early universe was in a QGP state until its energy density had decreased sufficiently , as a result of the adiabatic expansion of the universe, that it could make the transition to ordinary (confined) matter.

Experiments to create the QGP and measure the critical temperature have been carried out for more than 20 years, studying collisions of heavy nuclei (e.g. Au, Pb or U) and analyzing the fragments and produced particles emanating from such collisions. During that period center of mass energies per pair of colliding nucleons have risen steadily from the $\sqrt{s_{NN}} \approx 1$ GeV domain of the Bevalac at LBNL, to energies of $\sqrt{s_{NN}} = 5$ GeV at the AGS at BNL, and of $\sqrt{s_{NN}} = 17$ GeV at the SPS accelerator at CERN. No decisive proof of QGP formation was found in the experiments at those energies, although a number of signals suggesting the formation of a 'very dense state of matter' were found at SPS (ref. CERN press release and papers).

With the Relativistic Heavy Ion Collider, RHIC, at Brookhaven National Laboratory a new chapter in the story of the production and study of nuclear matter at extreme energy density and temperature has begun. In collisions between gold nuclei at 100AGeV+100AGeV at RHIC the total energy in the center of mass is almost 40TeV, the largest so far achieved in nucleus-nucleus collisions under laboratory conditions. This energy is so large that conversion of a sizeable fraction of the initial kinetic energy into matter production creates many thousands of particles in a limited volume leading to unprecedented large energy densities and thus ideal conditions for the formation of the quark gluon plasma.

RHIC started regular beam operations in the summer of year 2000 with a short commissioning run colliding Au nuclei at $\sqrt{s_{NN}} = 130$ GeV). The first full run at the top energy ($\sqrt{s_{NN}} = 200$ GeV) took place in the fall/winter of 2001/2002. The third RHIC run during the winter/spring of 2003 focussed on d+Au and p+p reactions. Recently in 2004, a long high luminosity Au+Au run at $\sqrt{s_{NN}} = 200$ GeV and a short run at ($\sqrt{s_{NN}} = 63$ GeV) have been completed. The collected data from the last run are currently being analyzed and only a few very preliminary sample results are available.

The main aim here is to review the available information obtained from these first experiments with the purpose of determining what the experimental results, accumulated so far, allow us to say about the high density state of matter that is created at RHIC in collisions between heavy atomic nuclei.

We concentrate primarily on results from the BRAHMS detector, one of the four major detectors at RHIC, but naturally also refer to results obtained by the other three experiments at RHIC (STAR, PHENIX and PHOBOS) insofar as they complement or supplement information obtained from BRAHMS. The large number of articles from the four experiments at RHIC may be found on their respective homepages (ref. 9-12 of GandMcL). Recent extensive theoretical reviews and commentaries may be found in (refs. GandMcL-nucl-th0405013, Shuryak-hep-ph/0405066, etc...).

The BRAHMS experiment is a two arm magnetic spectrometer with excellent momentum resolution and particle identification capabilities for hadrons. The two spectrometers subtend only a small solid angle (a few msr) each, but they can rotate in the horizontal plane about the collision point enabling the collection of data on hadron production over a wide rapidity range (0-4), a unique capability among the RHIC experiments. For details about the BRAHMS detector system we refer the reader to [1,2].

2. What is a QGP and what does it take to see it?

The predicted transition from ordinary matter, which consists of hadrons inside which quarks and gluons are confined, to the QGP, a matter state in which quark and gluons are no longer confined to volumes of hadronic dimensions, can in the simplest approach be likened to the transition between two thermodynamic states in a closed volume.

As energy is transferred to the lower energy state a phase transition, akin to a melting or evaporation process, to the higher energy state occurs. For a first order phase transition (PT), the transformation of one state into the other occurs at a specific temperature, termed the critical temperature, and the process is characterized by absorption of latent heat during the phase conversion leading to a constancy or discontinuity of certain thermodynamic variables as the energy density is increased. In this picture it is tacitly assumed that the phase transition occurs between states in thermodynamic equilibrium. From such thermodynamic considerations and from more elaborate models based on the fundamental theory for the strong interaction, Quantum Chromo Dynamics (e.g. lattice QCD calculations), estimates for the critical temperature and the order of the transition can made. Calculations indicate that the critical temperature should be $T_c \approx 150 - 180 MeV$ in the case of a vanishing baryon chemical potential (refs 17-20 of GandMcL). In general, a decreasing critical temperature with increasing chemical potential is expected. Likewise, at non-zero chemical potential a mixed phase of coexisting HG and QGP is predicted to exist in a certain temperature interval around the critical temperature. Recently calculational techniques have progressed to the point of allowing an extension of the lattice methods also to finite chemical potential (ref. Karsch et al).

The transition from ordinary matter (the hadron gas, HG) to the QGP is thus primarily a deconfinement transition. However, it is also expected, due to the vanishing interaction between partons in the QGP phase, that hadron masses will be strongly modified and in fact lowered. In the limit the hadrons are massless and thus identical (chiral symmetry). As a consequence of the QGP to HG transition, the chiral symmetry is broken and the hadrons acquire a definite mass. Thus the transition is also a chiral symmetry transition. General theoretical arguments have been advanced for the equivalence of the critical temperature for chiral symmetry restoration and deconfinement (ref.–CHECK THIS ??).

It is, however, at the onset not at all clear that the transition to the QGP, as it is expected to be recreated in nucleus-nucleus collisions, proceeds between states of thermodynamic equilibrium as sketched above. The reaction, from first contact of the colliding nuclei to freeze-out of the created fireball, occurs on a typical timescale of about 10 fm/c and is governed by complex reaction dynamics so that non-equilibrium features are important. Likewise there can be significant reinteraction of the strongly interacting components of the system, after its formation, that tends to smooth specific features associated with a phase transition.

Many potential experimental signatures for the existence of the QGP have been proposed. These can be roughly grouped into two classes: 1) *evidence for bulk properties consistent with QGP formation*, e.g. large energy density, entropy growth, plateau behavior of the thermodynamic variables, unusual expansion and lifetime properties of the system, presence of thermodynamic equilibration, fluctuations of particle number, charge etc, and 2) *evidence for modifications of specific properties of particles though to arise from their interactions with a QGP*, e.g. the modification of widths and masses of resonances, modification of particle production probabilities due to color screening (e.g. J/Psi suppression) and modification of parton properties due to interaction with other partons in a dense medium (e.g. jet quenching), etc.

We may now ask the following questions: 1) What is the requirement for calling a state of matter a QGP?, and 2) What would constitute proof of QGP formation according to that definition?

As far as the first question is concerned it would seem obvious that the the determining factor is whether the high density state that is created in the nuclear collisions clearly has properties that are determined by its partonic composition, beyond what is known at the nucleon level in elementary nucleon-nucleon collisions (e.g. p+p collisions). It has often been presupposed that the 'plasma' should be in thermodynamical equilibrium. However, it does not appear to be essential that equilibrium should be established as long as the system under consideration is one consisting of partons without imposed hadronic boundaries. Finally, it may be asked whether chiral symmetry restoration is essential. It would seem that even in a situation in which the partons of the system are still (strongly) interacting one may speak of a QGP as long as the constituents are not restricted to individual hadrons. Thus it would seem that *deconfinement* is the foremost property needed to define the QGP state, and the one that needs to be proven by experiment.

Clearly, the observation of all, or at least of a number of the effects listed above, in a mutually consistent fashion, would serve to constitute a strong case for the formation of a QGP, as long as the observed effects can be unambiguously related to expected properties of the QGP state. In particular, the observed effects must not be also describable within other frameworks, e.g. those based on purely hadronic interactions and not explicitly involving the partonic degrees of freedom. This suggests the requirement that a 'proof', in addition to having consistency with QGP formation, also must contain elements that are *only* describable in terms of QGP formation, phase transition etc.

Finally, if a sufficiently good case exists, we may also ask if there are any specific features that may *falsify* the conclusion. To our knowledge no tests have been proposed that may allow falsification of either a partonic scenario or a hadronic scenario, but it would be important if any such exclusive tests were to be formulated.

3. Reactions at RHIC: how much energy is released?

The stopping of atoms in matter is a long standing subject. Studies of the stopping of nuclei in collisions with each other are of more recent origin. For the subject at hand the degree of stopping, determines the amount of energy that can be converted into a material state such as the QGP.

A useful way to quantify the stopping is by the rapidity loss experienced by the baryons

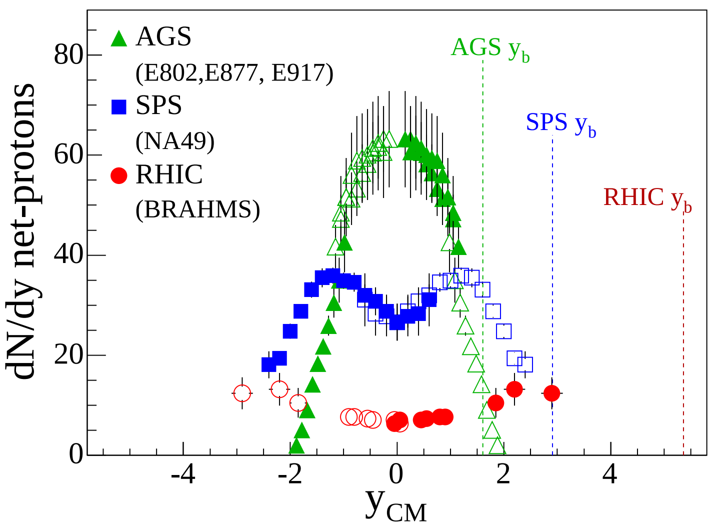

Figure 1. Preliminary rapidity densities of net protons (i.e. number of protons minus antiprotons) measured at AGS, SPS, and RHIC(BRAHMS). At RHIC, the full distribution cannot be measured with current experiments, but BRAHMS will be able to extend its measurements to y=3.5 in coming runs, corresponding to measurements at 2.3 degrees with respect to the beam.

in the colliding nuclei. Rapidity is defined as

$$y = \frac{1}{2} ln(\frac{E + p_z}{E - p_z}) = \frac{1}{2} ln(\frac{1 + \beta cos\theta}{1 - \beta cos\theta}) \qquad (1)$$

where E, pz, β and θ denote the total energy, longitudinal momentum, velocity and angle relative to the beam axis, respectively, of a particle. If incoming beam baryons have rapidity, y_b relative to the CM (which has $y = 0$) and average rapidity

$$< y >= \int_0^{y_b} y \frac{dN}{dy} dy \qquad (2)$$

after the collision, the rapidity loss is $\delta y = y_b - < y >$. Here dN/dy denotes the number of particles per unit of rapidity. Thus, for the extreme case of full stopping: $\delta y = y_b$. This corresponds to the situation found at very low energies where all the beam baryons loose all their kinetic energy. In the expression above a complication arises at CM energies large enough to allow for the formation of baryon-antibaryon pairs. Thus the baryon dN/dy distribution to be used is that for the net number of baryons (i.e. the difference between the number of baryons and antibaryons).

At AGS energies the number of produced antibaryons is quite small and the the net-baryon distribution is similar to the proton distribution. The net-proton rapidity distribution is centered around $y = 0$ and is rather narrow. The rapidity loss is about 1 for a beam rapidity of approx. 1.6. At CERN-SPS energies ($\sqrt{s_{NN}}$ = 17 GeV, 158 AGeV Pb+ Pb reactions) the rapidity loss is about 2 for a beam rapidity of 2.9, about the same relative rapidity loss as at the AGS. The fact that the rapidity loss is large on an absolute scale means, however, that there is still a sizeable energy loss of the colliding nuclei. This

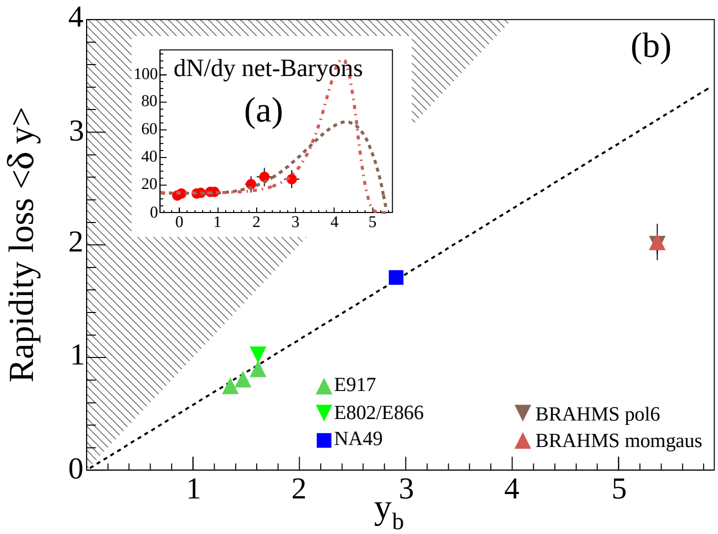

Figure 2. Upper panel: estimates of possible net-baryon distributions requiring baryon number conservation. We have assumed that $N(n) \approx N(p)$ and scaled hyperon yields at midrapidity to forward rapidity using HIJING. From these extremes, quite tight limits on the rapidity loss of colliding Au ions at RHIC can be set (lower panel).

energy is available for particle production and other excitations. Indeed, in collisions at the SPS, multiplicities of charged hadrons are about dN/dy=180 around y=0. At SPS another feature is visible (see fig. 1): the net proton rapidity distribution shows a double 'hump' with a dip around y=0. This is a consequence of two effects: the finite rapidity loss of the colliding nuclei and the finite width of each of the humps, which reflect the rapidity distributions of the protons in the colliding nuclei after the collisions. This picture suggests that the reaction at the SPS is beginning to be transparent in the sense that fewer of the original baryons are found at midrapidity after the collisions, in contrast to the situation at lower energies.

BRAHMS has measured the net proton rapidity distribution at RHIC in the interval $y = 0 - 3$ in the first run with (0-10%) central Au+Au collisions at full energy. The beam rapidity at RHIC is about 5.4. Details of the analysis may be found in refs.[3]. The results are displayed in fig. 1 together with the previously discussed net-proton distributions measured at AGS and SPS. It is notable that the RHIC distribution is both qualitatively and quantitatively different from those at lower energies.

The net number of protons per unit of rapidity around y=0 is only about 7 and the distribution is flat over at least the first unit of rapidity. The distribution increases in the rapidity range $y = 2 - 3$ to an average $dN/dy \approx 12$. We have not yet completed the measurements at the most forward angles (highest rapidity) allowed by the geometrical setup of the experiment, but we can exploit baryon conservation in the reactions to try to set limits on the relative rapidity loss at RHIC. This is illustrated in fig. 2, which shows various possible distributions whose integral areas correspond to the number of baryons present in the overlap between the colliding nuclei. From such distributions one may deduce a set of upper and lower limits for the rapidity loss at RHIC. In practice the situation is complicated by the fact that not all baryons are measured. We measure in

BRAHMS the direct protons, but only some of the decay protons from for example Λ. The limits shown in the figure include some reasonable estimates of these effects [3,6]. The conclusion is that the *absolute* rapidity loss at RHIC ($\delta y = 2.2 \pm 0.4$) is not appreciably larger than at SPS. In fact the *relative* rapidity loss is significantly reduced as compared to an extrapolation of the low energy systematics [4].

It should be noted that the rapidity loss is still significant and that, since the overall beam energy (rapidity) is larger at RHIC than at SPS, the *absolute energy loss* increases appreciably from SPS to RHIC thus making available a significantly increased amount of energy for particle creation in RHIC reactions.

In particular we have found that the average energy loss of the colliding nuclei corresponds to about 73 ± 6 GeV per nucleon. From our measurements of the particle production as a function of rapidity (pions, kaons and protons and their antiparticles) we can deduce not only the number of produced particles but also their average transverse momentum and thus their energy. Within systematic errors of both measurement we find that the particle production is consistent with the energy that is taken from the beam.

Thus the energy loss measurements clearly establish that as much as 26 TeV kinetic energy is removed from the beam per central Au+Au collision. This energy is available for particle production in a small volume immediately after the collision.

4. Energy density

The stopping scenario that we observe at RHIC and which was outlined in the previous section indicates that the reaction can be viewed as quite transparent (opaque is perhaps a better word). After the collision, the matter and energy distribution can be conceptually divided up into two main parts, namely a so-called fragmentation region consisting of the excited remnants of the colliding nuclei which have experienced an average rapidity loss of about 2.2 and a central region in which few of the original baryons are present but where significant energy density is collected. This picture is consistent with the schematic one already proposed by Bjorken 20 years ago [5].

The central region (an interval around midrapidity) is decoupled from the fragments. In the theoretical scenario the energy removed from the kinetic energy of the fragments is initially stored in a color field strung between the receding partons that have interacted. The linear increase of the color potential with distance eventually leads to the production of quark-antiquark pairs. Such pairs may be produced anywhere between the interacting partons leading to an approximately uniform particle production as a function of rapidity. In this picture, the properties of the particle production is also uniform as a function of rapidity (boost invariance). If the density of produced quark-antiquark pairs is sufficiently high, the average distance between them will be low and the binding potential between the colored objects will be small. The objects will become asymptotically free and exist in a plasma like state until the subsequent expansion and lowered density leads to confinement and hadronization.

Figure 3 shows the overall multiplicity of charged particles observed in Au+Au collisions at RHIC [2,7] for various collision centralities and as a function of pseudorapidity (pseudorapidity, η, is defined as $\eta = ln(cot(\theta/2))$ and is a customary rapidity variable for non identified particles). The figure shows that the multiplicity at RHIC is about

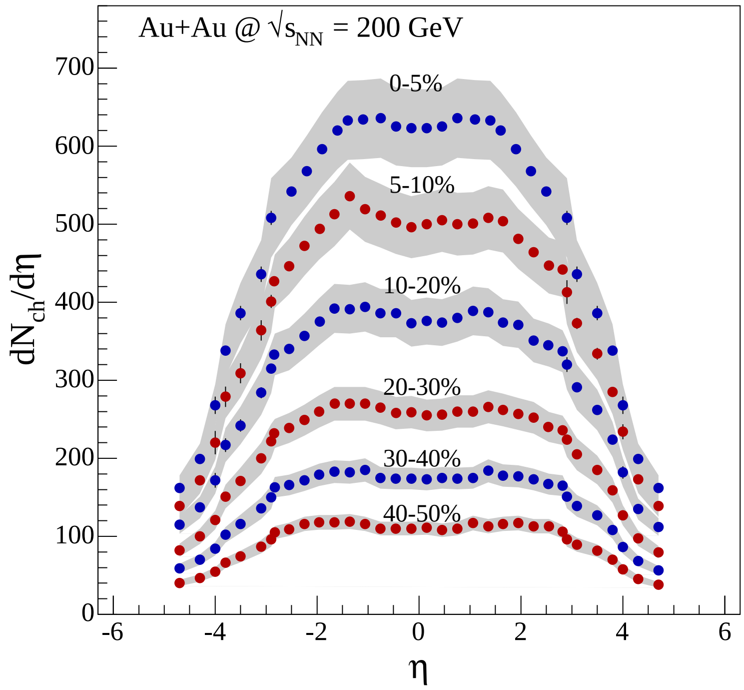

Figure 3. Pseudorapidity densities (multiplicities) of charged particles measured by BRAHMS for $\sqrt{s_{NN}}$ = 200 GeV) Au+Au collisions. The various distributions correspond to collision centralities 0-5% (top), 5-10%,10-20%,20-30%,30-40%, 40-50%. The integral of the most central distribution corresponds to about 4600 charged particles [2].

$dN/d\eta = 625$ charged particles per unit of rapidity around $\eta = 0$ for central collisions. This production of charged particles in central collisions exceeds the particle production seen in p+p collisions at the same energy by about 40%, when the yield seen in p+p collisions is multiplied by the number of participant nucleon pairs in the overlap region between the colliding nuclei.

Integration of the charged particle pseudorapidity distributions corresponding to central collisions tells us that about 4600 charged particles are produced in each of the 5% most central collisions. Since we only measure charged particles, and not the neutrals, we multiply this multiplicity by 3/2 to obtain the total particle multiplicity of about 7000 particles.

From the measured spectra of pions, kaons and protons and their antiparticles as a function of transverse momentum we can determine the average transverse momentum for each particle species (fig. **??**). This allows us to estimate the initial energy density from Bjorkens formula:

$$\epsilon = \frac{1}{\pi R^2 \tau} \frac{d < E_t >}{d\eta} \tag{3}$$

where we can make the substitution $d < E_t > = < m_t > dN$ and use quantities from the measured spectral distributions. Since we wish to calculate the energy density in the very early stages of the collision process we may use for R the radius of the overlap disk

Figure 4. Multiplicity of charged particles per participant pair as a function of $\sqrt{s_n n}$. WHO HAS OR MAKES THIS PLOT?

between the colliding nuclei, thus neglecting transverse expansion. The formation time is more tricky. It is often assumed to be of the order of 1 fm/c, a value that may be inferred from the uncertainty relation an the typical relevant energy scale (200 MeV). Under these assumptions we find that $\epsilon > 5GeV/fm^3$. This value of the initial energy exceeds the energy density of a nucleus by a factor of 30 , the energy density of a baryon by a factor of 10, and the critical energy density for QGP formation that is predicted by lattice QCD calculations by a factor of 5.

We may argue that the time at which the energy density should be estimated is the time relevant for the passage of the two nuclei through each other. As seen from the CM frame (which, for Au+Au collisions, is identical with the laboratory frame of reference) the nuclei are Lorentz contracted by a factor of 100, thus only having longitudinal thicknesses of the order of 0.15 fm. The typical traversal time is thus of the order of 0.15 fm/c. This leads, utilizing the equation above, to an estimated initial energy density of about $35GeV/fm^3$. This value exceeds the energy density of the baryon by a factor of about 70 and the predicted critical density by a factor of 35.

The particle multiplicities that are observed at RHIC indicate that the energy density associated with particle production in the initial stages of the collisions largely exceeds the energy density of hadrons.

5. Is there thermodynamical and chemical equilibrium at RHIC?

It has traditionally been considered important to determine whether there is thermodynamical equilibration of the 'fireball', in relativistic collisions in general, and at in RHIC in particular. The main reason is that, if there is thermalization, the simple two phase model may be invoked and the system should evidence the recognizable features of a phase transition. In nuclear collisions, however, the time scale available for equilibration is very short and the entire system only lives in the order of 10 fm/c. Consequently, it is not evident that the system will evolve through equilibrated states. If equilibrium is established, it would suggest that the system existed for a short time in a state with sufficiently short mean free path. A central issue is whether equilibrium is established in the hadronic cloud in the later stages of the collisions just prior to freeze-out or whether it is established on a partonic scale prior to hadronization. Thus, even if equilibration *per se* is probably not a requirement for defining the QGP, it may prove to be an important tool in *identifying* the QGP.

5.1. Particle yields

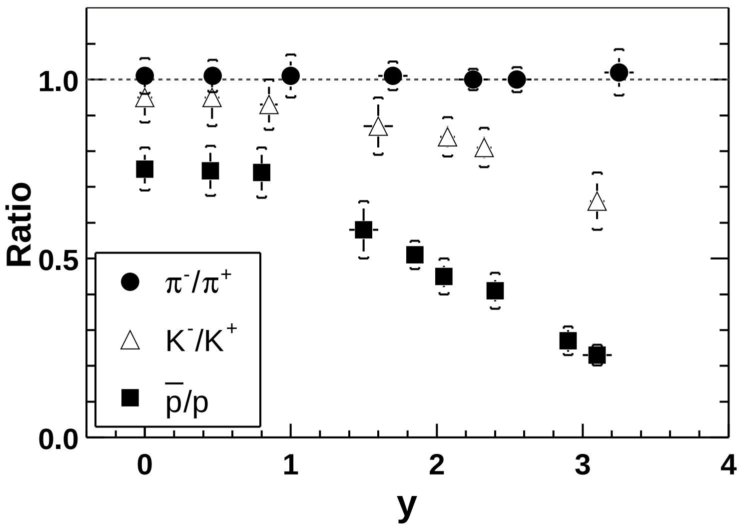

Figure 5. Ratios of antiparticles to particles (pions, kaons and protons) as a function of rapidity for $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions measured by the BRAHMS experiment [8]. For the first time in nuclear collisions an approximate balance between particles and antiparticles is seen around midapidity.

Figure 6 shows a recent and more detailed study of the particle production in central collisions as a function of rapidity [14,**?**]. The figure shows the rapidity densities of pions and kaons for central collisions. From such distributions we can construct the ratio of the yields of particles and their antiparticles as a function of rapidity. Figure 5 shows the ratios of yields of antihadrons to hadrons (posititive pions, kaons and protons and their antiparticles). The ratio is seen to be approaching unity in an interval of about 1.5 units of rapidity around midrapidity, suggesting that the particle production is predominantly from pair creation. This is exactly true for pions (ratio of 1), but less so for kaons (ratio= 0.95) and protons (ratio= 0.76). The reason is that there are other processes that break the symmetry between particles and antiparticles that depend on the net-baryon distribution discussed in the previous section. One such process that is relevant for kaons is the associated production mechanism (e.g. $p + p \to p + \Lambda + K^+$) which leads to an enrichment of positive kaons in regions where there is an excess of baryons. Support for this view is given by fig. 7, which shows the systematics of kaon production relative to pion production as a function of center of mass energy. At AGS, where the net proton density is high at midrapidity, the rapidity density of K^+ strongly exceeds that of K^-. In contrast, at RHIC, production of K^+ and K^- is almost equal. This situation changes, however, at larger rapidities where the net proton density increases.

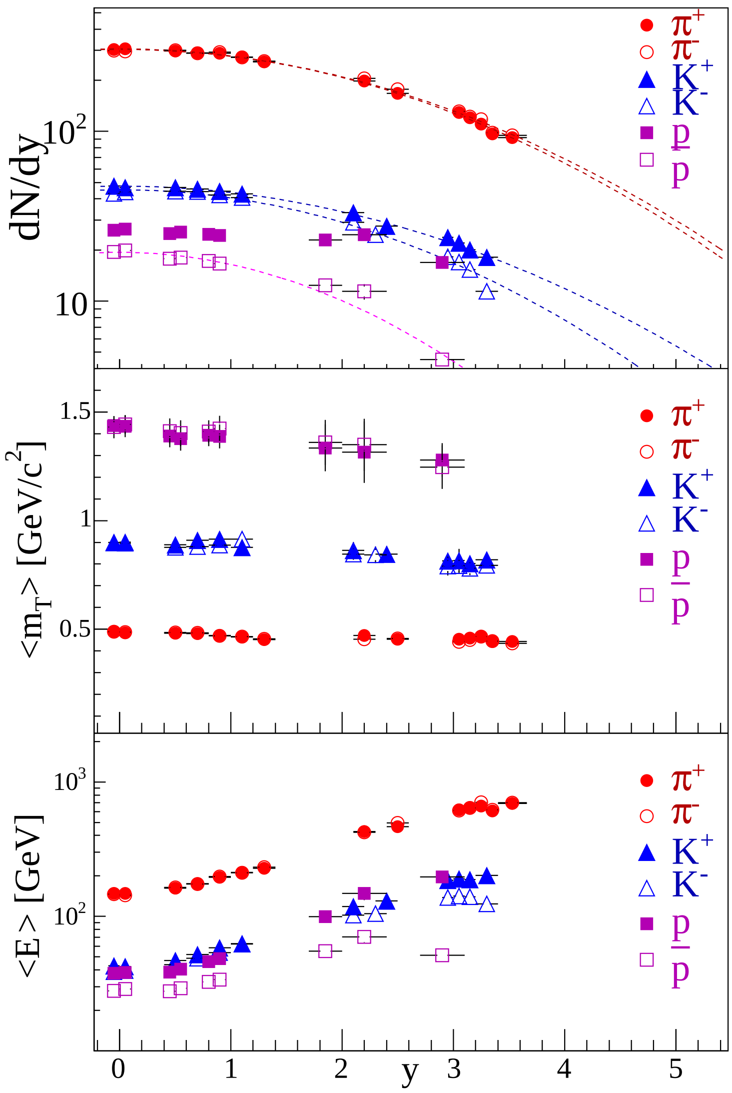

Figure 6. Rapidity density distribution for positive and negative pions and kaons. Data points collected at positive y have been reflected around y=0.

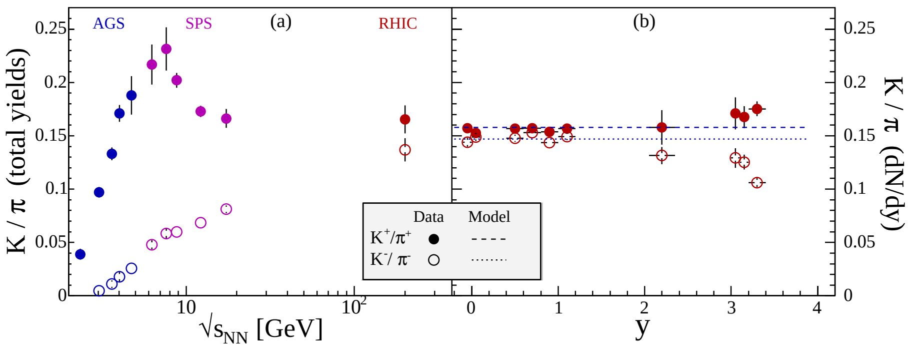

Figure 7. Ratios of kaons and pions of both charge signs as a function of center of mass energy in the nucleon-nucleon system at midrapidity. At top RHIC energy the two ratios are about the same and equal to 0.15.

The particle yields measured by BRAHMS also lend themselves to an analysis of the charged particle production in terms of the statistical model [8],[9–12]. Figure **??** shows the ratios of negative kaons to positive kaons as a function of the corresponding ratios of antiprotons to protons for various rapidities at RHIC. The data are for central collisions, and the figure also displays similar ratios for heavy ion collisions at AGS and SPS energies. There is a striking correlation between the RHIC/BRAHMS kaon and proton ratios over 3 units of rapidity. Assuming that we can use statistical arguments based on chemical and thermal equilibrium at the quark level, the ratios can be written

$$\frac{\rho(\bar{p})}{\rho(p)} = exp(\frac{-6\mu_{u,d}}{T}) \tag{4}$$

and

$$\frac{\rho(K^-)}{\rho(K^+)} = exp(\frac{-2(\mu_{u,d} - \mu_s)}{T}) = exp(\frac{2\mu_s}{T}) \times [\frac{\rho(\bar{p})}{\rho(p)}]^{\frac{1}{3}} \tag{5}$$

where ρ, μ and T denote number density, chemical potential and temperature, respectively. From equation 4 we find the chemical potential for u and d quarks (often called the baryochemical potential) to be around 25 MeV, the lowest value yet seen in nucleus-nucleus collisions. Equation 5 tells us that for a vanishing strange quark chemical potential we would expect a power law relation between the two ratios with exponent 1/3. The observed correlation is well described by the relationship $\rho(K^-)/\rho(K^+) = \rho(\bar{p})/\rho(p)^{0.24}$, i.e. with an exponent that is close to 1/4 suggesting, a finite value of the strange quark chemical potential.

A more elaborate analysis for a grand canonical ensemble assuming charge, baryon and strangeness conservation can be carried out by fitting these and many other particle ratios observed at RHIC by the four experiments in order to obtain the chemical potentials and temperatures. It is found that a very large collection of such particle ratios are extremely well described by the statistical approach.

An example of such a procedure is shown in fig. 8 and displayed with the full line [13]. Here the temperature is 170MeV. The point to be made here is that the calculation agrees with the data over a wide energy range (from SPS to RHIC) and over a wide range of rapidity at RHIC. This may be an indication that the system is in chemical equilibrium over the considered $\sqrt{s}$ and y ranges (or at least locally in the various y bins). Separate measurements at RHIC of, for example, elliptical flow also point to local equilibration around midrapidity.

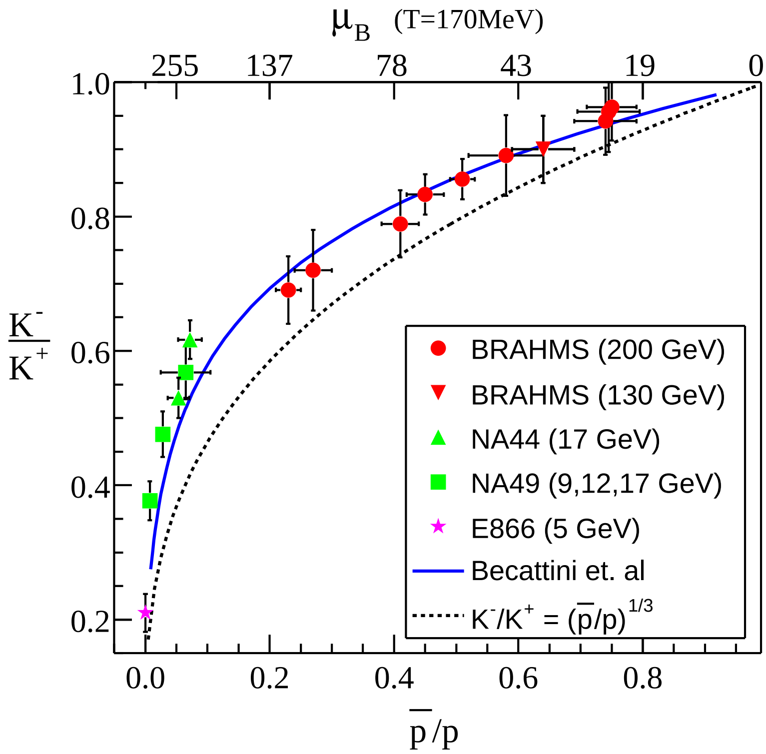

Figure 8. Correlation between the ratio of charged kaons and the ratio of antiprotons to protons. The dashed curve corresponds to equation 3 in the text. The full drawn curve is a statistical model calculation with a chemical freeze-out temperature of 177MeV.

5.2. Flow

The properties of the expanding matter in the later stages of the collisions up to the moment when interactions cease (kinetic freeze out) can be studied from the momentum distribution of the emitted particles.

The slopes of spectra of emitted particles depend in general on the temperature of the source from which they were created and on kinetic effects that may alter the expected Maxwellian distribution, such as a velocity component resulting from an outwards pressure leading to an outwards flow of the matter. This flow is expected, in the case of (at least local) thermal equilibrium and sufficient density, to be describable by concepts derived from fluid dynamics. It is to be noted that the slopes of spectra reflect the particle distributions at the time when interactions have ceased and thus the obtained physical quantities should be associated with the conditions at freeze-out.

The simplest analysis parametrizes the inverse slopes of particle spectra (the apparent temperature) as the sum of a thermal term and a kinetic (flow) term ($T_{eff} = T_{th} + m <$

$\beta >^2$, where m and $< \beta >$ are the particle rest mass and its average transverse flow velocity. A more refined analysis employs a parametrization of the spectrum shape which also includes a description of the radial dependence of the flow velocity (the so-called blastwave approach). The result of such analyses performed simultaneously on several particle/antiparticle species indicates that the thermal (freezeout) temperature is in the range T= 120-140 MeV and that the average flow velocity is about $0.5c - 0.6c$. The first quantity is found, as expected, to be lower than the temperature of the chemical freeze out discussed in the previous subsection. Indeed, it would be expected that the freeze-out of particle ratios occurs earlier than the kinetic freeze out of the particles. The flow velocity component is substantially larger than what was observed at SPS energies. This is consistent with a large pressure gradient in the transverse direction resulting from a large initial density.

Fig.10 shows results from analysis of mirapidity particle spectra from the BRAHMS experiment using the blastwave approach.

Figure 9. Temperature and chemical potential as a function of rapidity (GET FROM MM: LEFT SIDE OF PLOT IN MM's QM2004 PLENARY PAPER).

Another powerful tool to study the thermodynamic properties of the source is the analysis of the azimuthal momentum distribution of the emitted particles relative to the event plane (defined as the direction of the impact parameter). This distribution is usually parametrized as a series of terms depending on $cos(n(\phi - \phi_r))$. The coefficient (v_1) to the n=1 term measures the so-called directed flow and the coefficient (v_2) to the n=2 term measures the elliptic flow. Elliptic flow has been analyzed at RHIC (refs...) and has been found to reach (for many hadron species) large (v_2) values consistent with the hydrodynamical limit and thus of equilibration. It has been proposed (refs. xxx) that the observed persistence of azimuthal momentum anisotropy indicates that the system has reached local equilibrium very quickly and that the equilibrium can only be established at the *partonic* level when the system is very dense and has many degrees of freedom. This explanation presupposes however that there are many interactions and thus that the

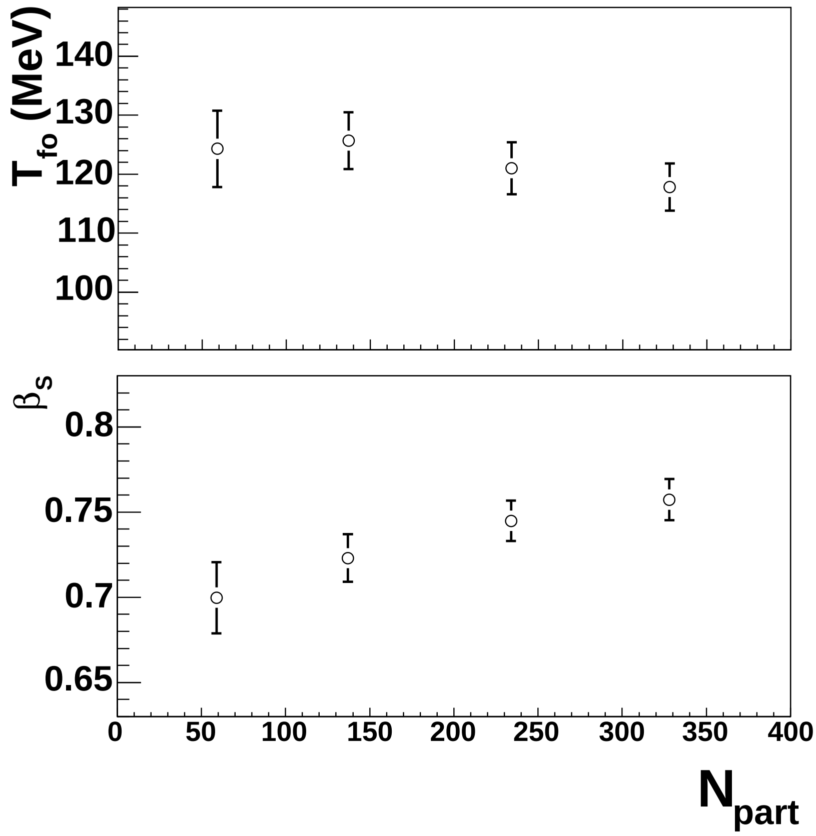

Figure 10. Temperature and transverse flow velocity as a function of collision centrality for Au+Au collisions at midrapidity.

dense partonic phase is still strongly interacting.

6. High pt suppression. The smoking gun of QGP?

The discussion in the previous sections indicates that the conditions for particle production in a interval $|y| < 1.5 - 2$ at RHIC are radically different than for reactions at lower energies. At RHIC the central zone is nearly baryon free, the considered rapidity interval appears to approximately exhibit the anticipated boost invariant properties, the particle production is large and dominated by pair production and the energy density appears to exceed significantly the one required for QGP formation. The overall scenario is therefore consistent with particle production from the color field, formation of a QGP and subsequent hadronization. Correlation and flow studies suggest that the lifetime of the system is short ($< 10 fm/c$) and, for the first time, there is strong evidence suggesting thermodynamic equilibrium already at the partonic level.

But, is this interpretation unique? And, can more mundane explanations based on a purely hadronic scenario be excluded? In spite of the obvious difficulties in reconciling the high initial energy density with hadronic volumes, a comprehensive answer to this question requires the observation of an effect that is directly dependent on the partonic or hadronic nature of the formed high density zone.

6.1. High pt suppression at midrapidity: final state partonic energy loss?

Such an effect has recently been discovered at RHIC and is related to the suppression of the high transverse momentum component of hadron spectra in central Au+Au collisions as compared to scaled momentum spectra from p+p collisions [16–19]. The effect, originally proposed by Bjorken, Gyulassy and others [5,26,25] is based on the expectation of a large energy loss of high momentum partons scattered in the initial stages of the collisions in a medium with a high density of free color charges. According to QCD colored objects may lose energy by radiating gluons as bremsstrahlung. Due to the color charge of the gluons, the energy loss is proportional to the square of the length of color medium traversed. Such a mechanism would strongly degrade the energy of leading partons resulting in a reduced transverse momentum of leading particles in the jets that emerge after fragmentation into hadrons. The STAR experiment has shown that the topology of high pt hadron emission is consistent with jet emission, so that we may really speak about jet-suppression.

The two upper rows of fig. 11 show our [15,16] measurements of the so-called nuclear modification factors for *unidentified* charged hadrons from Au+Au collisions at rapidities $\eta = 0$ and 2.2. The nuclear modification factor is defined as:

$$R_{AA} = \frac{d^2N^{AA}/dp_t d\eta}{N_{bin} d^2N^{NN}/dp_t d\eta} \tag{6}$$

It involves a scaling of measured nucleon-nucleon transverse momentum distributions by the number of expected incoherent binary collisions, N_{bin} (see [20,21]. In the absence of any modification resulting from the 'embedding' of elementary collisions in a nuclear collision we expect $R_{AA} = 1$ a high p_t. At low p_t, where the particle production follows a scaling with the number of participants, the above definition of R_{AA} leads to $R_{AA} < 1$

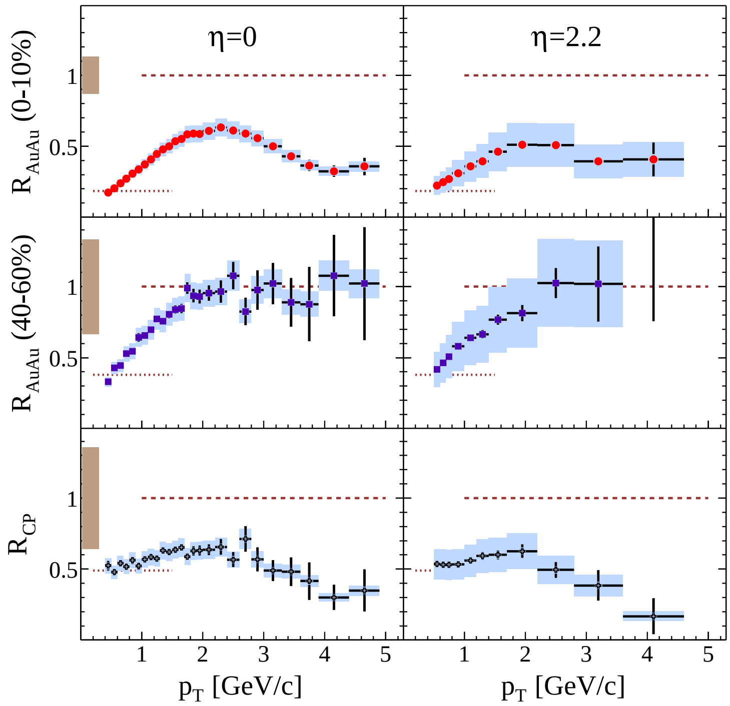

Figure 11. Nuclear modification factors R_{AuAu} as defined in the text, for central and semi-peripheral Au+Au collisions at midrapidity (left) and forward rapidity (right). The lower row shows the factor R_{cp}, i.e the ratio of the R_{AuAu} for central and peripheral collisions, which has the property of being independent of the p+p reference spectrum.

for $p_t < 2GeV/c$. In fact, it is found that $R_{AA} > 1$ for $p_t > 2GeV/c$ in nuclear reactions at lower energy. This effect, called the Cronin effect, is associated with initial multiple scattering of high momentum partons.

Figure 11 demonstrates that, surprisingly, $R_{AA} < 1$ also at high p_t for central collisions at both pseudorapidities, while $R_{AA} \approx 1$ for more peripheral collisions. It is remarkable that the suppression that is observed at $p_t \approx 4GeV/c$ is very large, amounting to a factor of 3 for central Au+Au collisions as compared to $p + p$ and a factor of more than 4 as compared to the more peripheral collisions. Such large suppression factors are observed at both pseudorapidities.

It has been conjectured that the observed high p_t suppression might be the result of an entrance channel effect, for example due to a limitation of the phase space available for parton collisions related to saturation effects [27] in the gluon distributions inside the swiftly moving colliding nucleons (which have $\gamma = 100$). As a test of these ideas we have determined the nuclear modification factor for 100 AGeV d + 100 AGeV Au minimum bias collisions. The resulting R_{dAu} is shown in fig. 12 where it is also compared to the R_{AuAu} for central collisions previously shown in fig. 11. No high-p_t jet suppression is observed for d+Au. In fact, the R_{dAu} distribution measured for d+Au shows the Cronin type enhancement [28] observed at lower energies [22–24]. At $p_t \approx 4GeV/c$ we find a ratio $R_{dAu}/R_{AuAu} \approx 5$. These observations are consistent with the smaller transverse dimensions of the overlap disk between the d and the Au nuclei and also appear to rule out initial state effects.

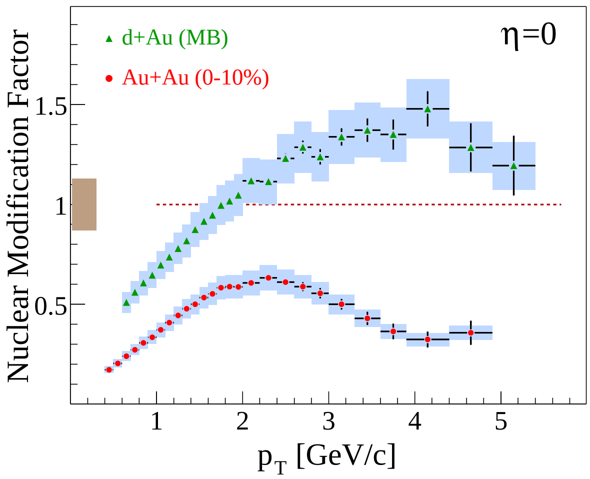

Figure 12. Nuclear modification factors measured for central Au+Au collisions and minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, evidencing the important high pt suppression observed in central Au+Au collisions.

The very large suppression observed in central Au+Au collisions must be quantitatively understood and requires systematic dynamic modelling. At $\eta = 0$ the particles are emitted at 90 degrees relative to the beam direction, while at $\eta = 2.2$ the angle is only about 12 degrees. In a naive geometrical picture of an absorbing medium with cylindrical symmetry around the beam direction, the large suppression seen at forward angles suggests that the suppressing medium is extended also in the longitudinal direction. Since the observed high p_t suppression is similar or even larger at forward rapidity as compared to midrapidity (see fig. 13) one might be tempted to infer a longitudinal extend of the dense medium which is approximately similar to its transverse dimensions ($R \approx 5fm$), and from this a life time longer than $5fm/c$. However, the problem is more complicated, due to the significant transverse and in particular longitudinal expansion that occurs as the leading parton propagates through the medium, effectively reducing the densities of color charges seen. High pt suppression at forward rapidities may also be expected due to the possible existence of a Color Glass Condensate phase in the colliding nuclei (see the discussion in the next section).

There is little doubt that systematic studies of the high p_t-jet energy loss as a function of the thickness of the absorbing medium obtained by varying the angle of observation of high p_t jets relative to the beam direction will be required in order to understand the properties of the dense medium. Among the RHIC experiments BRAHMS experiment is uniquely suited to carry out such a *QGP tomography.*

6.2. The flavor composition

With its excellent particle identification capabilities BRAHMS can also study the dependence of the high-pt suppression on the type of particle. Preliminary results (ref.

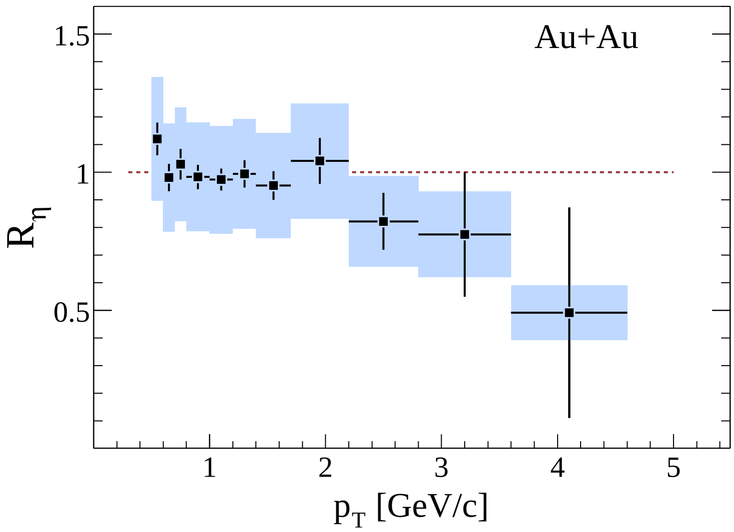

Figure 13. Ratio, R_η, of the suppression factors R_{cp} at pseudorapidities $\eta = 0$ and $\eta = 2.2$ shown in figure 9. The figure suggest that high p_t suppression persists (and is even more important) at forward rapidity than at $\eta = 0$.

qm2002, qm2004) indicate that mesons (pions and kaons) experience high pt suppression while baryons (protons) do not. The reason for this difference is a present not well understood. From a theoretical viewpoint mesons with $pt > 2GeV/c$ are describable in perturbative QCD, while baryons with $2GeV/c < pt < 5GeV/c$ fall outside a perturbative treatment.

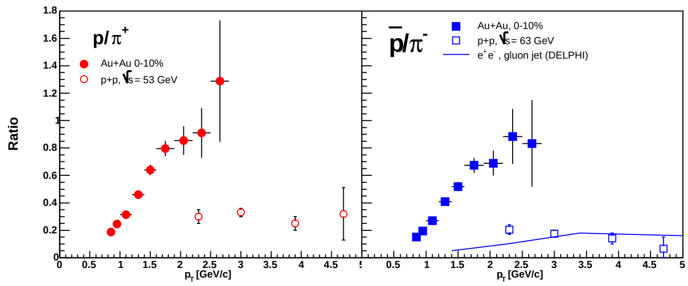

Figure 14. p/π^+ (left) and $\bar{p}/\pi^-$ (right) ratios at mid-rapidity for 0-10% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The error bars show the statistical errors. The systematic errors are estimated to be less than 8%. Data at $\sqrt{s} = 63$ GeV $p + p$ collisions [?] are also shown. The solid line is the $(p + \bar{p})/(\pi^+ + \pi^-)$ ratio measured in gluon jets [?].

The observed difference may be due to the fact that baryons, due to their larger mass, are more sensitive to flow than mesons with the consequence that their transverse momentum spectrum is flatter than for mesons, thus compensating for a possible high pt suppression similar to that seen for the mesons. It is also possible that the difference reflects details associated with the the fragmentation mechanism that leads to different degrees of suppression of the high pt component for 2 quark and 3 valence quark systems. Finally the difference may reflect the penalty associated with recombination of 3 quarks relative to 2 quarks in a medium with a high density of quarks.

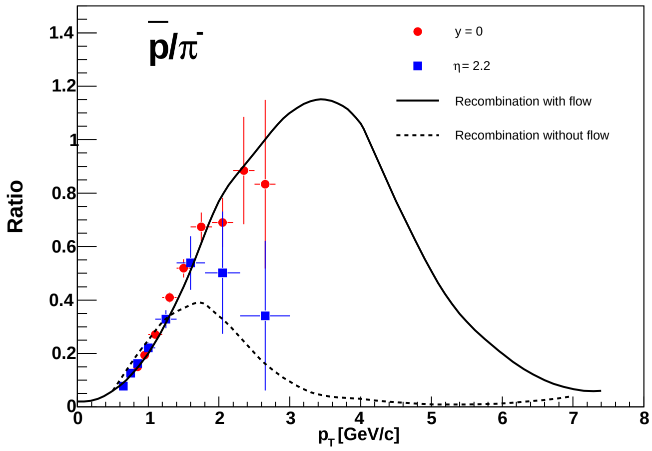

Figure 15. Ratios of $\bar{p}/\pi^-$ calculated by the parton recombination model with (solid curve) and without (dashed curve) collective flow in the quark-gluon plasma together with our measurements. BRAHMS preliminary

Figure 14 shows a recent investigation by BRAHMS (ref. qm2004) of the baryon to meson ratios p/π^+ and $\bar{p}/\pi^-$ at mid-rapidity as a function of p_T for the 0-10% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The ratios increase rapidly at low p_T and the yields of both protons and anti-protons are comparable to the pion yields for $p_T > 2$ GeV/c. The corresponding ratios for $p_T > 2$ GeV/c observed in $p+p$ collisions at $\sqrt{s} = 63$ GeV [?] and in gluon jets produced in $e^+ + e^-$ collisions [?] are also shown. In hard-scattering processes described by pQCD, the p/π^+ and $\bar{p}/\pi^-$ ratios at high p_T are determined by the fragmentation of energetic partons, in a manner independent of the initial colliding systems (agreement within the uncertainties between $p+p$ and $e^+ + e^-$ collisions). Thus, the clear increase in the p/π^+ and $\bar{p}/\pi^-$ ratios at high p_T from the $p+p$ and $e^+ + e^-$ to the central Au+Au collisions requires production mechanisms other than pQCD.

Figure 15 shows the comparison of the data at $\eta = 0, 2.2$ to a parton recombination model [?]. The solid and dashed curves correspond to calculations on $\bar{p}/\pi^-$ ratio at mid-rapidity with and without collective flow in the quark-gluon plasma, respectively. The calculation with a flow velocity of $0.5c$ reproduces the data at mid-rapidity while the data at $\eta = 2.2$ indicate that a smaller collective flow is required at forward rapidities.

The experimental and theoretical investigation of these questions is still only in its infancy. The issues can and will be addressed in depth through the analysis of the large data set collected by BRAHMS in the high luminosity Au+Au run of year 2004.

6.3. High pt suppression at lower energy?

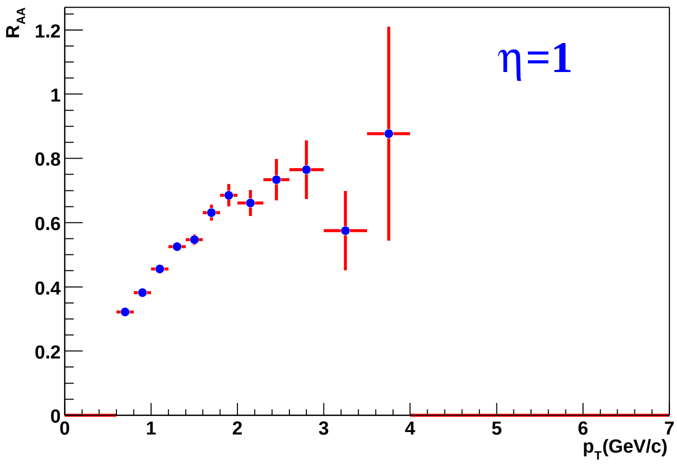

Figure 16. Plot of 63 GeV high pt supp. Preliminary. GET EPS FROM IAN OR CLAUS

The short commissioning run for Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV has allowed us to carry out a first analysis of the high pt suppression of charged hadrons at an energy of about 1/3 the maximum RHIC energy and about 3.5 times the maximum SPS energy. Preliminary results are shown in figure **??** for nuclear modification factor calculated for the sum of all charged hadrons measured at 45 degrees($\eta = 1.1$) with respect to the beam direction. The data have been compared to reference spectra measured in $\sqrt{s_{NN}} = 63$ GeV p+p collisions at the CERN-ISR. Figure **??** shows that the degree of high pt suppression at the lower energy is less important than at $\sqrt{s_{NN}} = 63$ GeV. For comparison, at SPS energies no high pt suppression was observed.

7. The color glass condensate: a model for the initial state of nuclei?

As part as the study of the high pt suppression in nucleus-nucleus collisions BRAHMS has investigated the rapidity dependence of the nuclear modification factors as a function of rapidity ($\eta = 0, 1, 2.2, 3.2$) in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. As discussed in the previous section the modification factors are consistent with the absence of high pt suppression around midrapidity. This may be taken as evidence for the fact that the high pt suppression seen in Au+Au collisions around $y = 0$ is not due to particular conditions in the colliding nuclei (initial state effects).

At forward rapidity, however, BRAHMS has discovered (ref. PRL subm), in d+Au collisions, a marked high-pt suppression (figs. **??**,**??**) starting already at $\eta = 1$ and

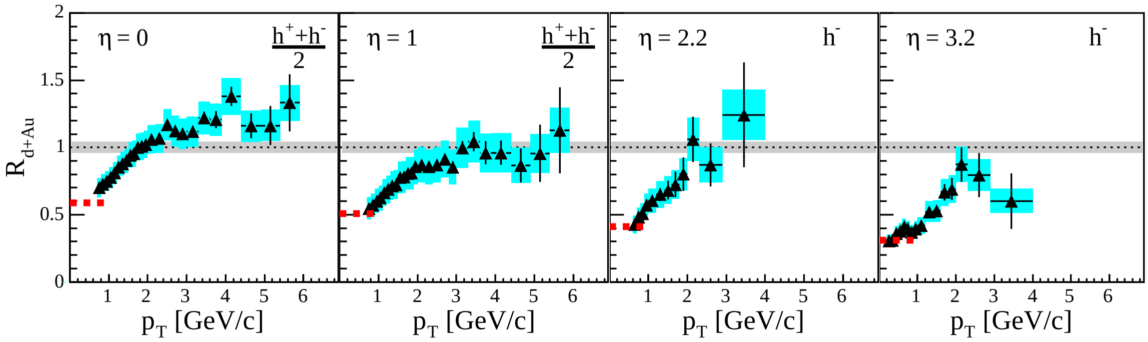

Figure 17. Nuclear modification factors measured in d+Au collisions at pseudorapidities $\eta = 0, 1, 2.2, 3.2$ for central collisions.

increasing smoothly in importance with increasing pseudorapidity (up to $\eta = 3.2$). It has been proposed that this effect at forward rapidity is related to the initial conditions of the colliding d and Au nuclei in particular to the existence of the Color Glass Condensate (CGC).

The CGC is a proposed description of the ground state of the nuclei prior to collisions 8(refs. 25,26,27,28,29,30 of GandMcL). The basic idea is, that nuclei contain a large number of low-x gluons (x is the fraction of the nucleon momentum carried by the considered parton) that appears to diverge with decreasing x. At small x however the gluon wavefunctions in the colliding nuclei are highly delocalized, thereby enabling gluon-gluon interactions (gluon fusion) leading to a depletion of the number of low x gluons in a certain p-t range. This mechanism prevents an 'infrared catastrophe', since the number of low-x gluons saturates. Such effects appear to be seen in lepton-hadron collisions at HERA (refs. 24 of GandMcL).

The transverse momentum transfer scale for the onset of gluon saturation depends on the gluon density (and thus on the number of participating nucleons), and is connected with the rapidity (y) of measured particles by $Q_s^2 \sim A^{\frac{1}{3}} e^{\lambda y}$ suggesting that saturation effects may best be studied at large y, or at large values of the related pseudorapidity $\eta = -ln(tan(\frac{\theta}{2}))$, i.e at small angles θ relative to the beam direction.

Collisions between heavy ions with energies E=$100AGeV$ provide a window to the low-x gluon distributions of swiftly moving nuclei. In particular, head-on collisions between deuterons and gold nuclei in which hadrons, produced mostly in gluon-gluon collisions, are detected, close to the beam direction but away from the direction of motion of the gold nuclei, allow the probing of the low-x components of the wave function of the gold nuclei.

Figure17 shows the nuclear modification factors obtained at the four rapidities for d+Au collisions and figure **??** the respective central to peripheral ratios. At present quantitative theoretical predictions of this effect are not available, but the observations seem to be supported in a qualitative fashion by the CGC model. However a more detailed understanding of this phenomenon requires further comparison to quantitative predictions

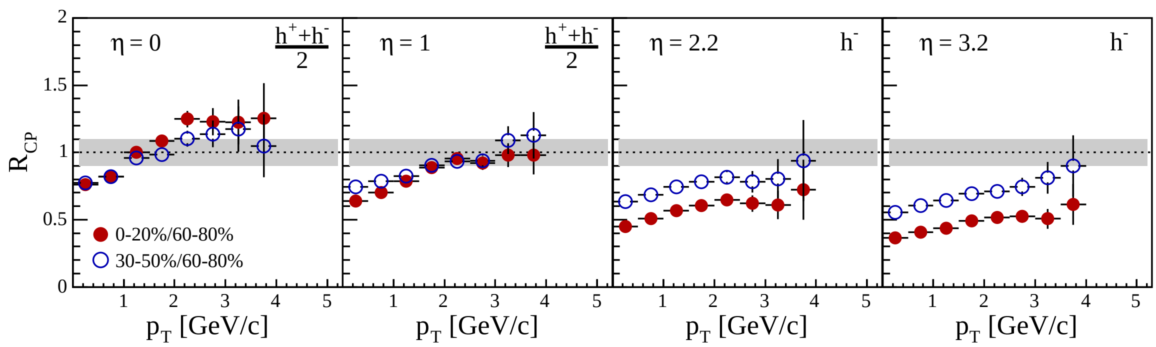

Figure 18. Plot of RCP in d+Au.

of various theoretical models (e.g., CGC, gluon shadowing, hadronic models).

Most recently we have carried out the first analysis of the nuclear modification factors for $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions in the rapidy range $\eta = 2.9-3.5$ using data collected by BRAHMS in the 2004 RHIC run. The results are consistent with the persistence of high pt suppression into this rapidity range for Au +Au collisions, thus suggesting that there may be two competing mechanisms responsible for the observed high p-t suppression in energetic Au+Au collisions, each active in its particular rapidity window.

It has been proposed (ref. GandMcL) that the high pt suppression observed around midrapidity reflects the presence of an incoherent (high temperature) state of quarks and gluons while the the high pt suppression observed at forward rapidities bears evidence of a dense coherent partonic state.

8. Conclusions and perspectives

The results from the first round of RHIC experiments clearly show that studies of high energy nucleus-nucleus collisions have moved a qualitatively new physics domain characterized by a high degree of reaction transparency leading to the formation of a near baryon free central region . There is, in spite of this, appreciable energy loss of the colliding nuclei, so the conditions for the formation of a very high energy density zone with approximate balance between matter and antimatter, in an interval of $|dN/dy| < 2 \pm 0.5$ around midrapidity are present. The indications are that the initial energy density is considerably larger than $5GeV/fm^3$, i.e. well above the energy density at which it begins to be difficult to conceive of hadrons as isolated and well defined entities. Analysis within the framework of the statistical model of the relative abundances of many different particles containing the three lightest quark flavors suggest chemical equlibrium at a temperature in the vicinity of $T = 175MeV$ and near zero baryo chemical potential. This temperature agrees with the prediction of lattice CQD calculations. The conditions necessary for the formation of a deconfined system of quarks and gluons therefore appear to be present.

However, there are a number of features, early on considered as defining the concept of the QGP, that do not appear to be realized in the current reactions, or at least have not (yet?) been identified in experiment. These are associated with the expectations that a QGP would be characterized by a vanishing interaction betweens quarks and thus exhibit the features of chiral symmetry restoration and that the system would exhibit a clear phase transition behavior, e.g. the features of a first order phase transition as lattice QCD calculations have predicted a zero chemical potential. Likewise, it was originally expected that a QGP phase created in nuclear collisions would be characterized by a long lifetime (up to 100 fm/c) and by the existence of a mixed phase exibiting large fluctuations of characteristic parameters. In contrast, the body of existing measurements suggest a short lifetime of the system, a large outward pressure and significant interactions most likely at the parton level that result in a seemingly equilibrated system with fluid like properties. Thus the high density phase that is observed, is not identical to the the idealized QGP as it was imagined a decade or two ago.

The central question is however, as discussed in the introductory chapters of this document, whether the properties of the matter as it is created in todays high energy nucleus nucleus collisions clearly bears the imprint of a system characterized by quark and gluon degrees of freedom over a range larger that the characteristic dimensions of the nucleon. We know that in nuclei the strong interaction is mediated by a color neutral objects (mesons). Is there experimental evidence that clearly demonstrates interactions based on the exchange of objects with color over distances larger than those of conventional confined objects? The best candidate for such an effect is clearly the suppression of high pt particles observed in central Au+Au collisions by the four experiments at RHIC. The remarkably large effect that is observed (a suppression by a factor of 3-5 as compared to peripheral and d+Au collisions) appears readily explainable by radiation losses due to the interaction of high pt partons with an extended medium (of transverse dimensions considerably larger than nucleon dimensions) consisting of color charges. Current theoretical investigations which recently have progressed to attempt a unified description of the reaction evolution indicate that scenarios based on interactions between hadronic objects cannot reproduce the magnitude of the observed effect.

The interpretation of current data relies heavily on theoretical input and modelling, in particular on the apparent necessity to include partonic degrees of freedom in order to arrive at a consistent description of many of the phenomena observed in the experimental data. Seen from a purely experimental point of view this situation is somewhat unsatisfying, but probably not unexpected, nor avoidable, considering the complexity of the reaction and associated processes.

It is also clear that the unravelling of the physics of the matter state(s) observed at RHIC has just begun. In spite of the impressive advances that have been made in the last 3 years there are still many issues to be understood in detail, such as the differences in the high pt suppression of baryons and mesons and the quantitative energy and rapidity dependence of the final and initial state high pt suppression quenching. Undoubtedly the continued experiments will shed new light on these and many other questions. We should not forget, however, that there are also significant challenges for theory. In the opening chapters of this document we remarked on the requirement that scientific paradigms must be falsifiable. We have yet to see a fully self consistent calculation of the entire reaction evolution at RHIC that in an unambiguous way demonstrates the impossibility of a hadronic description.

In conclusion we find that the body of information obtained by BRAHMS and the other RHIC experiments in conjunction with the available theoretical studies is strongly suggestive of a high density system that cannot be characterized solely by hadronic degrees of freedom but requires a partonic description. At the same time intriguing suggestions of a coherent partonic state at low x in the colliding nuclei has been found.

9. Acknowledgements

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