BRAHMS Collaboration results for Relativistic Heavy Ion Collisions [1]

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Abstract

In this work we review very briefly a few of the most important results obtained by the BRAHMS Collaboration on the properties of the collisions of heavy ions at relativistic energies. The discussion is general and aims to ilustrate the most important achievements of our collaboration during the RHIC run period with short discussions and references to articles which treat the subjects in more detail.

1 Introduction

The purpose of heavy ion collisions at high energies is to study the very hot and dense medium created in such violent events. In the beginning of high energy physics, when the quark model was formulated for the first time, it was phenomenologically suggested [1] that a large density of deconfined quarks and gluons might be created for a short time in the relativistic nuclear collisions. In the present time, it is generally thought that the early universe was initially in this state, also called quark gluon plasma (QGP), until its energy decreased to values allowing for confinement.

Although a number of signals suggesting the formation of a very dense medium were found at SPS energies $\sqrt{s_{NN}} = 17GeV$, no decisive proof was found at the experiments in the energy range $\sqrt{s_{NN}} \approx (1-17)GeV$ [2]. With the Relativistic Heavy Ion Collider, RHIC, the center of mass energy in central $Au+Au$ collisions at 100 AGeV+100 AGeV increased with one order of magnitude giving the opportunity to study the nuclear matter under unprecedented conditions of temperature and density.

2 Experimental issues

The BRAHMS experiment [3] is a two arm magnetic spectrometer with very good momentum resolution and particle identification capabilities. The two spectrometer arms have a very small solid angle coverage but they can be rotated in order to collect data on hadron production over a wide rapidity range (0-4). Both spectrometers use tracking chambers and magnets for momenta measurements and time of flight and/or Cherenkov detectors for charged hadron

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identification. BRAHMS setup also includes a set of global detectors used for multiplicity mesurements and for triggering purposes.

3 Bulk properties of the hot and dense nuclear matter

One of the first questions which arise when dealing with a nuclear collision is how much initial kinetic energy will be released in the reaction volume. We can answer to this question by measuring the average rapidity loss experienced by the baryons in the colliding nuclei. The average rapidity loss, or the stopping [4], can be estimated from $< \delta y >= y_b - < y >$ where

$$< y >= \int_0^{y_b} y \frac{dN}{dy} dy / \int_0^{y_b} \frac{dN}{dy} dy \tag{1}$$

is the average rapidity of the baryons after the collision. dN/dy is the number of net-baryons.

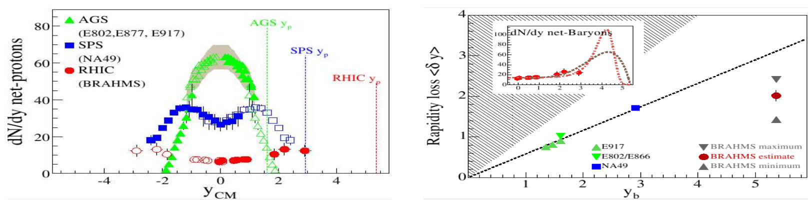

Figure 1: Left: Rapidity density of net protons measured at AGS, SPS and RHIC (BRAHMS). Right: Average rapidity loss versus beam rapidity; the insert shows two posible net-baryon distributions respecting baryon number conservation.

In Fig. 1 left we show the distribution of net-protons over rapidity measured by BRAHMS [5] and by 2 older experiments at lower energies, AGS and SPS. We observe that between the AGS and RHIC energy results there is a clear qualitative change. The net-proton distribution at AGS is peaked on mid-rapidity and close to the scenario of full baryon stopping while the same distribution at RHIC energy shows a wide plateau at mid-rapidity characterized by very low net-proton values (≈ 7 at $y = 0$). Unfortunately, the BRAHMS setup cannot cover the entire rapidity range up to beam rapidity, but using the baryon number conservation we can impose limits on the average rapidity loss (see Fig.1right). The calculated average absolute rapidity loss for Au+Au collisions at RHIC energies is $\delta y = 2.0 \pm 0.4$ which is not much greater than the one at SPS but the absolute energy loss is appreciably higher. The energy released in the collision volume was calculated to be about 73 ± 6GeV per nucleon at a beam energy of 100GeV per nucleon.

The collision scenario observed at RHIC suggests a significant amount of reaction transparency. This transparency started to show up for the first time

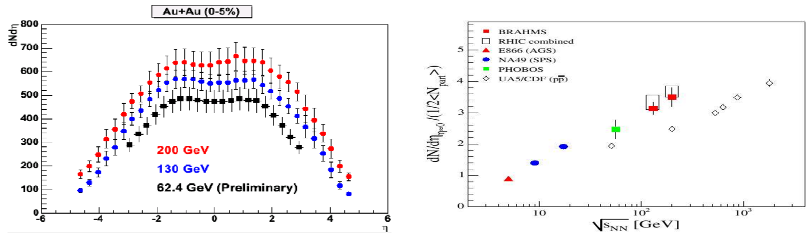

Figure 2: Left: Pseudo-rapidity densities of charged particles measured by BRAHMS at $\sqrt{s_{NN}} = 62.4, 130$ and 200 GeV. Right: $dN/d\eta$ at $\eta = 0$ normalized to the number of participant pairs vs. $\sqrt{s_{NN}}$.

at top SPS energies, where the net-proton distribution versus rapidity shows 2 symmetric maximums separated by a small dip around mid-rapidity [5](see 1 left). At RHIC, from the net-baryon distribution behaviour with rapidity we can deduce that after the collision we have two different regims which mix in different proportions depending on rapidity. The first region, dominating at mid-rapidity, has a very small net-baryon content but a huge energy density in the form of color fields according to the Bjorken scenario of full transparency [6]. All this energy is available for particle creation through quark-antiquark pairs. The second region is at higher rapidities and is dominated by the remnants of the initial colliding nucleons.

In Fig.2 left we show the charged particle distribution as a function of pseudo-rapidity for central Au+Au collisions at 3 different energies [8]. At the top RHIC energy, the multiplicity is about $dN/d\eta = 625$ charged particles per unit of rapidity around $\eta = 0$. By integrating this distribution we obtain that the total number of charged particles produced is approximately 4600 particles. Fig.2 right shows that the charged particle production in central nucleus-nucleus collisions exceeds the particle production in p+p collisions at the same energies, when the yields are scaled to the number of participant pairs [7]. This fact is correlated with the smaller average rapidity loss observed in p+p collisions.

In Fig.3 left we show the dN/dy distributions as a function of rapidity for pions, kaons and protons together with their anti-particles. All the distributions are well fitted with a Gaussian, except for the proton distribution which contains an important fragmentation component. In the same figure we show the measured average transverse momentum for different rapidity values [9]. From this data, according to Bjorken's scenario, we can estimate the initial energy density using the following formula [6]:

$$\epsilon = \frac{1}{\pi R^2 \tau} \langle m_T \rangle \frac{dN}{dy} \tag{2}$$

Here R is the transverse radius of the collision region which in the initial stage can be approximated with the radius of the overlap disk between the colliding nuclei. The formation time, τ, [10] is difficult to be determined exactly, so here we use a conservative value of $\tau = 1 fm/c$. This value can be inffered from the

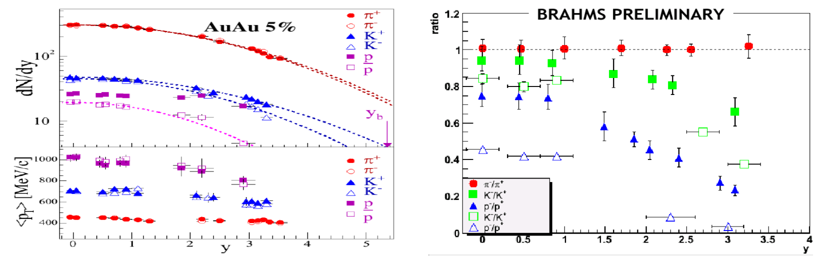

Figure 3: Left: Rapidity density distributions for positive and negative pions, kaons and protons. Below we show average p_t distributions as a function of rapidity. Right: Ratios of antiparticles to particles as a function of rapidity for $\sqrt{s_{NN}} = 62.4$ and 200GeV.

uncertainty principle by considering a typical relevant energy scale of 200 MeV. With these assumptions, the energy density obtained is $\epsilon \approx 5GeV/fm^3$ which exceeds with a factor of 10 the energy density of a baryon and with a factor of 5 the critical energy density for QGP formation $\epsilon_{crit} = 1GeV/fm^3$.

In Fig.3 right we show the anti-particle/particle ratios versus rapidity [8] for Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV. We observe that at mid-rapidity there is an approximate balance between particles and antiparticles for the higher beam energy which supports the idea that the main mechanism for particle production in this kinematical region is pair creation. For the lower energy, the kaon and proton ratios are lower at all rapidities but show the same behaviour. Except for pions, all the other ratios are falling at $y > 1$ due to the influence of the net-baryon rich medium created at forward rapidities.

4 High p_T suppression

In the previous sections we showed that the conditions for particle production in the mid-rapidity region at RHIC energies are very different than for nuclear collisions at lower energies. The energy density reached is much higher than the one hypothesised for the QGP creation. Bjorken, Gyulassy and others [11] proposed the idea of a large energy loss of high momentum partons, hard-scattered in the initial stages of the collisions, in a medium with a high density of free color charges. This effect was measured by BRAHMS [12] using the so called nuclear modification factors defined like:

$$R_{AA} = \frac{d^2N^{AA}/dp_t d\eta}{\langle N_{bin}\rangle \, d^2N^{NN}/dp_t d\eta}, \tag{3}$$

where $\langle N_{bin}\rangle$ is the number of incoherent binary collisions. It is expected that in the absence of any modification due to the nuclear medium, the A+A collisions should be just a superposition of N+N collisions and the R_{AA} factors should be 1 at high p_T.

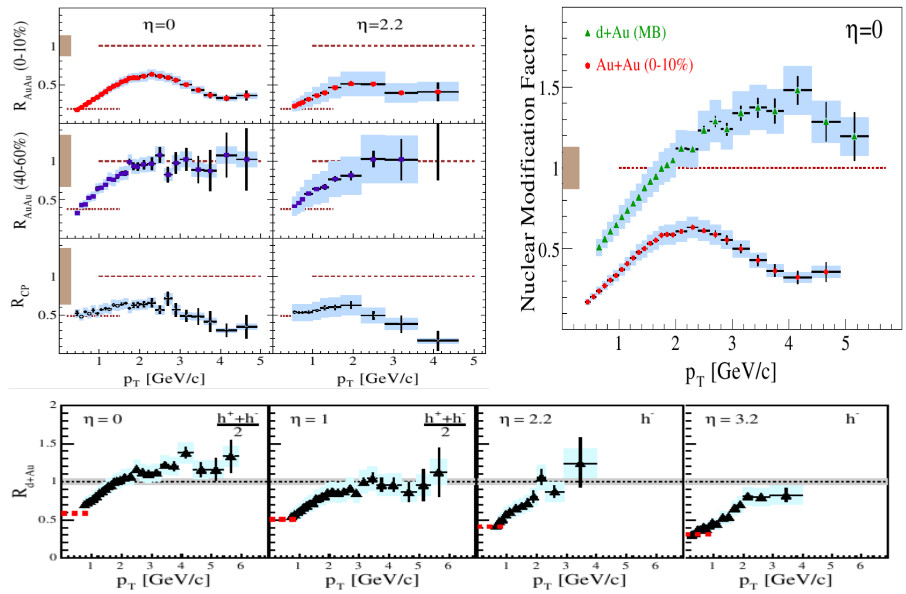

Figure 4: Top-left: Nuclear modification factors R_{AuAu} for central(top row) and semi-peripheral(middle row) Au+Au collisions at $\sqrt{s_{NN}} = 200GeV$ at $\eta = 0$ (left column) and $\eta = 2.2$ (right column); The lower row shows the factor $R_{CP} = R_{AA}(0-10\%)/R_{AA}(40-60\%)$. Top-right: Nuclear modification factors measured for central Au+Au collisions and minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200GeV$. Bottom: Nuclear modification factors measured by BRAHMS for the 10% most central d+Au collisions at $\sqrt{s_{NN}} = 200GeV$ in different η intervals.

Figure 4 top-left shows the measured nuclear modification factors for central and semi-central collisions at mid-rapidity and forward pseudo-rapidity. Experimentally we observe that in central collisions, at high p_T, $R_{AA} < 1$ for both pseudo-rapidity cases. For the more peripheral collisions we observe that $R_{AA} \approx 1$.

It was suggested that the high pt suppression at mid-rapidity might be due to some initial state effects like saturation in the gluon distributions inside the fast moving nuclei [13]. This would produce a similar suppression in collisions where no QGP formation is expected, like in d+Au collisions. In figure 4 top-right is plotted the nuclear modification factor measured in $d-Au$ collisions at $\sqrt{s_{NN}} = 200GeV$ at mid-rapidity [12]. The R_{dAu} shows only the Cronin enhancement similar to the one observed in lower energy data and no high p_t suppression.

At forward rapidity, the high p_t suppression is present also in $d+Au$ collisions (see fig.4 bottom) suggesting an initial state effect [14]. Among the first explanations proposed was a reduction of the number of low-x gluons in the parton distribution functions of the swiftly moving nuclei due to gluon shadowing or the possible formation of a dense coherent system of soft gluons called the Color Glass Condensate. Such an initial-state effect might also contribute to the strong forward rapidity suppresion in Au+Au collisions.

5 Conclusions

In the previous sections we briefly discussed the highlights of BRAHMS experiment results. The energy loss measurements clearly establish that in Au+Au collisions as much as 73% of the initial beam energy is deposited in the reaction region and is available for particle production. The particle multiplicities observed indicate that the energy density achieved in the initial stage largely exceeds the critical energy density needed for QGP formation. The suppression of high p_t particles at mid-rapidity seen in central Au+Au collisions at RHIC evidences the interaction of hard-scattered partons with the high energy density medium created in the collisions. The suppression of high p_t hadrons at forward rapidity is an effect which might be related to saturation of nuclear gluon distribution functions.

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