Rapidity Dependence of High p_T Suppression in Au+Au and d+Au Collisions at $\sqrt{s_{NN}}$=200 GeV.

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We present spectra of charged hadrons from Au+Au and d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV measured with the BRAHMS experiment at RHIC. The spectra for different collision centralities are compared to spectra from nucleon-nucleon collisions at the same energy scaled by the number of binary collisions. The resulting ratios (nuclear modification factors) for central $Au + Au$ collisions at $\eta = 0$ and $\eta \approx 2$ evidence a strong suppression in the high p_T region (>2 GeV/c). In contrast the d+Au nuclear modification factor (at $\eta = 0$) exhibits an enhancement of the high p_T yields. These measurements indicate a high energy loss of the high p_T particles in a medium created in the central Au+Au collisions. The lack of suppression in d+Au collisions rules out initial state effects as explanation for the suppression in the central Au+Au collisions.

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Collisions between heavy nuclei (eg. Au) in the energy domain now accessible at the Relativistic Heavy Ion Collider (RHIC) are expected to lead to the formation of an extremely hot high density region exhibiting features characteristic of quark deconfinement, the quark-gluon plasma (QGP). The first experiments with Au+Au collisions at 100 AGeV + 100 AGeV suggest that very high energy densities ($\epsilon > 5GeV/fm^3$) are achieved in the initial stages of such collisions. Furthermore, the reaction mechanism at RHIC has new features as compared to lower energies, evidencing a high degree of nuclear transparency (as may be deduced from the low rapidity density of net protons that is measured in a region around midrapidity ($|y| < 1.5$) ([1]). This picture brings to mind the boost invariant scenario for such collisions first proposed by Bjorken (ref), in which the colliding nuclei suffer only a moderate relative rapidity loss and where the subsequent particle production can be primarily traced to quark-antiquark pair production from the breaking of color strings between scattered partons. Furthermore, studies of the particle production (ref. BRAHMS and PHOBOS mult. paers) and the dynamics of the expanding hadronic cloud that subsequently forms (ref spctra STAR and PHENIX and BRAHMS QM2002) , suggest that the system, at least in later stages of the collision, may be in thermal and chemical equilibrium. An analysis of particle ratios, at midrapidity indicates that the baryochemical potential has been reduced to 29 MeV [**?**],[9]. This set of observations naturally leads to speculation about whether a high density deconfined partonic state is indeed formed in Au+Au collisions at RHIC.

In order to investigate the conditions prevailing early in the evolution of the system it has been proposed (ref. Bjorken, Wang+Gulyassy etc...) that the study of high momentum scattered particles may be a good probe of the conditions of the original medium. Such particles, which are associated with jet production from initial hard parton scatterings, are predicted to experience attenuation and energy loss as they traverse a dense hadronic medium with a high density of color charges due to induced gluon radiation, resulting in a reduction of the high transverse momentum component of their spectra. This process is referred to as p_T suppression.

In this Letter, we report on measurements of spectra of charged hadrons from Au+Au collisions at $\sqrt{s_{NN}} = 200$ AGeV at pseudorapidities $\eta = -ln(tan(\theta/2)) = 0$ and $\eta = 2.2$, where θ is the angle of emission relative to the beam direction. The spectra, which have been measured as a function of the collision centrality, are compared to reference data from elementary $p + \bar{p}$ collisions at the same energy and rapidity, using a scaling to the estimated number of binary collisions. We have also measured similar spectra (for minimum bias collisions) for the reaction $d + Au$ at $\sqrt{s_{NN}} = 200$ AGeV. For central $(0 - 10\%)$ Au+Au collisions we find a strong suppression of the high transverse momentum component $(p_t > 2GeV/c)$ of the spectra as compared to the scaled $p+\bar{p}$ spectra. This suppression diminishes significantly as the collision centrality decreases. In contrast no suppression is observed for the d+Au collisions.

BRAHMS consists of two magnetic spectrometers (the MidRapidity Spectrometer, MRS and the Forward Spectrometer, FS) that for the present measurements were positioned at 90 degrees and 12 degrees relative to the beam direction and thus measure hadrons and antihadrons with rapidities in the range $y \approx 0$ and $y \approx 2.2$. In addition to the spectrometers a set of global detectors were used for miminum bias trigger and event characterization.

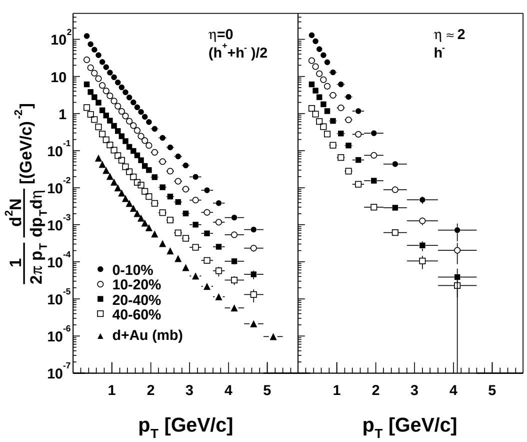

FIG. 1: Spectra of charged hadrons for centrality cuts $0-10, 10-20, 20-40 and 40-60 percent$ of the total reaction cross section for Au+Au collisions at $\sqrt{s_{nn}} = 200$ AGeV and for pseudorapidities around $\eta = 0$ (left panel) and $\eta = 2.2$ (right panel). The left panel also shows the spectrum for elementary p+p-bar collisions from UA1, scaled to $\eta = 0$. All displayed spectra have been scaled by the indicated factor for clarity.

In the Au+Au run the data acquisition was triggered by a signal corresponding to one or more neutrons in each of the two Zero Degree Calorimeter (ZDC) counters. Simulation studies using GEANT show that this corresponds to approximately 97% of the Au+Au interaction cross section. An additional trigger based on the charged particle multiplicity in the midrapidity region, selected the most central events $(0- \approx 25\%)$ in parts of the Au+Au run. In the d+Au run, scintillator counters (INEL) were placed around the nominal intersection point (IP) at $z = \pm1.6, \pm4.2$ and $z = \pm6.6m$. Signals from these counters were used as the minimum bias trigger, which selected $\approx 91\% \pm 3\%$ of the $2.4b$ d+Au inelastic cross section. Additional spectrometer trigger were added to enhance the track sample. Further details of the experimental setup and operation can be found in [4, 5, 10].

Centrality selection of the Au+Au collisions was done using global multiplicity detectors positioned around the nominal intersection point (IP). The position of the actual intersection point is determined with a precision of $\sigma < 1.8$ cm by the use of arrays of beam counters (BB) placed at about $z = 2m$ on either side of the collision zone. For the d+Au reaction study the vertex measurement by the INEL counters has a resolution of approximately 9 cm. By combining the information from the vertex determined by the INEL counters, the BB counters and the tracks in first TPC of the midrapidity spectrometer the true vertex distribution was obtained and used for (vertex dependent) event normalization. In addition, fiducial cuts in the spectrometer opening are applied.

Figure 1 shows measured spectra for charged hadrons $(h^+ + h^-)/2$ at 90 degrees (right panel) and for negative hadrons (h^-) at 12 degrees (left panel), corresponding to pseudorapidities ($\eta = 0$ and 2.2). The displayed spectra correspond to centralities (0%-10%,10%-20%,20%-40%,40%-60%). The spectra have been constructed from measurements with various fields settings of the magnets in the MRS and FS, respectively. Spectra have been corrected for the finite acceptance of the spectrometers, for the tracking efficiency, and where applicable, for the triggering efficiency. No decay corrections have been applied. Also shown in the figure is the 'reference' spectrum for $p+\bar{p}$ collisions measured by the UA1 experiment at CERN-SPS [7]. This spectrum was measured in the range $|\eta| < 2.5$). To be able to compare it to our data, which are confined to narrower rapidity intervals, we have used a momentum dependent correction factor estimated with the use of the HIJING code (ref...). This code, based on PYTHIA (ref.), reproduces p+p collisions well. We have compared our corrected spectrum at midrapidity with the 100AGeV+100AGeV $p + p$ distribution, recently measured by the STAR collaboration (ref...). We find excellent agreement. No similar comparison is available for the more forward ra-

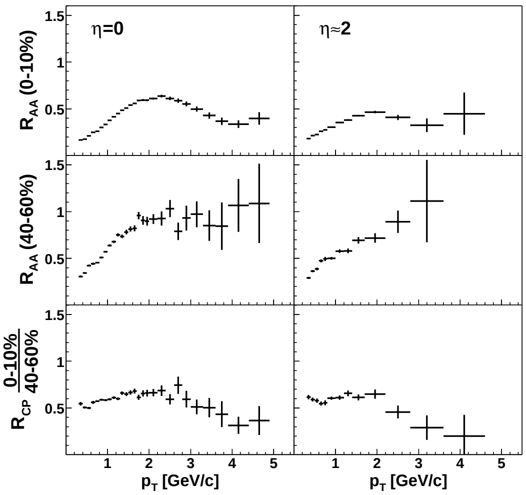

FIG. 2: Top row: Nuclear modification factors R_{AuAu} as a function of transverse momentum for Au+Au collisions at $\eta = 0$ and $\eta = 2.2$ for $0 - 10\%$ most central collisions. Middle row: same as top row, but for centralities $40 - 60\%$. Bottom row: ratio of the R_{AuAu}factors for the most central and most peripheral collisions at the two rapidities. The dotted and dashed lines show the expected value using number of participants scaling and number of binary collisions scaling, respectively. Error bars are statistical. The grey bands indicate the systematic errors.

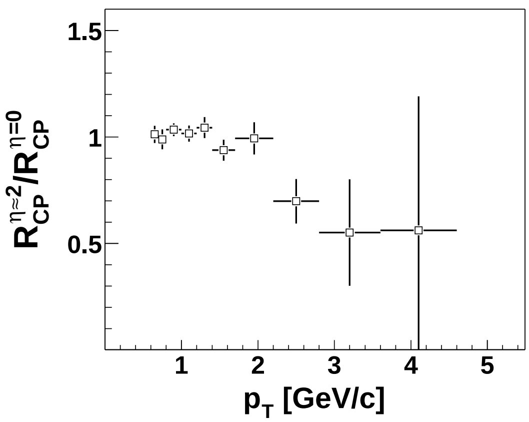

FIG. 3: Ratio of R_{cp} distributions at $\eta = 0$ and $\eta = 2.2$ from the bottom row of figure 3.

pidity. Consequently, we use the model-scaled $p + \bar{p}$ spectrum for the following comparisons, noting that HIJING predicts a momentum dependent difference between negatively and positively charged hadrons at forward rapidities.

A useful way to compare the momentum spectra from nucleus-nucleus collisions to those from p+p collisions, is to scale the normalized p+p spectrum (assuming a p+p inelastic cross section of 42 mb) by the number of binary collisions (N_{bin}) corresponding to the centrality cuts applied to the nucleus-nucleus spectra and construct the ratio. This ratio is called the nuclear modification factor, R_{AA}. The used N_{bin} values have been obtained from the HIJING code. For the various centrality cuts in Au+Au they are. (..,...,...,...). For the d+Au reaction we have used $N_bin = 7$.

Figure 2 (upper two rows) shows the ratios R_{AuAu}, as a function of transverse momentum for different centrality cuts for the Au+Au measurements at $\eta = 0$ and 2.2, respectively. The salient features of the distributions is a rise from about 0.2 in the range $p_t = 0.5 - 2GeV/c$ to a value in the range 0.5 to 0.9. This part of the spectrum is normally associated with soft collisions and should therefore scale with the number of participants, wherefore a scaling with the (larger) N_{bin} reduces R_{AuAu} in this momentum interval. (FIX) Beyond $p_T \approx 2$GeV/c, R_{AuAu} is expected to be close to 1. In fact measurements of R_{AuAu} at CERN-SPS for $\sqrt{s_{NN}} = 17$ GeV collisions for neutral pions (ref: WA98) , negative hadrons(ref: NA49) and charged pions (ref: CERES) show that R_{AA} is equal to 1 at $p_T = 1.5$ GeV/c and increases to about 1.5 at $p_T = 3$GeV/c. This is called the Cronin effect (ref. Cronin etc.) and generally explained as being due to multiple scattering of nucleons in the initial stages of the collision. Above $p_T > 2$GeV/c the R_{AuAu} distributions shown in fig. 2 are systematically lower than 1 for the central collisions at, while they tends towards 1 for the peripheral collisions. Indeed, for the most central collisions at both rapidities, R_{AuAu} is only about 0.4 at $p_T \approx 3$ GeV/c. The high p_T component of the Au+Au spectra is therefore suppressed by a factor of 3-4 as compared to the SPS results at lower energies. We note, however, that due to the lack of an independent measurement of the p+p reference spectrum at forward rapidity, the systematic error on the R_{AuAu} y=2.2. is large and model dependent. We estimate it to 20%. We estimate that the systematic error on N_bin is about 10% for the most central collisions, increasing to about 20% for the most peripheral collisions. The two lower panels in fig.2 show the ratio of the R_{AuAu} distributions for the most central collisions relative to the least central at the two rapidities. We call this the R_{cp} ratio. Both ratio distributions clearly show a significant suppression of the high p_t component for the central collisions. The advantage of using this measure is that it is independent of the used reference and of most systematic errors influencing the hadron yields from the Au+Au reactions.

In figure 3 we present the ratio of the R_{cp} distributions, shown in figure 2, corresponding to $\eta = 2.2$ and $\eta = 0$. This ratio is, in contrast to the R_{cp} ratios, also free from systematic errors arising from the determination of N_bin values corresponding to the considered

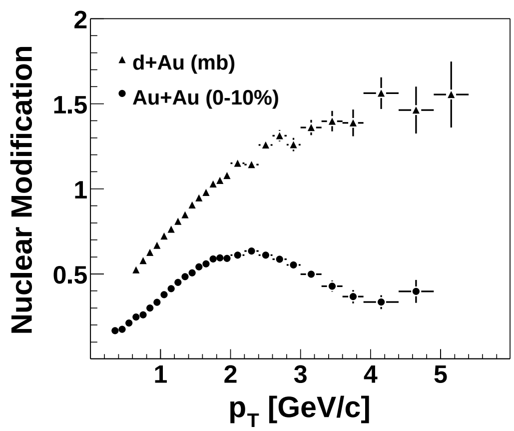

FIG. 4: Nuclear modification factor measured for near minimum bias collisions of D+Au at $\sqrt{s_{nn}} = 200$ AGeV. Error bars represent statistical errors. Systematic errors are denoted by the shaded band.

centrality cuts. The figure shows that, within errors, the degree of high pt suppression (at $p_t > 2GeV/c$) observed at $\eta = 0$ and at $\eta = 2.2$ is similar or perhaps even superior at the more forward rapidities than at midrapidity.

For comparison to the results obtained for the Au+Au collisions we have investigated the d+Au reaction at the same energy and at $\eta = 0$). In figure 4 we present the corresponding R_{dAu} distribution, analyzed in the same way as the Au+Au collisions, and using the same reference spectrum, appropriately scaled by the relevant N_{bin}. We have applied no centrality cuts, so the distribution reflects our minimum bias collision data, which correspond to $\approx 91\%$ of the total reaction cross section. We have verified that the shape of the R_{dA} distribution is roughly similar for different centrality cuts. It is striking that the R_{dAu} factor shows no suppression of the high p_T component. Rather, it shows an enhancement, as has been found at lower energies.

From these measurements we conclude that central collisions between Au+Au nuclei exhibit a very significant suppression of the high transverse momentum component as compared to $p + p$ collisions. This suppression appears to be directly correlated with the size of the participant zone, as demonstrated by the fact that the much smaller participant zone resulting from the d+Au collisions shows no suppression and by the fact that more peripheral collisions between the Au nuclei show less suppression than the corresponding central collisions. It is reasonable to surmise that the effect is related to medium effects tied to a large volume with high energy density. It has been proposed that gluon saturation effects in the colliding Au+Au nuclei, i.e entrance channel effects, resulting from their high laboratory energy, might limit the phase space available for the production of high momentum particles in the collisions. Such an explanation appears improbable in view of the results for the d+Au measurements which utilize projectiles at the same energy.

In summary, the BRAHMS measurements demonstrate a significant suppression of the high p_T component of tranverse momentum spectra for hadrons measured at two rapidities. The suppression is seen to diminish with decreasing collision centrality and is seen to be absent in collisions between a light mass nucleus and a gold nucleus. The latter observation appears to rule out possible entrance channels effectscontributing to the observed suppression in collisions between large nuclei. We conclude that the observed suppression is consistent with significant medium effects in the most violent collisions, i.e those that have the largest participant volumes. The fact that the suppression persists at forward rapidity suggests that the volume which causes the suppression is extended also in the longitudinal direction. Whether the observed effect is tied to absorbtion or energy loss of high momentum particles at the partonic level (i.e. in the very initial stages of the collisions) or to some other mechanism is as yet unclear and warrants further systematic investigations, notably by studying the effect over the largest possible rapidity range and by carrying out experiments at lower beam energies.

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[1] Quark Matter 2002, BRAHMS collaboration Nucl. Phys. A715 (2003) xxx, and P. L. Christiansen, Ph. D. thesis, Univ. Copenhagen, June 2003.
[2] Quark Matter 2002, BRAHMS collaboration Nucl. Phys. A715 (2003)715.
[3] I. G. Bearden *et al.*, BRAHMS Collaboration, Phys. Rev. Lett. **90**, 112305 (2003)
[4] I. G. Bearden *et al.*, BRAHMS Collaboration, Phys. Lett. B **523**, 227 (2001).
[5] I. G. Bearden *et al.*, BRAHMS Collaboration, Phys. Rev. Lett. **88**, 202301 (2002).
[6] B. B. Back *et al.*, PHOBOS Collaboration, Phys. Rev. Lett. **88**, 022302 (2002).
[7] C. Albajar et al. Nucl. phys. B355(1990) 261.
[8] J. D. Bjorken, Phys. Rev. D**27**, 140 (1983).
[9] P. Braun-Munzinger *et al.*, Phys. Lett. B **518**, 41 (2001).
[10] M. Adamczyk *et al.*, BRAHMS Collaboration, Nucl. Instr. and Meth., A499 (2003) 437.