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. The spectra 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. multiplicity papers from 4 experiments) and the dynamics of the expanding hadronic cloud that subsequently forms, suggest that the system, at least in later stages of the collision, may be in thermal and chemical equilibrium. At midrapidity, an analysis of particle ratios, indicates that the baryochemical potential has been reduced to 29 MeV [**?**],[8]. 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 as described below. 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 apparent suppression is observed for the d+Au collisions.

BRAHMS consists of two magnetic spectrometers (the MidRapidity Spectrometer, MRS and the Forward Spectrometer, FS) that together can cover the angular range from 2.3 degrees to 90 degrees relative to the beam direction and thus measure hadrons and antihadrons with rapidities in the range $0 < y < 4$. Particles are deflected in room temperature dipole magnets. Their directions before and after entering the region of vertical magnetic field is determined by the use of Time Projection Chambers and Drift Chambers. From the bending angle we determine the momentum of the particles. We estimate that the momentum resolution is (typically) $\Delta p/p =$ at $p = xx$ GeV/c and ... at .... . The experiment also has excellent particle identification (PID) capabilities. In this work, we concentrate on the spectra of charged hadrons (h^+ and h^-), for which this PID capability is not used. In addition to the spectrometers a set of global detectors were used for miminum bias trigger and event characterization.

In the Au+Au run the data aquisition was triggered by a signal corresponding to one or more neutrons in each of the 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= +-2, and +-3 m (check). Signals from these counters were used as the minimum bias trigger, which selected approximately 90% of the d+Au cross section. Additional spectrometer trigger were added to enhance

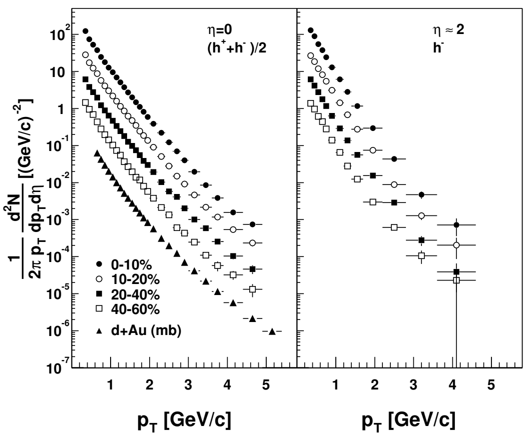

FIG. 1: Spectra of charged hadrons for centrality cuts $0-10, 10-20, 20-40 and 40-60 percent$ of the total reaction cross section for Au+Au collisions at $\sqrt{s_{nn}}$ = 200 AGeV and for pseudorapidities around $\eta = 0$ (left panel) and $\eta =$ 2.2 (right panel). The left panel also shows the spectrum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

the track sample. Further details of the experimental setup and operation can be found in [4, 5, 9].

Centrality selection of the Au+Au collisions is 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 $\sigma < 3$ cm by the use of arrays of beam counters (BB) placed at about 2m away 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 is applied to avoid systematic errors due to edge effects.

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 width of the selected rapidity intervals are (..) and (..) respectively. The displayed spectra correspond to various 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. Spectra have also been corrected for effects due to the momentum resolution (FIX details...). Also shown in the figure is

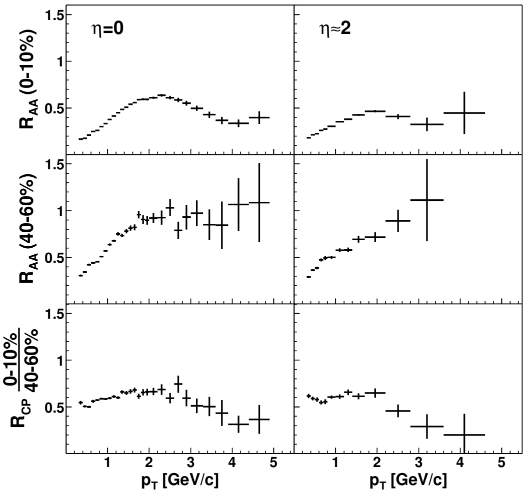

FIG. 2: Top row: Nuclear modification factors R_{AuAu} as a function of transverse momentum for Au+Au collisions at $\eta = 0$ and $\eta = 2.2$ for $0 - 10\%$ most central collisions. Middle row: as top row, but for centralities $40 - 60\%$. Bottom row: ratio of the R_{AuAu}factors at the two rapidities for the most central and most peripheral collisions. 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.

the 'reference' spectrum for $p + \bar{p}$ collisions measured by the UA1 experiment at CERN-SPS (ref...). 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 based used a momentum dependent correction factor estimated with the use of the HIJING code (ref...). This code, based on PYTHIA, has been tuned to reproduce p+p collisions. 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 rapidity. Consequently we use the model-scaled $p + \bar{p}$ spectrum for the following comparisons, noting that HIJING predicts a difference between negatively and positively charged hadrons at foreard 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 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} (FIX: Formula). The used N_{bin} values have been obtained from the HIJING code. For the various centrality cuts in Au+Au they are. ..,...,...,... and for the d+Au reaction we have used $N_bin = 7$.

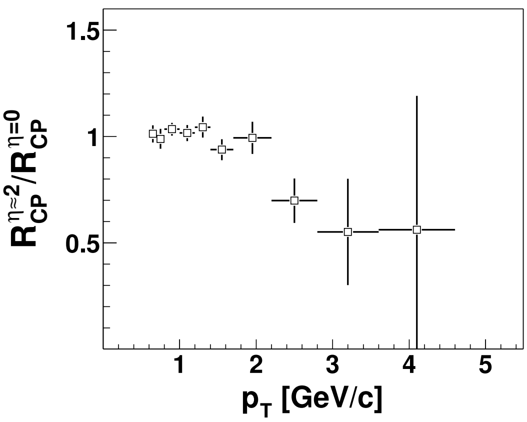

FIG. 3: Ratio of R_{cp} distributions at $\eta = 0$ and $\eta = 2.2$ from the bottom row of figure 3.

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 $p_T \approx$ 2GeV/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 $p_T =$ 3GeV/c. This is called the Cronin effect ref. Cronin etc.) and explained as being due to multiple scattering of nucleons in the initial stages of the collision. Above $p_T >$ 2GeV/c the R_{AA} 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. The two lower panels in fig.2 show the ratio of the R_{AuAu} distributions for the most central collsions 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.

In figure 3 we present the ratio of the R_{cp} distributions from $\eta = 0.0$ and $\eta = 2.2$. This ratio has the advantage that it is to a large extent free from systematic errors arising from the normalization to the

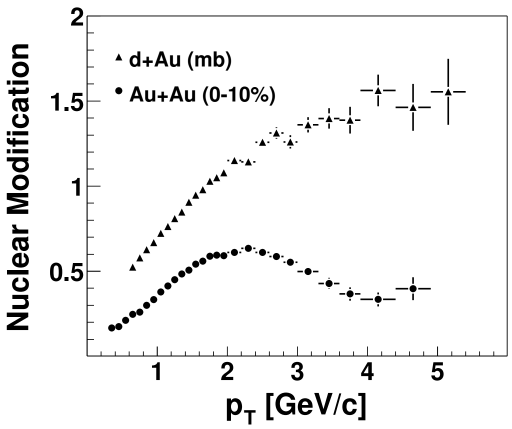

FIG. 4: Nuclear modification factor measured for near minimum bias collisions of D+Au at $\sqrt{s_{nn}} = 200$ AGeV. Error bars represent statistical errors. Systematic errors on the ratio are $20 percent$

spectra from elementary collisions. The figure shows that, within errors, the degree of high pt suppression observed at $\eta = 0$ and at $\eta = 2.2$ is similar or perhaps even superios at the more forward rapidities.

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 N_{bin}. We have applied no centrality cuts, so the distribution reflects our minimum bias collision data, which correspond to $\approx 90\%$ 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 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 collsions. Such an explanation appears improbable in view of the results for the d+Au measurements which utilize projectiles (of which one is larger) 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. 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 rapidities 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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