Transverse Momentum Spectra in Au+Au and d+Au Collisions at $\sqrt{s_{NN}}$=200 GeV and the Pseudorapidity Dependence of High p_T Suppression

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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 $\mathrm{p}+\bar{\mathrm{p}}$ 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 $\eta = 2.2$ 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 the medium created in the central Au+Au collisions. The lack of suppression in d+Au collisions makes it unlikely that initial state effects can explain the suppression in the central Au+Au collisions.

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Collisions between heavy nuclei 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 possibly exhibiting features characteristic of quark deconfinement, *i.e.* the quark-gluon plasma (QGP). The first experiments with Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV suggest that very high energy densities ($\epsilon > 5$ GeV/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, indicating a high degree of nuclear transparency (as may be deduced from the low net proton rapidity density measured in the region around midrapidity ($|y| < 2$) [1]). This resembles the scenario proposed by Bjorken [2], in which the colliding nuclei suffer a moderate relative rapidity loss and where subsequent particle production in the boost invariant midrapidity region arises primarily from quark-antiquark pair production from the breaking of color strings between the interacting partons. Additionally, studies of the particle production [3, 4] 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. An analysis of particle ratios at midrapidity indicates that the baryochemical potential is low ($\mu_B < 30$ MeV) [5]. This set of observations naturally leads to speculation about whether a high density deconfined state of quarks and gluons 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 [2, 6, 7] that high momentum particles may be a good probe of the conditions of the produced medium. Such particles are associated with jet production from initial hard parton scatterings and are predicted to suffer energy loss due to induced gluon radiation as they traverse a medium with a high density of color charges, resulting in a depletion of the high transverse momentum component of their spectra. This high p_T suppression has been of much recent interest [8, 9, 10, 11].

In this Letter, we report on measurements of charged hadrons from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV 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 $\mathrm{p}+\bar{\mathrm{p}}$ collisions at the same energy using a scaling to our acceptance and to the estimated number of binary collisions. We have also measured similar spectra (for minimum bias (MB) collisions) for the reaction d+Au at $\sqrt{s_{NN}} = 200$ GeV in order to probe the possible role of initial state effects and the influence of the participant volume. For central $(0-10\%)$ Au+Au collisions we find a strong suppression of the high transverse momentum component ($p_T > 2$ GeV/c) of the spectra as compared to the scaled $\mathrm{p}+\bar{\mathrm{p}}$ spectra. This suppression diminishes significantly as the collision centrality decreases. In contrast, an enhancement is observed for the d+Au collisions.

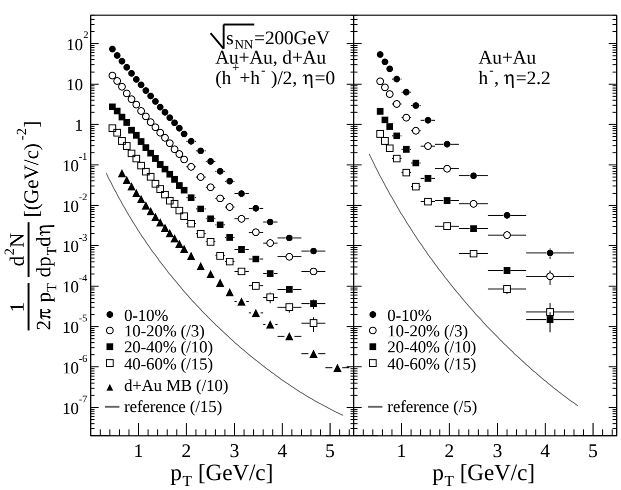

FIG. 1: Invariant spectra of charged hadrons from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for pseudorapidities $\eta = 0$ (left panel) and $\eta = 2.2$ (right panel). Various centrality cuts are shown for Au+Au. The $\mathrm{p}+\bar{\mathrm{p}}$ reference spectra (appropriately acceptance scaled) are shown for comparison. The left panel also shows the d+Au spectrum. For clarity, some spectra have been divided by the indicated factors.

BRAHMS consists of two magnetic spectrometers (the MidRapidity Spectrometer, MRS, and the Forward Spectrometer, FS) that for the present measurements were positioned at 90° (MRS) and 12° (FS) relative to the beam direction and measured hadrons (h^+) and antihadrons (h^-) at pseudorapidities in the ranges $|\eta| < 0.1$ and $2.1 < \eta < 2.3$, respectively. In addition, a set of global detectors were used for miminum bias trigger and event characterization. In the Au+Au run this trigger selected approximately 95% of the Au+Au interaction cross section. An additional hardware trigger selected the $\approx 25\%$ most central events for parts of the Au+Au run. In the d+Au run, scintillator counters (INEL) were placed around the nominal intersection point (IP) at $z = \pm 1.6, \pm 4.2$ and ± 6.6m, and used as the minimum bias trigger, selecting $\approx 91\% \pm 3\%$ of the $2.4b$ d+Au inelastic cross section. Spectrometer triggers were added to enhance the track sample. Further details of the experimental setup and operation can be found in refs. [3, 12]. Centrality selection for the Au+Au collisions was done using multiplicity detectors positioned around the IP. The IP position is determined with a precision of $\sigma < 0.9$ cm by the use of arrays of beam counters (BB) placed at $z = \pm 2.2$m. For the d+Au reaction study the vertex measurement by the INEL counters has a resolution of approximately 9 cm.

Figure 1 shows measured invariant spectra for charged hadrons $(h^+ + h^-)/2$ at 90° (left panel) and for negative hadrons (h^-) at 12° (right panel), corresponding to $\eta = 0$ and 2.2. The displayed spectra for Au+Au collisions are for centralities of 0–10%, 10–20%, 20–40%, and 40–60%. The spectra are from measurements at various magnetic fields and have been corrected for the acceptance of the spectrometers and for the tracking efficiency. No decay corrections have been applied. Also shown in the figure is our measured spectrum from d+Au collisions. The reference is from $\mathrm{p}+\bar{\mathrm{p}}$ collisions measured in the range $|\eta| < 2.5$ by the UA1 experiment at CERN [13]. To compare with our spectra we apply a p_T and η dependent correction estimated using the HIJING (v. 1.383) code [14], which reproduces the main features of p + p collisions well. We have compared our corrected spectrum at $\eta = 0$ with the $\sqrt{s}$=200 GeV p+p distribution recently measured by the STAR collaboration [15] and find excellent agreement. No similar comparison is available for the more forward rapidity. Consequently, we use the model–scaled $\mathrm{p}+\bar{\mathrm{p}}$ spectrum for comparison, noting that HIJING predicts a p_T dependent difference between h^- and $(h^+ + h^-)/2$ at $\eta = 2.2$. This has been taken into account in constructing the h^- reference spectrum used for the $\eta = 2.2$ analysis.

A useful way to compare the spectra from nucleus-nucleus collisions to those from nucleon-nucleon collisions is to scale the normalized p+p spectrum (assuming $\sigma^{pp}_{inel} = 42mb$) 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, $R_{AA} = (\sigma^{pp}_{inel}/N_{bin})(d^2N^{AA}/dp_T d\eta)/(d^2\sigma^{pp}/dp_T d\eta)$.

Figure 2 (upper two rows) shows the ratios R_{AuAu}, as a function of p_T for different centrality cuts for the Au+Au measurements at $\eta = 0$ and 2.2. For the most central $(0-10\%)$ bin we use $N_{bin} = 897 \pm 117$, and for the most peripheral $(40-60\%)$ $N_{bin} = 78 \pm 26$. For the d+Au reaction we have used $N_{bin} = 7.2 \pm 0.3$.

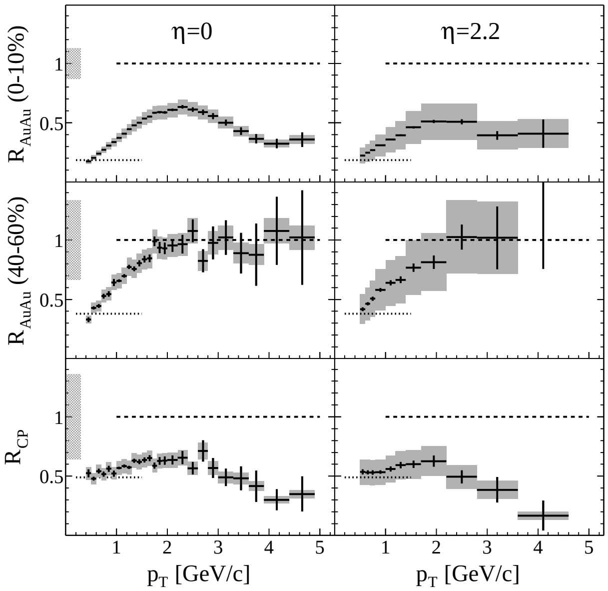

FIG. 2: Top row: Nuclear modification factors R_{AuAu} as a function of transverse momentum for Au+Au collisions at $\eta = 0$ and $\eta = 2.2$ for the $0-10\%$ most central collisions. Middle row: as top row, but for centralities $40-60\%$. Bottom row: ratio of the R_{AuAu} factors for the most central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

The R_{AuAu} rise from values of 0.2–0.4 at low p_T to a maximum at $p_T \approx 2$ GeV/c. The low p_T part of the spectrum is associated with soft collisions and should therefore scale with the number of participants. Thus the applied scaling with the (larger) N_{bin} value reduces R_{AuAu} at the lower p_T. Beyond $p_T \approx 2$ GeV/c, R_{AuAu} is expected to be close to 1. In fact, measurements at CERN-SPS for $\sqrt{s_{NN}} = 17$ GeV collisions for neutral pions [16], negative hadrons [17] and charged pions [18] 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 [19]. This is the Cronin effect [20] attributed to multiple scattering of partons in the initial stages of the collision. Above $p_T \approx 2$ GeV/c the R_{AuAu} distributions shown in fig. 2 decrease and are systematically lower than unity for the central collisions, while they remain near 1 for more peripheral collisions. Indeed, for the most central collisions at both pseudorapidities, R_{AuAu} is only about 0.4 at $p_T \approx 4$ 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 and by a factor of two compared to simple binary scaling. We note, however, that because we lack an independent measurement of the p + p reference spectrum at forward rapidity, the systematic error on R_{AuAu} at $\eta = 2.2$ is estimated to be $\sigma_{sys} \approx 30\%$ at high p_T. In order to remove this large, and model dependent systematic error from our reference spectra, we form the ratio $R_{cp} = \frac{N_{bin}(P)}{N_{bin}(C)} \times [\frac{d^2N}{p_T\, dp_T\, d\eta}|_C]/[\frac{d^2N}{p_T\, dp_T\, d\eta}|_P]$, where 'C' and 'P', denote the most central and peripheral bins, respectively. As can be seen in the bottom panels of fig. 2, R_{cp} shows a clear decrease for $p_T > 2$ GeV/c for both $\eta = 0$ and $\eta = 2.2$.

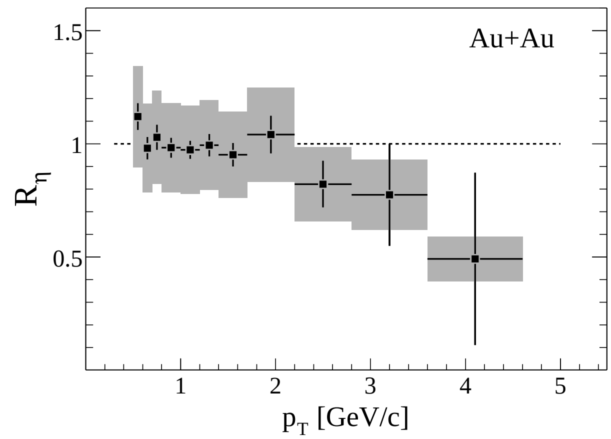

FIG. 3: Ratio R_η of R_{cp} distributions at $\eta = 2.2$ and $\eta = 0$. Statistical errors are indicated by the bars, while systematic errors are shown by the grey bands.

We investigate the pseudorapidity dependence of the high p_T suppression using the ratio $R_\eta = R_{cp}(\eta = 2.2)/R_{cp}(\eta = 0)$. This ratio, shown in fig. 3, is free from systematic errors arising from the determination of the N_{bin} values corresponding to the centrality cuts. Figure 3 shows that, within errors, the degree of high p_T suppression (for $p_T > 2$ GeV/c) observed at $\eta = 2.2$ is similar to or larger than at $\eta = 0$. We note that one might naively expect the suppression to be proportional to the measured $dN/d\eta$ for charged particles which in turn is expected to be proportional to $dN_{gluon}/d\eta$. Since the measured $dN/d\eta$ distributions [3, 4] are roughly flat in this rapidity region, one would expect similar suppression factors. However, the strength of the underlying suppression mechanism (partonic or hadronic) may depend on the pseudorapidity density, wherefore it is important to explore the details of p_T suppression over a wide rapidity region.

For comparison to the results obtained for the Au+Au collisions we have investigated the d+Au reaction at the same energy at $\eta = 0$. In fig. 4 we present the corresponding R_{dAu} distribution, analyzed in the same way as the Au+Au collisions. We have applied no centrality cuts, so the distribution reflects our minimum bias collision data. It is striking that R_{dAu} shows no suppression of the high p_T component. Rather, it shows an enhancement, similar to the one observed at lower energies.

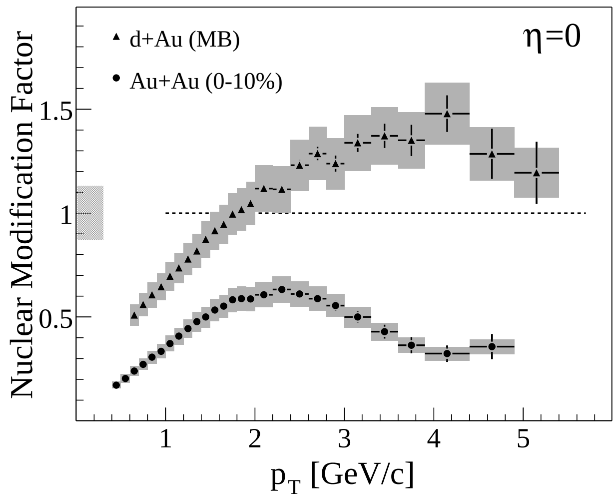

FIG. 4: Nuclear modification factor measured for minimum bias collisions of d+Au at $\sqrt{s_{NN}} = 200$ GeV compared to central Au+Au collisions. Error bars represent statistical errors. Systematic errors are denoted by the shaded bands. The grey band at $p_T = 0$ is the uncertainty on the scale of R_{AuAu}.

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 nucleon–nucleon collisions. This suppression appears to be directly correlated with the size of the participant volume, as demonstrated by the fact that the much smaller participant volume 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 [21] that gluon saturation effects in the colliding Au+Au nuclei, *i.e.* initial state effects resulting from the high laboratory energy of the colliding nuclei might limit the phase space available for the production of high momentum particles. 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 transverse momentum spectra for hadrons measured at two rapidities for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The suppression is seen to diminish with decreasing collision centrality and is absent in d+Au collisions. In fact, the observation of a Cronin enhancement in d+Au reaction seems to exclude possible initial state effects contributing to the observed suppression in collisions between large nuclei. We conclude that the observed suppression in Au+Au is consistent with significant medium effects in the most violent collisions, *i.e.* those that have the largest participant volumes. The persistance of the suppression to $\eta = 2.2$ suggests that the volume which causes the suppression is extended also in the longitudinal direction. Whether the observed suppression is tied to absorption or energy loss of scattered high momentum partons by a dense partonic medium [22], to absorption at a later hadronic stage [23] or to some other mechanism is as yet unclear. This clearly warrants further systematic investigations, notably by studying the effect over the largest possible rapidity range with identified particles in order to probe varying source conditions and absorption mechanisms and by carrying out experiments at lower beam energies.

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