On the high-p_t suppression of charged hadrons from 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 scaled to spectra from $p + \bar{p}$ collisions at the same energy measured by the UA1 experiment. The resulting ratios of such spectra for (nuclear modification factors) at ($\eta = 0$) and ($\eta = 2$) evidence a strong suppression at $p_t > 2GeV/c$ as compared to similar data at lower energy. In contrast the d+Au ratios do not exhibit suppression of the high p_t yields. A possible explanation for these observations is the absorbtion or energy loss of leading partons due to strong medium effects in the central Au+Au collisions, over the rapidity range $\eta = 0 to 2.2$. The lack of suppression in D+Au collisions is consistent with the smaller system dimensions and appears to rule out effects due to parton saturation effects in the colliding nuclei.

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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 region with a high density of quark and gluons, exhibiting features characteristic of quark deconfinement, the so called quark-gluon plasma (QGP). The first experiments with Au+Au collisions at 100 AGeV+ 100 AGeV already 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 pseudorapidity density of net protons that is measured in a region around midrapidity ($|y| < 1.5$) ([1],(ref: Star, Phobos and Phenix). 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 rapidity loss and where the bulk of particle production occurs via quark-antiquark pair production from the breaking of color strings between scattered partons. Studies of the particle production (ref. multiplicity papers from 4 experiments) and the dynamics of the expanding hadronic cloud that subsequently forms, furthermore 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 about 20 MeV [**?**],[8]. The set of these observations naturally leads to speculations about whether a high density deconfined partonic state is indeed formed in Au+Au collisions at RHIC.

In order to probe 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. Indeed, such particles, which are associated with jet production from initial hard parton scatterings, may experience attenuation and energy loss as they traverse a dense hadronic medium due to induced gluon radiation, resulting in a reduction of the high transverse momentum component of their spectrum. This is the so-called high-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 centrality of the collisions, 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. We find a strong suppression of the high transverse momentum component ($p_t > 2GeV/c$) of the spectra for central ($0-5\%$) Au+Au collisions as compared to the scaled $p + \bar{p}$ spectra. This suppression is seen to diminish significantly as the collision centrality decreases. In contrast no such suppression is observed for the D+Au collisions.

The experiments were done with the BRAHMS spectrometer. This instrument, which is located at the 2'clock intersection area of the RHIC accelerator complex, consists of two magnetic spectrometers (the MidRapidity Spectrometer, MRS and the Forward Spectrometer, FS) that together can cover the angular range from 90 degrees to 2.3 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 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 .... . Furthermore the experiment has excellent particle identification (PID) capabilities, which are achieved through the use of several segmented scintillator time of flight hodoscopes and a Ring Imaging Cerenkov detector. In this work, we concentrate on the spectra of charged hadrons (h and h^-), wherefore the PID capability is not used. Centrality selection is done using global multiplicity detectors positioned around the nominal intersection point (IP). By measuring charged particles in these arrays we are sensitive to about 97% of the nuclear interaction cross section for Au+Au reactions. The position of the actual intersection point is determined by the use of arrays of beam counters placed at about 2m on either side of the collision zone. The IP position can be determined more accurately in the subsequent off-line analysis by pointing tracks measured in the MRS back to the beam line. Further details of the spectrometer arrangement and operation can be found in [4, 5, 9]. For the D+Au reaction studies, additional scintillator counters, placed close to the beam pipe at z= +-2, and +-3 m (check) from the IP, were used to trigger the data collection. We estimate that these counters allow us to measure approximately 90% of the reaction cross section. For the D+Au reaction studies we have employed spectrometer triggers to enhance the data collection. The efficiencies of these triggers have been taken into account.

Figure 1 shows measured spectra for charged hadrons $(h + +h-)/2$ at 90 degrees, left panel, and for h^- at 12 degrees, right panel, corresponding to pseudorapidities ($\eta = 0 and 2.2$). The width of the rapidity intervals are (..) and (..) respectively. The displayed spectra correspond to various centralities (....). 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. Various fiducial cuts selecting tracks pointing back to the vertex have been applied. Spectra have also been corrected for effects due to the momentum resolution. Also show in the figure is the 'reference' spectrum for $p + \bar{p}$ collisions measured by the UA1 collaboration at the SPS at CERN (ref...). This spectrum was measured in the range $\eta = 0, 2.5$. To be able to compare it to our data, which are defined 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...), has been tuned to reproduce p+p collisions over a wide energy range. 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 and we consequently use the model-scaled $p + \bar{p}$ spectrum for the following comparisons.

A useful way to compare the momentum spectra from nucleus-nucleus collisions to those from p+p reactions, 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}. (Add FORMULA?) The used N_{bin} values have been obtained from the HIJING code. For the various centrality cuts in Au+Au theyare. ..,...,...,... and for the D+Au reaction we have used $N_{bin} = 7$.

Figures 2 and 3 show the R_{AA} ratios 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_{AA} in this momentum interval. Beyond $p_t \approx 2GeV/c$, R_{AA} is expected to be close to 1. In fact measurements of R_{AA} at CERN-SPS for $\sqrt{s_{nn}} = 17$ AGeV collisions for neutral pions (ref: WA98) , negative hadrons(ref: NA49) and charged pions (ref: CERES) show that R_{AA} is equal to 1 at $p_t = 1.5GeV/c$ and increases to about 3 at $p_t = 3GeV/c$. This effect has been explained (ref. Cronin etc.) as being due to multiple scattering of nucleons in the initial stages of the collision. A salient feature of the R_{AA} distributions shown in figs. 2 and 3 is that R_{AA} is systematically lower than 1 for the central collisions at $p_t > 2GeV$), while it tends towards 1 for the peripheral collisions. Indeed, for the most central collisions at both rapidities, the R_{AA} is only about 0.4 at $p_t \approx 3GeV/c$. 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 observe that the high p_t suppression for the most peripheral centrality bin at $\eta = 2.2$ appears to be more pronounced than for $\eta = 0$, although we also remark that our systematic error at this angle, estimated to be about 20%, combined with the large statistical errors at high p_t, at the present stage precludes a more significant comparison.

In order to further study the observed suppression of the high p_t component, which is seen in 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_{AA} 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 corresponds to approximately minimum bias collision data, with a slight bias towards more central collisions (90% of the total reaction cross section). It is striking that the R_{AA} 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 $p + \bar{p}$ 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 (which has a much reduced participant zone) 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, resulting from their high laboratory energy, might limit the phase space available for the production of high momentum particles. Such an entrance channel effect appears improbable in view of the $D + Au$ measurements which utilize projectiles (of which one is large) at the same energy.

In summary, the BRAHMS collaboration, has demonstrated 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 may indicate 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 will warrant further systematic investigations, notably by studying the effect over the largest possible rapidity range and by carrying out experiments at lower beam energies.

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.

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FIG. 2: Nuclear modification factor R_{AA} for Au+Au collisions at $\eta = 0$ as a function of transverse momentum for the 4 centrality bins shown in figure 1. The dotted lines show the expected value using participant scaling and binary collision scaling, respectively. Error bars are statistical.

FIG. 3: Nuclear modification factors for Au+Au at $\eta = 2.2$, otherwise see caption of figure 2.

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 $20 percent$

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