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System Size and Centrality Dependence of Charged Hadron Transverse Momentum Spectra in Au + Au and Cu + Cu Collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV

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We present transverse momentum distributions of charged hadrons produced in Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The spectra are measured for transverse momenta of $0.25 < p_T < 5.0$ GeV/c at $\sqrt{s_{NN}} = 62.4$ GeV and $0.25 < p_T < 7.0$ GeV/c at $\sqrt{s_{NN}} = 200$ GeV, in a pseudorapidity range of $0.2 < \eta < 1.4$. The nuclear modification factor R_{AA} is calculated relative to $p + p$ data at both collision energies as a function of collision centrality. At a given collision energy and fractional cross section, R_{AA} is observed to be systematically larger in Cu + Cu collisions compared to Au + Au. However, for the same number of participating nucleons, R_{AA} is essentially the same in both systems over the measured range of p_T, in spite of the significantly different geometries of the Cu + Cu and Au + Au systems.

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The yield of charged hadrons produced at midrapidity in Cu + Cu collisions at energies of $\sqrt{s_{NN}} = 62.4$ and 200 GeV has been measured with the PHOBOS detector at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. The data are presented as a function of transverse momentum (p_T) and collision centrality. The goal of these measurements is to study the possible formation of a new form of matter through modification of particle production compared to nucleon-nucleon collisions at the same energy.

This measurement was motivated by results from Au + Au collisions for $\sqrt{s_{NN}} = 62.4$, 130, and 200 GeV. Hadron production at these energies was found to be strongly suppressed relative to expectations based on an independent superposition of nucleon-nucleon collisions at p_T of 2–10 GeV/c [1–5]. The modification of high-p_T hadron yields has commonly been investigated using the nuclear modification factor R_{AA}, defined as

$$R_{AA}(p_T) = \frac{\sigma_{pp}^{\mathrm{inel}}}{\langle N_{\mathrm{coll}}\rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}. \qquad (1)$$

A value of $R_{AA} = 1$ is obtained if particle production scales with the average number of binary nucleon-nucleon collisions $\langle N_{\mathrm{coll}}\rangle$ within a heavy-ion collision. Instead, for the production of charged hadrons in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, values of $R_{AA} \approx 0.2$ are observed at $p_T = 4$ GeV/c [2–4].

Such a suppression had been predicted to occur as a consequence of the energy loss of high-p_T partons in the dense medium formed in Au + Au collisions [6]. This hypothesis is also supported by the observed absence of this effect in deuteron-gold collisions at the same collision energy [7–10].

The results presented here for Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV bridge the gap between the Au + Au and d + Au systems, allowing a unique examination of the dependence of high-p_T suppression on system size. A careful comparison of Cu + Cu and Au + Au spectra to model calculations at high p_T can elucidate the dependence of absorption on path length, especially as one expects a different distribution of path lengths for jets produced in the two systems even for the same N_{part}.

The data were collected using the PHOBOS two-arm magnetic spectrometer. Details of the experimental setup can be found in Ref. [11]. The primary event trigger used the time difference between signals in two sets of 10 Čerenkov counters, located at $4.4 < |\eta| < 4.9$, to select collisions that were close to the nominal vertex position along the beam axis.

For the analysis presented here, events were divided into centrality classes based on the total energy deposited in the

TABLE I. Details of the centrality classes used in this analysis. Bins are expressed in terms of percentage of the total inelastic Cu + Cu cross section.

Centrality	$\langle N_{\rm part}^{62.4} \rangle$	$\langle N_{\rm coll}^{62.4} \rangle$	$\langle N_{\rm part}^{200} \rangle$	$\langle N_{\rm coll}^{200} \rangle$
45%–50%	⋯	⋯	21 ± 3	22 ± 4
35%–45%	⋯	⋯	29 ± 3	33 ± 5
35%–40%	31 ± 3	33 ± 5	⋯	⋯
25%–35%	41 ± 3	49 ± 6	43 ± 3	56 ± 6
15%–25%	59 ± 3	80 ± 7	62 ± 3	94 ± 8
6%–15%	81 ± 3	125 ± 9	84 ± 3	144 ± 11
0%–6%	101 ± 3	170 ± 12	104 ± 3	197 ± 14

octagon silicon detector, covering pseudorapidities $|\eta| < 3.2$. A full detector simulation using HIJING events [12,13] was used to estimate $\langle N_{\rm part} \rangle$ for each centrality class, and the corresponding $\langle N_{\rm coll} \rangle$ values were obtained from a Monte Carlo Glauber calculation [12,14]. For these calculations, as well as for the determination of R_{AA} at 62.4 and 200 GeV, we used $\sigma_{pp}^{\rm inel} = 36 \pm 1$ and 42 ± 1 mb, respectively [15]. The results are listed in Table I. The systematic uncertainty on these values comes primarily from the uncertainty on our estimate of the measured fraction of the total inelastic cross section, which is calculated by a variety of methods in a range of pseudorapidity regions [14]. The uncertainty also covers the range of efficiencies measured using HIJING and AMPT [13,16].

Figure 1 demonstrates that the value of $\langle N_{\rm coll} \rangle$ is essentially the same in Au + Au and Cu + Cu for the same value of $\langle N_{\rm part} \rangle$. Thus, the comparison of these two systems does not allow one to distinguish between scaling with participants or collisions.

The event selection and track reconstruction procedure for this analysis closely followed the previously published analysis of Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV [5]. Events with a primary vertex position within ±10 cm of the nominal vertex position were selected. Only particles traversing a full spectrometer arm were included in the analysis, resulting in a low transverse momentum cutoff at $p_T \approx 0.2$ GeV/c.

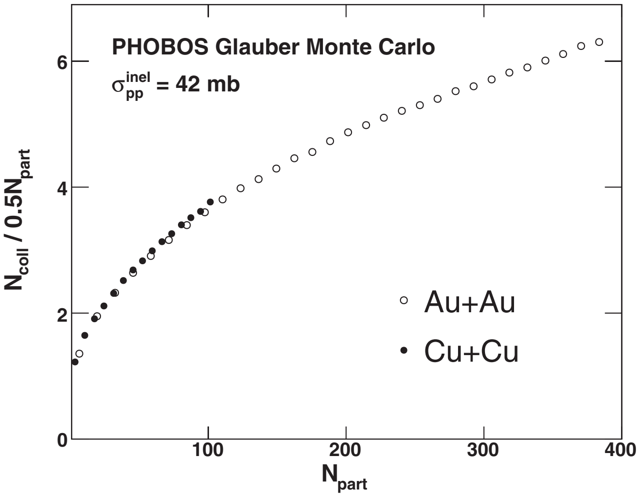

FIG. 1. Mean number of collisions per participant pair for Au + Au (open symbols) and Cu + Cu (solid symbols) at $\sqrt{s_{NN}} = 200$ GeV.

The transverse momentum distribution for each centrality bin was corrected separately for the geometrical acceptance of the detector, the inefficiency of the tracking algorithm, secondary and incorrectly reconstructed particles, and the distortion due to binning and momentum resolution. The relative importance of these corrections and their estimated systematic uncertainties are similar to those reported in the previous analysis [5].

In Fig. 2, we present the invariant yield of charged hadrons as a function of p_T, obtained by averaging the yields of positive and negative hadrons. Data are shown for each centrality bin at both energies and are averaged over a pseudorapidity interval $0.2 < \eta < 1.4$.

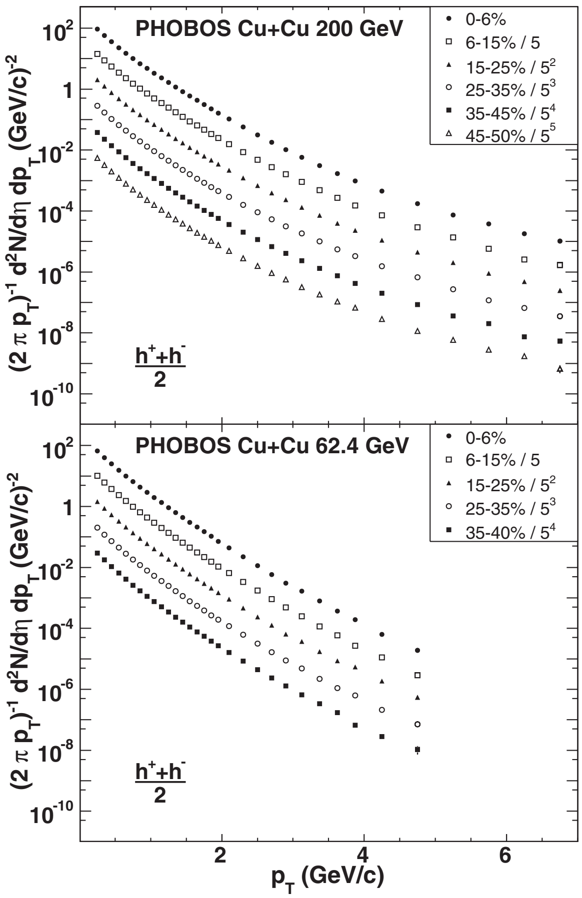

FIG. 2. Top: Invariant yields for charged hadrons from Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV, in the pseudorapidity interval $0.2 < \eta < 1.4$ as a function of p_T for 6 centrality bins. Bottom: The same for $\sqrt{s_{NN}} = 62.4$ GeV. For clarity, consecutive bins are scaled by factors of 5. Statistical and systematic uncertainties are smaller than the symbol size.

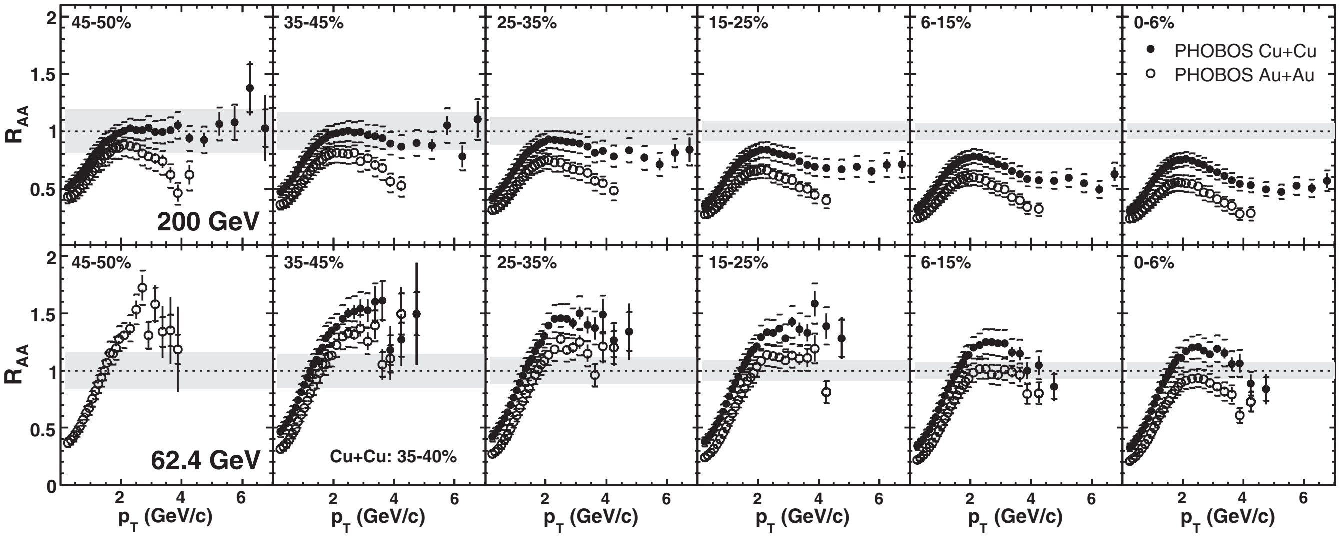

FIG. 3. Nuclear modification factor $R_{AA}(p_T)$ at midrapidity in bins of fractional cross section at $\sqrt{s_{NN}} = 200$ GeV (top row) and $\sqrt{s_{NN}} = 62.4$ GeV (bottom row), for Cu + Cu (solid symbols) and Au + Au (open symbols). Systematic errors are shown with brackets (90% C.L.). The gray band represents the relative uncertainty on $\langle N_{\rm coll}\rangle$.

The centrality evolution of $R_{AA}(p_T)$ at midrapidity for Cu + Cu collisions is shown in detail in Fig. 3. As a comparison, we also include the results from Au + Au collisions [4,5] using the same centrality binning. As indicated, the most peripheral bin shown for 62.4 GeV Cu + Cu is 35%–40% central, due to the limited efficiency of our vertex reconstruction for low multiplicity events.

At both collision energies, we notice that, in the same bin of fractional cross section, R_{AA} is systematically higher in Cu + Cu compared to Au + Au. At $\sqrt{s_{NN}} = 200$ GeV (top row), the Cu + Cu spectra exhibit a high-p_T suppression, relative to binary collision scaling, ranging from approximately 0.5 in the most central events to virtually no suppression in the most peripheral events.

For both collision energies, the spectral shape of central Cu + Cu events appears to be very similar to the shape of peripheral Au + Au events at the same number of participants. This is illustrated in Fig. 4, where we present R_{AA} versus the number of participating nucleons for both Cu + Cu and Au + Au collisions [4,5] in bins of p_T. Since the previously published PHOBOS results did not achieve the statistics that now allow measurements of Cu + Cu spectra out to $p_T = 7$ GeV/c, we include results from the PHENIX Collaboration [2] for comparison.

The result illustrated in Fig. 4 is strikingly simple. Over the broad range of p_T that we measure, the bulk particle production seems to depend only on the size of the overlapping system; that is, the Cu + Cu and Au + Au spectra are similar for the same number of participants (or binary collisions—see Fig. 1). Although the measured centrality ranges in Au + Au and Cu + Cu collisions have less overlap at $\sqrt{s_{NN}} = 62.4$ GeV, this observation appears to hold at the lower energy as well (Fig. 5).

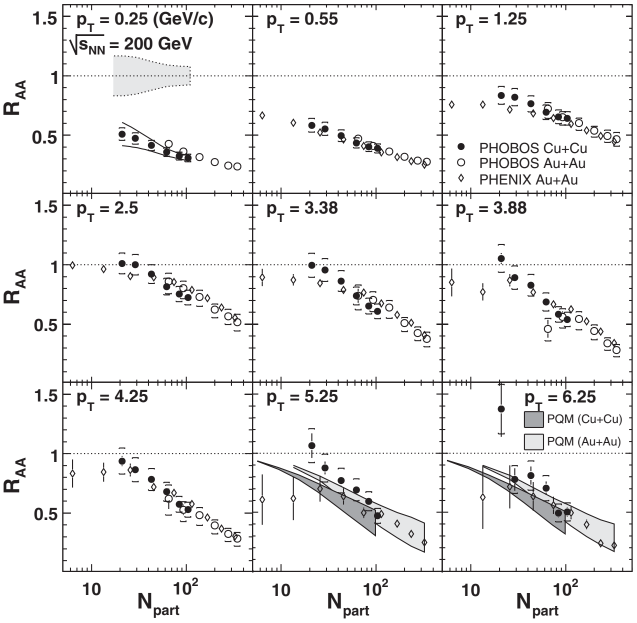

FIG. 4. Nuclear modification factor R_{AA} in bins of p_T versus $N_{\rm part}$ at $\sqrt{s_{NN}} = 200$ GeV, for Cu + Cu (solid symbols) and Au + Au (open symbols) [2,4]. The gray band in the first frame represents the relative uncertainty on $\langle N_{\rm coll}\rangle$, and the solid lines show the effect of this uncertainty on the measured R_{AA}. At high p_T, bands are shown representing the predictions of a parton quenching model [17].

At high p_T, a number of predictions have been made for the Cu + Cu system using models that successfully describe the centrality dependence of hadron yields and back-to-back correlations in Au + Au [17–19]. One such model is the parton quenching model (PQM) [17], which

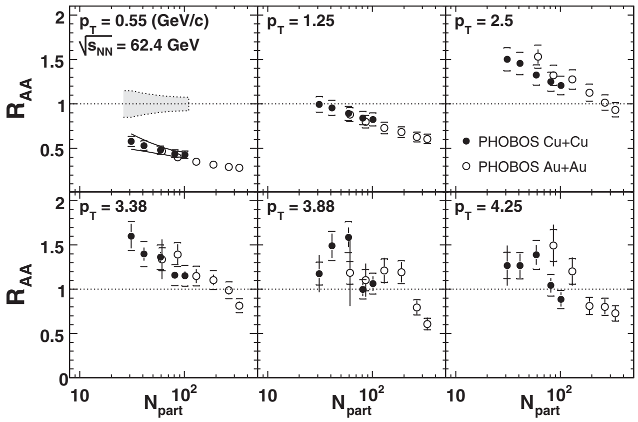

FIG. 5. Nuclear modification factor R_{AA} in bins of p_T versus N_{part} at $\sqrt{s_{NN}} = 62.4$ GeV, for Cu + Cu (solid symbols) and Au + Au (open symbols) [5].

utilizes Baier-Dokshitzer-Mueller-Peigné-Schiff quenching weights [20] and a realistic collision geometry to describe partonic energy loss. Although the centrality evolution of the Au + Au spectra are well fit by PQM, our Cu + Cu results suggest that this model slightly overestimates the suppression in the smaller system as shown in Fig. 4; thus, this prediction does not exhibit the observed N_{part} scaling. Our conclusion is consistent with the prediction of a simple jet absorption model, whose only inputs are a Glauber-based collision geometry and a quadratic dependence of absorption on a path length in an expanding medium [19]. Using the absorption coefficient that describes the 200 GeV Au + Au data, this model gives R_{AA} values which depend only on N_{part}, in agreement with our observation.

Particle production at $p_T > 1$ GeV/c in heavy-ion collisions is expected to be influenced by many effects. These include p_T broadening due to initial and final state multiple scattering (the "Cronin effect"), the medium-induced energy loss of fast partons, and the effects of collective transverse velocity fields as well as parton recombination [21]. Considering the significantly different geometries of Au + Au and Cu + Cu collisions with the same number of participant nucleons, it is not obvious, *a priori*, that these effects should conspire to give similar spectra in both systems over such a large range in p_T. A full explanation of this observation, which appears to be a fundamental feature of heavy-ion collisions at these energies, may well present a challenge to theoretical models of heavy-ion collisions.

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