Abstract. A brief overview of the current results and conclusions from the PHOBOS experiment at the Relativistic Heavy Ion Collider (RHIC) is given. No evidence is found for non-monotonic behavior of observables measured by PHOBOS in the RHIC energy region. Convincing evidence is found that we have created a state of matter with high energy-density, that is nearly net-baryon free and is strongly interacting. The data are found to exhibit "simple" scaling behaviors, which include extended longitudinal scaling and scaling with the number of participating nucleons. The Au+Au collision charged particle data also exhibit a remarkable factorization of collision energy and geometry.

1. Introduction
This report focuses on results from the PHOBOS experiment at the Relativistic Heavy-Ion Collider (RHIC). A primary, and unique, strength of the PHOBOS detector is its ability to measure the total charged particle multiplicity due to the ∼ 4π acceptance of the detector. The detectors that allow the measurement of charged particle multiplicity (dN_{ch}/dη) over the broad pseudorapidity range (|η| < 5.4) are the midrapidity Vertex detector (|η| < 1), the centrally...
Figure 1. An early PHOBOS result showing the collision energy dependence of the midrapidity pseudorapidity density of charged particle production per participant pair in central heavy-ion collisions at RHIC (solid points) compared to both lower energy heavy-ion data from the SPS and AGS, as well as results from $\bar{p}+p$ collisions [2].

located Octagon barrel ($|\eta| < 3.2$), and a series of six Ring counters ($3.1 < |\eta| < 5.4$), all of which surround a thin beryllium beam-pipe. The physics capabilities of PHOBOS are expanded with a midrapidity 16-layer Spectrometer (located in an $\approx 2$ Tesla double-dipole magnet), two TOF walls (for extended particle ID), along with a suite of additional detectors for triggering and centrality determination. The majority of the PHOBOS detector is based on the technology of silicon pad sensors, see Ref. [1] for details.

2. Evolution of Global Observables with Energy and Centrality

Already in 2002, with the availability of $\sqrt{s_{NN}} = 56, 130$ and 200 GeV Au+Au collision data at RHIC, PHOBOS results demonstrated a lack of any dramatic non-logarithmic energy dependence in the midrapidity charged particle pseudorapidity density, as seen in Fig. 1. It is important to note that these measured total charged particle multiplicities are dominated by the emission of low $p_T$ ($\leq 1.5$ GeV/c) particles. This early result for the bulk charged particle multiplicity has been strengthened by additional RHIC data at 19.6 GeV, which confirmed the measurement from the highest energy SPS heavy-ion data. The PHOBOS results for Au+Au collisions at 62.4 GeV will be forthcoming. The centrality dependence of these same midrapidity yields also exhibited no dramatic variations from the lowest to the highest RHIC collision energy, as seen in Fig. 10.

The energy and centrality dependence of elliptic flow ($v_2$) for bulk charged particle production is given in Figs. 2 and 3. The most striking feature of these data is the triangular shape for $v_2(\eta)$ with a relatively sharp peak at midrapidity, which is pointedly non-boost-invariant in character. In addition, a smooth evolution of the same basic $v_2(\eta)$ shape is seen both as a function of energy (Fig. 2) and centrality (Fig. 3). The lack of centrality dependence with shape in $\eta$ is illustrated more clearly by the inset to Fig. 3, which shows that the ratio of peripheral data to central data is constant, within errors, in the pseudorapidity range of $-2 < \eta < 2$.

Expanding the study of charged particle production to include the transverse momentum dependence, PHOBOS finds a smooth evolution in the $p_T$ dependence of charged particle production, as illustrated through measurement of the nuclear modification factor, $R_{AA}$ (see Ref. [5] and Fig. 12). This lack of dramatic variation in the shape of $R_{AA}$, with both centrality...
and energy, persists past $p_T = 4$ GeV, currently the highest transverse momentum published by PHOBOS for Au+Au collisions.

We close this section with the mention of two additional PHOBOS results. First, a monotonic behavior of the HBT radii is seen in central Au+Au collisions at both 62.4 and 200 GeV for $R_o$, $R_s$ and $R_l$, measured as a function of the pair transverse momentum, $k_T$ [6]. In fact, the values of the HBT radii at equivalent $k_T$ are identical at the two energies, within errors. Second, a smooth evolution of identified antiparticle to particle ratios near midrapidity is observed as a function of energy for central Au+Au collisions [7]. No evidence for any sudden change in baryon density is found. Instead there is a steady rise of the ratios towards unity with increasing collision energy.

Thus the picture that emerges from the global observables measured by PHOBOS in Au+Au collisions is one of remarkable regularity, even over a factor of ten change in collision energy.

### 3. Properties of the Created “State of Matter”

One of the first questions to be asked in studies of relativistic heavy-ions is; what is the energy-density of the created matter? A primary reason this value is of great interest stems from the remarkable theoretical study of high temperature QCD afforded by the techniques of lattice gauge theory. These theoretical calculations indicate that, for low baryon density, there is a phase transition in QCD matter at a critical temperature that corresponds to an energy density of $\sim 1$ GeV/fm$^3$ [9]. The antiparticle to particle ratios data tell us we have a low baryon density, with $\mu_B \approx 27$ MeV for central collisions at the highest RHIC energy [7]. The measurements of the charged particle production near midrapidity, coupled with knowledge of the average $\langle p_T \rangle$ of those particles, affords an estimate of the energy density created in the collision. The largest uncertainty is the equilibration time, $\tau_{eq}$. Conservative estimates put $\tau_{eq} \leq 2$ fm/c which leads to a lower limit for the energy density at full RHIC energy of $\geq 3$ GeV/fm$^3$ [16]. This energy density is $\sim 6$ times the energy density inside nucleons, $\sim 20$ times that inside nuclei and quite comfortably above the QCD phase threshold of $\sim 1$ GeV/fm$^3$ predicted by the lattice calculations. It seems quite plausible that we have created a very interesting and new “state of
Figure 4. The centrality dependence of the nuclear modification factor, $R_{dAu}$, for d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. For the most central 0-20% of the d+Au collisions it is also compared to $R_{AA}$ for central (0-6%) Au+Au collisions, where it is clearly evident that at higher transverse momentum ($p_T$) the heavy-ion data is strongly suppressed relative to both the binary-scaling limit of 1, as well as to the d+Au data at the equivalent pseudorapidity range of $\eta = 0.2 - 1.4$ (in the direction of the deuteron). [8].

The properties of this matter appear to be rather strongly interacting in nature. In the PHOBOS data, this conclusion rests on the three pillars of; high $p_T$ suppression (Fig. 4), the magnitude of elliptic flow (Fig. 5) and the measured low $p_T$ yields of identified particles (Fig. 6).

First, the suppression of high $p_T$ particles in central Au+Au collisions, and the corresponding lack of suppression at midrapidity for d+Au, can be naturally understood as the result of a significant level of interaction between the produced high momentum particles and the created state of matter. Second, the magnitude of the elliptic flow parameter, $v_2$, is important because if there were no interactions, then there would be no mechanism for the assymmetric shape of the initial colliding nuclei overlap to impact on the final azimuthal distribution of the observed particles. Furthermore, at low $p_T$, the magnitude of $v_2$ reaches the hydrodynamic limit predicted for an ideal fluid, as shown by the solid line in Fig. 5. Third, the invariant yield of very low momentum particles does not exceed expectations based on simple extrapolation from higher $p_T$, as shown in Fig. 6. An enhancement of low $p_T$ particles could be expected for a weakly-interacting system, but not for a strongly-interacting system, with the correspondingly large pressure gradients that act to accelerate particles with very low momenta.

Thus the defining properties of this produced state of matter appear to be a high energy-density, approaching a baryon-free environment, and strongly interacting; perhaps similar to an ideal fluid.

4. “Simple” Scaling Behaviors
The data measured by PHOBOS exhibit four distinct scaling behaviors. The first two, extended longitudinal scaling and scaling by the number of participants, are discussed below. Two
Figure 5. Transverse momentum ($p_T$) dependence of the elliptic flow parameter, $v_2$, for the most central 50\% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [4].

Figure 6. The invariant yield of very low momentum $\pi$, K and p (closed symbols) produced in central (0-15\%) collisions as a function of $p_T$ as measured by PHOBOS [10], and compared to extrapolations of fits to PHENIX measurements [11] at intermediate $p_T$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Figure 7. The pseudorapidity dependence of the charged particle density, $dN_{ch}/d\eta'$, for central (0-6\%) Au+Au collisions plotted in the approximate rest frame of one of the colliding beams (i.e. $\eta' = |\eta| - y_{beam}$) [14].

Figure 8. The pseudorapidity dependence of the elliptic flow parameter, $v_2$, for central (0-40\%) Au+Au collisions plotted in the approximate rest frame of one of the colliding beams (i.e. $\eta' = |\eta| - y_{beam}$) [3].

additional behaviors, the apparent universality of total charged particle production [12] and the transverse mass scaling in particle spectra for d+Au collisions [13], will not be discussed here and the interested reader is encouraged to examine the cited references.

The feature of extended longitudinal scaling is apparent when either the charged particle pseudorapidity density, $dN_{ch}/d\eta$, or the elliptic flow parameter, $v_2$, is viewed in the approximate rest frame of one of the colliding nuclei, i.e. on an x-axis scale of $\eta' = |\eta| - y_{beam}$ (see Figs. 7 and 8). What is immediately observed is that the Au+Au data from different energies all converge near the beam rapidity, and furthermore, that this convergence not only extends significantly away from beam rapidity but also grows in extent with increasing collision energy. This feature
Figure 9. Centrality ($N_{\text{part}}$) dependence of the integrated charged particle production per participant pair for Au+Au collisions (at the three given collision energies) and for d+Au and Σ+p at $\sqrt{s_{NN}} = 200$ GeV [16]. Note the logarithmic x-axis scale for $\langle N_{\text{part}} \rangle$.

is reminiscent of the more limited phenomena of “limiting fragmentation” first observed in Σ+p collisions. In the PHOBOS data, the more general feature of extended longitudinal scaling is not only manifest in $v_2$ and $dN_{ch}/d\eta'$ for central Au+Au collisions, but also for non-central Au+Au $dN_{ch}/d\eta'$ data [14] as well as for $dN_{ch}/d\eta'$ in d+Au collisions [15].

As mentioned in the introduction, one of the strengths of the PHOBOS detector is the ability to measure the total charged particle production, $N_{\text{ch}}$. This result is given in Fig. 9 for Au+Au collisions at three different energies and for d+Au collisions at 200 GeV, all as a function of the centrality of the collision. The striking feature of this result is that $N_{\text{ch}}$ scales amazingly well with the number of participant pairs to the extent that, within errors, $N_{\text{ch}}$ per participant pair is flat for both Au+Au and d+Au collisions at all energies studied, as a function of the measured region of collision centrality. In addition, looking only at 200 GeV data, there is a difference in the overall scale of charged particle production between the Σ+p and d+Au data, which themselves are in good agreement, and the Au+Au heavy-ion data, which has a larger $N_{\text{ch}}$ per participant pair. This observation is discussed in more detail in Ref. [12].

5. Factorization of Energy and Centrality

The last feature of the PHOBOS data that we discuss is an apparent factorization of collision energy and centrality, first observed in the midrapidity charged particle pseudorapidity density [17]. The midrapidity $dN_{ch}/d\eta$ per participant pair for Au+Au collisions is given in Fig. 10 at the lowest (solid squares) and highest (solid circles) RHIC energies, along with lines from two calculations and one fit, see Ref. [18] for more details. The first indication of the factorization of energy and centrality can be seen from the simple two component fit (dotted lines)

$$\frac{dN_{ch}}{d\eta} = n_{pp}((1-x)\frac{\langle N_{\text{part}} \rangle}{2} + x\langle N_{\text{coll}} \rangle).$$

The free “fit” parameter is $x$; $N_{\text{part}}/2$ is the number of participant pairs, $N_{\text{coll}}$ is the number of binary (nucleon-nucleon) collisions, and the overall scale is given by $n_{pp}$ the yield measured in elementary $p(\Sigma)p$ + p collisions (also given by the open symbols). Although there are large (systematic) errors involved, we find the data from both energies to be consistent with the same “fit” parameter of $x \sim 0.13$, indicating a common factorization into a centrality dependent
Figure 10. Centrality ($N_{\text{part}}$) dependence of the midrapidity pseudorapidity density per participant pair at $\sqrt{s_{NN}} = 19.6$ and 200 GeV Au+Au collisions [18]. Error ellipses represent 90% C.L. limits.

Figure 11. Centrality ($N_{\text{part}}$) dependence of the ratio, $R_{200/19.6}$, of the midrapidity pseudorapidity density per participant pair for Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ and 200 GeV [18].

component ($x$) and a collision energy component (set by the overall scale of $n_{pp}$). This factorization is even more evident in Fig. 11, where the ratio of the data from both energies is given. In this case we see the remarkable feature that the ratio is flat with collision centrality.

The observation of $N_{\text{part}}$ scaling in the total charged particle multiplicity and only a small fraction of binary collision ($N_{\text{coll}}$) scaling manifest in the midrapidity data motivates a closer examination of the binary collision scaling assumption that is inherent in the standard definition of the nuclear modification factor, $R_{AA}$. This is done in Fig. 12 through the use of two modified nuclear modification factors, $R_{AA}^{N_{\text{part}}}$ and $R_{PC}^{N_{\text{part}}}$. The factor $R_{AA}^{N_{\text{part}}}$, shown along the middle panels of Fig. 12, is the standard nuclear modification factor but with the Au+Au data normalized per participant pair, instead of per collision. The factor $R_{PC}^{N_{\text{part}}}$ (the bottom panels) is simply a ratio of peripheral Au+Au data to the most central (0-6%) one, with each normalized by their corresponding number of participants. We make two observations. First, comparing the top ($R_{AA}$) and middle ($R_{AA}^{N_{\text{part}}}$) panels, we see that yields normalized by $N_{\text{part}}$ are simply less centrality dependent. We can start to see the same type of factorization evident in the “bulk” midrapidity yields, but now as a function of $p_T$. Second, comparing the middle ($R_{AA}^{N_{\text{part}}}$) and bottom ($R_{PC}^{N_{\text{part}}}$) panels, we see that by taking ratios of peripheral to central data independently for each energy gives a result that is very similar at both energies and only has a weak $p_T$ dependence. In other words the data appears to factorize in both energy and centrality, now also as a function of $p_T$.

6. Conclusions
The data from RHIC thus far indicates that we have created a state of matter with high energy-density, that is nearly net-baryon free and that is strongly interacting. The transition to this new state of matter does not show abrupt changes in observables measured by PHOBOS. The data exhibit many “simple” scaling behaviors and factorizations that serve to unite the data. This suggests strong global constraints and illustrates the importance of the collision geometry in the initial state and the very early evolution of the colliding system.
Figure 12. Centrality evolution of $R_{AA}$ and two modified nuclear modification factors ($R_{Npart}^{AA}$ and $R_{Npart}^{PC}$) as a function of transverse momentum, $p_T$, for Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ (closed circles) and 200 (open circles) GeV [5].

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