PHYSICAL REVIEW C **74**, 021902(R) (2006)

Centrality and energy dependence of charged-particle multiplicities in heavy ion collisions in the context of elementary reactions

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(Received 11 January 2005; revised manuscript received 24 February 2006; published 22 August 2006)

The PHOBOS experiment at the BNL Relativistic Heavy Ion Collider has measured the total multiplicity of primary charged particles as a function of collision centrality in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$, 130, and 200 GeV. An approximate independence of $\langle N_{\mathrm{ch}}\rangle/\langle N_{\mathrm{part}}/2\rangle$ on the number of participating nucleons is observed, reminiscent of "wounded nucleon" scaling ($N_{\mathrm{ch}} \propto N_{\mathrm{part}}$) observed in proton-nucleus collisions. Unlike $p+A$, the constant of proportionality does not seem to be set by the $pp/\overline{p}p$ data at the same energy. Rather, there seems to be a surprising correspondence with the total multiplicity measured in e^+e^- annihilations, as well as the rapidity shape measured over a large range. The energy dependence of the integrated multiplicity per participant pair shows that e^+e^- and $A+A$ data agree over a large range of center-of-mass energies ($\sqrt{s} > 20$ GeV), and $pp/\overline{p}p$ data can be brought to agree approximately with the e^+e^- data by correcting for the typical energy taken away by leading particles. This is suggestive of a mechanism for soft particle production that depends mainly on the amount of available energy. It is conjectured that the dominant distinction between $A+A$ and $p+p$ collisions is the multiple collisions per participant, which appears to be sufficient to substantially reduce the energy taken away by leading particles.

DOI: 10.1103/PhysRevC.74.021902 PACS number(s): 25.75.Dw

Central collisions of two gold nuclei at the top energy of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory produce thousands of charged particles. These are the largest particle multiplicities generated in manmade subatomic reactions. The hope is that these complex systems may reveal evidence of the creation and decay of a quark-gluon plasma (QGP), in which quarks and gluons are allowed to explore a volume larger than that of a typical hadron.

The high multiplicities in heavy ion collisions typically arise from the large number of nucleon-nucleon collisions that occur, with many of the nucleons struck several times as they pass through the oncoming nucleus. Studies of proton-nucleus collisions demonstrated that the total multiplicity (N_{ch}) is not proportional to the number of binary collisions (N_{coll}) in the reaction, but rather scales more closely with the number of "wounded nucleons" which participate inelastically (N_{part}) [1,2]. For example, the number of participants is $N_{\mathrm{part}} = 2$ for a proton-proton collision and $N_{\mathrm{part}} = N_{\mathrm{coll}} + 1$ for a proton-nucleus collision. Thus, by scaling the particle yields by $N_{\mathrm{part}}/2$, data from heavy ion collisions may be directly compared with similar yields in elementary pp, $\overline{p}p$, or even the annihilation of e^+e^- into hadrons.

While both e^+e^- and $pp/\overline{p}p$ collisions must ultimately allow a description based on quantum chromodynamics (QCD), which is the theory of the strong interaction, the evolution of these two systems tends to be understood in different ways. The large momentum transfer to the outgoing produced quark and antiquark in e^+e^- reactions allows the use of perturbative QCD (pQCD) to describe the spectrum of quarks and gluons radiated as the system fragments [3]. Minimum bias collisions of hadrons are not considered to be amenable to such a perturbative description, since the transverse momentum exchanges involved are typically less than 1 GeV/c. Instead, phenomenological approaches (e.g., PYTHIA [4]) are used to describe most of the (predominantly soft) particles produced in high energy pp or $\overline{p}p$ collisions.

In this Rapid Communication, we report results from the PHOBOS experiment on the total multiplicity of primary charged particles $\langle N_{\mathrm{ch}}\rangle$ as a function of N_{part} for Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6, 130, and 200 GeV, where $\sqrt{s_{NN}}$ is the nucleon-nucleon center-of-mass energy. Comparisons with $pp/\overline{p}p$ and e^+e^- data are made to investigate how these possibly different mechanisms of particle production apply in the context of heavy ion collisions.

The PHOBOS multiplicity detector consists of two arrays of silicon detectors which cover nearly the full solid angle for collision events. The "octagon" detector surrounds the interaction region with a roughly cylindrical geometry covering $|\eta| < 3.2$. Two sets of three "ring" detectors are placed far forward and backward of the interaction point and surround the beam pipe, covering $3 < |\eta| < 5.4$. The methods used for measuring the multiplicity of charged particles as well as for determining $\langle N_{\mathrm{part}}\rangle$ have been described in more detail in Refs. [5,6].

In principle, one could present the total number of particles only measured in the fiducial acceptance of the detector ($|\eta| < 5.4$). However, it has already been noticed that the centrality evolution of $dN_{\mathrm{ch}}/d\eta$ in Au+Au collisions is not just a change in yield, but a change in shape, with the pseudorapidity shape in peripheral collisions being somewhat wider than that observed in central collisions [7]. Thus, it is necessary to correct for the unmeasured yield in a centrality-dependent manner.

Using the data presented in Ref. [6], Fig. 1(a) shows $dN_{\mathrm{ch}}/d\eta/\langle N_{\mathrm{part}}/2\rangle$ averaged over the forward and backward hemispheres for the 3% most central Au+Au events at $\sqrt{s_{NN}}$ = 200 GeV. The systematic errors (representing a 90% C. L. interval) depend on η and are shown on the figure as a shaded band. To correct for the acceptance loss, we used several methods inspired by the observed "limiting fragmentation" seen in the lower energy PHOBOS data relative to the higher energy data when shown as a function of $\eta' = \eta - y_{\mathrm{beam}}$ [6]. PHOBOS data from $\sqrt{s_{NN}}$ = 19.6 GeV for $\eta > 2.5$, shifted by $\Delta\eta = y_{200} - y_{19.6} = 2.32$ (the difference in beam rapidities between the two energies), displays the limiting fragmentation behavior [6]. This effectively extends the rapidity coverage to $\eta \sim 8$. A Woods-Saxon-like function for $dN/d\eta$ [8] fit to the Au+Au data also provides a reasonable description of the $dN/d\eta$ distribution and extrapolates through the lower energy central data as well. Thus, in one method, we integrate $dN_{\mathrm{ch}}/d\eta$ for $\sqrt{s_{NN}}$ = 130 and 200 GeV for $\eta' < 0$ and use the PHOBOS data at $\sqrt{s_{NN}}$ = 19.6 GeV for $\eta' > 0$. We also integrate the Woods-Saxon-like fits, similar to that shown in Fig. 1(a), for $|\eta| < 8$. These two approaches agree within 2% for central events, but differ up to 8% in more peripheral events, where one expects spectator-related effects in the far forward region, so we average the two results to achieve the final estimate of the total charged-particle multiplicity. For the lowest RHIC energy, we simply integrate the charged particles in the PHOBOS acceptance and average this with the integral of the functional fits, which differ by up to 15% in the most peripheral data considered here.

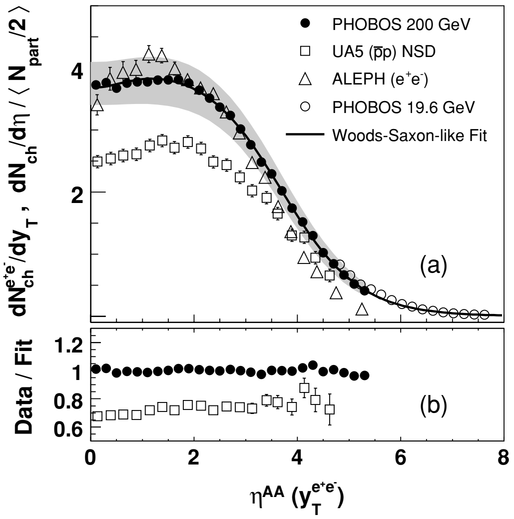

FIG. 1. (a) $dN_{\mathrm{ch}}/d\eta/\langle N_{\mathrm{part}}/2\rangle$ of charged particles produced in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 and 19.6 GeV (shifted by $\Delta\eta = 2.32$), compared with elementary systems. A fit to the 200 GeV Au+Au data is shown. The e^+e^- data are plotted as a function of y_T, the rapidity relative to the thrust axis, always assuming the pion mass. (b) PHOBOS and UA5 data divided by a Woods-Saxon-like fit to the 200 GeV Au+Au data.

In Fig. 2, $\langle N_{\mathrm{ch}}\rangle/\langle N_{\mathrm{part}}/2\rangle$ is shown for PHOBOS data at three RHIC energies as a function of N_{part}. The 90% C. L. systematic error on the centrality dependence of $\langle N_{\mathrm{ch}}\rangle/\langle N_{\mathrm{part}}/2\rangle$ is shown as a shaded band and represents a combination of several factors, dominated by the uncertainty of the extrapolation procedure to extract N_{ch} over the full solid angle. This figure shows that the heavy ion data are consistent with wounded nucleon scaling over the measured centrality range, since the multiplicity is proportional to N_{part} ($N_{\mathrm{ch}} \propto N_{\mathrm{part}}$). This constancy of $\langle N_{\mathrm{ch}}\rangle/\langle N_{\mathrm{part}}/2\rangle$ is a striking feature in view of the various particle production mechanisms (e.g., jet fragmentation, quark recombination, statistical hadronization) expected to be relevant in heavy ion collisions.

In proton-nucleus data at lower energies, one also observes that the total multiplicity scales linearly with N_{part}, proportional to the multiplicity measured in pp collisions at the same center-of-mass energy [1]. Nonsingle diffractive (NSD) proton-antiproton data exist at 200 GeV, but neither inelastic nor NSD data exist for the other two RHIC energies. For

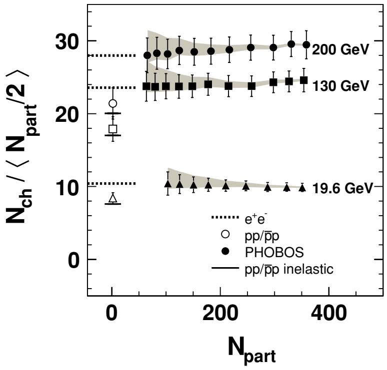

FIG. 2. $\langle N_{\mathrm{ch}}\rangle/\langle N_{\mathrm{part}}/2\rangle$ vs N_{part} for $\sqrt{s_{NN}}$ = 19.6, 130, and 200 GeV (closed symbols). Error includes contributions from the uncertainty on the overall N_{ch} scale and N_{part} scale. Shaded band shows the uncertainty on the extrapolation procedure as a 90% C. L. interval. Open symbols show UA5 data at 200 GeV and results from an interpolation of NSD data at other energies. Dotted lines show the values from the e^+e^- fit.

energies where no data exist, we use parametrizations of *pp* data from Ref. [9], $\langle N_{\text{ch}}\rangle = -4.2 + 4.69 s^{0.155}$ for inelastic, and $\langle N_{\text{ch}}\rangle = -7.5 + 7.6 s^{0.124}$ for nonsingle diffractive collisions.

In $A{+}A$ collisions, N_{ch} clearly scales linearly with N_{part}, but *not* proportionally to the multiplicity measured in *pp* collisions at the same energy, as was observed in proton-nucleus collisions at different beam energies. Rather, it scales with a value that is about 40% higher than in *pp*. To understand this difference, it is useful to compare the total multiplicity produced in other strongly interacting systems, including the final state in e^+e^- annihilations to hadrons. In Fig. 2, the total multiplicity in e^+e^- annihilations, derived from a fit detailed below, are depicted by dotted lines. One can see that the constant of proportionality for $N_{\text{ch}} \propto N_{\text{part}}/2$ is approximately the multiplicity measured in the e^+e^- reactions.

To make sure these comparisons are justified over the full phase space, we compare the longitudinal distributions in Au+Au, $pp/\overline{p}p$, and e^+e^- data. We use only central Au+Au data for the remaining comparisons since they represent the least amount of residual spectator matter that may contaminate the dN/dy distribution at very forward pseudorapidities.

In Fig. 1(a), the 3% most central Au+Au data are compared with $dN_{\text{ch}}/d\eta$ for NSD $\overline{p}p$ collisions [10] and dN/dy_T for e^+e^- collisions (with cuts applied to reject large initial-state photon radiation) [11] at $\sqrt{s} = 200$ GeV. The variable y_T is the rapidity of charged particles relative to the event thrust axis, assuming the pion mass for all particles. JETSET calculations indicate that the y_T distribution is slightly narrower than the corresponding pseudorapidity distribution in e^+e^- collisions, with a difference in particle density of less than ±10% for $|\eta|$ and $|y_T| < 4$ [4]. The same calculations also show that the choice in kinematic variables does not explain the difference in the forward region (above $|\eta| = 4$), although this may not be surprising, as this region may well show some residual effect of the presence of participating nucleons.

It is observed that Au+Au, $\overline{p}p$, and e^+e^- data are similar in shape at the same $\sqrt{s}$, and that Au+Au and e^+e^- data also agree in magnitude. The agreement in shape of Au+Au and $\overline{p}p$ data over a large range in η is shown in Fig. 1(b).

Because of the weak (constant within errors) centrality dependence established in $A{+}A$ collisions, one can compare the total multiplicity as a function of $\sqrt{s_{NN}}$ without consideration of the centrality dependence. In Fig. 3(a), data on $\langle N_{\text{ch}}\rangle$ from $pp, \overline{p}p, e^+e^-$, and central heavy ion collisions (scaled by $\langle N_{\text{part}}/2\rangle$) are compared over a wide range of $\sqrt{s}$ and $\sqrt{s_{NN}}$. The data and systematic errors for the total multiplicity in $pp, \overline{p}p$, and e^+e^- are available from Ref. [12], and no further corrections are applied. The errors shown are the quadratically combined statistical and systematic errors. Heavy ion data are shown for central Au+Au events at RHIC (this work), Au+Au events from E895 at the Alternating Gradient Synchrotron (AGS) ($\sqrt{s_{NN}} = 2.6{-}4.3$ GeV) [13] and Pb+Pb events from NA49 at the CERN Super Proton Synchrotron (SPS) ($\sqrt{s_{NN}} = 8.6$, 12.2, and 17.3 GeV) [14]. A PHOBOS Au+Au data point at $\sqrt{s_{NN}} = 56$ GeV has been added by using the measured value at midrapidity [15] and the limiting fragmentation distribution described in Ref. [6] to approximate the shape of the full distribution. Finally, data points using PHOBOS d+Au data at $\sqrt{s_{NN}} = 200$ GeV [16] are also shown, and they compare well with the UA5 $\overline{p}p$ results at the same energy. All errors shown for the heavy ion data are systematic.

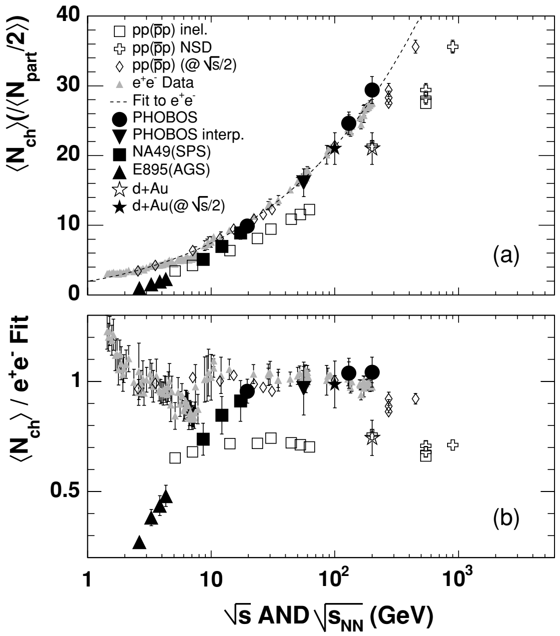

FIG. 3. (a) Total charged multiplicity $\langle N_{\text{ch}}\rangle$ for $pp, \overline{p}p, e^+e^-$, d+Au, and central Au+Au events as a function of $\sqrt{s}$. *pp* data are inelastic, while $\overline{p}p$ data are NSD. Au+Au data are normalized by $N_{\text{part}}/2$. Dotted line is a QCD expression fit to the e^+e^- data. Diamonds are the $pp/\overline{p}p$ data with $\sqrt{s_{\text{eff}}} = \sqrt{s}/2$. Open and closed stars are for minimum-bias d+Au data at $\sqrt{s} = 200$ GeV and $\sqrt{s_{\text{eff}}} = 100$ GeV. (b) Data in (a) divided by the e^+e^- fit, to allow direct comparison of different data at the same $\sqrt{s}$.

Perturbative QCD calculations are able to predict the dependence of the total multiplicity in e^+e^- collisions as a function of $\sqrt{s}$, $N_{e^+e^-}(s) = C\alpha_s(s)^A \exp[\sqrt{B/\alpha_s(s)}]$, with $A = 0.427$ and $B = 2.88$ fully calculable within pQCD [17] and $\alpha_s(s) \propto \ln(s/\Lambda^2_{\text{QCD}})$. The QCD scale Λ_{QCD} is set to 225 MeV, leaving only a constant of proportionality C free to fit to the experimental data. A fit to the e^+e^- data has been made with the expression ("e^+e^- Fit") and has been used in Fig. 3(b) to scale all of the data by this function. Values from this function are shown in Fig. 2 for $\sqrt{s} = 19.6$ and 130 GeV, where measurements for e^+e^- do not exist.

Figure 3(b) shows that the $pp/\overline{p}p$ data are about 30% below e^+e^- over the full range of energies. However, rescaling the $\sqrt{s}$ of each point by a factor of 1/2, $\sqrt{s_{\text{eff}}} = \sqrt{s}/2$, brings the data into reasonable agreement with the e^+e^- trend, as shown by the open diamonds. This is consistent with measurements of leading protons in *pp* collisions, which find dN/dx_F (where $x_F = 2p_z/\sqrt{s}$ in the collider reference frame) to be approximately constant for nondiffractive events over a large range of $\sqrt{s}$ [18], and thus $\langle x_F\rangle \sim 1/2$. This phenomenon is well known as the "leading particle" effect when comparing $pp/\overline{p}p$ and e^+e^- total multiplicities. Basile *et al.* [19] found that the average multiplicity $\langle N_{\text{ch}}\rangle$ in *pp* collisions is similar to that for e^+e^- collisions with $\sqrt{s_{e^+e^-}} = \sqrt{s_{\text{eff}}}$, where $\sqrt{s_{\text{eff}}}$ is the *pp* center-of-mass energy minus the energy of the leading particles. Both the apparently common features of particle production and the concept of effective energy were explored by a variety of theoretical approaches [20–22], although none of these dealt directly with nucleus-nucleus collisions.

Unlike the $pp/\overline{p}p$ data, the heavy ion data do not follow the e^+e^- trend over the whole energy range. Instead, they lie below the pp data at AGS energies, cross through the pp data between AGS and SPS energies, and join smoothly with the e^+e^- data above the top SPS energy. Thus, at high energies, the multiplicity measured per participant pair in Au+Au collisions evolves in a similar way to e^+e^- data at the *same* $\sqrt{s}$. It seems that no correction for a leading particle is needed in heavy ion collisions. This may be plausible if one considers that an average participant suffers three or more collisions in the centrality range shown in this study [depending on the energy-dependent nucleon-nucleon inelastic cross section, $\sigma_{NN}(s)$]. This may be sufficient to reduce the leading particle effect sufficiently for each participant, and it may also explain the constant behavior of $\langle N_{\rm ch}\rangle/\langle N_{\rm part}/2\rangle$ with $N_{\rm part}$.

However, the rapid approach of $\langle N_{\rm ch}\rangle/\langle N_{\rm part}/2\rangle$ in central heavy ion collisions below $\sqrt{s_{NN}} \sim 20$ GeV toward the e^+e^- data clearly complicates any simple geometric interpretation, as all of the heavy ion data compared are for a similar range of impact parameters. One feature that might point to why the particle yields at the AGS and SPS are perhaps "suppressed" relative to e^+e^- data (and even to pp data at lower energies, as noted in Ref. [14]) is the ratio of net baryons to pions in the system. This ratio, which scales approximately as $N_{\rm part}/N_{\rm ch}$, is $O(50\%)$ at AGS energies [13], but $O(5\%)$ at RHIC [23]. In a thermal statistical approach [24], this reflects the decrease of the baryon chemical potential, which absorbs energy that would have gone into the total entropy, with increasing beam energy.

In conclusion, the PHOBOS experiment has measured the normalized charged-particle multiplicity $\langle N_{\rm ch}\rangle/\langle N_{\rm part}/2\rangle$ in Au+Au collisions as a function of the centrality of the collision ($N_{\rm part}$) for three RHIC energies. A very weak centrality dependence of $\langle N_{\rm ch}\rangle/\langle N_{\rm part}/2\rangle$ is observed, reminiscent of wounded nucleon scaling, but with a proportionality factor that is different than that seen in pp collisions.

Above CERN SPS energies, the total multiplicity per participating nucleon pair, $\langle N_{\rm ch}\rangle/\langle N_{\rm part}/2\rangle$, in central events evolves with $\sqrt{s}$ in the same way and is very close to the e^+e^- data. This is somewhat suggestive of a common mechanism of particle production in strongly interacting systems, controlled mainly by the amount of energy available for particle production. This may be related to the multiple collisions suffered by each participant nucleon, which could substantially reduce the leading particle effect seen in pp collisions and suggests that after the first few collisions per participant, the multiplicity per participant pair saturates near the value measured in e^+e^- reactions. Ultimately, the existence of simple scaling behavior with $\sqrt{s_{\rm eff}}$ and $N_{\rm part}$ indicates stronger constraints on particle production than previously considered theoretically. Without some overall constraint, it is difficult to understand how the various physics effects we typically assume contribute independently to the bulk particle production in $A+A$ collisions (whether soft physics such as energy stopping and statistical hadronization, or hard physics involving structure functions, nuclear shadowing, parton production, and energy loss and hadronization, e.g., as implemented in HIJING [25]) could scale so simply with $N_{\rm part}$ or share such a close relationship with the different collision systems discussed in this work. In any case, these results may provide a new perspective on particle production in heavy ion collisions.

This work was partially supported by the U.S. Department of Energy, Grant Nos. DE-AC02-98CH10886, DE-FG02-93ER40802, DE-FC02-94ER40818, DE-FG02-94ER40865, DE-FG02-99ER41099, and W-31-109-ENG-38, as well as the National Science Foundation, Grant Nos. 9603486, 9722606, and 0072204. The Polish groups were partially supported by KBN Grant No. 1 P03B 062 27. The NCU group was partially supported by NSC of Taiwan under Contract No. NSC 89-2112-M-008-024.

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