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Results from the PHOBOS experiment at RHIC

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Abstract. Au+Au collisions have been studied at center-of-mass energies of $\sqrt{s_{NN}}$= 56 and 130 GeV using the PHOBOS detector at RHIC. Charged particle multiplicities have been measured as a function of center-of-mass energy, centrality and pseudo-rapidity, η. A total of 4100±400 charged particles are observed in the pseudo-rapidity range $-5.4 < \eta < 5.4$ for the most central collisions. A strong elliptic flow signal is seen in peripheral collisions at $\eta = 0$. The measurement of an antiprotons to protons ratio of $\overline{p}/p = 0.60 \pm 0.04(stat) \pm 0.06(syst)$ indicates that a nearly baryon-free region is created at midrapidity.

Keywords: Relativistic heavy-ion collisions, charged particle multiplicity, elliptic flow, antiparticle - particle ratio
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1. Introduction

It is expected that heavy-ion collisions at ultra-relativistic energies may be able to re-create the conditions of density and extreme temperature that characterized the early universe about 10 μs after the Big Bang. Under these conditions it is expected that the quarks will be deconfined allowing their motion over an extended volume - a Quark-Gluon Plasma (QGP). Recreating these conditions in the laboratory has been the goal of the experimental heavy ion programs at the AGS, at the SPS, and most recently at RHIC. The experimental signatures for the creation of the QGP are, however, not very direct, and it has been found that several of the proposed signatures can be mimicked by purely hadronic scattering scenarios. Consequently, it is of central importance to develop theoretical models which describe the hadronic processes very accurately and test these against experimental data in order to be able to recognize the signals of the QGP, which may be very weak relative to the background of hadronic processes which occur in the later stages of evolution of the hot and dense system.

From data obtained with the PHOBOS detector in the first year of RHIC running, we have determined some of the important global parameters of ultra-relativistic Au+Au collisions at $\sqrt{s_{NN}}$=56 and 130 GeV. These include the multiplicity of charged particles, $dN_{ch}/d\eta$ at $\eta \approx 0$ for central collisions obtained at both energies, the evolution of $dN_{ch}/d\eta|_{|\eta|<1}$ with centrality at $\sqrt{s_{NN}}$=130, as well as the distribution of charged particles as a function of centrality. In addition, we have studied the reaction dynamics by measuring the elliptic flow as a function of centrality and pseudorapidity. Utilizing the capabilities of PHOBOS to identify particles and measure their momentum we have also studied the ratios of negative to positive pions, kaons and protons (anti-protons to protons).

2. Apparatus

The PHOBOS experimental setup, as illustrated in Fig 1., consists of four main components. 1) A set of detectors is devoted to event triggering and centrality determination. Two arrays of sixteen scintillator paddle detectors covering a pseudo-rapidity range of $|\eta|$=3-4.5 provide event triggering by the requirement that at least one detector in each array is hit. Identification of collisions is obtained from the relative timing of the paddle detectors. Based on this time information, the vertex position is constrained to occur within $\pm$75 cm of the nominal interaction point. Two Zero Degree Calorimeters are positioned 18.5 m from the interaction. These measure the zero-degree neutral energy from the collision (spectator neutrons) as an additional parameter in the determination of the centrality of the collision. Such calorimeters are common to all RHIC experiments. 2) A charged particle multiplicity detector consists of an octagonal barrel of Si pad detectors with almost hermetic coverage of $|\eta|$ <3.3. The pseudorapidity range 3.3< $|\eta|$ <5.4 is covered by three sets of Si ring detectors. The multiplicity detectors have only a single layer of Si, and consequently do not have any tracking capability. 3) A vertex finder consisting of two Si layers covers $|\eta|$ <0.92 in an azimuthal range of 45° above and below the beam. An accurate location of the collision vertex in the longitudinal direction is achieved using the high segmentation of this detector. 4) Particle identification and momentum analysis is achieved in two spectrometer arms located on either side of the interaction point consisting of 14 and 6 planes of finely segmented Si pad detectors, respectively. Half of the planes reside in a 2T magnetic field of opposing polarity in the two sides. Tracking of particles moving in the magnetic field combined with measurements of the average energy loss in the Si layers provides the basis for the particle identification and momentum measurement performed in the first year of RHIC operation. Two time-of-flight walls located behind one of the spectrometers will permit an extension of the momentum range for which charged particles can be unambiguously identified.

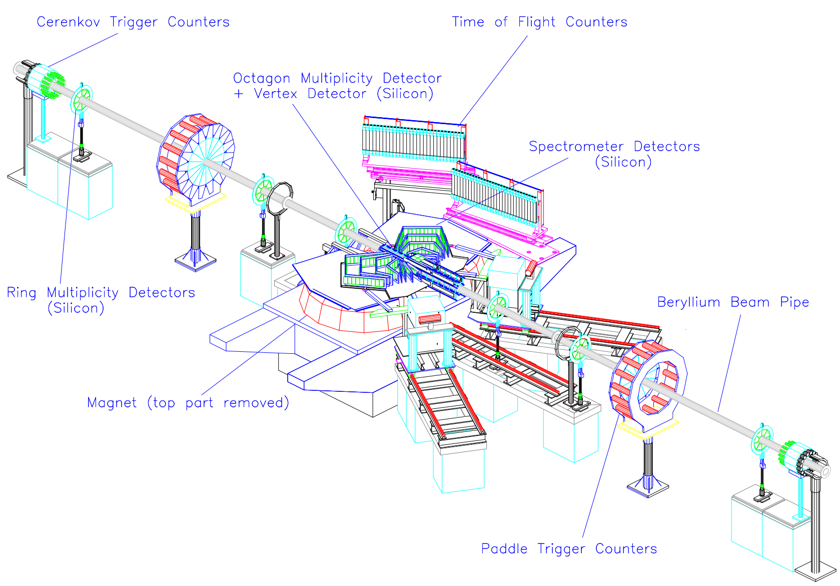

Fig. 1. Schematic layout of the PHOBOS detector identifying the various elements. The top yoke of the magnet is not shown.

3. Year 2000 run statistics

RHIC running in 2000 consisted of a period of machine commissioning during which Au beams were accelerated to achieve a center of mass energy per nucleon-nucleon collision of $\sqrt{s_{NN}}$=56 and 130 GeV. During this period PHOBOS recorded 6352 and 12074 collisions at $\sqrt{s_{NN}}$=56 and 130 MeV, respectively, using only a small subset of Si-detectors. The data recorded during this period were analyzed to obtain the first publication of physics results from RHIC [1]. After a 10 day intermission, during which the full Year 1 complement of detectors was installed, the RHIC operation was resumed with the acceleration of Au beams for a period of sustained running at $\sqrt{s_{NN}}$=130 GeV during which about 3.5 million collisions were recorded by PHOBOS.

4. Multiplicity - "tracklet" analysis

One of the simplest, but crucial, measurements in relativistic heavy ion collisions is the total number of particles created in the process of converting energy to matter. Theoretical predictions for this quantity differ substantially, albeit conserving the total overall mass/energy of the system. Experimentally, it is therefore important to measure the multiplicity of charged particles, which are expected to constitute the largest component of produced particles. Consequently, one of the first goals of PHOBOS was to determine the multiplicity of charged particles emitted at 90° to the beam axis, (η=0).

This measurement was performed by counting "tracklets" contructed from two-hit combinations in subsequent layers of Si-pad detectors and requiring that these tracklets point back to the event vertex, which was determined to an accuracy of $\approx 300\mu$m using a similar procedure. The tracklet analysis was performed for the two Si layers in the vertex detector (top and bottom separately) and using the first/second and the fifth/sixth detector planes in both spectrometer arms. Corrections for combinatorial backgrounds were obtained by interchanging detector planes in a way that preserves the geometry but removes all true two-hit combinations - a procedure made possible by the 180° rotational symmetry around the beam-line of the active elements used in this analysis. The efficiency for finding tracklets was estimated on the basis of simulations using events from the HIJING event generator [2] propagated through the full analysis chain for which the detector response and secondary particle production has been simulated by using the GEANT 3.21 simulation package.

Since the PHOBOS setup contains multiple Si planes only in the mid-rapidity region, the results from this analysis were obtained for the pseudorapidity interval $|\eta|$ <1. The results are presented as a function of centrality expressed in terms of the number of nucleons participating in the collision, N_{part}. This quantity is based on Monte Carlo simulations (using HIJING events), which relate N_{part} to the number of charged particles hitting the scintillator paddle trigger detectors. A detailed description of this analysis is given in [3]. In Fig. 2, the solid triangles represent the measured mid-rapidity multiplicity of charged particles scaled by the number of participant nucleon pairs, $N_{pair} = 0.5N_{part}$ plotted as a function of N_{part}. Depending on centrality, N_{part}, the scaled multiplicity ranges from $dN_{ch}/d\eta/0.5N_{part} \approx 2.9$ to 3.5, which is substantially larger than observed in single $p\overline{p}$ collisions (solid circle) demonstrating the additional charged particle/ entropy production associated with secondary collisions within the collision volume.

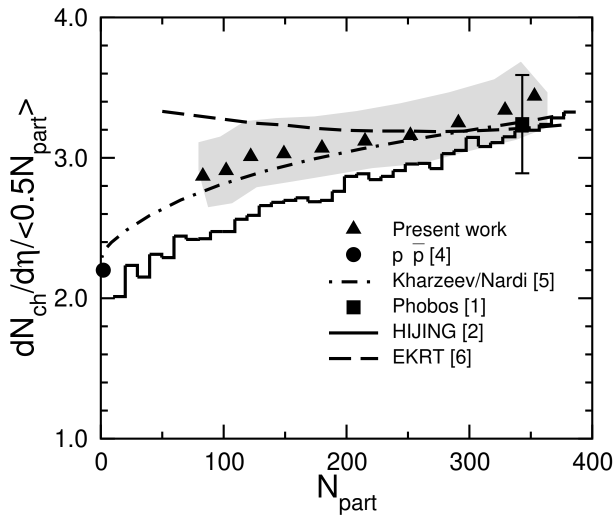

Fig. 2. Charged particle multiplicity per participant pair is shown as a function of the number of participants, N_{part} (closed triangles) and compared with $p\overline{p}$ collisions (solid circle) [4], and early PHOBOS result (solid square) [1]. The error band (shaded) combines the error on $dN_{ch}/d\eta|_{|\eta|<1}$ and N_{part}. Theoretical calculations are shown as solid histogram (HIJING)[2], dashed-dotted curve (KN)[5], and dashed curve (EKRT)[6]

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The comparison with theoretical calculations shown in Fig. 2 appears to favor the model of Kharzeev and Nardi[5], which was normalized to the early measurement for central collisions [1]. The relative importance of soft (hadron) and hard (parton) collisions in this model is obtained by assuming different scaling properties of the two collision types. The HIJING model [2] under predicts the data for all centralities but with increasing discrepancy for more peripheral collisions, whereas the parton saturation model of Eskola *et al* [6] over predicts the charged particle production in this range of centralities.

5. Multiplicity - hit counting

Since the solid angle outside of the mid-rapidity region is covered by only a single Si layer in the PHOBOS detector, a different analysis method was employed in order to obtain the charged particle multiplicity over the full range in pseudo-rapidity -5.4< η <5.4 covered by the octagon and ring detectors. This method is based on a simple counting of the number of Si-pads hit by charged particles, a hit being defined by an energy deposition greater than 80% of the peak observed for minimum ionizing particles (MIP's) after correction for angle of incidence and for signal sharing between neighboring pads for tracks incident at angles smaller than 45° (hit merging). The total number of particles is obtained by assuming that the probability for multiple hits in single pads follows a Poisson distribution the mean μ of which may be derived from the probability for finding empty channels $P(0)$, *i.e.* $\mu = -\ln[P(0)]$. Following Poisson statistics, the average number of particles traversing a hit pad, the occupancy, equals $\mu/[1-\exp(-\mu)]$, which is used to correct for multiple hits. Finally, a correction for background, weak decays and particle absorption in the beam pipe is derived from Monte Carlo simulations based on HIJING events. Resulting pseudorapidity distributions of the charged

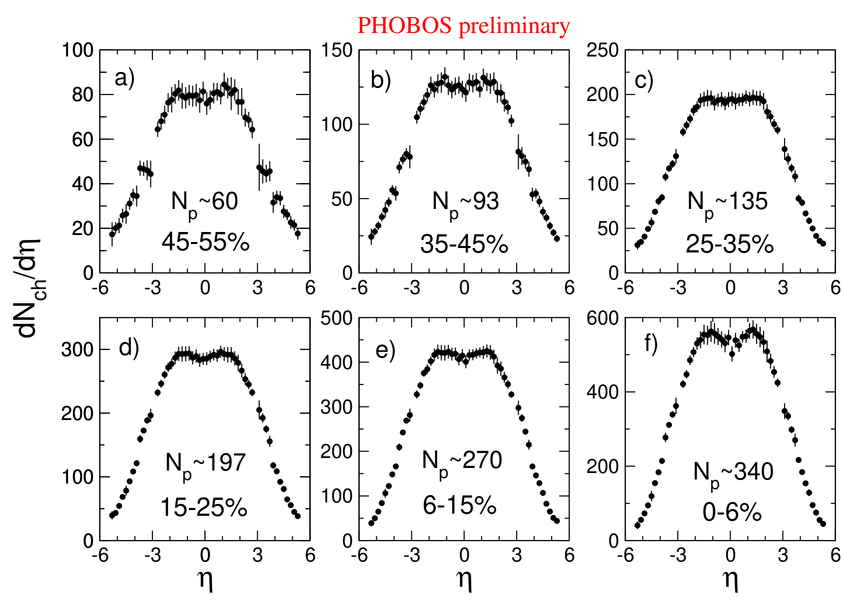

Fig. 3. Charged particle rapidity density per collision is shown as a function of pseudo-rapidity, η (closed circles) for six centrality bins.

particles are shown in Fig. 3 for six different centrality bins labeled as a function of the total observed cross section (counted from the central collisions) and the corresponding N_{part}. The shapes of these distributions are largely independent of centrality although the overall scale changes dramatically. There is a flat region around mid-rapidity ranging to about $\eta = \pm 1.5$, followed by a monotonic decrease towards the largest measured pseudorapidity of $\eta = \pm 5.4$. Calculations with the HIJING code reproduce the overall shape of the pseudorapidity distributions quite well. A detailed comparison reveals, however, that the HIJING distributions are generally narrower than those observed.

Since it appears that this measurement covers over 95% of the charged particles produced in the collisions (the spectator protons are expected to travel in the beam tube) it is meaningful to integrate these distributions to obtain an estimate of the total number of charged particles produced in the collisions.

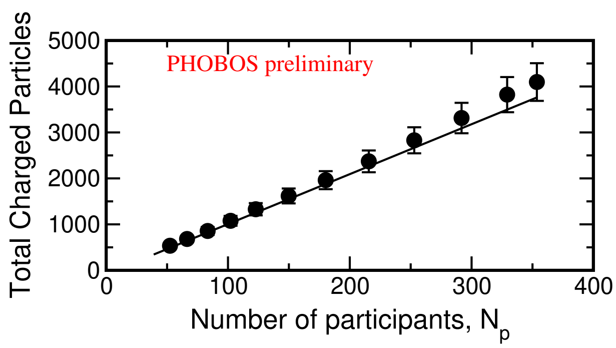

Fig. 4. The total number of charged particle emitted in the pseudorapidity range $|\eta| < 5.4$ (closed circles) is compared to the predictions of the HIJING model (solid line).

These results are presented in Fig. 4 as open circles. An almost linear dependence on N_{part} is observed, reaching a maximum value of $N_{ch}^{tot} = 4100 \pm 400$ for the most central collisions. Assuming isospin independence, this corresponds to a total number of more than 6000 particles produced in central Au+Au collisions at this energy. The HIJING prediction (solid line) is in quite good agreement with the data. The model underestimates the total number of charged particles within this range of pseudorapidity by less than 10%.

6. Charged particle flow

A unique feature of heavy ion reactions is the possibility of collective motion of particles generated in the collision. Because of the high density of energetic particles over an extended volume it is possible to generate pressure gradients as in a hydrodynamic medium and thus, in principle, study its equation of state by observing signals which are sensitive to the coherent motion of particles. One example of such an observable is radial flow which manifest itself as differences in the inverse spectral slope for particles of different mass. On the basis of this type of analysis, average radial flow velocities in excess of about 50% of the speed of light have been found at SPS and RHIC energies.

In the present experiment, the elliptic flow of charged particles has been studied by measuring the azimuthal asymmetry in the charged particle emission on an event-by-event basis. This analysis is based on an estimate of the reaction plane, *i.e.* the plane containing the impact parameter and the beam axis, by a Fourier analysis of the azimuthal particle distribution. The accuracy of this reaction plane determination is estimated by dividing single events into two sub-events and studying the difference of the reaction plane angles, ψ_1 and ψ_2 obtained by analyzing the sub-events separately. A correction for multiple hits of individual Si-detector pads in a way similar to the one used in the analysis of the charged particle multiplicity described above is also applied to the data.

Only the part of the PHOBOS detector which has approximate azimuthal symmetry is used for the elliptic flow analysis, *i.e.* the parts of the octagon multiplicity detector which do not have openings for the spectrometer and vertex detectors, and the six ring detectors. The elliptic flow coefficient, v_2 was obtained from a Fourier analysis of the azimuthal particle distribution relative to the reaction plane using the expression

$$\frac{dN}{d(\Phi - \Psi_R)} = N_0[1 + 2v_1 \cos(\Phi - \Psi_R) + 2v_2 \cos(2(\Phi - \Psi_R))], \tag{1}$$

where $\Phi - \Psi_R$ is the difference between the azimuthal angle Φ of the detected particle and the reaction-plane angle Ψ_R, v_1 and v_2 are the directed and elliptic flow coefficients, respectively, and N_0 is a normalization constant. The directed flow, v_1 is not significantly different from zero, whereas the elliptic flow strength, v_2 is surprisingly large compared to the values found at AGS and SPS energies. The centrality dependence of v_2 at mid-rapidity, $|\eta| < 1$, is shown in Fig. 5a, the centrality being expressed in terms of the normalized paddle signal. The v_2-coefficient is seen to reach a maximum value of v_2=0.06 for peripheral collisions, and decreases to zero for central collisions as required by symmetry arguments. The present results are in good agreement with those recently published by the STAR collaboration [7] and represent a substantial fraction of the v_2 strength predicted by hydrodynamical models [8].

A unique feature of the PHOBOS detector is the ability to measure charged particle emission over the entire pseudorapidity range of $-5.4 < \eta < 5.4$. The elliptic flow coefficient v_2 is thus shown for minimum bias events over the full η range in Fig. 5b exhibiting a sharp maximum at midrapidity and a steady fall off toward zero at the ends of the measured pseudo-rapidity range. The sharpness of the peak structure at mid rapidity may be partly a consequence of plotting v_2 as a function of pseudorapidity as has been pointed out by Peter Kolb [8] .

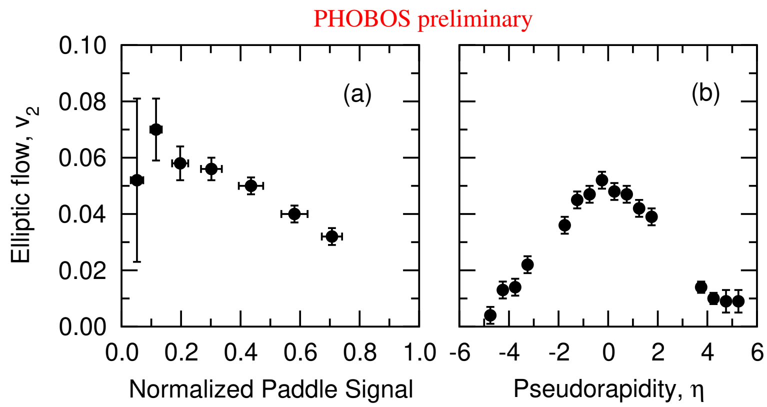

Fig. 5. Elliptic flow coefficient, v_2 is plotted as a function of the normalized paddle signal, (a) and as a function of pseudorapidity for minimum bias events (b).

7. Antiparticle - particle ratios

The relative production rate of anti-particles to particles in the hot and dense collision zone is of importance for the characterization of its thermodymanic characteristics. At AGS energies, a strong suppression of the anti-proton to proton ratio has been observed in Au+Au collisions [9], which reflect the fact that the majority of baryons in the midrapidity region originate from the incoming Au nuclei. At SPS energies a strong increase in the $\overline{p}/p$-ratio has been observed [10] indicating a reduced dominance of primordial baryons at mid-rapidity. At the full RHIC energies it has been expected that the midrapidity region would be essentially baryon free, *i.e* that the high energy density results in the creation of an equal number of baryons and anti-baryons.

The ratio of negatively to positively charged particles was measured in the PHOBOS spectrometer by tracking the particles through the 14 Si-pad detector planes and their momenta was determined from the curvature the tracks in the 2T magnetic field. Particle identification was achieved by measuring the average energy deposited in the 300μm thick Si wafers as a function of momentum. Systematic errors in determining the absolute number of particles and anti-particles were strongly reduced by studying only their ratio as a function of the magnetic field polarity.

In Fig. 6 the production ratios for $\pi^-/\pi^+, K^-/K^+$, and $\overline{p}/p$ obtained in the present work (solid circles) are shown as a function of particle mass. These results are compared to recent results [11] from the STAR collaboration (open circles). Clearly, there is very good agreement between the two results, which exhibit a pro-

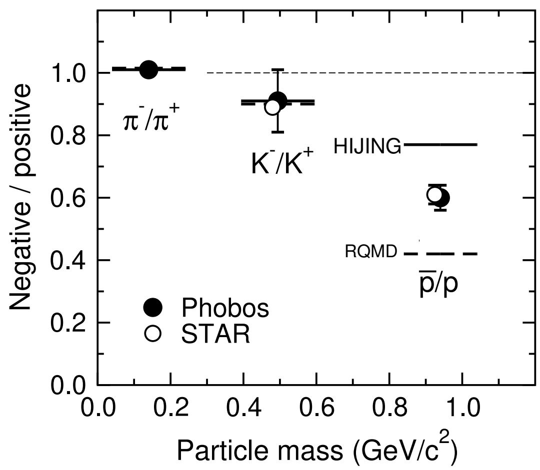

Fig. 6. Antiparticle/particle ratios are plotted as a function of mass (solid circles) and compared with results from STAR open circles.

gressive deviation of the negative/positive ratio from unity with increasing particle mass. The $\overline{p}/p$-ratio falls between the predictions of the HIJING [2] and the Relativistic Quantum Molecular Dynamics models (RQMD) [12], which provides clues about an inadequate inclusion of baryon stopping, baryon pair production and/or anti- baryon annihilation mechanisms in these models. A further differentiation between these different mechanisms may be possible when absolute production rates for the different particles become available.

8. Conclusion

The first year of RHIC running has proven to be very successful. The PHOBOS detector operated essentially flawlessly through the running period providing a wealth of data on Au+Au collisions at both $\sqrt{s_{NN}}$=56 and 130 GeV. The physics measurements concentrated on obtaining information on the basic parameters of the collisions. The overall entropy production was studied via the total charged particle multiplicity as well as its dependence on collision energy, centrality and pseudorapidity. The elliptic flow observable was found to be surprisingly close to the hydrodynamic limit. Finally, the antiparticle/particle ratio was measured to yield information on the baryochemical potential of the system in the mid-rapidity region. It is expected that the limit of a baryon-free region at midrapidity will be approximately reached at the full RHIC energy of $\sqrt{s_{NN}}$=200 GeV being probed in the Year 2001 running period.

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