PHYSICAL REVIEW C **71**, 021901 (2005)

Charged antiparticle to particle ratios near midrapidity in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV

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(Received 2 September 2004; published 15 February 2005)

The ratios of the yields of primary charged antiparticles to particles have been obtained for pions, kaons, and protons near midrapidity for $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Ratios of $\langle \pi^-/\pi^+ \rangle = 1.000 \pm 0.012$ (stat.) ± 0.019 (syst.), $\langle K^-/K^+ \rangle = 0.93 \pm 0.05$ (stat.) ± 0.03 (syst.), and $\langle \bar{p}/p \rangle = 0.85 \pm 0.04$ (stat.) ± 0.03 (syst.) have been measured. The reported values represent the ratio of the yields averaged over the rapidity range of $0.1 < y_\pi < 1.3$ and $0 < y_{K,p} < 0.8$, and for transverse momenta of $0.1 < p_T^{\pi,K} < 1.0$ GeV/c and $0.3 < p_T^p < 1.0$ GeV/c. Within the uncertainties, all three ratios are consistent with the values measured in $d +$ Au collisions at the same energy. The data are compared to results from other collision systems and energies.

DOI: 10.1103/PhysRevC.71.021901 PACS number(s): 25.75.−q

Relativistic heavy ion collisions allow for the study of strongly interacting matter in the high-temperature and low baryochemical potential regime of the phase diagram of nuclear matter. Smaller collision systems provide valuable reference information necessary to interpret the results obtained from more complicated heavy ion collisions. In this paper, the ratios of the yields of antiparticles to particles for primary charged pions, kaons, and protons emitted in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV, determined using data collected by the PHOBOS detector during the 2003 run of the Relativistic Heavy Ion Collider (RHIC), are presented.

Comparisons of $d +$ Au and Au + Au data suggest that the conditions created in the two collision systems differ [1]. Whether these different conditions influence the particle ratios was explored by comparing the values measured in $d +$ Au and Au + Au collisions as a function of centrality [2]. This study can be extended to lower multiplicity environments through the analysis of $p + p$ collisions. To compare particle ratios measured in different collision systems the number of collisions experienced by each participating nucleon, ν, is used as a measure of collision centrality. This parameter is useful in the study of the $\bar{p}/p$ ratio, which is sensitive to the interplay between the baryon number transport and antibaryon-baryon pair production processes. In the $p + p$ collision system each participating nucleon experiences only one collision. In the $d +$ Au collision system, ν is defined as the number of collisions experienced by each participating nucleon from the deuteron, $\nu \equiv N_{\text{coll}}/N_{\text{part}}^d$, where N_{coll} and N_{part}^d are the number of binary collisions and the number of participants in the deuteron, respectively. The $d +$ Au particle ratios have been measured over a range of ν from 2 to 8 [2]. Measurement of the antiparticle to particle ratios in the $p + p$ collision system extends the range over which the ratios are known to the simplest possible nuclear system.

The analysis reported here is nearly identical to that described in Ref. [2] with two important exceptions. First, to increase the trigger efficiency, the primary event trigger was provided by two sets of 16 scintillator paddle counters located −3.21 m (PN) and +3.21 m (PP) from the nominal interaction point along the longitudinal (z) axis. The paddle counters cover a pseudorapidity range of $3 < |\eta| < 4.5$. A triggered event required a coincidence between the paddle counters, PN and PP, within $\Delta t \leqslant 10$ ns. For this data set, 29 million triggered events were collected. Second, the offline event selection criteria were modified in accordance with the primary event trigger. A more restrictive timing requirement was applied to the paddle coincidence ($\Delta t < 5$ ns) to provide the vertexing algorithm [2] with a restricted range within 75 cm of the nominal vertex ($z = 0$ cm). Events with a reconstructed vertex of $|z| < 8$ cm were used to ensure that particles of both charges were properly reconstructed in the spectrometer for both magnet polarities. For this range of vertices, the

TABLE I. Summary of analyzed event and particle counts.

Polarity	Events	π^-	π^+	K^-	K^+	$\bar{p}$	p
−	2537906	5233	24478	287	899	506	1141
+	1686214	16235	3500	551	190	585	396

trigger samples $62 \pm 4\%$ of the total inelastic collision cross section as determined using HIJING [3] and a full GEANT [4] simulation of the PHOBOS detector. After requiring a valid vertex reconstruction, $48 \pm 5\%$ of the total inelastic cross section is available for analysis.

The tracking algorithm and particle identification cuts used in this analysis and consequently the kinematic acceptance are identical to those described previously [2]. Pions, kaons, and protons are measured over the rapidity ranges of $0.1 < y_\pi < 1.3$ and $0 < y_{K,p} < 0.8$. As a function of transverse momentum, the acceptance for pions and kaons is $0.1 < p_T^{\pi,K} < 1.0$ GeV/c and that for protons is $0.3 < p_T^p < 1.0$ GeV/c. Table I provides a summary of the event and particle statistics in this data set.

Particles of a given charge bend in the same direction as do their oppositely charged counterparts in the reversed polarity magnetic field; hence, they have the same kinematic acceptance. The average kinematic values ($\langle p_T \rangle$, $\langle p_T^2 \rangle$, $\langle y \rangle$) for antiparticles and particles bending in the same direction are found to agree within 5%.

The raw antiparticle to particle ratios are determined independently for each bending direction from the statistically weighted average of the ratios over subsets of the data, as described in Ref. [5], thus eliminating the need to apply an acceptance correction. Polarity-dependent systematic effects that are the same for the two bending directions, such as field strength dependence, are removed by averaging the ratios measured for the two bending directions [5]. Polarity-dependent systematic effects that are different for each bending direction, such as the z-vertex distribution, are corrected for as described previously [2].

The systematic errors in the ratios were determined by varying the criteria used for event selection, track selection, and particle identification. The magnitudes of the errors are of the order of 2–3% and are similar to those reported for the $d+$Au data [2].

The effect of sampling only a fraction of the total inelastic cross section was examined by dividing up the data set based on the energy deposited in the ring counters [6], which is proportional to the charged particle multiplicity. Within the statistical uncertainty, no significant difference was observed between the antiparticle to particle ratios obtained for the highest and lowest multiplicity events.

The $\langle \bar{p} \rangle / \langle p \rangle$ ratio is corrected for the asymmetric absorption of antiprotons versus protons in the detector materials, contamination by secondary particles, and feed-down from hyperon decay. The magnitudes of the correction factors are the same as reported in Ref. [2] with the exception of the correction for secondary particles, which was found to be $2.1 \pm 0.3\%$ (stat.) in the $p+p$ data set and $1.6 \pm 0.3\%$ (stat.) in the $d+$Au data set. The total corrections to the pion and kaon data are small [2] and are reflected in the final systematic errors of the ratios.

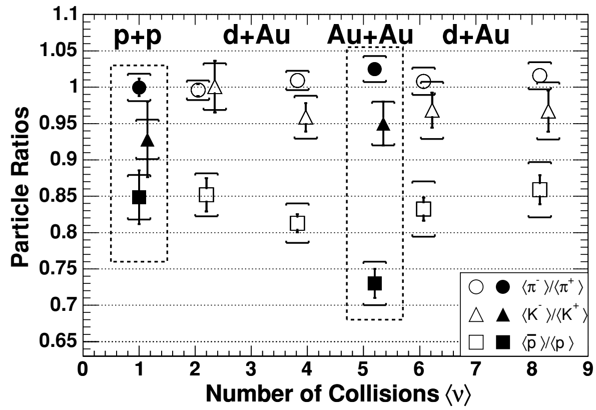

FIG. 1. Particle ratios as a function of centrality for each species for the $p+p$, $d+$Au, and 12% most central Au + Au collision systems at $\sqrt{s_{NN}} = 200$ GeV. The brackets represent the total systematic error. The value of $\langle \nu \rangle$ has been shifted by $+0.15$ for the measured $\langle K^-/K^+ \rangle$ ratios for clarity.

After applying all of the corrections, the antiparticle to particle ratios and associated statistical and systematic errors within the PHOBOS acceptance are as follows:

$$\langle \pi^-/\pi^+ \rangle = 1.000 \pm 0.012\,(\text{stat.}) \pm 0.019\,(\text{syst.}),$$
$$\langle K^-/K^+ \rangle = 0.93 \pm 0.05\,(\text{stat.}) \pm 0.03\,(\text{syst.}),$$
$$\langle \bar{p}/p \rangle = 0.85 \pm 0.04\,(\text{stat.}) \pm 0.03\,(\text{syst.}).$$

Figure 1 shows the final particle ratios for the $p+p$, $d+$Au, and 12% most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, plotted as a function of ν [2,5]. In the Au + Au collision system, ν is defined as $\nu \equiv N_{\text{coll}}/(N_{\text{part}}/2)$, where N_{coll} and N_{part} are the number of binary collisions and the total number of participants, respectively. The errors shown in brackets represent the total systematic error. For

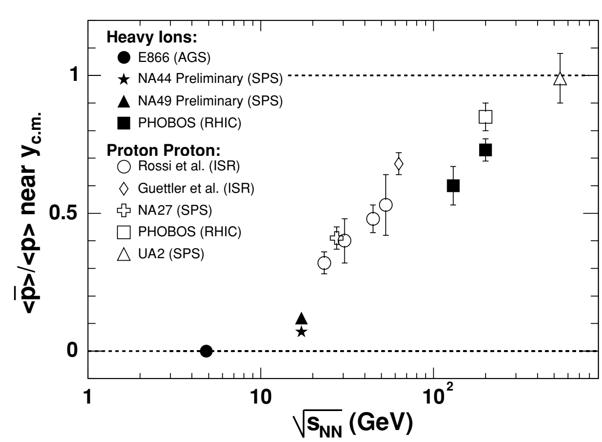

FIG. 2. Antiproton to proton ratio near midrapidity as a function of $\sqrt{s_{NN}}$ for $p+p$ collisions (open symbols) and central heavy ion collisions (filled symbols). The error bars represent the statistical and systematic errors in the measurements added in quadrature.

the $d+$ Au data this quantity is calculated by adding the scale and point-to-point errors reported in Ref. [2] in quadrature. The d + Au and $p + p$ data sets were both collected during the 2003 RHIC run whereas the Au + Au data are from the 2001 run. Within the errors, the ratios measured in the $p + p$ and d + Au collision systems for all values of ν agree. However, the $\langle\bar{p}\rangle/\langle p\rangle$ ratio for Au + Au data is significantly lower than those observed in $p + p$ and $d+$ Au collisions.

The difference in the $\langle\bar{p}\rangle/\langle p\rangle$ ratio in $p + p$ and Au + Au collisions can be investigated further by examining the evolution of the ratio as a function of collision energy. The $\langle\bar{p}\rangle/\langle p\rangle$ ratio near midrapidity as a function of center-of-mass energy for $p + p$ collisions is shown in Fig. 2 using open points [7–10]. The data indicate a smooth evolution from low to high energy. Also shown in Fig. 2 as filled symbols is the $\langle\bar{p}\rangle/\langle p\rangle$ ratio near midrapidity for central heavy ion collisions [5,11–14]. The $\langle\bar{p}\rangle/\langle p\rangle$ ratio in heavy ion collisions at RHIC energies has also been reported at a variety of energies and centralities [15–20]. In general, there is good agreement between the different measurements, but some small discrepancies remain to be resolved. Figure 2 presents the results from PHOBOS for 130- and 200-GeV Au + Au collisions [5,11], both of which have similar acceptances as reported here for 200-GeV $p + p$ collisions.

The antiparticle to particle ratios have now been measured in both $p + p$ and heavy ion collisions at the same energy using the same detector. A suppression of the $\langle\bar{p}\rangle/\langle p\rangle$ ratio is observed in the heavy ion data relative to $p + p$ over approximately an order of magnitude in the collision energy. The evolution of the ratio as a function of center-of-mass energy seems to be similar in shape for the two systems, with the heavy ion data offset by a factor of about 2 in collision energy. The results reported in this paper will provide input to theoretical comparisons of the relative degree of baryon transport and antibaryon-baryon pair formation observed in $p+p$ and heavy ion collisions as well as further information concerning the different dynamics that influence the evolution of each system.

This work was partially supported by U.S. DOE Grants DE-AC02-98CH10886, DE-FG02-93ER40802, DE-FC02-94ER40818, DE-FG02-94ER40865, DE-FG02-99ER41099, and W-31-109-ENG-38, by U.S. NSF Grants 9603486, 0072204, and 0245011, by Polish KBN Grant 1-P03B-062-27(2004-2007), and by NSC of Taiwan Contract NSC 89-2112-M-008-024.

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