# Rapidity dependence of deuteron production in Au+Au collisions at $\sqrt{s_{_{\rm NN}}}$ = 200 GeV

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We have measured the distributions of (anti)-protons and (anti)-deuterons produced in high energy heavy ion Au+Au collisions at RHIC over a very wide range of transverse and longitudinal momentum. We present our results in the context of coalescence models. In particular we extract the "volume of homogeneity" and the average phase space density for protons and anti-protons. Near central rapidity the coalescence parameter  $B_2(p_T)$  and the phase space density are very similar for both protons and anti-protons. For protons we see little variation of either  $B_2(p_T)$  or  $f(p_T)$ as the rapidity increases from 0 to 3.1. These results are in contrast to lower energy data where the proton and anti-proton  $B_2$  and phase space densities are different at y=0 and both  $B_2$  and f depend strongly on rapidity. These results suggest a difference in freeze-out dynamics at RHIC compared to lower energy collisions.

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## I. INTRODUCTION

Deuterons and other heavier nuclear fragments detected in heavy ion collisions are thought to be produced via a process called coalescence. Baryons which are close enough in phase space, i.e. in position and momentum space "coalesce" to form the composite. In free space, such a reaction would be  $p + n \rightarrow d + \gamma$ ; while in a heavyion collision the surrounding hot and dense medium ensure energy and momentum conservation. As the clusters are formed inside the expanding system created in the A+A collisions, they continue to interact and may be broken up back into nucleons. These competing mechanisms last until the later stages of the expansion. Due to its low binding energy, the detected deuterons will stop undergoing other scatterings very near kinetic freeze-out and are thus considered an ideal probe to the latest spacetime properties of the system.

All coalescence models share the same simple assumption about yields of clusters, which for deuterons would be written as:

$$E_{d} \cdot \frac{d^{3}N_{d}}{dp_{d}^{3}} = B_{2}(E_{p} \cdot \frac{d^{3}N_{p}}{dp_{p}^{3}})^{2}, \qquad (1)$$

where it is assumed that the unmeasured neutron spectra are identical to the measured proton spectra and that the momentum of the deuteron is trivially the sum of the nucleon momenta. Note that at  $\sqrt{s_{\rm NN}} = 4.9$  GeV the measured n/p ratio has a value of  $1.19 \pm .08$  and is independent of  $m_T$  [1]. In models that assume thermalized distributions of nucleons,  $B_2$  carries information about the cluster since it is inversely proportional to the volume of the system in coordinate space [2–4]. For low and intermediate energy heavy ion collisions and high energy pA collisions, the measured  $B_2$  is independent of energy and  $p_T$  and is consistent with measurements of the deuteron wave-function [5]. At higher energies,  $\sqrt{s_{\rm NN}} \ge 4.9$  GeV,  $B_2$  decreases with energy and increases with  $p_T$  [6–10].

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This is consistent with the formation of deuterons in an expanding medium [11–13]. The connection of  $B_2$  to coordinate space is highlighted in coalescence models that use the so called Wigner functions to write the yield of clusters as convolutions of nucleon distributions in momentum and space-time and the deuteron wave function as the coalescence function. Approximating the deuteron wave function by a Gaussian distribution, and assuming that the region where coalescence is possible has also a Gaussian shape with width  $R_G$  [14], one can write:

$$(R_G^2 + \frac{\delta^2}{2})^{3/2} = \frac{3}{2} \cdot \frac{\sqrt{\pi^3}\hbar^3}{B_2 \cdot m_p c^2}$$
(2)

where  $m_p$  denotes the proton mass. The  $\delta$  parameter accounts for the size of the deuteron and has a value of  $\delta = 2.8$  fm. One advantage of this ansatz is that it facilitates comparison to interferometry radii. The deuteron wave-function is more accurately represented by the Hulthen form which has an exponential tail [15]. For the  $B_2$  values reported in this paper the error in  $R_G$ from using Eq. 2 is less than 0.2 fm [16]. Near midrapidity  $B_2$  has been found to decrease as a function of energy up to  $\sqrt{s_{\rm NN}} = 17.3$  GeV [19] before flattening out at RHIC energies [20, 21]. This is similar to the behavior seen in HBT radii [22].

It is also conceivable that when we have a strongly interacting plasma of quarks and gluons deuterons may be formed by direct coalescence of quarks. It should be noted for  $p_T > 1.5$  GeV/c the elliptic flow per quark for deuterons scales as  $p_T/n_{quark}$  just as it does for lighter hadrons [6].

The average of the phase space density  $f(\mathbf{x}, \mathbf{p})$  over the system volume at freeze-out time is a quantity which when compared to Bose-Einstein or Fermi-Dirac statistics allows the assessment of the degree of chemical or kinetic equilibrium reached by the system at that stage. This quantity also carries information about the possible multiple-particle symmetrization effects i.e. pion condensates and is related to the entropy of the system. The spatial average phase space density is defined as the following ratio:

$$\langle f \rangle(\mathbf{p}) \equiv \frac{\int d^3x f^2(\mathbf{x}, \mathbf{p})}{\int d^3x f(\mathbf{x}, \mathbf{p})},\tag{3}$$

where the integration is carried over spatial coordinates bound by the volume of the system at freeze-out. With the formal definition of phase space density for a particle of spin J written as:

$$f(\mathbf{x}, \mathbf{p}) \equiv \frac{(2\pi\hbar)^3}{(2J+1)} \frac{d^6N}{dp^3 dx^3}.$$
 (4)

For a system in chemical equilibrium at a temperature T and chemical potential  $\mu$ 

$$f(E) = \frac{1}{e^{(E-\mu)/T} \pm 1},$$
(5)

where E is the energy and  $\pm 1$  selects bosons or fermions. For a dilute system, *i.e.*  $f \ll 1$ , Eq. 5 gives

$$f_d \approx e^{-(E_d - \mu_p - \mu_n)/T}.$$
(6)

Since  $E_d = m_T \cosh(y)$ , one would expect the phase space density to be an exponential in  $m_T$ . Note in this simple derivation, we are ignoring the collective motion of the of particles. At  $\sqrt{s_{NN}} = 17$  GeV, it was found that strong longitudinal flow could significantly reduce the pion phase space density [23]. Also at this energy the inverse slope of the phase space density was found to increase with particle mass in a manner suggestive of transverse flow [24]. Because  $E_d = E_n + E_p$ , Eq. 6 implies that

$$f_d(\mathbf{x}, \mathbf{P}) = f_p(\mathbf{x}, \mathbf{p}) \cdot f_n(\mathbf{x}, \mathbf{p}) = f_p(\mathbf{x}, \mathbf{p})^2.$$
(7)

To extract the average phase space density of protons one can then replace the square term in the numerator of Eq. 3 by the phase space density of deuterons:

$$\langle f_p \rangle = \frac{1}{3} \left( E_d \frac{d^3 N_d}{d p_d^3} \right) / \left( E_p \frac{d^3 N_p}{d p_p^3} \right).$$
 (8)

One can then make use of the assumption that deuterons are formed by coalescence and satisfy Eq. 1 to obtain an expression for the average phase space of protons similar to what Bertsch originally suggested for pions; dividing the spectrum by the product of the HBT radii [25, 26]:

$$\langle f_p \rangle = \frac{1}{2} \cdot E_p \frac{d^3 N_p}{dp^3} \frac{\sqrt{\pi^3} \cdot \hbar^3}{R_G^3 \cdot m_p c^2}.$$
 (9)

Note this represents the maximum phase space density which is at the center of the Gaussian source [26]. The phase space densities calculated using Eq. 8 have the expected exponential dependence in  $m_T$ . When using Eq. 9 one introduces the assumption that deuterons are produced via coalescence and that the homogeneity volume extracted from deuteron distributions is also the volume of the proton source. The calculation of the phase space density of protons using these assumptions is close in value to the one obtained from an assumed thermal equilibrium and has the same behavior in  $m_T$ . This suggests that the system has evolved into chemical equilibrium at freeze-out. To ease the comparison with lower energy data we have decided to use Eq. 8 to calculate the phase density.

The coalescence parameter and the phase space density recast the information contained in the proton and deuteron spectra into "dynamic" and "chemical" terms. The coalescence parameter  $B_2$  can be interpreted in terms of a "radius of homogeniety" which depends upon the temperature of the system and the radial flow. Indeed one confirmation that we are actually seeing coalescence would be if the this radius was consistent with the appropriate HBT radii. This was checked at  $\sqrt{s_{_{\rm NN}}}=17.3$  GeV by comparing  $R_G$  to radii extracted from pp and  $\pi\pi$  correlation measurements [16–18]. The magnitude of the phase space density is sensitive to the chemical potential of the system while its energy dependence derives from the temperature and flow of the matter. In this paper, we use the very large angular and momentum ranges of the two BRAHMS spectrometers to measure the rapidity dependence of the size and phase space density of the (anti)-proton distributions for central Au+Au collisions.

## II. ANALYSIS

The data in this paper were collected by the BRAHMS experiment during the RHIC run of 2004. The data presented here comes from a subset of the collected data and it focuses on 0-20% central Au-Au collisions at  $\sqrt{s_{_{\rm NN}}} = 200$  GeV are analysed in four rapidity bins: (-0.1, 0.1), (0.5, 1.0), (1.5, 2.5), and (2.8, 3.2).

# A. Detector System

The BRAHMS experimental setup consists of two movable magnetic spectrometers, the Forward Spectrometer (FS) that can be rotated from  $2.3^{\circ}$  to  $15^{\circ}$ , and the Mid-Rapidity Spectrometer (MRS) that can be rotated from  $34^{\circ}$  to  $2.3^{\circ}$  degrees relative to the beam line, a set of global detectors consisting of silicon and scintilator tile arrays used to measure multiplicities, as well as fast Cherenkov counters at high rapidity used to measure luminosity, to determine the interaction vertex, and to provide a start time for time-of-flight measurements.

The MRS has two Time Projection Chambers (TPCs), TPM1 and TPM2, situated in field free regions in front and behind a dipole magnet. This assembly is followed by a highly segmented scintillator time-of-flight wall at 4.51 m. The FS consists of 4 dipole magnets D1, D2, D3 and D4 with a total bending power of up to 9.2 Tm. The spectrometer has 5 tracking stations T1 through T5. T1 and T2 are TPCs placed in front of and after the second dipole D2. T3, T4 and T5 are drift chambers with T3 in front of D3, T4 between D3 and D4, and T5 after D4 and just in front of the Ring Imaging Cherenkov (RICH) [27]. Details on the BRAHMS experimental setup can be found in Ref. [28] and in Ref. [29] for tracking in the MRS.

### B. Tracking

Local tracks are first determined in the TPCs and Drift Chambers, which are all situated in field free region. The resulting straight-line track segments in two tracking chambers located on either side of a magnet are matched using the effective edge approximations generating matched tracks. Local tracks and local matched tracks are combined in the FS to form complete tracks. The complete tracks are refitted to deduce the final momenta. Tracks in the FS are required to project through the magnet D1 onto the nominal beamline. Track quality cuts are applied for the final track selection.

We correct our raw momentum distributions for tracking detector efficiency and geometrical acceptance. GEANT 3.21 is used to correct for absorption, multiple scattering, and energy loss in the detectors [30]. We assume that deuteron absorption factorizes from other effects and model it as the square of the proton absorption correction (at  $p_T/2$ ) [16].

## C. Particle Identification

In the midrapidity region, particle identification is done using time of flight measurements, while at forward rapidities we also use the RICH. At y=0 and 0.75 we select (anti-)protons using a  $3\sigma$  cut on  $m^2 = p^2(\frac{c^2L^2}{t^2} - 1)$ , where L is the length of the path followed by a particle, t its time of flight and c the speed of light. For deuterons a simple  $3\sigma$  cut around the (anti-)deuteron mean mass is used. At forward rapidities the RICH provides proton deuteron PID separation. The ring radius in the RICH depends on the particle's velocity. For a particle of mass m in our RICH  $R \approx 9.2(1 - (p/p_{thres})^2)$  cm where  $p_{thres} = m16.1c$ . The PID performance is shown in Fig. 1, where the bands represent the limits used for the analysis. Because of various inefficiencies about 3%of particles moving faster than their Cherenkov threshold don't produce a ring. Protons and deuterons with momenta between the kaon and proton thresholds do not make a ring. The contamination from mis-identified kaons and pions are subtracted to deduce the proton spectrum in this momentum range (neglecting the small fraction of deuterons). This procedure cannot be used in the region between the proton and deuteron thresholds since the contaminations from pions, kaons and protons dominates the small deuteron yield.

## D. Feed-down corrections

We have corrected our data to account for the hyperons that decay into protons using the method described in [31]. The correction factor, C, is given by:

$$C = \frac{N_p}{N_p + N_\Lambda + N_{\Sigma^+}},\tag{10}$$

where  $N_p$  is the number of primary protons and  $N_{\Lambda}$  and and  $N_{\Sigma^+}$  are the number of protons coming from  $\Lambda$  and  $\Sigma^+$  decay respectively. Near central rapidity we have used the lambda spectra measured by PHENIX [32] and estimated the  $\Sigma/\Lambda$  ratio from lower energy results. Since



FIG. 1: Ring radius versus momentum for particles with  $y \approx 3$  showing the pion, kaon, proton and deuteron separation. The selected proton and deuterons are within the selected bands.

there are no measurements of  $\Lambda$ s at forward rapidities we have estimated the  $\Lambda/p$  ratio based on thermal models that were fitted to the rapidity densities of charged pions, kaons, protons and anti-protons measured by BRAHMS in the forward region. We find that  $dN_{\Lambda}/dy/dN_{p}/dy$ varies only slowly in the model with rapidity up to rapidities  $y \approx 4$ . The systematic error from uncertainties on the yields and the model extrapolation is estimated to be less than 3%. The correction factor also depends on the  $p_T$  dependence of the  $\Lambda/p$  ratio. BRAHMS has found that the mean transverse kinetic energy scales linearly with the mass of the particle with a slope that depends only weakly on rapidity [33]. We have used these systematics to estimate the inverse slope (T) of the  $\Lambda$  $m_T$ -distribution. To estimate the systematic error on the  $p_T$  dependence of the correction factor we have taken the limiting cases of  $T_{\Lambda} = T_p$  and  $T_{\Lambda} = T_p m_{\Lambda}/m_p$ . This produces an error on the correction factor that is almost zero at  $p_T = 1 \text{ GeV/c}$  and reaches -9%, +6% at  $p_T = 2 \text{ GeV/c}$ . The correction factor as a function of  $p_T$  and rapidity is shown in Fig. 2. It varies only weakly with rapidity and has a systematic error that is small in comparison to the statistical errors on  $B_2$  and the phase space density. At  $p_T = 2 \text{ GeV/c}$  the total error from the feed-down correction reaches a value of 19% for  $B_2$  and 10% for the phase space density.

## III. RESULTS

Figure 3 shows our invariant proton and deuteron spectra versus  $p_T$  for the four measured rapidity bins. We fit exponentials in  $m_T$  to the spectra and extract the invariant yields, dN/dy and inverse slopes T. These are listed in Table I. The yields, of p, d,  $\bar{p}$  and  $\bar{d}$  fall steadily from y=0 to y=3. The inverse slopes of particles and antiparticles are very similar but those of the (anti)-deuterons are about 15% higher than those of the (anti)-protons. For the protons and anti-protons the inverse slopes de-



FIG. 2: The  $p_T$  dependent feed-down correction factors for protons versus  $p_T$  and rapidity. The 3 sets of lines show the effect of various scenarios for the difference in shape between proton the and  $\Lambda$  spectra. Systematic errors on the correction due to uncertainties in the yield ratio of protons and lambdas are shown by the bands to the left of the plots. The curves for anti-protons are very similar.

		Proton			Deuteron	
у	$p_T$ fit	dN/dy	T MeV	$p_T$ fit	dN/dy	T MeV
0.0	0.7 - 4.0	$27.9\pm0.1$	$354 \pm 2$	0.7 - 3.3	$0.136 \pm 0.007$	$423\pm23$
		$20.8\pm0.1$	$352\pm1$		$0.081 \pm 0.005$	$404\pm29$
0.8	0.5 - 4.0	$26.0\pm0.1$	$356 \pm 1$	0.7 - 3.5	$0.117 \pm 0.003$	$463 \pm 14$
		$17.9\pm0.1$	$361\pm1$		$0.071\pm0.003$	$403\pm20$
2.0	0.5 - 3.0	$20.9\pm0.2$	$314\pm3$	0.8 - 2.8	$0.082\pm0.011$	$460 \pm 110$
3.1	0.5-4.0	$\overline{23.4\pm0.1}$	$\overline{282 \pm 1}$	2.0-3.5	$0.25_{0.08}^{+0.30}$	$310\pm90$

TABLE I: Inverse slopes, T (MeV), and dN/dy derived from fitting spectra. The lower row at rapidities y = 0 and y = 0.75 is for the anti-particles. Errors are statistical only.

creases steadily with rapidity but we lack sufficient statistics to see a rapidity dependence in the deuteron slopes.

Figure 4 shows  $B_2$  versus  $m_T$  and rapidity.  $B_2$  increases with  $p_T$  which is consistent with previous experiments [19, 21]. Using Eq. 2, we find that the source radius at y = 0 falls from 4.6  $\pm$  0.2 fm to 3.0  $\pm$  0.4 fm as  $m_T$  increase from 0.7 to 2.0 GeV. This is consistent with the  $m_T$  dependence of HBT radii,  $R \propto 1/\sqrt{m_T}$  that has been observed by PHENIX and STAR [22] and also at SPS energies, [18]. The solid line in each rapidity panel represents an exponential fit to our data at y=0. We see no evidence of any rapidity dependence of  $B_2(p_T)$ . The proton and anti-proton  $B_2$  values are very close at this energy implying a similar source size. This is in contrast to  $\sqrt{s_{\rm NN}} = 17.3$  GeV where the anti-proton source was found to be larger than the proton source [16].

Figure 5 shows the average phase space density  $\langle f \rangle (m_T)$  for protons and anti-protons as a function of



FIG. 3: (Anti)-proton and (anti)-deuteron  $p_T$  spectra at various rapidities. The filled symbol part of the spectra show the  $p_T$  intervals used in the coalescence analysis. Note the limits for the deuteron range are exactly twice those used for the protons.



FIG. 4:  $B_2(p_T)$  at several rapidities for central Au+Au collisions at  $\sqrt{s_{\rm NN}} = 200$  GeV.

rapidity. The phase space density decreases as the  $m_T$  increases as expected from Eq. 5. The solid curve in each panel of Fig. 5 is a exponential fit to the proton density at y=0. We see little rapidity dependence of  $\langle f \rangle (p_T)$ . By fitting the proton and anti-proton phase densities we find  $\mu = 71 \pm 24$  MeV to be compared to the value of 22 MeV extracted with statistical models [34]. Near y=0 the anti-protons have a slightly smaller value of phase space

density compared to that of protons. At  $\sqrt{s_{\rm NN}} = 17.3$  GeV the anti-proton phase space density was 38 times smaller [16] suggesting a much larger chemical potential at the lower energy. The inverse slope derived from the phase space density is  $T = 610 \pm 40$  MeV. This is consistent with data at  $\sqrt{s_{\rm NN}} = 17$  GeV but much higher than at  $\sqrt{s_{\rm NN}} = 4.9$  GeV where the inverse slope is about 350 MeV, see Fig. 6. It should be noted that the deuteron, proton, kaon and pion spectra can be well described by blast wave fits which suggest that this increase in the inverse slope is largely driven by an increase in radial flow. Accordingly, the phase density of pions is characterized by a much smaller inverse slope ( $\approx 140$  MeV) than that of protons [16].

Figures 4 and 5 imply that the volume of homogeniety,  $1/B_2$ , and the phase space vary very little with rapidity at  $\sqrt{s_{\rm NN}} = 200$  GeV. This is in stark contrast to the situation at lower energy. Table II shows the rapidity dependence of  $B_2$  and the phase space density at  $p_T = 0$  for central Pb+Pb collisions at  $\sqrt{s_{\rm NN}} = 17$  GeV [9, 16, 35]. Finally, Fig. 6 shows the evolution of the phase space density near mid-rapidity as the energy of the system grows from AGS to RHIC values. The phase space density of protons decreases with energy while that of anti-protons increases.



FIG. 5: The (anti)-proton phase space density  $\langle f \rangle (m_T/A)$  for central  $\sqrt{s_{\rm NN}} = 200$  GeV Au+Au collisions at several rapidities.



FIG. 6: The proton phase space density as a function of  $\sqrt{s_{\text{NN}}}$  and  $m_T$  at y=0, [8, 16, 19, 35]

# IV. SUMMARY

Near central rapidity the proton and anti-proton phase space densities are very similar, suggesting a small chemical potential. The coalescence parameters for deuterons and anti-deuterons are also very close, suggesting similar freeze-out volumes for protons and anti-protons. This similarity is not seen at lower energies. The deuteron coalescence parameter  $B_2$  increases with  $p_T$  but at a given  $p_T$  it is independent of rapidity. This suggests that the volume of homogeneity for protons is almost constant from y=0 to y=3.1. The proton phase space density also shows no significant rapidity dependence, while depending strongly on  $m_T$  and  $\sqrt{s_{\rm NN}}$ .

	$(p_T =$	= 0)	y=(	).2	y=0.	8	y = 1.3	3	
	$B_2 *$	$10^{4}$	$7.9 \pm$	0.8	$8.1\pm0$	0.3	$13.7 \pm 2$	2.7	
	f * 1	$10^{3}$	$1.9\pm$	0.1	$2.5\pm0$	0.2	$3.3 \pm 0$	).3	
$(p_T =$	= 1.3)	y=	=0.0	y	=1.0	2	y = 2.0	y	=3.1
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	= 0.5	$8.1 \pm 0$	$\pm 0.4$	10.6 =	$0 \pm 0.7$	10.0	$8.8\pm1.0$	$B_2 * 10^4$	
$f * 10^{3}   2.9 \pm 0.4   2.9 \pm 0.2   3.1 \pm 1.0   2.3 \pm 0.2   3.1 \pm 0.2   3.1$	= 1.0	$2.3 \pm 1$	E 1.0	3.1 =	$\pm 0.2$	2.9	$2.9\pm0.4$	$f * 10^{3}$	[

TABLE II: The rapidity dependence of  $B_2$  and the f for (Top) Pb+Pb collisions at  $\sqrt{s_{\rm NN}} = 17.3$  GeV and (Bottom)  $\sqrt{s_{\rm NN}} =$ 200 GeV AuAu collisions. For the 17.3 GeV data the centrality is 23% for at y=0.2 [35] and 20% at y=0.8 and 1.3 [9, 16].

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