Deuteron and Antideuteron Production in Au+Au Collisions at √s_NN = 200 GeV

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The production of deuterons and antideuterons in the transverse momentum range $1.1 < p_T < 4.3$ GeV/$c$ at midrapidity in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV has been studied by the PHENIX experiment at RHIC. A coalescence analysis, comparing the deuteron and antideuteron spectra with that of proton and antiproton, has been performed. The coalescence probability is equal for both deuterons and antideuterons and it increases as a function of $p_T$, which is consistent with an expanding collision zone. Comparing (anti)proton yields, $\bar{n}/n = 0.73 \pm 0.01$, with (anti)deuteron yields, $\bar{d}/d = 0.47 \pm 0.03$, we estimate that $\bar{n}/n = 0.64 \pm 0.04$. The nucleon phase space density is estimated from the $p_T$ spectrum.

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Ultrarelativistic heavy-ion collisions are used to study the behavior of nuclear matter at extreme conditions of temperature and density, similar to those that existed in the universe a few microseconds after the Big Bang. Previous measurements indicate that high particle multiplicities [1] and large $p/p$ ratios prevail at the Relativistic Heavy-Ion Collider (RHIC), which is expected for a nearly net baryon-free region [2]. As the hot, dense system of particles cools, it expands and the mean-free path increases until the particles cease interacting (“freeze-out”). At this point, light nuclei such as deuterons and antideuterons ($d$ and $\bar{d}$) can be formed, with a probability proportional to the product of the phase space densities of its constituent nucleons [3,4]. Thus, the invariant yield of deuterons, compared to the protons [5,6] from which they coalesce, provides information about the size of the emitting system and its space-time evolution.

PHENIX [7] at RHIC is a versatile detector designed to study the production of leptons, photons, and hadrons over a wide momentum range. In this Letter, results on $d$ and $\bar{d}$ production in Au + Au interactions at $\sqrt{s_{NN}} = 200$ GeV are presented. For the sake of brevity, in the rest of this Letter, our statements will generally apply to both particles and antiparticles.

The east central tracking spectrometer in the PHENIX detector [5,7,8] is used in this analysis. The information from the PHENIX beam-beam counters (BBCs) and zero-degree calorimeters (ZDCs) is used for triggering and event selection. The BBCs are Čerenkov counters surrounding the beam pipe in the pseudorapidity interval $3.0 < |\eta| < 3.9$, and provide the start timing signal. The ZDCs are hadronic calorimeters 18 m downstream of the interaction region and detect spectator neutrons in a narrow forward cone. Particle identification in the central rapidity region is achieved by measuring momentum (by drift chamber) and time of flight (by time-of-flight detector). The drift chamber (DC) and two layers of pad chambers are used for tracking and momentum reconstruction [8]. The time-of-flight (TOF) detector spans the pseudorapidity range $|\eta| < 0.35$ and $\Delta \phi = \pi/4$ azimuthally. The TOF consists of plastic scintillators, with a combined time resolution of $\pm 115$ ps. The TOF thus provides identification of $d$ and $\bar{d}$ in the transverse momentum ($p_T$) range $1.1 < p_T < 4.3$ GeV/$c$, for minimum bias events, and two centrality bins: 0%–20% (most central) and 20%–92% (noncentral). The data set for this analysis includes $21.6 \times 10^6$ minimum bias events. The minimum bias cross section corresponds to $92.2^{+3.5}_{-3.0}$% of the total inelastic Au + Au cross section (6.9 b) [9]. Using the momentum determined by the DC, which has a resolution of $\delta p/p \approx 0.7\% \oplus 1\% p$ GeV/$c$, and the time of flight from the event vertex provided by the TOF, the mass of the particle is determined. The $d$ and $\bar{d}$ yields are obtained by fitting the mass squared distributions to the sum of a Gaussian signal and an exponential background. Examples of mass squared distributions with fits for antideuterons in minimum bias collisions are shown in Fig. 1.

The raw yields are corrected for effects of detector acceptance, reconstruction efficiency, and detector occupancy. Corrections are determined by reconstructing single deuterons simulated using GEANT [10] and a detector response model of PHENIX, using the method described in [6]. The track reconstruction efficiency decreases in high multiplicity events because of high detector occupancy. This effect can be slightly larger for slower, heavier particles, due to detector dead times between successive hits. Occupancy effects on reconstruction efficiency ($\approx 83.5\%$ for 0%–20% most central events) are evaluated by embedding simulated single particle Monte Carlo (MC) events in real events. Since the hadronic interactions of nuclei are not treated by GEANT, a correction needs to be applied for the hadronic absorption of $d$ and $\bar{d}$ (including annihilation). The $d$- and the $\bar{d}$-nucleus cross sections are calculated from parametrizations of the nucleon and antinucleon cross sections:

$$\sigma_{d/\bar{d}A} = \left[ \sqrt{\sigma_{N/A} + \Delta_d} \right]^2. \quad (1)$$

The limited data available on deuteron induced interactions [11] indicate that the term $\Delta_d$ is independent of the nuclear mass number $A$ and that $\Delta_d = 3.51 \pm 0.25$ mb/$A^{1/2}$. The hadronic absorption varies only slightly over the applicable $p_T$ range and is $\approx 10\%$ for $d$ and $\approx 15\%$ for $\bar{d}$. The background contribution from deuterons knocked out due to the interaction of the produced particles with the beam pipe is estimated using simulations and is found to be negligible in the momentum range of our measurement.

Figure 2 shows the corrected $d$ and $\bar{d}$ invariant yields as a function of transverse mass $m_T$ in the range $1.1 < p_T < 4.3$ GeV/$c$, for minimum bias events, and two centrality bins: 0%–20% (most central) and 20%–92% (noncen-

FIG. 1 (color online). Histograms of the mass squared for identified antideuterons in the transverse momentum range $1.1 < p_T < 3.5$ GeV/$c$ (in 400 MeV/$c$ increments), with Gaussian fits including an exponential background.
The deuteron inverse slopes of 300 and mean transverse momentum are tabulated in Table I. The deuteron inverse slopes of each bin, the extent of which is indicated by the width of the gray bars along the x axis.

Systematic uncertainties have several sources: errors in particle identification, DC-TOF hit match efficiency, the uncertainty in momentum scale, and uncertainties in occupany corrections. All the systematic uncertainties are added in quadrature, depicted by the gray bars in Fig. 2.

The $p_T$ spectra $Ed^3N/d^3p$ are fitted in the range $1.1 < p_T < 3.5$ GeV/c to an exponential distribution in $m_T = \sqrt{p_T^2 + m^2}$. The inverse slopes ($T_{\text{eff}}$) of the spectra are tabulated in Table I. The deuteron inverse slopes of $T_{\text{eff}} = 500–520$ MeV are considerably higher than the $T_{\text{eff}} = 300–350$ MeV observed for protons [5,6]. The invariant yields and the average transverse momenta ($\langle p_T \rangle$) are obtained by summing the data over $p_T$ and using a Boltzmann distribution, $\frac{dN}{dm_T} \propto m_T e^{-m_T/T_{\text{eff}}}$, to extrapolate to low $m_T$ regions where we have no data. The extrapolated yields constitute $\approx 42\%$ of our total yields. The rapidity distributions, $dN/dy$, and the mean transverse momenta, $\langle p_T \rangle$, are compiled in Table I for three different centrality bins. Systematic uncertainties in $dN/dy$ and $\langle p_T \rangle$ are estimated by using an exponential in $p_T$ and a “truncated” Boltzmann distribution (assumed flat for $p_T < 1.1$ GeV/c) for alternative extrapolations.

With a binding energy of 2.24 MeV, the deuteron is a very loosely bound state. Thus, the observed deuterons can be formed only at a later stage in the collision. The proton and neutron must be close in space and tightly correlated in velocity to coalesce. As a result, $d$ and $d$ yields are a sensitive measure of correlations in phase space at freeze-out and can provide information about the space-time evolution of the system. If deuterons are formed by coalescence of protons and neutrons, the invariant deuteron yield can be related [12] to the primordial nucleon yields by

$$E_d \frac{d^3N_d}{d^3p} \bigg|_{p_T=0} = B_2 \left( E_p \frac{d^3N_p}{d^3p} \right)^2,$$

where $B_2$ is the coalescence parameter with the subscript implying that two nucleons are involved in the coalescence. The above equation includes an implicit assumption that the ratio of neutrons to protons is unity. The proton and antiproton spectra [6] are corrected for feed-down from $\Lambda$ and $\bar{\Lambda}$ decays by using a MC simulation tuned to reproduce the particle ratios: ($\Lambda/p$ and $\bar{\Lambda}/\bar{\bar{p}}$) measured by PHENIX at 130 GeV [13].

Figure 3 displays the coalescence parameter $B_2$ as a function of $p_T$ for different centralities. Thermodynamic models [4] predict that $B_2$ scales with the inverse of the effective volume $V_{\text{eff}}$ ($B_2 \propto 1/V_{\text{eff}}$). The lower $B_2$ in more central collisions may thus reflect the increase in the participant volume with centrality. We also observe that $B_2$ increases with $p_T$. This is consistent with an expanding

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**Table I.** The inverse slope parameter $T_{\text{eff}}$ obtained from a $m_T$ exponential fit to the spectra along with multiplicity $dN/dy$ and mean transverse momentum $\langle p_T \rangle$ obtained from a Boltzmann distribution for different centralities.

| $T_{\text{eff}}$ [MeV] | Deuterons | Antideuterons |
|------------------------|-----------|---------------|
| Minimum bias           | 519 ± 27  | 512 ± 32      |
| 0%–20%                 | 536 ± 32  | 562 ± 51      |
| 20%–92%                | 475 ± 29  | 456 ± 35      |
| $dN/dy$                |           |               |
| Minimum bias           | 0.0250±0.0006(stat) | 0.0117±0.0003(stat) |
| 0%–20%                 | 0.0727±0.0022(stat) | 0.0336±0.0057(stat) |
| 20%–92%                | 0.0133±0.0004(stat) | 0.0066±0.0015(stat) |
| $\langle p_T \rangle$ [GeV/c] |           |               |
| Minimum bias           | 1.54±0.04(stat) | 1.52±0.05(stat) |
| 0%–20%                 | 1.58±0.02(stat) | 1.62±0.01(stat) |
| 20%–92%                | 1.45±0.05(stat) | 1.41±0.06(stat) |
source because position-momentum correlations lead to a higher coalescence probability at larger \( p_T \). The \( p_T \) dependence of \( B_2 \) can provide information about the density profile of the source as well as the expansion velocity distribution. It has been shown \[14,15\] that a Gaussian source density combined with a linear flow velocity profile leads to a constant \( B_2 \) with \( p_T \). This is not supported by our data, which show a rise in \( B_2 \) with \( p_T \). An increase of \( B_2 \) with \( p_T \) can be achieved if the Gaussian source density is replaced with a flat distribution \[14,15\]. The increase is a consequence of the flat density distribution giving greater weight to the outer parts of the system where the flow is strongest when a linear velocity profile is used.

Figure 4 compares \( B_2 \) for most central collisions to results at lower \( \sqrt{s} \) \[16--21\]. Note that \( B_2 \) is nearly independent of \( \sqrt{s} \), indicating that the source volume does not change appreciably with center-of-mass energy (with the caveat that \( B_2 \) varies as a function of \( p_T \), centrality, and rapidity). This observation is consistent with what has been observed in Bose-Einstein correlation Hanbury Brown-Twiss analysis at RHIC \[22\] for identified particles. The coalescence parameter \( B_2 \) for \( d \) and \( \bar{d} \) is equal within errors, indicating that nucleons and antinucleons have the same temperature, flow, and freeze-out density distributions.

The \( \bar{d}/d \) ratio is independent of centrality and \( p_T \) within errors. The average value of \( \bar{d}/d \) is \( 0.47 \pm 0.03 \), consistent with the square of the ratio \( \bar{p}/p = 0.73 \pm 0.01 \) \[6\] within statistical and systematic uncertainties. This is expected if deuterons are formed by coalescence of comoving nucleons and \( \bar{p}/p = \bar{n}/n \). The ratio \( \bar{n}/n \) can, however, be estimated from the data based on the thermal chemical model. Assuming thermal and chemical equilibration, the chemical fugacities are determined from the particle/anti-particle ratios \[14\]:

\[
\frac{E_A(d^3N_A/d^3p_A)}{E_A(d^3N_\bar{A}/d^3\bar{p}_A)} = \exp\left(\frac{2\mu_\Lambda}{T}\right) = \lambda_A^2. \tag{3}
\]

Using the ratio \( p/\bar{p} \), the extracted proton fugacity is \( \lambda_p = \exp(\mu_p/T) = 1.17 \pm 0.01 \). Similarly, using the \( d/\bar{d} \) ratio, the extracted deuteron fugacity is \( \lambda_d = \exp[(\mu_p + \mu_\Lambda)/T] = 1.46 \pm 0.05 \). From this, the neutron fugacity can be estimated to be \( \lambda_n = \exp(\mu_B/T) = 1.25 \pm 0.04 \), which results in \( \bar{n}/n = 0.64 \pm 0.04 \). The extracted \( \bar{p}/p \) and \( \bar{n}/n \) ratios are in agreement with what one would expect from the initial neutron excess in the Au nucleus if the same number of \( \text{(anti)} \)deuterons and \( \text{(anti)} \)protons are produced in the collision. Thermal models predict \[23\] \( \bar{d}/d = 0.52 \) and \( \bar{n}/n = 0.73 \) for \( T = 177 \) MeV and \( \mu_B = 29 \) MeV.

Finally, the coalescence requirement allows us to estimate the nucleon phase space distribution, i.e., the average number of nucleons per cell \((d^3p d^3x)/h\) in phase space. We define the phase space distribution averaged over the source volume as

\[
\langle f(p) \rangle = \frac{1}{2S + 1} \frac{(2\pi\hbar)^3}{V} \frac{d^3N}{dp^3}, \tag{4}
\]

where \( 2S + 1 \) is the spin degeneracy factor. From the coalescence equation \[15\], \( f_A(\vec{r}, \vec{p}) = \langle f(\vec{r}, \vec{p}/A) \rangle \), we can thus calculate \( f(\vec{r}, \vec{p}) \) as a function of \( p_T \) from the measured invariant yields, if we assume that the protons, neutrons, and deuterons are emitted from the same volume. The results are shown in Fig. 5. The phase space density is well below 1 in the range of our measurement, and much lower than what has been found for pions produced in Au + Au collisions previously \[24\].

To summarize, the transverse momentum spectra of \( d \) and \( \bar{d} \) in the range \( 1.1 < p_T < 4.3 \) GeV/c have been measured at midrapidity in Au + Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV, and are found to be less steeply falling than proton (and antiproton) spectra. The extracted coalescence parameter \( B_2 \) increases with \( p_T \), which is indicative of an expanding source. The results rule out a Gaussian source density distribution combined with a linear flow velocity profile and seem to favor a flat density distribution. The \( B_2 \) measured in nucleus-nucleus collisions is independent of \( \sqrt{s_{NN}} \) above 12 GeV, consistent with the energy depen-
dence of the source radii extracted from Bose-Einstein correlation measurements. $B_2$ is equal within errors for both deuterons and antideuterons. From the measurements, it is estimated that $\bar{n}/n = 0.64 \pm 0.04$.

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