Deuteron and antideuteron measurements in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC-PHENIX

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Abstract In Run-7 of RHIC operations PHENIX has recorded over 5.4 billion minimum bias events, facilitating a detailed study of deuteron and antideuteron production as a function of centrality and up to transverse momentum of $p_T = 5$ GeV/c. We present transverse momentum p_T and transverse mass m_T spectra, mean transverse momentum $\langle p_T \rangle$, source parameters, particle ratios, and nuclear modification factor R_{CP} . Deuteron and antideuteron spectra are compared to those of other identified particles and to hydrodynamical predictions.

1 Introduction and physics motivation

Light (anti)nuclei, such as (anti)deuterons, are formed in the later phases of heavy ion collisions. As such, there is much interest in these particles as they carry information on source dynamics and final state effects. Additionally, they serve as a means of indirect measurements of neutrons, owing to the fact that they are formed from both (anti)protons and (anti)neutrons. Hereafter, the terms proton, neutron, and deuteron will be used to refer to both particles and antiparticles for the sake of clarity and brevity.

The probability of a neutron and a proton coalescing into a deuteron is proportional to the product of their phase space distributions [1, 2]. Because of their very low binding energy, it is not expected that any deuterons produced in earlier stages of the fireball survive the repeated scattering events. Comparisons between deuteron and proton spectra can provide information about the size of the emitting system and its space-time evolution [3, 4].

2 Experiment and analysis

2.1 Dataset and cuts

The data presented here were collected during the RHIC Run-7, in 2007. This was a Au + Au run with collisions at $\sqrt{s_{NN}} = 200$ GeV. The PHENIX Collaboration recorded nearly 5.5 billion minimum bias (MB) events. In this study, 1.9 billion of those were used. The PHENIX MB trigger is a concurrence measurement of at least 1 particle incident on both beam-beam counters, located at $3.0 < |\eta| < 3.9$. Additionally, events are selected to be occurring with collision vertex located within $|z| < 30$ cm of the center of the PHENIX coordinate system along the beam axis.

This study makes use of the PHENIX central arms. Specifically, we use the tracking system, which is composed of the drift chambers (DC) and three layers pad chambers (PC); and the time-of-flight west (TOF.W) detector. Tracks were selected based on the criteria that they were high quality DC/PC1 tracks and they matched hits in the PC2 and PC3 within 3σ from the center of the residual distribution of spatial coordinates ϕ and z . Additionally, spatial track-matching at the 3σ level was also required in the TOF.W.

2.2 Particle identification and yield extraction

The deuterons are identified by the reconstruction of their mass using the momentum determined by the DC and the velocity obtained from the time of flight and path length measurements.

The TOF.W was operated for the first time in Run-7. It is based on multi-gap resistive plate chamber (MRPC) technology, achieving an intrinsic timing resolution of $\sigma_t = 75$ ps, which allows for excellent PID capabilities. The timing resolution of the TOF.W allows for proton deuteron separation to much higher p_T than presented in this study; however, this study is limited by statistics and background. On the low p_T

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side, the limitation is the much lower statistics caused by the reduced rapidity acceptance.

To extract the yield, a m^2 spectrum is made in p_T bins, the background is fitted with an exponential function, the peak is fitted with a Gaussian distribution, and the yield is extracted by integrating under the Gaussian. The yields are corrected for detector acceptance and occupancy, reconstruction efficiency, and survival probability. Tracking efficiency and acceptance corrections are estimated using Monte Carlo simulations. Detector occupancy is estimated using embedding simulations. Survival probability is estimated similarly to how it is in the previous PHENIX study on deuterons [5]. This approach is a modified version of what is presented in [6], with experimental data on the deuteron interaction cross-sections being taken from [7, 8]. Systematic uncertainties are estimated based on these corrections.

3 Results

3.1 Centrality dependence of spectral shapes

Figure 1 shows the p_T spectra results for all 5 centrality classes, 0–10%, 10–20%, 20–40%, 40–60%, 60–92%, and MB for deuterons and antideuterons, respectively. Apparent is the flattening of the spectrum going from peripheral to central collisions, which is consistent with expectations from radial flow.

Figure 2 shows the m_T spectra results for the most central (left side) and most peripheral (right side), contrasted with spectra for other particle species; the $\pi/K/p$ data are taken from [3]. For the most central events, the deuteron slope is appreciably flatter than that of the proton. Typical hydrodynamical behavior is observed in that the particle slope

Fig. 1 Transverse momentum distribution of deuterons for all 5 centrality classes plus MB. The black lines represent the statistical errors, the shaded bands represent the systematic errors

changes with mass and at high p_T , where hydrodynamics doesn't play a role, they have the same slope. Conversely, for peripheral collisions, in which hydrodynamical effects are negligible, there is minimal difference between the slopes of the various particles.

A more quantitative measure of the spectral shape is the mean transverse momentum. Figure 3 shows mean p_T as a function of the number of nucleons participating in the collision, $\langle p_T \rangle$ vs. N_{part} . We define $\langle p_T \rangle$ in the following way:

$$\langle p_T \rangle = \frac{\int_0^\infty p_T^2 f(p_T) dp_T}{\int_0^\infty p_T f(p_T) dp_T}, \quad (1)$$

Fig. 2 Transverse mass distribution of $\pi/K/p/d$ for central 0–10% (left), and peripheral 60–92% (right). The errors bars are statistical errors only. The $\pi/K/p$ data are taken from [3]

Fig. 3 Average transverse momentum vs number of participants of positive particles (left) and negative particles (right). The $\pi/K/p$ data are taken from [3]. The shaded bands on the deuterons represent the systematic error

where $f(p_T)$ is simply the momentum distribution of the particle. To evaluate this, we must divide it into three pieces. For the range $0 \text{ GeV/c} < p_T < 1.1 \text{ GeV/c}$, we use a Boltzmann distribution fitted to the lowest 3 data points. For the range $1.1 \text{ GeV/c} < p_T < 4.2 \text{ GeV/c}$, the range for this study, we simply integrate the data numerically. Lastly, for the range $4.2 \text{ GeV/c} < p_T < \infty$, we again assume a Boltzmann distribution and integrate up to 10 GeV/c , beyond which the contribution to the yield becomes negligible. To evaluate the systematic uncertainty, we use different fitting functions to describe the data and calculate the various percent-differences. The systematic errors are represented in Fig. 3 as shaded bands. As has been seen in previous studies, such as [3], $\langle p_T \rangle$ is at a minimum for the lowest N_{part} and then rises as N_{part} increases before reaching a plateau, with this becoming more pronounced as particle mass increases. This trend is seen with the deuterons, as illustrated in Fig. 3.

3.2 Blastwave fits

Due to the overall very good qualitative agreement between radial flow considerations and the experimental results seen so far, it is interesting to check for quantitative agreement with hydrodynamics models. Here we consider a very simple “blastwave” model, which can be summarized by the following relation determining the momentum spectra for various particles:

$$\frac{1}{p_T} \frac{dN}{dp_T} = A \int dx f(x) x m_T K_1 \left(\frac{m_T \cosh \rho}{T_{fo}} \right) \times I_0 \left(\frac{p_T \sinh \rho}{T_{fo}} \right), \quad (2)$$

where $x = r/R$ and $\rho = \tanh^{-1}(\beta_T r/R)$, with transverse flow velocity β_T and freezeout temperature T_{fo} being the free parameters of the fit. The normalization constant A is also a free parameter but it does not affect the spectral shapes.

This equation considers all particles produced in all states of the fireball evolution. However, as prescribed in [9], one can make certain adjustments to account for the nature of cluster particles, such as deuterons. The quantum mechanical corrections affect only the normalization constant A and not the spectral shapes, therefore they have no effect on determining β_T and T_{fo} . Various factors of two come into play and most of them cancel. The one thing that changes is that the spatial distribution function, written above as $f(x)$, is squared. In the case of a Gaussian density profile, this has the effect of narrowing the distribution. In the case of a flat, or box, density profile, this has no effect.

In previous studies, blastwave fits using a Gaussian density profile have been successfully used to describe produced hadron spectra [3]. It should be noted, however, that

the Gaussian density profile produces the same m_T slope for protons and deuterons [9] which is not observed in the data. In this study, we fitted the $\pi/K/p$ spectra and used the extracted parameters to predict the spectral shape for the deuterons. As expected, the Gaussian density profile did not reproduce the deuteron spectra, thus we performed a fit using a box density profile. Figure 4 shows the fit results using a box profile for p_T spectra, in the 0–10% centrality bin. As seen in Fig. 4, the results of this fit do not describe the deuteron spectra well. In the next step a different (independent) fit for the deuterons is used. Figure 5 shows the same data with the separate deuteron fit, and the agreement is much better. Our results indicate that within this model that the deuterons do not freezeout contemporaneously with the produced hadrons. However, one should keep in mind that this is a simplistic model, and a more detailed description of the dynamics is necessary to fully understand the freezeout conditions.

Fig. 4 Blastwave fits for positive particles (*left*) and negative particles (*right*) using the same fit parameters for deuterons as all produced hadrons. The $\pi/K/p$ data are taken from [3]

Fig. 5 Blastwave fits for positive particles (*left*) and negative particles (*right*) using separate fit parameters for deuterons and produced hadrons. The $\pi/K/p$ data are taken from [3]

3.3 Coalescence parameter

The invariant deuteron yields can be related to the primordial nucleon yields as [10]:

$$E_d \frac{d^3 N_d}{dp_d^3} \Big|_{p_d=2p_p} = B_2 \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^2, \quad (3)$$

where B_2 is the (two-nucleon) coalescence parameter. This relation assumes that the neutron and proton have identical phase space densities. The proton spectra from [3] in conjunction with the deuteron spectra presented here are used to determine B_2 as a function of p_T and N_{part} .

Figure 6 shows B_2 as a function of p_T for the various centrality classes. For all centrality classes, B_2 increases as a function of p_T . This is consistent with an expanding source due to position-momentum correlations, which lead to a higher coalescence probability at higher momentum. Also, notice that the centrality classes line up nicely on top of one another, with most central at the bottom and most peripheral at the top. This is because in the most central collisions the source is the largest, and so the average separation between the nucleons is the largest, and therefore the probability of coalescence is at a minimum.

The coalescence parameter can also be used to determine the source size at freeze-out. Thermodynamic models [1, 2] predict that B_2 scales linearly with the inverse of the effective volume V_{eff} . In Fig. 7, $1/B_2$ is plotted as a function of N_{part} for two fixed p_T bins. The data show a linear rise of $1/B_2$ as a function of N_{part} . Since bulk particle production also goes as N_{part} , this measurement has the remarkable implication that freezeout occurs at a constant particle density.

Using the same thermodynamical mode, with a fireball in thermal and chemical equilibrium, we extract a numerical

Fig. 6 Coalescence parameter as a function of transverse momentum in various centrality classes for deuterons (*left*) and antideuterons (*right*). The shaded bands indicate the systematic errors

value for the radius of the source. A Gaussian source density profile was used in order to facilitate comparisons with HBT measurements. Figure 8 shows the radius r as a function of $N_{part}^{1/3}$. The results are in good qualitative and semi-quantitative agreement with the Bertsch-Pratt radius parameter determined from HBT pion-pion correlations reported in [11].

3.4 Particle ratios

As discussed previously, deuterons are formed from protons and neutrons. As such, deuteron measurements can be used to extract certain information on neutron production.

3.4.1 Antideuteron to deuteron yield ratio

The ratio $\bar{d}/d$ can be used to determine $\bar{n}/n$. At first brush, based on the assumption that neutron and proton production are similar, one would expect $\bar{d}/d$ to be consistent with $(\bar{p}/p)^2$. This is in fact the case. We extract

Fig. 7 Inverse coalescence parameter as a function of the number of participants. The shaded bands indicate the systematic errors

Fig. 8 Radius as a function of the cube root of the number of participants. The shaded bands indicate the systematic errors

$\bar{d}/d = 0.47 \pm 0.01$ (statistical) ± 0.05 (systematic). This result is identical to that reported in [5] and is consistent with $(\bar{p}/p)^2 = (0.73 \pm 0.01)^2 = 0.53 \pm 0.01$. Using somewhat more sophisticated considerations, one can use the various particle ratios to determine the respective fugacities and chemical potentials. Because the deuteron chemical potential is simply the sum of the proton and neutron chemical potentials, one can use the already determined proton and deuteron chemical potentials to extract the neutron chemical potential, and in turn use that to calculate the fugacity and obtain $\bar{n}/n = 0.64 \pm 0.01$ [5]. Figure 9 shows the $\bar{d}/d$ ratio for MB events.

3.4.2 Deuteron nuclear modification factor

Nuclear modification factors are used to study partonic energy loss in the QGP. It has been observed [12] that mesons show suppression in all available p_T ranges, whereas baryons begin suppressed but become unsuppressed at intermediate p_T . The nuclear modification factor for the deuteron can be used to estimate that of the neutron. The ratio of the yield of particles in central collisions to the yield of particles in peripheral collisions normalized to the respective number of binary collisions N_{coll} is defined to be R_{CP} . In this study we define the deuteron R_{CP} in the following way:

$$R_{CP} = \frac{Yield_d^{0-20\%}}{Yield_d^{60-92\%}} \frac{\langle N_{coll}^{60-92\%} \rangle}{\langle N_{coll}^{0-20\%} \rangle} \quad (4)$$

It is expected that, as a baryon, the neutron should have a similar R_{CP} to that of the proton, but of course this needs to be verified. The deuteron R_{CP} can be used to check this. Figure 10 shows the deuterons R_{CP} . The deuteron p_T has been divided by 2 ($d_{p_T} = 2p_{p_T}$) to facilitate the comparison based on the momentum of the primordial nucleon.

Fig. 9 Ratio of antideuteron to deuteron yield as a function of transverse momentum. The shaded bands are the systematic errors

Fig. 10 Nuclear modification parameter for deuterons and antideuterons, compared to proton data from [3]. Deuteron p_T is divided by 2 to facilitate comparison. The shaded bands on the deuteron data are the systematic errors. The shaded magenta band indicates the systematic error on the proton data

Quite surprising is the result that the maximum of the R_{CP} reaches a value of well in excess of 1. One can make a guess for what the deuteron R_{CP} should be based on the assumption made for (3). If we rewrite the deuteron R_{CP} in terms of that of the proton, we get

$$R_{CP}^{deuteron} = \frac{B_2^{0-20\%}}{B_2^{60-92\%}} (R_{CP}^{proton})^2 \frac{\langle N_{coll}^{0-20\%} \rangle}{\langle N_{coll}^{60-92\%} \rangle}. \quad (5)$$

Noting that B_2 is inversely proportional to N_{part} , this can be rewritten as

$$R_{CP}^{deuteron} = \frac{\langle N_{part}^{60-92\%} \rangle}{\langle N_{part}^{0-20\%} \rangle} (R_{CP}^{proton})^2 \frac{\langle N_{coll}^{0-20\%} \rangle}{\langle N_{part}^{60-92\%} \rangle}. \quad (6)$$

Finally, recognizing that for peripheral collisions N_{coll} and N_{part} are roughly equal, while for central collisions N_{coll} is greater than N_{part} by roughly a factor of 3, we get

$$R_{CP}^{deuteron} \approx 3(R_{CP}^{proton})^2. \quad (7)$$

4 Conclusion

We have presented various measurements of deuterons and antideuterons produced in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These measurements have extended reach and finer binning in p_T and more centrality classes than previous studies. The p_T and m_T spectra and $\langle p_T \rangle$ vs. N_{part} results are consistent with radial flow considerations. The results from using a simple blastwave hydrodynamics model to fit the spectra suggest that the deuterons do not freeze-out contemporaneously with produced hadrons. The coalescence parameter goes inversely to N_{part} , which implies

that freezeout occurs at a common particle density. The antideuteron to deuteron ratio and deuteron nuclear modification factor infer that neutron production is similar to proton production.

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