Study of production of (anti)deuteron observed in Au+Au collisions at $\sqrt{s_{NN}}=14.5, 62.4$ and 200 GeV

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Abstract

Transverse momentum distributions of deuterons and anti-deuterons in Au+Au collisions at $\sqrt{s_{NN}}=14.5, 62.4$ and 200 GeV with different centrality are studied in the framework of the multi-source thermal model. Transverse momentum spectra are conformably and approximately described by the Tsallis distribution. The dependence of parameters (average transverse momenta, effective temperature and entropy index) on event centrality are obtained. It is found that the parameters increase with increase of the average number of particles involved in collisions, which reveals the nuclear stopping degree increases with collision centrality.

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I. INTRODUCTION

The study of strongly interacting matter at extreme temperatures and densities is provided a chance by heavy-ion collisions at ultra-relativistic energies \(^{1-5}\). The production mechanism of nuclei in ultra-relativistic heavy ion collisions deserves more investigation since it may give important message on the quantum chromodynamics (QCD) phase transition from quark-gluon plasma (QGP) to hadron gas (HG) \(^{6,7}\). The RHIC is scheduled to run at the energies which are around the critical energy of phase transition from hadronic matter to QGP \(^{8}\). The theoretical study of nuclei and anti-nuclei has been undertaken for many years, for example the thermal model and coalescence model \(^{9-13}\). In particular, the study of transport phenomena is major important to the understanding of many fundamental properties \(^{14}\). The spectra of transverse momentum of particles produced in high energy collisions are of high interest as soon as they provide us with an important information of the kinetic freeze-out state of the interacting system \(^{15}\). At the stage of kinetic freeze-out, the effective temperature is not a real temperature, and it describes the sum of excitation degree of the interacting system and the effect of transverse flow \(^{16}\).

In this paper, using the Tsallis distribution \(^{17-19}\) in the multisource thermal model to simulate the transverse momentum distributions of (anti-)deuterons in Au+Au collisions at RHIC, we compare them with experiment data taken from the STAR Collaboration \(^{20}\). The main purpose of this work is to extract the information on effective temperature, because it allows us to extract the kinetic freeze-out temperature.

II. THE MODEL AND METHOD

The model used in the present work is the multisource thermal model \(^{21-23}\). In this model, many emission sources are formed in high-energy nucleus-nucleus collisions. The different distributions can describe the emission sources and particle spectra, such as the Tsallis distribution, the standard (Boltzmann, Fermi-Dirac and Bose-Einstein) distributions, the Tsallis+standard distributions \(^{24-29}\), the Erlang distribution \(^{21}\), etc. The Tsallis distribution can be described by two or three standard distribution.

The experimental data of the transverse momentum spectrum of the particles are fitted by using the Tsallis distribution which can describe the temperature fluctuation in a few
sources to give an average value. The Tsallis distribution has many function forms [17–19, 24–31].

In the rest frame of a considered source, we choose a simplified form of the joint probability density function of transverse momentum ($p_T$) and rapidity ($y$) [8],

$$f(p_T, y) \propto \frac{d^2N}{dydp_T} = \frac{gV}{(2\pi)^2} p_T \sqrt{p_T^2 + m_0^2} \cosh y \times [1 + \frac{q-1}{T}(\sqrt{p_T^2 + m_0^2} \cosh y - \mu)]^{-\frac{q}{q-1}}. \quad (1)$$

Here, $N$ is the particle number, $g$ is the degeneracy factor, $V$ is the volume of emission sources, $m_0$ is the rest mass of the studied particle, $T$ is the temperature which describes averagely a few sources (local equilibrium states), $q$ is the entropy index which describes the degree of non-equilibrium among different states, $\mu$ is the chemical potential which is related to $\sqrt{s_{NN}}$ [32]. In the RHIC energy region, $\mu$ is approximately zero. We can extract the values of $T$, $q$ and $V$ from reproducing the particle spectra, where $T$, $q$ are fitted independently for the studied particle, and $V$ is related to other parameters.

The Monte Carlo distribution generating method is used to obtain $p_T$. Let $r_1$ denote the random numbers distributed uniformly in $[0, 1]$. A series of values of $p_T$ can be obtained by

$$\int_0^{p_T} f_{p_T}(p_T)dp_T < r_1 < \int_0^{p_T+dp_T} f_{p_T}(p_T)dp_T. \quad (2)$$

Here, $f_{p_T}$ is the transverse momentum probability density function which is an alternative representation of the Tsallis distribution as follows:

$$f_{p_T}(p_T) = \frac{1}{N} \frac{dN}{dp_T} = \int_{y_{min}}^{y_{max}} f(p_T, y) dy. \quad (3)$$

where $y_{max}$ and $y_{min}$ are the maximum and minimum rapidity, respectively.

Under the assumption of isotropic emission in the source rest frame, we use the Monte Carlo method to acquire the polar angle:

$$\theta = 2\arcsin \sqrt{r_2}. \quad (4)$$

Thus, we can obtain a series of values of momentum and energy due to the momentum $p = \frac{p_T}{\sin \theta}$ and the energy $E = \sqrt{p^2 + m_0^2}$. Therefore, the corresponding values of rapidity can be obtained according to the definition of rapidity.

### III. RESULTS AND DISCUSSION

#### A. Transverse momentum spectra

Fig. 1 demonstrates mid-rapidity ($|y|<0.3$) transverse momentum spectra for deuterons
FIG. 1: Deuterons transverse momentum spectra in Au+Au collisions at \( \sqrt{s_{NN}} = 14.5 \) GeV for 0–10%, 10–20%, 20–40%, 40–60% and 60–80% centralities. Calculations are shown by the solid lines. Experimental data taken from the STAR Collaboration \(^\text{[20]}\) are represented by the symbols.

In Au+Au collisions at \( \sqrt{s_{NN}} = 14.5 \) GeV for 0–10%, 10–20%, 20–40%, 40–60% and 60–80% centralities. The symbols represent the experimental data of STAR Collaboration \(^\text{[20]}\). The solid lines are our calculated results fitted by using the Tsallis distribution based on eq. (1) at mid-rapidity. The values of the related parameters \( T, q \) are given in Table 1 along with the \( \chi^2/dof \) (\( \chi^2 \) and number of degree of freedom). It is found that the calculations of the Tsallis distribution are in keeping with the experimental data well.

In Fig. 2, Fig. 3, the curves and symbols are similar to Fig. 1. Fig. 2 demonstrates mid-rapidity (\( |y| < 0.3 \)) transverse momentum spectra for deuterons in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV for 0–10%, 10–20%, 20–40%, 40–60% and 60–80% centralities. The values of the related parameters \( T, q \) are given in Table 2 and 3 along with the \( \chi^2/dof \) (\( \chi^2 \) and number of degree of freedom). It is found that the calculations of the Tsallis distribution are in keeping with the experimental data well.

In Fig. 4, Fig. 5, Fig. 6 (anti-deuterons), the curves and symbols are similar to Fig. 1. One
FIG. 2: Deuterons transverse momentum spectra in Au+Au collisions at $\sqrt{s_{NN}}=62.4$ GeV for 0 – 10%, 10 – 20%, 20 – 40%, 40 – 60% and 60 – 80% centralities. Calculations are shown by the solid lines. Experimental data taken from the STAR Collaboration are represented by the symbols.

one can see that the calculations also can describe approximately the experimental data of anti-deuterons with different centrality intervals of event. The values of the related parameters $T, q$ are given in Table 1, 2 and 3.

B. Average transverse momenta

Fig. 7 presents the centrality dependence of deuterons and anti-deuterons average transverse momenta ($\langle p_T \rangle$) at mid-rapidity ($|y|<0.3$) for $\sqrt{s_{NN}}=14.5, 62.4$ and 200 GeV. The hollow symbols are the experiment data taken from the Fig. 1-6, and the solid symbols are the calculations of the Tsallis distribution. One sees in this figure that the calculations can describe the experimental data well in the range of the errors permitted. For deuterons, the values of average transverse momenta in the different incident energy get closer with decrease of centrality percentage. It has indicated that the nuclear stopping degree increases
FIG. 3: Deuterons transverse momentum spectra in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV for $0 - 10\%$, $10 - 20\%$, $20 - 40\%$, $40 - 60\%$ and $60 - 80\%$ centralities. Calculations are shown by the solid lines. Experimental data taken from the STAR Collaboration are represented by the symbols.

TABLE I: Values of $T$, $q$, and $\chi^2/dof$ corresponding to the curves in figs. 1 and 4.

| Figure | Type 1 | Type 2 | $T$ (GeV) | $q$        | $\chi^2/dof$ |
|--------|--------|--------|-----------|------------|--------------|
| Fig. 1 | d      | 0-10%  | $0.507 \pm 0.028$ | $1.205 \pm 0.159$ | 0.099        |
|        |        | 10-20% | $0.487 \pm 0.022$ | $1.185 \pm 0.158$ | 0.055        |
|        |        | 20-40% | $0.447 \pm 0.044$ | $1.165 \pm 0.109$ | 0.055        |
|        |        | 40-60% | $0.387 \pm 0.041$ | $1.105 \pm 0.076$ | 0.110        |
|        |        | 60-80% | $0.347 \pm 0.011$ | $1.005 \pm 0.009$ | 1.136        |
| Fig. 4 | $\bar{d}$ | 0-10%  | $0.507 \pm 0.001$ | $1.205 \pm 0.001$ | 0.388        |
|        |        | 10-20% | $0.487 \pm 0.001$ | $1.165 \pm 0.001$ | 0.268        |
|        |        | 20-40% | $0.447 \pm 0.001$ | $1.145 \pm 0.001$ | 0.376        |
|        |        | 40-60% | $0.387 \pm 0.001$ | $1.055 \pm 0.001$ | 0.619        |
|        |        | 60-80% | $0.347 \pm 0.001$ | $1.025 \pm 0.001$ | 1.006        |
FIG. 4: Anti-deuterons transverse momentum spectra in Au+Au collisions at $\sqrt{s_{NN}}=14.5$ GeV for $0-10\%$, $10-20\%$, $20-40\%$, $40-60\%$ and $60-80\%$ centralities. Calculations are shown by the solid lines. Experimental data taken from the STAR Collaboration are represented by the symbols.

TABLE II: Values of $T$, $q$, and $\chi^2/dof$ corresponding to the curves in figs. 2 and 5.

| Figure | Type 1 | Type 2 | T (GeV)    | q           | $\chi^2/dof$ |
|--------|--------|--------|------------|-------------|--------------|
| Fig. 2 | d      | 0-10%  | 0.607 ± 0.001 | 1.215 ± 0.057 | 0.052        |
|        |        | 10-20% | 0.567 ± 0.001 | 1.195 ± 0.042 | 0.073        |
|        |        | 20-40% | 0.527 ± 0.003 | 1.175 ± 0.023 | 0.083        |
|        |        | 40-60% | 0.507 ± 0.004 | 1.135 ± 0.011 | 0.138        |
|        |        | 60-80% | 0.487 ± 0.004 | 1.045 ± 0.004 | 0.260        |
| Fig. 5 | $\bar{d}$ | 0-10%  | 0.607 ± 0.003 | 1.215 ± 0.002 | 1.430        |
|        |        | 10-20% | 0.567 ± 0.001 | 1.195 ± 0.005 | 1.402        |
|        |        | 20-40% | 0.527 ± 0.001 | 1.175 ± 0.004 | 1.791        |
|        |        | 40-60% | 0.507 ± 0.001 | 1.135 ± 0.002 | 1.649        |
|        |        | 60-80% | 0.487 ± 0.001 | 1.035 ± 0.001 | 2.917        |
FIG. 5: Anti-deuterons transverse momentum spectra in Au+Au collisions at $\sqrt{s_{NN}}=62.4$ GeV for 0 – 10%, 10 – 20%, 20 – 40%, 40 – 60% and 60 – 80% centralities. Calculations are shown by the solid lines. Experimental data taken from the STAR Collaboration are represented by the symbols.

TABLE III: Values of $T$, $q$, and $\chi^2$/dof corresponding to the curves in figs. 3 and 6.

| Figure | Type | Type 2 | $T$ (GeV) | $q$     | $\chi^2$/dof |
|--------|------|--------|-----------|---------|--------------|
| Fig. 3 | d    | 0-10%  | 0.667 ± 0.005 | 1.235 ± 0.020 | 0.080 |
|        |      | 10-20% | 0.647 ± 0.003 | 1.215 ± 0.016 | 0.040 |
|        |      | 20-40% | 0.627 ± 0.004 | 1.195 ± 0.034 | 0.005 |
|        |      | 40-60% | 0.607 ± 0.001 | 1.175 ± 0.005 | 0.057 |
|        |      | 60-80% | 0.547 ± 0.002 | 1.045 ± 0.003 | 0.658 |
| Fig. 6 | \(\bar{d}\)| 0-10%  | 0.667 ± 0.001 | 1.232 ± 0.005 | 0.066 |
|        |      | 10-20% | 0.647 ± 0.001 | 1.205 ± 0.005 | 0.030 |
|        |      | 20-40% | 0.627 ± 0.001 | 1.195 ± 0.004 | 0.040 |
|        |      | 40-60% | 0.607 ± 0.001 | 1.175 ± 0.002 | 0.052 |
|        |      | 60-80% | 0.547 ± 0.001 | 1.045 ± 0.001 | 0.148 |
FIG. 6: Anti-deuterons transverse momentum spectra in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV for 0 – 10%, 10 – 20%, 20 – 40%, 40 – 60% and 60 – 80% centralities. Calculations are shown by the solid lines. Experimental data taken from the STAR Collaboration [20] are represented by the symbols.

with collision centrality.

C. Dependence of parameters on number of participating nucleons

Fig. 8 and Fig. 9 give the change trends of parameters ($T$ and $q$) with the average number of participants for deuterons and anti-deuterons produced in Au+Au collision at mid-rapidity ($|y|<0.3$) for $\sqrt{s_{NN}}=14.5$, 62.4 and 200 GeV. The symbols represent the parameter values extracted from Fig. 1-3 and Fig. 4-6 and listed in Table 1-3.

From Fig. 8 and Fig. 9, we can see that the values of parameters increase with decrease of centrality percentage. It can be explained by the more nuclei involved in the collision, the more intense the collision, the higher the temperature of the collision center, and the higher the corresponding effective temperature. The dependence of effective temperature on collision energy increases with the increase of collision energy. Under the same collision parameters, the entropy increases with the increase of collision energy, indicating that the
FIG. 7: Deuterons and anti-deuterons average transverse momenta ($\langle p_T \rangle$) as a function of $\langle N_{\text{part}} \rangle$ at mid-rapidity ($|y|<0.3$) for $\sqrt{s_{NN}}=14.5$, 62.4 and 200 GeV. Calculations are shown by the solid symbols. Experimental data taken from the Fig. [1-6] are represented by the hollow symbols.

higher the collision energy is, the more different microscopic states the particle may have, and the less time it takes to form the final state particle. The kinetic freeze-out temperature can be extracted from the effective temperature, the correlation between Kinetic freeze-out temperature and centrality will be focused in the future work.

IV. SUMMARY AND OUTLOOK

In summary, we have presented the transverse momentum distributions of (anti-)deuterons in Au+Au collisions at RHIC for 0 – 10%, 10 – 20%, 20 – 40%, 40 – 60% and 60 – 80% centralities. The Tsallis distribution in the multisource thermal model has been used in all calculations. Based on this model, we have investigated transverse momentum distributions of (anti-)deuterons, and the law between effective temperature and entropy with the centrality of collision. In conclusion, it can give the agreement between calculation results and the experimental data. The effective temperature and the entropy
FIG. 8: Dependence of $T$ on the average number of participants for deuterons and anti-deuterons in events with different centrality intervals. The symbols represent the parameter values listed in Table 1, 2 and 3.

index extracted from $d$ and $\bar{d}$ increase with decrease of centrality percentage at the same incident energy. And at the same collision centrality, they increase with increase of incident energy. But the Kinetic freeze-out temperature and the evolution of time during the collision have yet to be studied in depth.

**Data Availability**

The data used to support the findings of this study are included within the article and are cited at relevant places within the text as references.

**Conflict of Interests**

The author declare that there is no conflict of interests regarding the publication of this paper.
FIG. 9: Dependence of $q$ on the average number of participants for deuterons and anti-deuterons in events with different centrality intervals. The symbols represent the parameter values listed in Table 1, 2 and 3.

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