Rapidity density distributions of identified particles and light nuclei in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV using Boltzmann-Gibbs thermodynamics and its implication

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Abstract

We investigate the rapidity density distributions of identified particles and light nuclei produced in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV, measured by the STAR experiment at the BNL Relativistic Heavy Ion Collider (RHIC), using a fireball model with Boltzmann-Gibbs thermodynamics. The fireball model provides a satisfactory description of the experimental data for identified mesons and baryons across all centrality classes. This overall consistency demonstrates that the fireball model with Boltzmann-Gibbs thermodynamics offers a coherent framework for characterizing the system' s thermal and longitudinal dynamical properties in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. While the model reasonably reproduces the rapidity density distributions of deuterons (d) produced in central and semi-central collisions, it fails to reproduce their rapidity density distributions in peripheral collisions, as well as those for heavier light nuclei with $A \geq 3$. These results imply that light nuclei produced in high-energy heavy-ion collisions originate from a different particle production mechanism than the identified hadrons, which indirectly supports the nucleon coalescence mechanism for light nuclei production.

Full Text

Preamble

Rapidity density distributions of identified particles and light nuclei in Au+Au collisions at

3 GeV using Boltzmann-Gibbs thermodynamics and its implication

sN N = Xi-Yao Guo,1 Zhen Xie,1 Jun-Qi Tao,2, 3 Hua Zheng,1, ∗ Wen-Chao Zhang,1 Li-Lin Zhu,4 Xing-Quan Liu,5 Zhi-Guang Tan,6 Xiao-Zhi Bai,2 and Dai-Mei Zhou2 1School of Physics and Information Technology, Shaanxi Normal University, Xi' an 710119, China 2Key Laboratory of Quark Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China 3School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen (CUHK-Shenzhen), Guangdong 518172, China 4College of Physics, Sichuan University, Chengdu 610064, China 5Key Laboratory of Radiation Physics and Technology of the Ministry of Education, Institute of Nuclear Science and Technology, Sichuan University, Chengdu 610064, China 6School of Electronic Information and Electrical Engineering, Changsha University, Changsha 410003, China We investigate the rapidity density distributions of identified particles and light nuclei produced in Au+Au sN N = 3 GeV, measured by the STAR experiment at the BNL Relativistic Heavy Ion Collider collisions at (RHIC), using a fireball model with Boltzmann-Gibbs thermodynamics. The fireball model provides a satisfac- tory description of the experimental data for identified mesons and baryons across all centrality classes. This overall consistency demonstrates that the fireball model with Boltzmann-Gibbs thermodynamics offers a coher- ent framework for characterizing the system' s thermal and longitudinal dynamical properties in Au+Au colli- sN N = 3 GeV. While the model reasonably reproduces the rapidity density distributions of deuterons sions at (d) produced in central and semi-central collisions, it fails to reproduce their rapidity density distributions in peripheral collisions, as well as those for heavier light nuclei with A $\geq$ 3. These results imply that light nuclei produced in high-energy heavy-ion collisions originate from a different particle production mechanism than the identified hadrons, which indirectly supports the nucleon coalescence mechanism for light nuclei production.

Keywords: Boltzmann-Gibbs distribution, rapidity density distribution, transverse momentum distribution, particle production mechanism, fireball model

INTRODUCTION

Quantum chromodynamics (QCD) predicts that under ex- tremely high temperatures and densities, strongly interacting nuclear matter undergoes a transition to a deconfined phase with quarks and gluons as degrees of freedom, known as the quark-gluon plasma (QGP) [1-4]. High energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) provide a unique oppor- tunity to create and study its properties. Since the collision processes can not be measured directly, the final-state observ- ables are primarily used to infer the dynamics and proper- ties of the system created in heavy-ion collisions [5-7]. The transverse momentum (pT) spectra and rapidity density dis- tributions (dN dy) of particles are two fundamental observables that provide essential insights into the thermodynamic and dynamic evolution of the system. They are widely used to validate theoretical models, constrain their parameters, and elucidate particle production mechanisms [8–21].

To understand the physics occurring in the collision sys- tem, both extensive statistics (Boltzmann-Gibbs distribution) and non-extensive statistics (Tsallis distribution) are widely used in the literature [13, 22–29]. Extensive statistics, such as hydrodynamics model based on the local equilibrium assumption [20, 30–32] and the Thermal-Fist model [33–35], have achieved great success in describing the results ∗ Corresponding author: zhengh@snnu.edu.cn from heavy-ion collisions. However, considering the ex- pansion dynamics of the collision system and the fact that the Boltzmann-Gibbs distribution can only describe particle transverse momentum spectra in the low pT range, re- searchers have also adopted non-extensive statistics, which has successfully described the results from heavy-ion colli- sions [36–40].

In the Tsallis distribution, a non-extensive parameter q is introduced to characterize the degree of non- equilibrium in the system. When q → 1, the Tsallis distribu- tion reduces to the Boltzmann-Gibbs distribution which was discussed in the textbook by Tsallis in 1988 [41].

Over the past two decades, the STAR Collaboration at the RHIC has conducted the Beam Energy Scan (BES) program using Au+Au collisions to probe the QCD phase diagram.

Many studies in the literature have analyzed the pseudora- pidity density distributions and transverse momentum spectra of charged particles to extract information about the collision system, employing a variety of models, such as HIJING [42], AMPT [43], SMASH [44], PACIAE [45–47], hydrodynamic models [31, 32], fireball model [22, 48], etc.. In our previ- ous works [27–29], we applied the fireball model based on Tsallis thermodynamics to systematically study the pseudora- pidity density distributions and transverse momentum spectra of charged particles in pp, pA and AA collisions. Our re- sults demonstrated that the fireball model provides a universal framework for describing particle production in high energy physics. Notably, it successfully predicted the pseudorapidity density distributions of charged particles produced in pp colli- sN N = 5.02 sions at TeV [27, 28]. Recent measurements by the STAR Collabora- s = 13 TeV and Pb+Pb collisions at tion have provided high-precision data on identified hadrons sN N = 3 GeV [49–and light nuclei in Au+Au collisions at 51]. In particular, these measurements provide transverse mo- mentum spectra and rapidity density distributions of identi- fied particles and light nuclei simultaneously. This motivates us to examine the fireball model further and extract the under- lying physics of these collisions.

For Au+Au collisions at sN N = 3 GeV, the transverse momentum spectra of produced identified particles are con- centrated in the low-pT region due to energy conservation, with most values below about 2 GeV/c. Fitting these spectra with Tsallis distribution yields a non-extensive parameter q very close to 1. Thus for practical reasons, we adopt the fire- ball model with Boltzmann-Gibbs distribution, similar to the approach used in Cleymans' works [52, 53]. Unlike previous investigations, we extend the fireball model to describe both identified particles and light nuclei. This extension allows us to explore the implication of the fireball model for the pro- duction mechanism of light nuclei, a topic that is still under debate.

The paper is organized as follows. In Sec. II, the fire- ball model with Boltzmann-Gibbs thermodynamics is briefly introduced. The model results are shown and discussed in Sec. III. First, the transverse momentum spectra of parti- cles are fitted individually using Boltzmann-Gibbs distribu- tion to extract the effective temperature T at different cen- trality classes. Then the fireball model is used to describe the rapidity density distributions of identified particles and light nuclei, respectively. The implication for the production mechanism of light nuclei is also discussed. A brief summary is drawn in Sec. IV.

II. THEORETICAL FRAMEWORK AND FORMULAS The transverse momentum distribution of particles emitted from a thermal source is given by [36]: dpTdy mT cosh y (2π)3 (cid:18) mT cosh y − µ (cid:19) where V is the volume, g is the degeneracy of the particle states, mT = (cid:112)p2 0 is the transverse mass, m0 is the particle rest mass, µ is the chemical potential, and T is the effective temperature. At mid-rapidity (y = 0), Eq. (1) can be rewritten as [8, 54]:

T + m2 along the rapidity axis, described by a distribution function ν(yf) [56, 57]. For symmetric collision systems, the fireball distribution function ν(yf) is typically assumed to be the sum of two Gaussian functions: ν(yf) = (cid:20) (cid:20) (cid:21) (yf − y0)2 (yf + y0)2 (cid:21) where y0 and σ are free parameters corresponding to the cen- tral position and width of the fireball distribution, respec- tively. These parameters are determined from experimental data. The collective contributions of these fireballs determine the transverse momentum and rapidity density distributions of the final-state particles [56–58]. Therefore, the particle trans- verse momentum distribution can be expressed as: pTdpTdy (cid:90) ∞ (cid:20) ν(yf) mT cosh(y − yf) (2π)2 (cid:21) mT cosh(y − yf) dyf , × exp where N is the total particle multiplicity, and A is a normal- ization constant that ensures conservation of the total particle multiplicity, i.e., (cid:90) ∞ (cid:90) ∞ pTdpTdy pTdpTdy = N.

The rapidity density distribution dN dy of particles is obtained by integrating Eq. (4) over the transverse momentum pT [56, (cid:90) ∞ dyf ν(yf) (cid:90) ∞ pTdpT mT cosh(y − yf) (2π)2 (cid:20) × exp mT cosh(y − yf) (cid:21) Equation (6) can be integrated analytically over the transverse momentum, yielding: (cid:90) ∞ × (cid:2)m2 dyf ν(yf) exp (2π)2 0 + 2m0T sech(y − yf) + 2T 2sech2(y − yf)(cid:3) . m0 cosh(y − yf) (cid:20) (cid:21) dpTdy (2π)3 mT exp (cid:16) (cid:17) Here, the factor containing the chemical potential and the vol- ume V are absorbed into V ′. By fitting the particle transverse momentum spectrum using Eq. (2), the effective temperature T can be extracted. This parameter characterizes the average kinetic energy of the final-state particles [55].

In the framework of the fireball model with Boltzmann- Gibbs thermodynamics, the system is assumed to consist of an ensemble of fireballs in local thermal equilibrium.

Multiple fireballs with different rapidities yf are distributed Once the effective temperature T is determined for a given centrality class, Eq. (7) can be used to reproduce the experi- mental rapidity density distribution data of the particles.

III. RESULTS AND DISCUSSION As mentioned in Sec. II, the effective temperature param- eter T is extracted by fitting the particle transverse momen- tum spectrum at mid-rapidity for a given centrality class using Fig. 1 [Figure 1: see original paper]. (Color online) Transverse momentum spectra of identified particles (K −, K 0 = 3 GeV. The curves represent the fitting results using Eq. (2). Experimental data are taken from Refs.[49-51].

S, p, ϕ, Λ, Ξ−, d) produced in Au+Au collisions at 0.40.50.60.70.80.9)c (GeV/Tp4-103-102-101-10-2) (GeV/c)ydTpdTpp/(2N2d0-10%10-40%40-60%-K 0.20.40.60.81.01.21.4)c (GeV/Tp5-104-103-102-101-10010-2) (GeV/c)ydTpdTpp/(2N2d0-10%10-20%20-30%30-40%40-60%60-80%0SK0.60.81.01.21.41.61.82.02.2)c (GeV/Tp4-103-102-101-10010110210-2) (GeV/c)ydTpdTpp/(2N2d0-10%10-20%20-40%40-80%p0.70.80.91.01.11.21.31.41.5)c (GeV/Tp6-105-104-103-102-10-2) (GeV/c)ydTpdTpp/(2N2d0-10%10-40%40-60%f0.40.60.81.01.21.41.61.82.0)c (GeV/Tp6-105-104-103-102-101-10010110-2) (GeV/c)ydTpdTpp/(2N2d0-10%10-20%20-30%30-40%40-60%60-80%L0.81.01.21.41.61.8)c (GeV/Tp6-105-104-103-102-10-2) (GeV/c)ydTpdTpp/(2N2d0-10%10-40%-X1.52.02.53.03.5)c (GeV/Tp7-106-105-104-103-102-101-10010110-2) (GeV/c)ydTpdTpp/(2N2d0-10%10-20%20-40%40-80%d

1 Eq. (2), based on data measured by the STAR Collaboration sN N = 3 GeV [49-51]. The ex- in Au+Au collisions at tracted T value is then substituted into Eq. (7) to study the corresponding rapidity density distribution of the identified particle or light nucleus. The experimental data include the transverse momentum spectra and rapidity density distribu- tions of identified particles (i.e., K −, K 0 S, p, ϕ, Λ, and Ξ−) and light nuclei (i.e., deuteron (d), triton (t), 3He, and 4He) across different centrality classes.

Figure 1 shows the transverse momentum spectra of iden- S, p, ϕ, Λ, Ξ−, and d produced tified particles, i.e., K −, K 0 sN N = 3 GeV. The experimental in Au+Au collisions at data points are shown with distinct markers (see the legend), and the solid lines represent the fitting results obtained using Eq. (2) with the least \$ \$2 method. Note that the transverse momentum ranges vary across different particle species. It is observed that the Boltzmann-Gibbs distribution in Eq. (2) reproduces the experimental data well within the measured pT range for all particle species and centrality classes investi- gated. The corresponding \$ \$2/ndf values are listed in Table 1 .

Similar fitting results are obtained for light nuclei with mass number A $\geq$ 3, i.e., t, 3He, and 4He, which are not shown here to save space. Their fit parameters have been listed in Table 1 for completeness.

Figure 2 [Figure 2: see original paper] presents the centrality dependence of the effective temperature T extracted for identified particles (K −, K 0 S, p, ϕ, Λ, Ξ−) and light nuclei (d, t, 3He, and 4He). The values of T exhibit a clear centrality dependence, decreasing mono- tonically from central to peripheral collisions, as indicated by the solid lines obtained from linear fits. This trend reflects the reduced energy density and weaker collective expansion in less overlapping systems. Such behavior is well known and is consistent with the centrality dependence of the aver- age transverse momentum of identified particles observed at this energy [49]. Central collisions involve a larger number of participating nucleons and higher energy deposition than peripheral collisions, leading to more frequent collisions and enhanced particle production, which in turn result in a higher effective temperature and average transverse momentum [60].

For Ξ−, its effective temperatures show no significant central- ity dependence within current experimental uncertainties. It is attributed to the limited number of available data points, i.e., only two data points for this case. A decreasing trend of the average transverse momentum of Ξ− with centrality has sN N = 62.4 GeV been observed in Au+Au collisions at [61]. However, this centrality dependence is very weak if only central and semi-central collisions are considered.

Using the effective temperature T extracted from the trans- verse momentum spectra, we employ Eqs. (3) and (7) to study the rapidity density distributions of various particles. Figure 3 [Figure 3: see original paper] shows the rapidity density distributions of identified particles and deuterons for different centrality classes in Au+Au colli- sN N = 3 GeV. Overall, the rapidity density distri- sions at butions of particles are symmetric about y = 0, as the results are presented in the center of mass frame of a symmetric col- lision system Au+Au. Remarkably, the model provides an excellent description of the experimental data for all identi- fied hadrons across the centrality classes. The correspond- Fig. 2. (Color online) The centrality (0 represents the most central collisions) dependence of the effective temperature T of identified sN N = 3 GeV. The solid lines particles in Au + Au collisions at are the linear fit results. ing \$ \$2/ndf values between the model description and exper- imental data are summarized in Appendix A. The shapes and magnitudes of the rapidity density distributions for identified particles agree with the measurements within uncertainties, indicating that the production of these hadrons is well gov- erned by the combined effects of thermal motion and lon- gitudinal expansion in a locally equilibrated source. These distributions exhibit a single-peak structure across most cen- trality classes, with the exception of the 40-60% and 60-80% centralities for protons and the 10-40%, 40-60% and 60-80% centralities for deuterons, which show a valley at y = 0 and two humps at forward and backward rapidities likely but not conclusive. For identified hadrons other than protons, this be- havior arises from nuclear stopping effects. For protons, it is attributed to the interplay between nuclear stopping effects and leading particles from the colliding nuclei [62, 63]. For deuterons, the model reproduces the data reasonably well for central and semi-central collisions (0-10% and 10-40%), but begins to underestimate the yield in peripheral collisions at forward and backward rapidity regions. The differing shapes of the rapidity density distributions may provide insight into the underlying particle production mechanisms.

To further explore the production mechanisms of light nu- sN N = 3 GeV, we investigate clei in Au+Au collisions at the rapidity density distributions of heavier light nuclei, i.e., tritons, 3He and 4He, produced at central collisions, using the fireball model with Boltzmann-Gibbs thermodynamics, as shown in Fig. 4 [Figure 4: see original paper]. The symbols represent experimental data taken from Ref. [51]. From the data, one can see that tritons and 3He are produced more abundantly than 4He, reflecting a mass hierarchy well known in heavy ion collisions. The yield of tritons is larger than that of 3He, despite both be- ing composed of three nucleons. This can be understood by the contribution of net neutrons in the colliding nuclei, which makes it easier to form tritons and results in their higher yield compared to 3He. Similar observations have been reported in UrQMD study of $\pi-$ + W reactions at Plab = 1.7 GeV, while 01020304050607080centrality [%]0.050.100.150.200.250.30(GeV)T-K0SKpfL-XdtHe3He4linear fit

5 sN N = 3 GeV across different centralities.

Fig. 3. The rapidity density distributions of identified particles produced in Au+Au collisions at The symbols are experimental data taken from Refs. [49-51]. The curves are the results from the fireball model with Boltzmann-Gibbs thermodynamics Eqs. (3) and (7). 1.5-1.0-0.5-0.00.51.01.5y0.000.010.020.030.040.050.060.070.08dy/dN0-10%10-40%40-60%-K1.5-1.0-0.5-0.00.51.01.5y0.00.10.20.30.40.50.60.70.80.91.0dy/dN0-10%10-20%20-30%30-40%40-60%60-80%0SK2.0-1.5-1.0-0.5-0.00.51.01.52.0y0102030405060708090100dy/dN0-10%10-40%40-60%60-80%p1.5-1.0-0.5-0.00.51.01.5y0.0000.0050.0100.0150.0200.025dy/dN0-10%10-40%40-60%f1.5-1.0-0.5-0.00.51.01.5y0.00.51.01.52.02.53.0dy/dN0-10%10-20%20-30%30-40%40-60%60-80%L1.5-1.0-0.5-0.00.51.01.5y0.0000.0020.0040.0060.0080.0100.0120.0140.0
10%10-40%-X2.0-1.5-1.0-0.5-0.00.51.01.52.0y0510152025dy/dN0-10%10-40%40-60%60-80%d

6 Table 1. The values of effective temperature T and \$ \$2/ndf are extracted by fitting the transverse momentum spectra of identified particles using Eq. (2) in Au + Au collisions at sN N = 3 GeV.

Particle Centrality 0-10% 10-40% 40-60% 0-10% 10-20% 20-30% 30-40% 40-60% 60-80% 0-10% 10-20% 20-40% 40-80% 0-10% 10-40% 40-60% 0-10% 10-20% 20-30% 30-40% 40-60% 60-80% 0-10% 10-40% 0-10% 10-20% 20-40% 40-80% 0-10% 10-20% 20-40% 40-80% 0-10% 10-20% 20-40% 40-80% 0-10% 10-20% 20-40% 40-80% T (GeV) 0.123 ± 0.0025 0.113 ± 0.0025 0.093 ± 0.0038

0.140 ± 0.0031 0.131 ± 0.0023 0.127 ± 0.0023 0.121 ± 0.0023 0.113 ± 0.0024 0.105 ± 0.0071 0.161 ± 0.0011 0.151 ± 0.0010 0.141 ± 0.0009 0.127 ± 0.0007 0.157 ± 0.0143 0.133 ± 0.0085 0.112 ± 0.0193 0.148 ± 0.0019 0.140 ± 0.0019 0.135 ± 0.0022 0.127 ± 0.0021 0.118 ± 0.0024 0.104 ± 0.0055 0.136 ± 0.0116 0.139 ± 0.0152 0.193 ± 0.0013 0.179 ± 0.0011 0.166 ± 0.0011 0.148 ± 0.0012 0.202 ± 0.0014 0.194 ± 0.0017 0.177 ± 0.0015 0.160 ± 0.0027 0.212 ± 0.0013 0.194 ± 0.0012 0.180 ± 0.0011 0.164 ± 0.0023 0.232 ± 0.0026 0.215 ± 0.0024 0.198 ± 0.0033 0.183 ± 0.0062 $ $2/ndf 5.88/10 4.09/10 3.20/5 1.41/8 3.95/9 1.47/9 1.27/9 2.96/7 1.18/4 39.03/14 26.98/14 19.72/14 6.62/14 0.61/3 2.29/3 0.25/3 19.98/14 11.33/14 4.26/12 4.57/12 6.74/11 2.77/8 0.22/2 0.25/2 71.78/8 50.92/8 17.81/8 2.36/7 59.87/5 32.52/5 18.54/4 4.98/3 90.14/5 56.83/5 31.98/5 8.8/4 23.97/3 12.85/3 4.64/3 0.21/2 the productions of tritons and 3He are found to be similar in $\pi-$ + C reactions at Plab = 1.7 GeV [64], supporting our interpretation. It is observed that the rapidity density distri- butions of the heavier light nuclei increase near $|y| = 0.7$, a feature that can not be described by the fireball model. Due to the same reason, the three-Gaussians function and the mod- ified generalized Gaussian function were used to fit their ra- pidity density distributions in experimental paper [51]. This suggests that the production mechanism of the heavier light nuclei differs from that of baryons and provides indirect sup- port for the nucleon coalescence mechanism [20, 65-68].

IV. CONCLUSION In this paper, we have studied the rapidity density distributions of identified particles and light nuclei for all central- sN N = 3 GeV using a ity classes in Au+Au collisions at fireball model with Boltzmann-Gibbs thermodynamics. The effective temperature T is extracted by fitting the transverse momentum spectra of particles using the Boltzmann-Gibbs distribution. The extracted T values decrease monotonically from central to peripheral collisions and can be described by a linear relation. The model successfully reproduces the ra- pidity density distributions of all identified hadrons from cen- tral to peripheral collisions, indicating that the production of these particles is consistent with emission from a locally ther- malized source undergoing longitudinal expansion. For the APPENDIX A The corresponding $ $2/ndf values between the fireball model description and the experimental data for the rapidity density distributions of various particles are summarized in Table 2 .

Table 2. The $ $2/ndf of the fitting results in Fig. 3.

Particle Centrality 0-10% 10-40% 40-60% 0-10% 10-20% 20-30% 30-40% 40-60% 60-80% 0-10% 10-20% 20-40% 40-80% 0-10% 10-40% 40-60% 0-10% 10-20% 20-30% 30-40% 40-60% 60-80% 0-10% 10-40% 0-10% 10-20% 20-40% 40-80% $ $2/ndf 3.55/17 3.48/17 6.30/17 0.20/13 0.32/13 0.25/13 1.20/13 0.48/13 5.63/11 3.00/17 2.94/17 6.36/17 5.39/17 0.24/5 0.01/5 0.002/5 0.31/15 0.34/15 0.37/15 0.15/15 0.16/15 4.33/15 0.91/5 0.03/5 3.53/17 3.38/17 30.26/17 42.61/17 http://doi.org/10.1016/j.nuclphysa.2016.06.003 [8] R. Gupta, A. Menon, S. Jain, and S. Jena, The The- oretical Description Transverse Momentum Spectra: A Unified Model. Universe 9, 111 (2023).

https://doi.org/10.3390/universe9020111 (STAR Collaboration), Rapid- ity and species dependence of particle production at large sN N = 200 GeV. Phys. Rev. C 76, 054903 (2007). transverse momentum for I. Abelev collisions [9] B. https://doi.org/10.1103/PhysRevC.76.054903 [10] Z. Xie, A.-K. Lei, H. Zheng, W. Zhang, D.-M. Zhou, Z.-L. She, Y.-L. Yan, and B.-H. Sa, Pseudorapidity density distributions of charged particles and transverse-momentum spectra of identi- fied particles in pp collisions in the PACIAE 4.0 model. Phys.

Rev. C 112, 014908 (2025). https://doi.org/10.1103/vfvt-m3dw [11] Z. Xie, A.-K. Lei, H. Zheng, W.-C. Zhang, D.-M. Zhou, Z.- L. She, Y.-L. Yan, and B.-H. Sa, Pseudorapidity dependence of charged-particle production in nonsingle diffractive pp col- Fig. 4. The rapidity density distributions of triton, 3He, and 4He pro- sN N = 3 GeV and 0-10% centrality. duced in Au+Au collisions at The symbols are experimental data taken from Ref. [51]. The curves are the results from the fireball model with Boltzmann-Gibbs ther- modynamics Eqs. (3) and (7). light nucleus d, the model still provides a reasonably good description. However, it fails to describe the rapidity density distributions of heavier light nuclei with mass number $A \geq 3$, i.e., tritons, 3He and 4He. The failure of the thermal fireball model to simultaneously describe both identified hadrons and light nuclei indicates that the production mechanism of light nuclei differs from that of identified particles, i.e., statistical hadronization from thermal sources, providing indirect sup- port for the nucleon coalescence mechanism in the production of light nuclei.

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Note: Figure translations are in progress. See original paper for figures.