Nuclear modification factors of pion and light nuclei in a framework of thermal model

C. S. Zhou,1,2 Y. G. Ma*,1,3 and S. Zhang1

1Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
2University of Chinese Academy of Sciences, Beijing 100049, China
3Shanghai Tech University, Shanghai 200031, China

(Dated: January 20, 2015)

The particle yields and the nuclear modification factor (R_{cp}) for π^±, p(\bar{p}), d(\bar{d}), t(\bar{t}) and ^3He(^4He) are studied in Au + Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV}/c \) based on the blast-wave model and nucleonic coalescence model. The influences of resonance decay on p(\bar{p}) and π yields, p/π-ratio and nuclear modification factors have been discussed. An apparent number-of-constituent-quark scaling of R_{cp} for p(\bar{p}) and π is presented. Similarly, the number-of-nucleon scaling of R_{cp} for p(\bar{p}), d(\bar{d}), t(\bar{t}) and ^3He(^4He) is also addressed.

PACS numbers: 25.75.Gz, 12.38.Mh, 24.85.+p

I. INTRODUCTION

Quantum chromodynamics (QCD) predicts the quark-gluon plasma (QGP) can be produced in ultra-relativistic heavy-ion collisions, such as at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory and Large Hadron Collider (LHC) at CERN, and the energy dependence is thought as one of important observables to study various aspects of the QCD phase diagram in the beam energy scan program at RHIC. Extensive experimental results in Au + Au collisions, including the particle and anti-particle production spectra, the nuclear modification factors (NMF) R_{AA} or R_{cp} of hadrons and baryon-to-meson ratios at \( \sqrt{s_{NN}} = 200 \text{ GeV}/c \) have been reported. Some thermal parameters of the QGP are extracted, such as the chemical freeze-out temperature T_{ch}, the baryon chemical potential \( \mu_B \) and the strangeness chemical potential \( \mu_S \) etc.

Relativistic hydrodynamics and thermal models are widely used to describe particle production. There are many successful models, such as the viscous hydrodynamic model VISH2+1, a multiphase transport (AMPT) model and the blast-wave model etc. For examples, the viscous hydrodynamic model VISH2+1 has successfully described the transverse momentum distributions of π and K. Similar model named HKM coupling with UrQMD for the hadronic scattering stage can also reproduce the yields and distributions of particles such as π, K, and p. The EPOS model aims at describing complete transverse momentum distributions of particles within the same dynamical picture. A multiphase transport (AMPT) model has been reconfigured to reproduce the p_T distribution of charged particles as well as their elliptic flow in Pb + Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). Besides the studies from hydrodynamics or transport models mentioned about, the thermal model has also successfully described the production of particles in heavy-ion collisions with a few parameters such as the chemical freeze-out temperature, the baryon chemical potential, and the fireball volume. From particle ratios, the thermal model can be used to obtain the chemical freeze-out properties, such as the chemical freeze-out temperature T_{ch} as well as the baryon (\( \mu_B \)) and the strangeness (\( \mu_S \)) chemical potential. By fitting the transverse momentum distribution, the blast-wave model has often been used to extract the kinetic freeze-out properties such as the kinetic freeze-out temperature T_{kin} and the radial flow velocity \( \langle \beta_r \rangle \). These thermal models have also been applied in experimental analysis to study the chemical and kinetic freeze-out properties. In addition, the DRAGON model, which stands for DRoplet and hAdron GenerAtOr for Nuclear collisions is a Monte Carlo droplet generator based on the blast-wave model and the THERMINATOR model has also been developed to study the phase-space distribution of produced hadrons at freeze-out stage. The DRAGON model is similar to THERMINATOR model, with the crucial difference that emission from fragments is included. Resonance decay is considered in the DRAGON model.

The nuclear modification factor R_{cp} is a very useful observable for studying the feature of QGP. Extensive studies have been carried out in both experimentally and theoretically. These studies indicate that the NMF, which can be represented either by the modification factor between nucleus-nucleus (AA) collisions and proton-proton (pp) collision R_{AA} or the one between the central collisions and peripheral collisions R_{cp}, is very useful for the study of the quantitative properties of the nuclear medium response when the high speed jet transverses it. In high transverse momentum (p_T) region, NMF is suppressed owing to jet quenching effect in hot-dense matter and thus has become one of the robust evidences on the existence of the Quark-Gluon-Plasma. In lower p_T region, radial flow boosts or the Cronin Effect competes with the quenching effect and enhances the NMF, which has been also demonstrated by the Relativistic Heavy-Ion Collider (RHIC) beam en-
energy scan (BES) project \cite{29}. Recently, the study of nuclear modification factor is also extended to intermediate-energy heavy-ion collisions and the radial flow effect on proton NMF has been quantitatively investigated \cite{30}. Comparing with $p$, $\pi$ and $K$ etc., $R_{cp}$ of light nuclei is not yet addressed. In the present study, obvious differences between the $R_{cp}$ of light nuclei are found for different nucleon number. With the help of the coalescence model \cite{31}, we found an approximate way to fit them by a number-of-nucleon scaling. Such scaling is also tried to be used to fit the $R_{cp}$ of $p$ and $\pi$. By the comparison of the contribution resonance decay for protons and pions, a large fraction of $p$ and $\pi$ produced at RHIC energy originates from resonance decays, especially for the large contributions from resonances at the low $p_T$ part of the $\pi$ spectra \cite{16,32}. Therefore the effect of resonance decay on the $R_{cp}$ needs to be addressed.

II. BLAST-WAVE MODEL

As discussed above, thermal model can describe particle yield by adjusting parameters such as the chemical freeze-out temperature $T_{ch}$, the baryon chemical potential $\mu_B$, the strangeness chemical potential $\mu_S$, and the system volume $V$. On the other hand, one can extract these quantities at chemical freeze-out stage through particle ratios. The particle density of species $i$ can be expressed as \cite{10,20,22}.

$$n_i(T_{ch}, \mu_B, \mu_S) = g_i \int \frac{d^3p}{(2\pi)^3} \left[ \exp \left( \frac{\sqrt{p^2 + m_i^2} - (\mu_B B_i + \mu_S S_i)}{T_{ch}} \right) \mp 1 \right]^{-1}$$

$$= I \left( g_i, \frac{m_i}{T_{ch}} \right) \sum_{n=1}^{\infty} \left( \pm 1 \right)^{n+1} \exp \left( n \frac{(\mu_B B_i + \mu_S S_i)}{T_{ch}} \right),$$

$$I \left( g_i, \frac{m_i}{T_{ch}} \right) = g_i \int \frac{d^3p}{(2\pi)^3} \left[ \sum_{n=1}^{\infty} \left( \pm 1 \right)^{n+1} \exp \left( -n \frac{\sqrt{p^2 + m_i^2}}{T_{ch}} \right) \right], \quad (1)$$

with the upper (lower) sign for bosons (fermions) and $g_i$ being the degeneracy factor. Assuming that the chemical equilibrium condition is satisfied, Eq. (1) essentially determines the fraction of particle species $i$. Within the framework of the blast-wave model, the fireball created in high-energy heavy-ion collisions is assumed to be in local thermal equilibrium and expands at a four-component velocity $u_{\mu}$. The phase-space distribution of hadrons emitted from the expanding fireball can be expressed as a Wigner function \cite{22,23,33}.

$$S(x, p)d^4x = \frac{2s + 1}{(2\pi)^3} m_i \cosh(y - \eta) \exp \left( -\frac{p_{\mu} u_{\mu}}{T_{kin}} \right) \Theta(1 - \tilde{r}(r, \phi)) H(\eta) \delta(\tau - \tau_0) d\tau d\eta dr d\phi, \quad (2)$$

where $s$, $y$, and $m_i$ are respectively the spin, rapidity, and transverse mass of the hadron, and $p_{\mu}$ is the four-component momentum. Equation (2) is formulated in a Lorentz covariant way, $r$ and $\phi$ are the polar coordinates, and $\eta$ and $\tau$ are the pseudorapidity and the proper time, respectively. $\tilde{r}$ is defined as

$$\tilde{r} = \sqrt{\frac{(x^1)^2}{R^2} + \frac{(x^2)^2}{R^2}}, \quad (3)$$

with $(x^1, x^2)$ standing for the coordinates in the transverse plane and $R$ being the average transverse radius. The kinetic freeze-out temperature $T_{kin}$ and the radial flow parameter $\rho_0$ are important in determining the transverse momentum spectrum, with the latter affecting the four-component velocity field. Since we are only interested in the $p_T$ spectrum at mid-rapidity, the pseudorapidity distribution $H(\eta)$ is not important. The $p_T$ spectrum can then be written as

$$\frac{dN}{2\pi p_T dp_T} = \int S(x, p)d^4x, \quad (4)$$

and the fraction of particle species $i$ and its phase-space distribution can be calculated from Eqs. (1) and (3).

Resonances may be produced from the fireball. Their lifetime is random according to exponential decay law $\exp(-\Gamma \tau)$. In our simulations, hadrons are emitted from the expanding fireball using a Wigner function (Eq. (2)). Of
course, there is also some coalescence models of quarks, which is another way to describe the yields of hadrons\textsuperscript{34,37}. However, the yields of those light nuclei are calculated by a nucleonic coalescence model:

$$E_A \frac{d^3 N_A}{d^3 P_A} = B_A \left( E_p \frac{d^3 N_p}{d^3 P_p} \right)^Z \left( E_n \frac{d^3 N_n}{d^3 P_n} \right)^{A-Z},$$

where

$$P_p = P_n = P_A/A,$$

and $B_A \sim (1/V)^{A-1}$ is related to the fireball volume in coordinate space\textsuperscript{31}.

### III. TRANSVERSE MOMENTUM SPECTRA

Transverse momentum ($p_T$) spectrum is a basic observable in heavy-ion collisions. Through transverse momentum spectrum, information of the system created in the collisions could be learned, such as kinetic freeze-out temperature and radial flow. If the spectrum is identified for different particles, the ratio between the particles can give the chemical freeze-out temperature and baryon (strangeness) chemical potentials. Usually, the $p_T$ spectra show a power-law distribution in peripheral $A + A$ or $p + p$ collisions but an exponential distribution in central $A + A$ collisions. This behaviour implies the system becomes more thermalized with sufficient particle interaction in central collisions in comparison with peripheral collisions.

In our simulation, the values of chemical and kinetic parameters are set as\textsuperscript{12}:

|        | $T_{kin}$ | $T_{ch}$ | $\mu_B$ | $\mu_S$ |
|--------|-----------|----------|----------|----------|
| central| 90.0MeV   | 157.9MeV | 22.0MeV  | 4.4MeV   |
| peripheral| 112.0MeV| 157.8MeV | 17.8MeV  | 2.5MeV   |

With these parameters, reasonable fits to the experimental data\textsuperscript{3} can be obtained for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV/c.

Figure\textsuperscript{3} shows the comparisons of the $p_T$ spectra of several light nuclei in central (0-12%) and peripheral (40-80%) Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV between the RHIC data and our simulations by blast-wave model. After a reasonable fit to the $p(\bar{p})$ and $n(\bar{n})$ spectra is done, and then the yield of other light nuclei is calculated by the nucleonic coalescence model, in which two parameters, $\Delta P$ and $\Delta R$, are used to reproduce the yields of light nuclei. For d and $\bar{d}$, $\Delta P = 0.107$ MeV and $\Delta R = 2 \times 1.45A^{1/3} = 3.654$ fm, and for $^3He(\bar{3}He)$, $\Delta P = 0.107$ MeV and $\Delta R = 2 \times 1.45A^{1/3} = 4.183$ fm.

When comparing our simulations with experimental yields of $p(\bar{p})$ and $\pi^\pm$, two different cases were presented, i.e. the calculated yields with and without resonances decay. For both $p(\bar{p})$ and $\pi^\pm$, simulation results fit the experimental data very well at low $p_T$ with the switching-on resonance decays. It is noticed that the description of the proton data for $p_T > 3$ GeV and $\pi^\pm$ data for $p_T > 2$ GeV is not as good. This can be understood recalling that for large $p_T$ the leading particle production mechanism is the fragmentation of fast moving partons, some of which fragment outside the fireball region and thus, that our description is not valid for these large $p_T$ particles. For the yields of light nuclei which are coalesced by nucleons, they agree with the data very well. The effect of resonance decay is relative significant for $\pi^\pm$ in comparison with $p(\bar{p})$ in our simulation, especially in larger $p_T$ region.

### IV. RESONANCE DECAY AND ITS EFFECT ON $R_{cp}$ OF $p(\bar{p})$ AND $\pi^\pm$

The nuclear modification factor $R_{cp}$ is defined as\textsuperscript{20}

$$R_{cp}(p_T) = \frac{\langle dN/dydp_T/\langle N_{bin}\rangle \rangle_{\text{central}}}{\langle d^2N/d^2p_Tdydp_T/\langle N_{bin}\rangle \rangle_{\text{peripheral}}},$$

where $\langle N_{bin}\rangle$ is the average number of binary nucleon-nucleon collisions per event.

The jets and high $p_T$ particles created in the early stage will lose most energy through interactions in the evolution of the system in central $A + A$ collisions and it is confirmed by suppression of $R_{cp}$ at high $p_T$ in experiment in collisions at 200 GeV/c Au + Au collisions.

Figure\textsuperscript{4} shows the $R_{cp}$ spectra of $p(\bar{p})$ and $\pi^\pm$ for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV/c. The ratio $\langle N_{bin}\rangle$ in data is about 15.77, so we choose $\langle N_{bin}\rangle_{\text{central}} = 15.77$ as a constant for all particles to calculate the $R_{cp}$. Simulation results of $R_{cp}$ can surprisingly fit the experimental data very well even in the region of underpredicted $p_T$ spectra at higher $p_T$. The reason is of course due to the cancelation of both underestimation of $p_T$ in both central and peripheral collisions in the present model. But one lesson should be learned here, i.e. to verifying a model, not only the $R_{cp}$ spectra should be shown but also the original $p_T$ spectra should be demonstrated. Otherwise the only good fit to $R_{cp}$ spectra may not illustrate the true physics.

In addition, various observables are also required for describing a complete physics. For an example, the ratio of $p/\pi$ can be used as another quantity to make comparison. The measured $p_T$ dependence of the baryon-to-meson ratio appears to be related to modifications in the hadronization mechanisms as it happens in a partonic medium. It was pointed out that $p_T$ dependence of the baryon-to-meson ratio should be sensitive to the hadronization scenario due to the different quark content of baryons and mesons and/or to radial flow of the bulk medium because of significant differences in baryon and meson masses. The $p/\pi^-$ data at mid-rapidity is well described by the Greco, Ko, and Levai quark coalescence model where the introduced coalescence involves partons from the medium (thermal) and partons from mini-jets\textsuperscript{32}. The Hwa and Yang quark recombination model is also successful in fitting BRAHMS and PHENIX mid-rapidity data for $p/\pi^+$\textsuperscript{34}.
Figure 5 presents comparisons of $p/\pi^+$ and $\bar{p}/\pi^-$ ratios as a function of $p_T$ for central (0-12%) and peripheral (40-80%) collision centralities, and $\bar{p}$ and $\pi^-$ have negligible final state interactions between produced hadrons. In lower $p_T$ region, the ratio can describe the data very well but it is overestimated even though it is similar to those from other thermal model calculations. The ratios as a function of $p_T$ are also consistent with the results from hydrodynamical models, i.e., the radial flow can push heavier particles to higher $p_T$. The deviation from the data when $p_T > 2$ GeV/c illustrate that the model fails to describe the correct physics in the higher $p_T$ region. The fall of our results for high $p_T$ baryonto-meson ratio and Ref. [34, 35] support the view of a baryonization process driven by parton recombination with negligible final state interactions between produced hadrons. For the resonance decay contribution, it seems similar in peripheral collisions for $p(\bar{p})$ and $\pi^+(\pi^-)$, but it becomes more significant for $\pi^+(\pi^-)$ in central collision which leads to a drop of $p/\pi^+$ and $\bar{p}/\pi^-$ in higher $p_T$ in comparison with the case w/o resonance decays. Again, the inclusion of resonance decays in the model is under the correct way along the physics.

Now let’s go back the phenomenology of $R_{cp}$. From Fig. 4 we observed that the location of $p_T$ where a peak appears for $R_{cp}$ occurs at different $p_T$ for protons and pions, and the ratio of these two location points of $p_T$ is about 3 : 2. It reminds us to think of the relevance between baryon and pion. In many previous studies, the hadrons in intermediate $p_T$ are proved to be formed by the number of constituent quark scaling [38]. Similarly, here we try to scale the $R_{cp}$ in a similar way.

We define a scaled $R_{cp}$ as

$$R_{cp}^*(p_T) = \frac{[Y(n \cdot p_T)]^{1/n} / \langle N_{bin} \rangle_{central}}{[Y(n \cdot p_T)]^{1/n} / \langle N_{bin} \rangle_{peripheral}}$$

$$= \left( \frac{R_{cp}(n \cdot p_T)}{\langle N_{bin} \rangle^c} \right)^{1/n} \frac{\langle N_{bin} \rangle^c}{\langle N_{bin} \rangle^p}, \quad (8)$$

where

$$Y(p_T) = d^2N/p_Tdydp_T, \quad (9)$$

and $n$ is the number of valence quarks ($n = 2$ for pion and $n = 3$ for baryon). Considering the coalescence of quarks, we set power exponent 1/n in our scaling.

In figure 6 two situations are presented: the one is with resonances decay, and the another is without resonances decay. The switching on or off for the resonance decay makes the $R_{cp}$ spectra obviously different for the $\pi^+$ case, while it does not change so much for the $p(\bar{p})$ case. In this model, the decayed $\pi$s are mainly from meson resonances such as $\eta$, $\omega$ and $K^*(892)^+$. And the
FIG. 2: (Color online) Comparison of transverse momentum spectra of $\pi^\pm$ and $p(\bar{p})$ in $0 - 12%$ centrality between the data and our simulations with or w/o the resonance decay contribution.

FIG. 3: (Color online) Same as Fig. 2 but for in $40 - 80%$ centrality.
decayed protons are always from N(1440), N(1535) and Δ which contribute pion production at the same time. From Eq. (1) and the mass of those particles mentioned above, it can be seen that the effect of resonance decay can be more remarkable for pion than for proton especially in high $p_T$ which is presented in Fig. 6. This result agrees with the opinion in Ref. [32]. If the resonance decay is taken into account, the scaled $R_{cp}$ (so called $R_{cp}^*$) becomes similar in shape, especially for the position of the peak, i.e. it seems that the one is a translation of the another. While, if the resonance decay is turn off, the $R_{cp}^*$ results become different in shape, but similar in number at high $p_T$.

V. $R_{cp}$ SCALING FOR LIGHT NUCLEI

After $R_{cp}$ for protons and pions are discussed, we move on the $R_{cp}$ for light nuclei. If there is a similar scaling of $R_{cp}$ for light nuclei, it certainly supports the coalescence mechanism for formation of light nuclei at kinetic freeze-out stage.

Figure 7(a) shows the $R_{cp}$ spectra of $p + \bar{p}$, $d + \bar{d}$, and $t + t + 3He + 3\bar{He}$ by our simulations, respectively. As known, the radial flow can push heavier particles to high $p_T$, therefore a right-shift for the peak of $R_{cp}$ for proton, deuteron and triton ($^3He$) is observed in the $p_T$ direction. From the figure, a big difference in $R_{cp}$ values and shapes among light nuclei with different atomic number emerges, and we will try to find the relevance of the different spectra.

Similarly, we consider the coalescence mechanism for light nuclei as baryon/meson does. As the yields of $p(\bar{p})$ and $n(\bar{n})$ are similar, we have the yields of light nuclei with $A$-mass number obey the Eq. (5), then

$$R_{cp}^p(p_T) = \left( R_{cp}^A(A \cdot p_T) \cdot \frac{\langle N_{bin} \rangle^c_A}{\langle N_{bin} \rangle^p_A} \right)^{1/A} \frac{\langle N_{bin} \rangle^c_A}{\langle N_{bin} \rangle^p_A},$$

where $c$ and $p$ mean central and peripheral collisions.

Due to the yield of light nuclei is proportional to $A$-th power, Figure 1 shows that when $A$ increases by 1, the difference between the $p_T$ spectra of central and peripheral collisions approximately increases by a factor of 10. But when we calculate the $R_{cp}$, the ratio of $N_{bin}$ remains as a constant closing to ten for all particles. These may be the reason why $R_{cp} >> 1$ when $A \geq 2$, and we try to scale the $R_{cp}$ for light nuclei.

$B_A$ in Eq. (5) is related to the fireball volume $V$ [31]. For certain centralities (0-12%/40-80%), $B_A$ can be regarded as a constant for different transverse momentum. Therefore, we define the similar scaled $R_{cp}$ for light nuclei as Eq. (8), namely

$$R_{cp}^{A}(p_T) = \left( R_{cp}^{A}(A \cdot p_T) \cdot \frac{\langle N_{bin} \rangle^c}{\langle N_{bin} \rangle^p} \right)^{1/A} \frac{\langle N_{bin} \rangle^c}{\langle N_{bin} \rangle^p},$$

where the number of nucleon $A$ is used as a scaling factor.

Figure 7(b) shows the scaled $R_{cp}$ spectra of $p + \bar{p}$, $d + \bar{d}$, and $t + t + 3He + 3\bar{He}$ . Indeed, the results of $R_{cp}^*(p_T)$ become similar after number-of-nucleon scaling even though some deviations remain which might come from $B_A$. In light of this study, we can investigate the $R_{cp}^*(p_T)$ for light nuclei experimentally to distinguished the formation mechanism of light nuclei in heavy ion collisions. The number-of-nucleon scaling of elliptic flow for light nuclei at low- [39] and intermediate- [10] energies also supports the coalescence mechanism for the formation of light nuclei at kinetic freeze-out stage in the reaction system.

VI. SUMMARY

Based on the blast-wave model and the coalescence model, the particle yields of $\pi$, $p$ and some light nuclei in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV/c have been investigated. The simulation results of $p_T$ spectra can fit the experimental data very well in the low $p_T$ region ($p_T < 3$ GeV for $p(\bar{p})$ and $p_T < 2$ GeV/c for $\pi^\pm$) but underestimate the yields at higher $p_T$. The later is originated from the inability of the thermal model itself. In order to understand the spectra more clean, the influence
FIG. 5: (Color online) $p/\pi^+$ (a, c) and $\bar{p}/\pi^-$ (b, d) ratios in central (upper) and peripheral (lower) collisions. Resonance decay effects are addressed in the figure.

FIG. 6: (Color online) $R_{cp}$ (left panels) and scaled $R_{cp}$ (right panels) spectra of $p(\bar{p})$ and $\pi^\pm$. Both cases for the inclusion of resonance decay (upper panels) or not (bottom panels) are displayed.
of resonance decay is addressed in the simulation. It is found that the resonance decay contribution for pions is significant in contrast to those for protons. Based on the transverse momentum spectra, the nuclear modification factors $R_{cp}$ of these particles are presented. Unlike the spectra themselves, the nuclear modification factor can apparently reproduce the data in whole studied $p_T$ region even for at higher $p_T$, which is due to the cancelation of both underpredicted yields in central and peripheral collisions. In this respect, we can say that the only nuclear modification factor is not enough to verify the model and the fits to spectra themselves are essential.

The resonance decay effects are checked for both spectra and $R_{cp}$. The shape of $R_{cp}$ spectra of $\pi$ can match the data very well with the resonances decay is taken into account, while that of $p$ keeps the similar shape and does not change very much. It also tell us that the peak of $R_{cp}$ at around 2 GeV/c for $\pi$ is originated from the resonance decayed pions. After the number-of-constituent-quark scaling, the results with resonances decay make the position of the peak in $R_{cp}$ spectra of $p$ and $\pi$ becomes very close and the shape of $R_{cp}^*$ of pions and protons becomes nearly similar except that a positive offset for protons is needed for matching the value of $R_{cp}^*$ of pions, which indicates that there is a similar $R_{cp}$ in the level of constituent quarks. This is a supplement for number-of-constituent-quark scaling besides elliptic flow.

The scaling of $R_{cp}$ has been also tested for light nuclei where the number-of-nucleon (NN) scaling is taken into account. The results display that the $R_{cp}$ spectra of different light nuclei become quite similar after the scaling, indicating that a rough NN-scaling remains for nuclear modification factor of light nuclei. This scaling behavior can be taken as a nucleon coalescence mechanism of light nuclei.

This work was supported in part by the Major State Basic Research Development Program in China under Contract No. 2014CB843400, the National Natural Science Foundation of China under contract Nos. 11421505, 11035009, 11220101005, 11105207 and U1232206.

---

[1] F. Karsch, Nucl. Phys. A 698, 199c (2002).
[2] I. Arsene et al. (BRAHMS Collaboration), Nucl. Phys. A 757, 1 (2005); B. B. Back et al. (PHOBOS Collaboration), ibid. A 757, 28 (2005); J. Adames et al. (STAR Collaboration), ibid. A 757, 102 (2005); S. S. Adler et al. (PHENIX Collaboration), ibid. A 757, 184 (2005).
[3] J. Tian, J. H. Chen, Y. G. Ma, X. Z. Cai, F. Jin, G. L. Ma, S. Zhang and C. Zhong, Phys. Rev. C 79, 067901 (2009).
[4] C. M. Ko, L. W. Chen, V. Greco, F. Li, Z. W. Lin, S. Plumari, T. Song and J. Xu, Nucl. Sci. Tech. 24, 050525 (2013).
[5] N. Yu, F. Liu, K. Wu, Phys. Rev. C 90, 024913 (2014).
[6] G. Y. Shao, M. Colonna, M. Di Toro, Y. Liu, B. Liu, Nucl. Sci. Tech. 24, 050523 (2013); F. M. Liu, Nucl. Sci. Tech. 24, 050524 (2013).
[7] B. Mohanty [STAR Collaboration], J. Phys. G 38, 124023 (2011).
[8] B.I. Abelev et al. (STAR Collaboration), Phys. Lett. B 655, 104 (2007).
[9] G. Agakishiev et al., Phys. Rev. Lett 108, 072301 (2012).
[10] B. I. Abelev et al. (STAR Collaboration), Science 328, 58 (2010).
[11] H. Agakishiev et al. (STAR Collaboration), Nature 473, 353 (2011).
[12] B.I. Abelev (STAR Collaboration), Phys. Rev. C 79, 034909 (2009).
[13] P. Braun-Munzinger, J. Stachel, Nature 448, 302 (2007).
[14] H. Song, S. A. Bass, U. Heinz, Phys. Rev. C 83, 024912 (2011).
[15] J. Xu, C. M. Ko, Phys. Rev. C 83, 034904 (2011); S. Pal and M. Bleicher, Phys. Lett. B 709, 82 (2012).
[16] E. Schneidmann, J. Solifrank, U. Heinz, Phys. Rev. C 48, 2462 (1993).
[17] Ju. A. Karpenko, Yu. M. Sinyukov, K. Werner, Phys. Rev. C 87, 024914 (2013); Yu. A. Karpenko, Yu. M. Sinyukov, J. Phys. G 38, 124059 (2011).
[18] K. Werner, I. Karpenko, M. Bleicher, T. Pierog, S. Forteboeuf-Houssais, Phys. Rev. C 85, 064907 (2012).
[19] P. Braun-Munzinger, J. Stachel, J. P. Wessels, and N.
Xu, Phys. Lett. B 344, 43 (1995); N. Xu and M. Kaneta, Nucl. Phys. A 698, 306 (2002).

[20] A. Andronic, P. Braun-Munzinger, and J. Stachel, Phys. Lett. B 673, 142 (2009).

[21] B. Abelev et al. (ALICE Collaboration), Phys. Rev. C 88, 044910 (2013).

[22] B. Tomášik, Comput. Phys. Commun. 180, 1642 (2009).

[23] M. Chojnacki, A. Kisiel, W. Florkowski, W. Broniowski, Comput. Phys. Commun. 183, 746 (2012); A. Kisiel et al., Comput. Phys. Commun. 174, 669 (2006).

[24] L. Xue, Y. G. Ma, J. H. Chen, S. Zhang, Phys. Rev. C 85, 064912 (2012).

[25] S. Zhang, L. X. Han, Y. G. Ma, J. H. Chen, C. Zhong, Phys. Rev. C 89, 034918 (2014); S. Zhang, Y. G. Ma, J. H. Chen, C. Zhong, Adv. Hep. Phys., accepted (2014).

[26] J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 91, 072304 (2003); Phys. Rev. Lett. 91, 172302 (2003).

[27] J.D. Bjorken, FERMILAB-PUB-82-59-THY and Erratum (unpublished); X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992); E. Wang, X.N. Wang, Phys. Rev. Lett. 87, 142301 (2001); G. L. Ma, Y.G. Ma, S. Zhang et al., Phys. Lett. B 647, 122 (2007).

[28] J. W. Cronin et al., Phys. Rev. Lett. 31, 1426 (1973); J. W. Cronin et al., Phys. Rev. D 11, 3105 (1975).

[29] S. P. Horvat et al. (STAR Collaboration), J. Phys.: Conf. Ser. 446, 012017 (2013).

[30] M. Lv, Y. G. Ma, G. Q. Zhang, J. H. Chen, D. Q. Fang, Phys. Lett. B 733, 105 (2014); Nucl. Techniques (in Chinese), 37, 100517 (2014).

[31] R. Scheibl and U. Heinz, Phys. Rev. C 59, 1585 (1999).

[32] J. Adams et al., Phys. Rev. Lett. 92, 112301 (2004).

[33] F. Retière and M. A. Lisa, Phys. Rev. C 70, 044907 (2004).

[34] R. C. Hwa, and C. B. Yang, Phys. Rev. C 67, 034902 (2003).

[35] V. Greco, C. M. Ko, and P. Levai, Phys. Rev. Lett. 90, 202302 (2003).

[36] R. J. Fries, B. Müller, C. Nonaka, S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003).

[37] F. L. Shao, T. Yao, Q. B. Xie, Phys. Rev. C 75, 034904 (2007).

[38] S. A. Voloshin, Nucl. Phys. A 715, 379c (2003).

[39] T. Z. Yan, Y. G. Ma, Z. Z. Cai et al., Phys. Lett. B 638, 50 (2006).

[40] J. Wang, Y. G. Ma, G. Q. Zhang, W. Q. Shen, Phys. Rev. C 90, 054601 (2014).