Light nuclei production in Au + Au collisions at $\sqrt{s_{NN}} = 7.7 - 80$ GeV from UrQMD model

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Light nuclei production in relativistic $^{197}$Au + $^{197}$Au collisions from 7.7 to 80 GeV is investigated within the Ultra-relativistic-Quantum-Molecular-Dynamics model (UrQMD) with a naive coalescence approach. The results display the production of light nuclei at mid-rapidity can essentially match up the experimental data and a slight enhancement of combined ratio of $N_pN_t/N_d^2$, which is sensitive to the neutron density fluctuations, occurs at around 20 GeV. However, considering the present UrQMD does not include the critical end point, this enhanced $N_pN_t/N_d^2$ ratio should be understood with caution. Furthermore, within different rapidity regions, the kinetic temperatures of different light nuclei are extracted by the Blast-wave model analysis and ratios among different light nuclei are also discussed.

I. INTRODUCTION

One of goals in relativistic heavy-ion collisions is to explore the phase diagram of Quantum Chromodynamics (QCD). The conjectured QCD phase diagram which can be expressed as a plot of temperature vs baryon chemical potential ($T$, $\mu_B$) has been several decades from the first drawing [1–5]. One of features in the QCD phase diagram is so-called the critical end point (CEP) [6] of the first order phase transition from hadronic phase to quark-gluon phase in this diagram which was first proposed in 1989 [7, 8]. This is a current challenge both from experimental and theoretical sides. There are many techniques so far to search for the location of this critical end point in phase diagram, such as the lattice calculations [9, 10], the ratio of viscosity to entropy density ($\eta/s$) [11, 12], cumulants (skewness and kurtosis) [13–15], conserved charge and baryon density fluctuations [5, 16, 17] as well as higher order moment [18–21] etc, however, no consensus was reached yet. Recently, as proposed by Ref. [22, 23] based on coalescence model as well as by preliminary results from the STAR collaboration with the Beam Energy Scan (BES) program, one found that there exists a non-monotonic relation of the ratio $N_tN_p/N_d^2$, which could be related to the neutron density fluctuation, as a function of center-of-mass energy $\sqrt{s_{NN}}$ [24, 25] and it triggers many interesting works on exploration of the ratios of light nuclei [25–28]. In Ref. [29], it is found that the first-order chiral phase transition can enhance the ratio of $N_tN_p/N_d^2$. These results suggest that realistic equation of state or CEP mechanism should be needed. In Ref. [30], one calculated baryon probability density by UrQMD and found no baryon density fluctuation as claimed by experimental indication. In this context, lots of efforts are still needed on addressing non-monotonic issue.

On the other hand, only midrapidity region was focused in most experimental measurements as well as theoretical calculations so far, and less efforts are paid on productions of light-nuclei and their ratios in large rapidity regions. For central collisions at a given energy, one can separate rapidity into various regions. If these various rapidity regions correspond to the various initial condition as $(T_0, \mu_{B0})$, then these initial conditions $(T_0, \mu_{B0})$ would have their own trajectory during cooling process. Thus we concern that the CEP could occur in an energy region with different rapidity windows. Therefore it is of interests to check the rapidity dependence of light-nuclei. Based upon the above arguments, we have two main motivation in this work. One is to investigate density fluctuations by the yield ratios of light nuclei in the midrapidity region, and another is to extract light-nuclei production and ratios in higher rapidity regions and see what difference from the midrapidity ones.

II. MODEL AND METHODOLOGY

A. UrQMD model and coalescence

The UrQMD model is one of microscopic models and extensively used in simulating the ultra-relativistic heavy ion collisions [31–34]. The mean field potential is taken into account as the collision c.m. energy $\sqrt{s_{NN}}$ which is less than 3.3 GeV, however, the present simulations which are above 7 GeV are only with cascade part. In UrQMD model, the degrees of freedom are hadrons and strings. The more details can be found in Refs. [31, 33, 34]. In many other works, thermal and statistical approaches are used to describe the production of light nuclei [35, 36]. Here by a coalescence mechanism with the final phase space information of baryons,
we can obtain production yields of light nuclei. For more
details, a light nucleus can be recognized by a so-called
minimum spanning tree (MST) clusterization algorithm
based on coordinate and momentum cuts, which was also
utilized to determine nuclear fragments in the Quantum
Molecular Dynamics simulations [37]. The yield of nu-
cleus is given by the condition of relative distance \( \Delta r <
3.575 \text{ fm} \) and relative momentum \( \Delta p < 0.285 \text{ GeV/c} \) as
in Ref. [38]. For simplicity, the spin and isospin factors
are not yet considered in this work. The UrQMD-3.3p1
version is applied to simulate central \(^{197}\text{Au} + ^{197}\text{Au} \) collisions
with impact parameters of \( b = 0 - 3 \text{ fm} \) at \( \sqrt{s_{NN}} = 7.7 \text{ GeV} \) to \( \sqrt{s_{NN}} = 80 \text{ GeV} \).

**B. Ratios and density fluctuation**

Light nuclei are usually formed during cooling process
of hot and dense medium and can then be used to ex-
tract important information of nucleon distributions at
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From Eq. (8), the light-nuclei ratio is relative to the neu-
tron density fluctuation. And the density fluctuations
would be amplified in the spinodal region of phase dia-
gram [19]. Results in Ref. [22] suggested that the yield
ratio of light nuclei in relativistic heavy-ion collisions can
be taken as a direct probe of the large density fluctuations
which might be associated with the QCD critical
phenomenon.

Moreover, other ratios of light-nuclei which involving
\(^3\text{He} \) were proposed in Ref. [26, 27],

\[
O_2 = \frac{N_{^4\text{He}} N_p}{N_{^3\text{He}} N_p}, \tag{9}
\]

\[
O_3 = \frac{N_{^4\text{He}} N_p}{N_{^3\text{He}} N_d}, \tag{10}
\]

\[
O_4 = \frac{N_{^4\text{He}} N_p^2}{N_d^2}. \tag{11}
\]

Since these above ratios have the same powers of fugacity
in denominators and numerators, so they can cancel and
eliminate the dependence of baryonic chemical potential.
From the results in Ref. [26, 27], one suggests that these
terms are sensible indicators of critical behavior. Also,
we found that only \( O_1 \) and \( O_2 \) is independent each other,
but \( O_3 \) can be expressed by \( O_1 \times O_2 \), and \( O_4 = O_3/\sqrt{N_{^3\text{He}}} \).

In our simulations, some single ratios such as the ratios
of neutron to proton (\( N_n/N_p \)), triton to \(^3\text{He} \) (\( N_t/N_{^3\text{He}} \)), and
\(^3\text{He} \) to \(^3\text{He} \) (\( N_{^4\text{He}}/N_{^3\text{He}} \)) are also considered.

## III. RESULTS AND DISCUSSION

### A. The yield of light nuclei and kinetic
temperature

Firstly, we consider the rapidity density \( (dN/dY) \) as a
function of \( \sqrt{s_{NN}} \) for two kinds of midrapidity cuts,
\( |Y| < 0.1 \) and \( |Y| < 0.3 \), as displayed in Fig.
1. The comparison is with the experimental results from
the STAR collaboration [25, 42–45] as shown with circles,
squares and inverted triangles. For both of \( |Y| < 0.1 \) and
\( |Y| < 0.3 \), \( dN/dY \) of protons decreases as the increas-
ing of \( \sqrt{s_{NN}} \) and they are coincident with data. For the
deuteron cases, they also decrease as the increasing of
\( \sqrt{s_{NN}} \). The values of \( dN/dY \) of deuteron are less than
those of data in \( |Y| < 0.1 \) window but it is coincident in
\( |Y| < 0.3 \) window. However, for triton production, there
is in a good agreement with that data within \( |Y| < 0.1 \)
cut but less than the data within \( |Y| < 0.3 \) cut. It indi-
cates that even though in midrapidity region the yields
of deuteron and triton are sensitively dependent of rapid-
ity window. Also for triton yield, one can see that large
fluctuations appear around 40 GeV within \( |Y| < 0.1 \) cut.
The yield of \( ^3\text{He} \) is similar to the yield of triton. For an-
tiparticle, the yield of anti-proton increases as \( \sqrt{s_{NN}} \) and
is close to the yield of proton at high energy as shown
with the purple dot-dash lines. The reason here is that
the STAR Collaboration with the midrapidity cuts |Y|<0.1 and |Y|<0.3, respectively. As an example, Y peak and Y f are marked in the insert for the 10 GeV case. In this work, we set |Y − Y peak| < 0.05Y peak and |Y + Y peak| < 0.05Y peak as ‘range1’, and |Y| < |Y| < |Y| + 0.2 is treated as ‘range2’. i.e. ‘range1’ corresponds to initial Au-like rapidity region and ‘range2’ to spectator (cold nucleus) region.

Transverse momentum distributions for proton, neutron, deuteron, and anti-proton in different rapidity ranges at √sNN = 10 GeV are shown in Fig. 3. The red dash curves are fitted lines with the Blast-wave model [46–50], i.e.,

$$\frac{dN}{p_Tdp_T} \propto \int_0^R r dr m_T I_0[p_T \sinh(\rho)] K_1[m_T \cosh(\rho)],$$

(12)

where mT = \sqrt{m^2 + p_T^2} is the transverse mass, r and R are the radial position and the maximum radial position, respectively. I_0 and K_1 are the modified Bessel functions, ρ is the boost angle which is tanh^{-1}[β(r)], β(r) = β_s(r/R) is a self-similar flow profile, β_s is the surface velocity, and α is an index factor which is corresponding to the shape of source. Kinetic temperatures are extracted by the Blast-wave fitting as shown in Fig. 4. One can see that the behaviors of temperature as a function of √sNN for proton, deuteron, triton, and 3He in different rapidity regions. For protons in both rapidity regions of |Y| < 1.0 and ‘range1’, kinetic temperatures increase as √sNN. Since both of them are related to the fireball due to the flat or single-peak rapidity distribution, the higher the collision energy, the hotter the proton’s temperature. For the rapidity region of |Y| < 1.0 which is with respect to the central area in the fireball there is higher temperature than the one of ‘range1’ which is outside area of the fireball. This is as discussed in Section I. In the ‘range2’ which are located in spectator region, the behavior of kinetic temperature is opposite. It indicates as collision energy increases, spectators pass through so fast that they are got less excited. Thus kinetic temperature goes down as increasing of energy. For the cases of deuteron, triton and 3He, all their kinetic temperatures are about 80 MeV which are less than the one of proton for |Y| < 1.0 and ‘range1’. It implies that the light nuclei such as deuteron, triton and 3He are mostly coming from non mid-rapidity region. From the rapidity distributions of deuteron, triton and 3He in Fig. 2, it is expected that temperature in the rapidity region of |Y| < 1.0 could be less than ones for ‘range1’ in Fig. 2(c), because the mid-rapidity region of |Y| < 1.0 for these nuclei is not really midrapidity particles, but just the tailed particles of Au-like region.
FIG. 2: (Color online) Rapidity distributions of various light nuclei in central (b < 3 fm) $^{197}$Au + $^{197}$Au collisions at different energies within the UrQMD model. In (c), $Y_{peak}$ and $Y_1$ indicates of the rapidity positions of first peak and valley in right-hand rapidity distribution at $\sqrt{s_{NN}} = 10$ GeV.

FIG. 3: (Color online) Transverse momentum $P_T$ distributions for proton (a), neutron (b), deuteron (c), and anti-proton (d) within various rapidity cuts in central (b < 3 fm) $^{197}$Au + $^{197}$Au collisions at c.m. energy $\sqrt{s_{NN}} = 10$ GeV with the UrQMD model. Red-dash curves are fitting lines with the Blast-wave (BW) model.

FIG. 4: (Color online) Kinetic temperature $T_{kin}$ for proton (a), neutron (b), deuteron (c), and anti-proton (d) as a function of c.m. energy $\sqrt{s_{NN}}$ within various rapidity cuts in central (b < 3 fm) $^{197}$Au + $^{197}$Au collisions with the UrQMD model.

B. The ratios of light nuclei

Ratios of $O_1$, $O_2$, $O_3$, and $O_4$ as a function of $\sqrt{s_{NN}}$ with different midrapidity cuts are shown in Fig. 5. For
$O_1$ which presents the neutron density fluctuation shown in Fig. 5(a), it seems to show a slight enhancement arising around 20 GeV and another broad peak emerges at 60 GeV with small midrapidity cuts as displayed with black solid-squares, blue solid-circles and black inverted triangles. However, the UrQMD model which we are using does not include any CEP mechanisms [30, 31, 33]. In this context, the enhancement around 20 GeV could not indicate the CEP. Also in the UrQMD model, only the hadron and string are taken into consideration, then it means that it might be inappropriate for higher energy (such as above 40 GeV) simulations even though we can reproduce appropriate light nuclei yields as depicted in Fig. 1. Thus the peak at 60 GeV should be also treated with caution. In other panels for $O_2$, $O_3$, and $O_4$, ratios are around 1-2 below 20 GeV and tends to zero as higher energies within midrapidity cuts because of the negligible $^4$He production beyond 20 GeV. Regardless, in Fig. 5(a) to 5(d) for higher midrapidity cuts with $|Y|<1.5$, the ratios increase as $\sqrt{s_{NN}}$. In particular, the ratios $O_3$ and $O_4$ are close to each other in all rapidity regions due to the similar production yield of triton and $^3$He which can be seen from next figure (Fig. 6(b)).

For the ratio of $N_n/N_p$ which is usually taken as a sensitive probe to neutron skin [51–53], we can see from Fig. 6(a) that for all midrapidity cuts the ratios decrease as the increasing of energy and all the ratios are the same at a given energy since neutrons and protons are basically coming from a single midrapidity source (participants). The ratios of triton to $^3$He in Fig. 6(b) for midrapidity cuts with $|Y|<1.0$ and $|Y|<1.5$ are showing nearly constant value as $\sqrt{s_{NN}}$ increases. According the nucleon component, one may expect $N_t/N_{^3He}$ has the same value as $N_n/N_p$. However, only up till high energy region, ratio of triton to $^3$He has the similar ratio of $N_n/N_p$. In low energy region, ratio of $N_n/N_p$ is affected by the initial isospin asymmetry which is 118/79 for $^{197}$Au. And also such initial isospin asymmetry seems to affect $N_{^4He}/N_{^3He}$ in low energy region. With the increasing of $\sqrt{s_{NN}}$, $N_{^4He}/N_{^3He}$ tends to the constant for each given rapidity window, indicating the relative production rate for $N_{^4He}/N_{^3He}$ keeps close at higher energies. In addition, the larger the rapidity region, the higher the $^4$He/$^3$He, which reflects that heavier light nuclei could be preferentially formed at larger rapidity.

As mentioned above, we separated the rapidity into various regions with boundary values of $Y_{peak}$ and $Y_1$. In Fig. 7(a), by comparing $O_1$ ratios among Inner region of $|Y|<0.2Y_1$ ($O_I$), Middle region of $|Y|<0.5Y_1$ ($O_M$), and Outside region of $0.5Y_1<|Y|<Y_1$ ($O_O$) inside the entire region of $-Y_1<Y<Y_1$, we found $O_I<0.95$ in $O_O$. It indicates that in Inner region, the matter is more uniform and would be less of neutron density fluctuations. And for Middle region, there are more kinds of particle

\[ \begin{align*}
\text{FIG. 5: (Color online) Ratios } O_1, O_2, O_3, \text{ and } O_4 \text{ as a function of } \sqrt{s_{NN}} \text{ for various midrapidity cuts at central (b } < 3 \text{ fm) } ^{197}\text{Au} + ^{197}\text{Au} \text{ collisions within the UrQMD model.}
\end{align*} \]

\[ \begin{align*}
\text{FIG. 6: (Color online) Ratios of } N_n/N_p, N_t/N_{^3He} \text{ and } N_{^4He}/N_{^3He} \text{ as a function of } \sqrt{s_{NN}} \text{ with various midrapidity cuts at central (b } < 3 \text{ fm) } ^{197}\text{Au} + ^{197}\text{Au} \text{ collisions within the UrQMD model.}
\end{align*} \]
spectator region drops quickly with \(N\) [54]. For then suggested as a neutron-skin probe at Fermi energy \(N\) to \(N\) are the same as discussed above, which indicates that \(N\) of the initial isospin asymmetry \(118/79 \approx 1.49\) as energy increases they tend to 1.4 which are close to symbols in the spectator region, the ratios of \(N\) obtained by the dominant similar trends to each other, which can be attributed to the dominant \(^4\)He in these ratios. In addition, \(O_3\) can be obtained by \(O_1 \times O_2\) or either by \(O_4 \times N_t/N_{^3\text{He}}\).

Furthermore, ratios of \(N_n/N_p\), \(N_t/N_{^3\text{He}}\) and \(N_{^4\text{He}}/N_{^3\text{He}}\) in various rapidity regions are shown in Fig. 8. In Fig. 8(a), except for the one of purple symbols in the spectator region, the ratios of \(N_n/N_p\) in all other regions are the same. For the purple symbols, as energy increases they tend to 1.4 which are close to the initial isospin asymmetry \(118/79 \approx 1.49\). The ratio of \(N_t/N_{^3\text{He}}\) in the spectator region keeps at value of 1.4 in Fig. 8(b). Both ratios of \(N_n/N_p\) and \(N_t/N_{^3\text{He}}\) are the same as discussed above, which indicates that \(N_t/N_{^3\text{He}}\) could be taken as a reasonable approximation to \(N_p/N_p\) as medium interaction is not very strong and then suggested as a neutron-skin probe at Fermi energy [54]. For \(N_{^4\text{He}}/N_{^3\text{He}}\) in Fig. 8(c), the values in the spectator region drops quickly with \(\sqrt{s_{NN}}\) but others show rather flat dependence of \(\sqrt{s_{NN}}\).

![FIG. 7: (Color online) Ratios \(O_1\), \(O_2\), \(O_3\), and \(O_4\) as a function of \(\sqrt{s_{NN}}\) for various midrapidity regions at central \((b < 3 \text{ fm})\) Au + Au collisions within the UrQMD model.](image)

![FIG. 8: (Color online) Ratios of \(N_n/N_p\), \(N_t/N_{^3\text{He}}\) and \(N_{^4\text{He}}/N_{^3\text{He}}\) as a function of \(\sqrt{s_{NN}}\) for various midrapidity regions at central \((b < 3 \text{ fm})\) \(^{197}\text{Au} + ^{197}\text{Au}\) collisions within the UrQMD model.](image)

**IV. CONCLUSION**

In this work, we extracted different single ratios and combined ratios of light nuclei by naive coalescence approach in the framework of UrQMD model. By comparing with the data, the yields of light nuclei seem reasonable. Meanwhile, kinetic temperatures of protons, deuterons, tritons and \(^3\)He in different rapidity regions are extracted based on the Blast-wave model assumption. For the combined ratio \(N_p/N_t/N_{^4n}\) in midrapidity region which is thought to be sensitive to neutron density fluctuation, it seems that a slight enhancement is observed around 20 GeV, however, it should not be over-explained as the sign of critical end point due to the physics ingredient of the UrQMD, which could be arisen by other...
mechanism or due to the less precision of this naive coalescence approach. Other combined ratios involved $^4\text{He}$ are also checked, and found very similar behavior due to the dominant role of $^4\text{He}$. Except for the midrapidity particles and their ratios, we also consider ratios of light nuclei in other rapidity regions. Based on the present results, it indicates that there are lots of information we can learn from the outside midrapidity while a suitable model is further expected.

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