The production of light (anti-)nuclei and (anti-)hypertriton in \( pp \) collisions at \( \sqrt{s} = 0.9, 2.76, \) and 7 TeV

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The production of light (anti-)nuclei and (anti-)hypertriton is investigated using the dynamically constrained phase space coalescence model (DCPC), based on the hadronic final states generated by the parton and hadron cascade model (PACIAE) in \( pp \) collisions at \( \sqrt{s} = 0.9, 2.76, \) and 7 TeV, within \( p_T < 3.0 \) GeV/c and \( |y| < 0.5 \) acceptances. The ALICE data of \( d \) and \( d \) yields, ratios, and the transverse momentum distribution are well reproduced with the corresponding PACIAE+DCPC results. The yields, ratios, and the transverse momentum distribution of \( ^3\text{He}, \ ^\Lambda\text{He}, \ ^\Lambda\text{H}, \) and \( ^\Lambda\text{H} \) were predicted. Furthermore, it is found that the yields of light nuclei and anti-nuclei depend on the mass number \( A \) of the matter produced, i.e., their yields decrease rapidly as the increase of mass number. The strangeness population factor \( S_1 = (\frac{1}{2}H/He)/(\Lambda/p) \) was found to be about 0.7 \( \sim \) 0.8, and was compatible with the experimental data.

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I. INTRODUCTION

The investigation of anti-nuclei production is of great importance in particle and nuclear physics, cosmology, and astrophysics. One believes that matter and anti-matter happened in equal abundance during the initial stage of the universe. However, how did this symmetry get lost in the evolution of the universe, which is still a mystery exists. The high energy accelerator experiment provides a chance to study the production of light nuclei and anti-nuclei.

In the last decades, the production of antimatter has been a focal of many experiments research. The STAR and PHENIX Collaborations have reported their light nuclei and anti-nuclei production data in Au+Au collisions within \( \sqrt{s_{NN}} = 7.7 \) GeV to 200 GeV. And ALICE has also published papers on the production of light (anti-)nuclei in \( pp \) collisions at \( \sqrt{s} = 0.9, 2.76, \) and 13 TeV, and Pb+Pb collisions in \( \sqrt{s_{NN}} = 6.3 \) GeV up to 2.76 TeV.

Theoretically, the nucleons and hyperons productions can be predicted by a transport model. Then, the light (anti-)nuclei production rates are computed using the statistical model or phase-space coalescence model. Some researches use the coalescence + blast-wave method, or a multiphase transport (AMPT) model and UrQMD model + thermal model to study the production of light nuclei and anti-nuclei in high energy nuclear-nuclear collisions. A dynamically constrained phase-space coalescence model (DCPC) was proposed and was used to investigate the production of light nuclei and anti-nuclei in high energy pp collisions. In this stage, a K factor is added to describe non-perturbative and higher order corrections. After parton rescattering the hadronization then proceeds. At last, a hadron rescattering is introduced, in which the two-body collision method is applied, until all hadrons have reached freeze-out.

In this paper, we first calculate the hadronic final state using the PACIAE model in the non-single diffractive (NSD) \( pp \) collisions at different Center-of-mass (c.m.) energies. Then, we can generate the light (anti-)nuclei using the DCPC model to investigate the production of the light nuclei (\( d, ^3\text{He} \) and \( ^\Lambda\text{H} \)) and their corresponding anti-nuclei (\( \bar{d}, \ ^\Lambda\text{He} \), and \( ^\Lambda\text{H} \)) in high energy \( pp \) collisions. In Sec. 2, we have introduced the PACIAE model and the dynamically constrained coalescence model (DCPC) briefly. In Sec. 3, our numerical results are presented and a short summary is presented in Sec. 4.

II. MODELS

The PACIAE model is based on PYTHIA6.4 model and is promoted to study the nucleus-nucleus collisions mainly, relying on the collision geometry and nucleon-nucleon (NN) total cross section. Compared with the PYTHIA, in the PACIAE model the string fragmentation is switched-off temporarily, and the (anti-)diquarks break randomly into (anti-)quarks, leading to forming the partonic initial state. Then parton rescattering is introduced, and using the \( 2 \rightarrow 2 \) (LOpQCD) parton-parton interaction cross-sections to calculate parton rescattering in QGM. In this stage, a K factor is added to describe non-perturbative and higher order corrections. After parton rescattering the hadronization then proceeds. At last, a hadron rescattering is introduced, in which the two-body collision method is applied, until all hadrons have reached freeze-out.

We generated the final state particles by the PACIAE model, and refer to DCPC model to calculate the light nuclei and anti-nuclei production. Considering quantum statistical mechanics, one can not precisely tell both positions and momentum of a particle in

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the phase-space, according to the uncertainty principle
\[ \Delta \vec{q} \Delta \vec{p} \geq 3h. \tag{1} \]

One may only know that the particle lies somewhere within a volume of \( \Delta \vec{q} \Delta \vec{p} \) or state inside a quantum box of six-dimension. A particle state occupies a volume \((h^3)\) within the six-dimension phase-space \(\boxed{21}\). Then, we may define an integral to directly estimate the yield for a single particle:
\[ Y_1 = \int_{H \leq E} \frac{d\vec{q}d\vec{p}}{3h}. \tag{2} \]

Here, \( H \) is the Hamiltonian and \( E \) is the energy of particle. The yield of \( N \) particles may be similarly estimated with
\[ Y_N = \int \cdots \int_{H \leq E} \frac{d\vec{q}_1d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{(3h)^N}. \tag{3} \]

While Eq.(3) should satisfy the limited conditions as follows:
\[ |\vec{q}_j| \leq D_0, (i \neq j; i, j = 1, 2, 3, ..., N), \]
\[ m_0 - \Delta m \leq m_{inv} \leq m_0 + \Delta m. \tag{4} \]

Where
\[ m_{inv} = \sqrt{(E_1 + E_2 + E_3)^2 - (\vec{p}_1 + \vec{p}_2 + \vec{p}_3)^2}, \tag{5} \]

\( |\vec{q}_j| \) stands for the distance between particles \(j\)-th and \(i\)-th, \(D_0\) and \(m_0\) are the diameter and rest mass of light nuclei and anti-nuclei, respectively. The \(p_i\) and \(E_i\) \((i = 1, 2, ..., N)\) are the momenta and energies of particles, respectively. \(\Delta m\) stands for the allowed uncertainty.

In Eq.(3), the integral of continuous distributions will be changed using the sum for discrete distributions, because the hadron momentum and position distributions are discrete in transport model simulation.

III. RESULTS AND DISCUSSION

We generate the final state hadrons by the transport model PACIAE. Then one can utilize the DCPC model to coalescence production of the light nuclei and anti-nuclei \(\boxed{20}\). The fitted parameters of the PACIAE model were selected as the default values of the PYTHIA6.4, except the Parj\( (1)\), Parj\( (2)\), with Parj\( (3)\) parameters and \(K\) factor were roughly fitted the proton and anti-proton from ALICE data in \(pp\) collisions at c.m. energy of 900 GeV, 2.76 TeV, and 7 TeV \(\boxed{20, 32, 38}\), as shown in Fig. 1. It shows that the results of PACIAE simulation are very close to the ALICE data. The parameters were fitted from figure 1 for Parj\( (1)\) = 0.07 (default value is 0.10), Parj\( (2)\) = 0.18 (0.30), Parj\( (3)\) = 0.40 (0.40), with \(K = 0.95\) (1.0 or 1.5), which were used to compute the yield of \(d, \bar{d}, ^3He, \bar{^3He}, \bar{^3}H, \bar{^3}H\), in \(pp\) collisions of the c.m. energy of 900 GeV, 2.76 TeV and 7 TeV relying on the final hadronic states from the PACIAE simulations. The consequent of light nuclei and anti-nuclei yields are shown on Table 1.

One can see in the Tab.1 that:

- The yield of (anti-)hypertriton is significantly less than that of (anti-)helium-3 computed by PACIAE model, since the yield of hyperons is less than that of (anti-)helium-3.
- When the c.m. energy increases from 900 GeV to 7 TeV, the (anti-)proton yield calculated by PACIAE simulations increases \(\sim 50\%\). That is less than the increase of light (anti-)nuclei (over 100\% for \(d, \bar{d}, \sim 60\%\) for \(^3He, \bar{^3}He\)). This may attribute to the stronger increase of available phase space in the anti-nuclei production than that in anti-hadron production.
- The yield of \(d, \bar{d}\) calculated by PACIAE+DCPC model is well consistent with ALICE experimental data in the range of uncertainty. Meanwhile, we predict the yield of \(^3He, \bar{^3He}, ^3\bar{H}, \bar{^3}H\) in \(pp\) collisions at c.m. energy of 900 GeV, 2.76 TeV, and 7 TeV using PACIAE+DCPC model.

Fig. 2 presents the transverse momentum spectrum of the integral yields of \(d, \bar{d}, ^3He, \bar{^3He}, ^3\bar{H}, \bar{^3}H\) calculated by the PACIAE+DCPC model with \(0 < p_T < 3\) GeV/c, \(|y| < 0.5\) in mid-rapidity \(pp\) collisions at c.m. energy of 0.9 TeV, 2.76 TeV, and 7 TeV, respectively. It can be seen that the transverse momentum spectrum of \(d, \bar{d}, ^3He, \bar{^3He}\) calculated by PACIAE+DCPC simulations is consistent with the result distribution of ALICE data \(\boxed{8}\). Then we predict the distribution of the transverse momentum spectrum of \(^3He, \bar{^3He}, ^3\bar{H}, \bar{^3}H\) in
Table I: The yields of the (anti-)nuclei and (anti-)hypertriton in $pp$ collisions at c.m. energy of 900 GeV, 2.76 TeV and 7 TeV calculated by the PACIAE+DCPC simulations, respectively. The ALICE data are taken from Ref. [8, 33–39].

| Particle | PACIAE+DCPC | ALICE |
|----------|-------------|--------|
|          | 0.9 TeV     | 2.76 TeV | 7 TeV | 0.9 TeV | 2.76 TeV | 7 TeV |
| $p$      | 0.082       | 0.090   | 0.124 | 0.083 ± 0.008 | 0.090 ± 0.007 | 0.124 ± 0.009 |
| $\bar{p}$ | 0.079       | 0.088   | 0.122 | 0.079 ± 0.008 | 0.088 ± 0.006 | 0.123 ± 0.010 |
| $\Lambda$ | 0.048       | 0.060   | 0.087 | 0.048 ± 0.005 | -             | 0.090 ± 0.007 |
| $\bar{\Lambda}$ | 0.047 | 0.060   | 0.086 | 0.047 ± 0.007 | -             | 0.089 ± 0.006 |
| $d^a$    | 1.06E-4     | 1.41E-4 | 2.04E-4 | (1.12 ± 0.13)E-4 | (1.53 ± 0.14)E-4 | (2.02 ± 0.17)E-4 |
| $\bar{d}^a$ | 9.83E-5   | 1.35E-4 | 1.98E-4 | (1.11 ± 0.13)E-4 | (1.37 ± 0.13)E-4 | (1.92 ± 0.15)E-4 |
| $^3H^b$  | 5.17E-8     | 7.98E-8 | 1.16E-7 | -             | -             | -             |
| $^3\bar{H}^b$ | 4.62E-8   | 7.28E-8 | 1.10E-7 | -             | -             | (1.10 ± 0.63)E-7 |
| $^3\Lambda^c$ | 2.36E-08 | 3.69E-08 | 5.62E-08 | -             | -             | -             |
| $^3\bar{\Lambda}$ | 2.06E-08 | 3.32E-08 | 5.23E-08 | -             | -             | -             |

$^a$ calculated with $\Delta m = 0.0030$;  
$^b,c$ calculated with $\Delta m = 0.0075$.

FIG. 2: The transverse momentum distribution of $d$, $\overline{d}$, $^3He$, $^3\overline{He}$, $^3\Lambda$, and $^3\overline{\Lambda}$ in $pp$ collisions at c.m. energy of 900 GeV, 2.76 TeV, and 7 TeV, which are calculated by the PACIAE+DCPC model simulations. The solid points are ALICE data and the data are multiplied with constant factors for clarity in figures.

In the high energy collisions, production mechanism is generated through hadron coalescence due to final-state correlations between particles. The ratios of particle yields can be predicted by the coalescence model, which have been checked for various particle species. Theoretically, the ratios of different (anti-)nuclei or (anti-)hypernuclei can be directly related to ratios of hadronic yields in the simple coalescence framework [40, 41]. E.g., if the $^3\Lambda$ and $^3\overline{\Lambda}$ are formed by coalescence of ($p+n+\Lambda$) and ($\bar{p}+\bar{n}+\overline{\Lambda}$), then the yield ratio of $^3\Lambda/^3\overline{\Lambda}$ should be proportional to ($p/(p+n)(\Lambda/\overline{\Lambda})$, and the other ratios are the same. The ratios can be written as following:

$$\frac{^3\Lambda}{^3\overline{\Lambda}} \approx \frac{p\Lambda}{p\overline{\Lambda}} \approx \frac{p}{\Lambda} \approx \frac{\Lambda}{p} \approx \frac{\Lambda}{\Lambda},$$

(6)

Once again, mixed ratios:

$$\frac{^3\Lambda}{^3He} \approx \frac{p\Lambda}{ppn} \approx \frac{\Lambda}{p},$$

(7)
TABLE II: The top section of the table show the ratio of anti-nuclei ($\bar{p}, \bar{\Lambda}, \bar{d}, \bar{^3}He,$ and $\bar{\Lambda}^3H$) to nuclei ($p, \Lambda, d, ^3He$ and $\Lambda^3H$) in $pp$ collisions at c.m. energies of 900 GeV, 2.76 TeV, and 7 TeV, followed by the mixed ratios between the different (anti-)nuclei. And the ratios of the (anti-)hyperon to (anti-)proton and (anti-)hypertriton to (anti-)helium-3 are shown at the bottom. ALICE data are taken from Ref. [8, 35–39].

| Particle | PACIAE+DCPC | ALICE |
|----------|-------------|--------|
|          | 0.9 TeV | 2.76 TeV | 7 TeV | 0.9 TeV | 2.76 TeV | 7 TeV |
| $\bar{p}/p$ | 0.963 | 0.978 | 0.984 | 0.952 ± 0.002 | 0.978 ± 0.002 | 0.992 ± 0.009 |
| $\bar{\Lambda}/\Lambda$ | 0.981 | 0.993 | 0.984 | 0.963 ± 0.023 | 0.979 ± 0.015 | 0.989 ± 0.014 |
| $\bar{d}/d$ | 0.927 | 0.954 | 0.967 | 0.991 ± 0.09 | 0.895 ± 0.05 | 0.950 ± 0.02 |
| $\bar{^3}He/\bar{^3}He$ | 0.893 | 0.935 | 0.948 | – | – | – |
| $\bar{\Lambda}^3H/\bar{\Lambda}^3H$ | 0.873 | 0.909 | 0.925 | – | – | – |
| $d/p$ | 1.29E-3 | 1.57E-3 | 1.65E-3 | (1.38 ± 0.186)E-3 | (1.48 ± 0.167)E-3 | (1.63 ± 0.170)E-3 |
| $d/\bar{p}$ | 1.24E-3 | 1.53E-3 | 1.62E-3 | (1.39 ± 0.205)E-3 | (1.31 ± 0.145)E-3 | (1.56 ± 0.170)E-3 |
| $^3He/d$ | 4.88E-4 | 5.52E-4 | 5.69E-4 | – | – | – |
| $\bar{^3}He/d$ | 4.70E-4 | 5.39E-4 | 5.56E-4 | – | – | (5.73 ± 3.26)E-4 |
| $\Lambda/p$ | 0.585 | 0.667 | 0.702 | 0.578 ± 0.082 | – | 0.726 ± 0.077 |
| $\bar{\Lambda}/\bar{p}$ | 0.595 | 0.670 | 0.705 | 0.595 ± 0.107 | – | 0.724 ± 0.076 |
| $\bar{\Lambda}^3H/\bar{\Lambda}^3H$ | 0.456 | 0.474 | 0.484 | – | – | – |
| $\bar{\Lambda}^3H/\bar{\Lambda}^3H$ | 0.446 | 0.456 | 0.475 | – | – | – |

FIG. 3: Integrated yields ($dN/dy$) of anti-nuclei (left panel) and nuclei (right panel) in the mid-rapidity $pp$ collisions at $\sqrt{s} = 900$ GeV, 2.76 TeV and 7 TeV, as a function of the atomic mass number $A$. The results are calculated by PACIAE+DCPC model (see open point). The ALICE data (solid point) is taken from [8, 35–39].

The yield ratio of anti-nuclei ($\bar{p}, \bar{\Lambda}, \bar{d}, \bar{^3}He,$ and $\bar{\Lambda}^3H$) to nuclei ($p, \Lambda, d, ^3He,$ and $\Lambda^3H$) and their mixed ratios ($\Lambda/p, \bar{\Lambda}/\bar{p}, \bar{^3}He/\bar{^3}He,$ and $\bar{\Lambda}^3H/\bar{\Lambda}^3H$) in $pp$ collisions at $\sqrt{s} = 900$ GeV, 2.76 TeV and 7 TeV are shown in the Table II. Obviously, the ratios of anti-nuclei and anti-hypertriton to the nuclei and hypertriton are all dependent of the c.m. energy, as same as their yields increase with the c.m. energy increase as shown in Table I. The ratios of the anti-particles to particles, as well as the (anti-)hypertriton to (anti-)nuclei ($\bar{^3}He/\bar{^3}He,$ $\bar{\Lambda}^3H/\bar{\Lambda}^3H$) are less than 1, which means that the yield of (anti-)hypertriton is less than that of (anti-)nuclei. Since the $\bar{^3}He$ and $\bar{\Lambda}^3H$ are formed by coalescence of $(\bar{\Lambda} + p + n)$ and $(\Lambda + p + n)$, then the production ratio of $\bar{^3}He$ to $\bar{\Lambda}^3H$ should be proportional to $(\bar{p}/p)^3 \bar{\Lambda}$, as Eq.(6). The calculated $\bar{^3}He/\bar{\Lambda}^3H$ ratio is consistent with the interpretation that the $\bar{^3}He$ and $\bar{\Lambda}^3H$ are formed by coalescence of $(\bar{\Lambda} + p + n)$ and $(\Lambda + p + n)$, respectively. And then the ratios $d$ to $d$ are consistent with $(\bar{p}/p)^2$, the ratios $\bar{^3}He/\bar{^3}He$ is approximately the same as $(\bar{p}/p)^3$, and the ratios $\bar{^3}He/\bar{^3}He$ is just approximately the $(\bar{p}^2\bar{\Lambda})/(p^2\Lambda)$. The simulation results ($d/d$) in our model are found to be in agreement with the experimental data from AL-
ICE experimental in pp collisions at $\sqrt{s} = 900$ GeV, 2.76 TeV and 7 TeV. Furthermore, the model predictions of $\Lambda H/3H$, $\Lambda^3He/3He$, $\Lambda^3H/3H$, and $\Lambda^3He/3He$ are also presented in Table II.

To further illustrate the mass and/or c.m. energy dependence of light nuclei and anti-nuclei production, Fig. 3 gives the integrated yield distributions of light nuclei ($p, d, ^3He$) and anti-nuclei ($\bar{p}, \bar{d}, ^3\bar{He}$), as the different atomic mass number $A$ ($A = 1$ to 3) in different c.m. energy of 0.9, 2.76, and 7 TeV, respectively. The hollow points represent our results computed using PACIAE+DCPC model in the mid-rapidity pp collisions at the LHC energy, with $pt < 3.0$ GeV and $|y| < 0.5$. The solid points show the data results of the ALICE experiment [8, 35–39]. The figure 3 shows that the yields of light nuclei and anti-nuclei decrease rapidly, as the atomic mass number $A$ increase. The integrated yield spans almost 6-orders of magnitude with striking exponential behavior. Fig. 3 shows that PACIAE+DCPC model results are in good agreement with the experimental data.

In order to compare (anti-)nuclei with (anti-)hypernuclei, we introduce the strangeness population factor [43, 44]

$$s_3 = \left(\frac{\Lambda}{\Lambda^3 H} \times p\right)/\left(\frac{H^3 e}{3He} \times \Lambda\right)$$

$$\overline{s}_3 = \left(\frac{\bar{\Lambda}}{\Lambda^3 H} \times \bar{p}\right)/\left(\frac{H^3 e}{3He} \times \bar{\Lambda}\right).$$

where, no $\Lambda$ decay to proton contribution. The ratio $S_3$ is sensitive to the local baryon-strangeness correlation [43–47], hence it can provide a possible chance to study the nature of matter created in the high energy collisions [48, 49]. The $S_3(s_3)$ values computed by the PACIAE+DCPC model for different c.m. energies of 900 GeV, 2.76 TeV and 7 TeV are shown in Fig. 4. These values are compared with the data from STAR [2], ALICE [43], and E864 [44]. The present results in pp collisions show the values of $S_3(s_3)$ about 0.7 – 0.8. These results are consistent with the experiment [2, 43, 44] within uncertainties.

### IV. CONCLUSION

The production of light (anti-)nuclei and (anti-)hypertriton is investigated using the dynamically constrained phase space coalescence model (DCPC), relied on the final state hadrons created by the parton and hadron cascade PACIAE model in pp collisions at the c.m. energy of 900 GeV, 2.76 TeV, and 7 TeV, with $pt < 3$ GeV/c and $|y| < 0.5$ acceptances. The calculation includes yield, yield ratio, transverse momentum distribution of $d, \bar{d}, ^3He, ^3\bar{He}, ^3H, \Lambda H$. The results of our calculations show significant dependence of the c.m. energy on the yields, ratios, and the transverse momentum distribution of $d, \bar{d}, ^3\bar{He}, ^3He, \Lambda H, \Lambda^3 H$. When the c.m. energy increases from 900 GeV to 7 TeV, the yield of light (anti-)nuclei and (anti-)hypertriton computed using PACIAE+DCPC simulations increases. The ratio of anti-deuteron to deuteron and $^3\bar{He}$ to $^3He$, and $^3\bar{He}$ to $^3H$ approaches 1 as the c.m. energy increases, indicating nuclei and anti-nuclei species are produced with similar abundance at LHC energies. We also found that the yields of light nuclei and anti-nuclei all decrease rapidly when the atomic mass number $A$ increase. The ALICE data of $d$ and $\bar{d}$ yields, ratios, and the transverse momentum distribution are well reproduced by the corresponding PACIAE+DCPC results. The yields, ratios, and the transverse momentum distribution of $^3He, ^3\bar{He}, \Lambda H, \Lambda^3 H$ was predicted by PACIAE in the mid-rapidity pp collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV. The strangeness population factor $S_3 = (\frac{\Lambda^3 H}{H^3 He})/(\Lambda/p)$ for matter and antimatter with the helium-3 is calculated to be about 0.7 – 0.8, which is compatible with the experimental data.

### V. ACKNOWLEDGMENT

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