Simulation of hypertriton productions in Pb-Pb collisions at ALICE energies using PACIAE model

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Abstract. In this work, the parton and hadron cascade model (PACIAE) and the dynamically constrained phase space coalescence model (DCPC) are used to investigate the production of hypertriton and antihypertriton in Pb-Pb collisions at $\sqrt{s_{NN}} = 0.9$, 2.76, 5.02 and 7 TeV. The model parameters are fixed by comparing the PACIAE result with ALICE data on Λ and p productions in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Then, the predetermined parameters are used in PACIAE and DCPC models to simulate the hypertriton production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The hypertriton and antihypertriton yields in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 0.9, 5.02 and 7 TeV are predicted in this work.

1. Introduction

Hypernucleus is a nucleus composed of at least one hyperon, a kind of baryons containing one or more strange (s) quarks, for example, the Λ, Σ, Ξ and Ω particles. The simplest hypernucleaus is hypertriton ${}^3_\Lambda H$. The study of hypernuclei productions play the most important role in theoretically and experimentally probing the hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions [1]. Moreover, the study of hypernuclei may provide information of the structure of neutron stars [2], which are believed consist of hyperons and nucleons [3, 4].

The production of single Λ hypernuclei and double $\Lambda\Lambda$ hypernuclei have been studied in many experiments. The $\Lambda\Lambda$ hypernucleus, ${}^4_{\Lambda\Lambda}H$, was explored by the experiment E906 at BNL−AGS (Brookhaven National Laboratory− Alternating Gradient Synchrotron, USA) [5]. In March 2010, the STAR Collaboration at RHIC announced the discovery of the anti-hypertriton ${}^3_\Lambda\overline{H}$ ($\bar{n} + \bar{p} + \bar{\Lambda}$) in the relativistic heavy ion collisions (Au+Au) at $\sqrt{s_{NN}} = 200$ GeV [3, 4, 6]. Note that the (anti) hypertriton (${}^3_\Lambda\overline{H}$) ${}^3_\Lambda H$ is the lightest type of (anti) hypernucleus consists of a (anti) proton, a (anti) neutron and a (anti) Λ [7]. The hypertriton and anti-hypertriton productions at STAR have been investigated by using the years 2004 and 2007 Au+Au data and identified via the secondary vertex of ${}^3_\Lambda H \longrightarrow {}^3He + \pi^-$ and ${}^3_\Lambda\overline{H} \longrightarrow {}^3\overline{He} + \pi^+$, respectively.

Recently, the hypertriton ${}^3_\Lambda H$ and anti-hypertriton ${}^3_\Lambda\overline{H}$ were produced in Pb-Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV at ALICE [8], using the first run data of LHC heavy ion collisions. The hypernuclei were recovered by calculating the invariant mass of the daughter particles of the reactions ${}^3_\Lambda H \longrightarrow {}^3He + \pi^-$ and ${}^3_\Lambda\overline{H} \longrightarrow {}^3\overline{He} + \pi^+$. Suggested in Ref. [8] the hypertriton can be observed in the channels ${}^3_\Lambda H \longrightarrow \pi^-(\pi^0) + {}^3He({}^3H)$, ${}^3_\Lambda H \longrightarrow \pi^-(\pi^0) + d + p(n)$ and

${}^3_\Lambda H \longrightarrow \pi^-(\pi^0)+p+n+p(n)$ while the production of anti-hypertriton can be considered via the anti particle production of the above channels. Since the production of hypertriton in Ref. [8] is limited to $\sqrt{s_{NN}} = 2.76$ TeV only, it is worthy to predict in this work for the production of hypertriton at other energies.

2. PACIAE and DCPC models

The PACIAE version 2.0 (PACIAE2.0) and DCPC models are used to investigate the productions of hypertriton and light nuclei in Pb-Pb collisions at LHC energy. The PACIAE model and DCPC model are briefly described in the section.

2.1. PACIAE model

A parton and hadron cascade model (PACIAE) [5-14] is based on PYTHIA, which can be used to simulate the nucleon-nucleon collisions and nucleus-nucleus collisions. The PACIAE2.0 consists of three versions as follows: PACIAE2.0a describing the relativistic elementary collisions (pp, $\bar{\text{p}}$p or e^+e^-); PACIAE2.0b as well as PACIAE2.0c describing the relativistic nucleus-nucleus (A+B, including p+A) collisions. The PACIAE2.0b which is appropriate to Pb-Pb reactions is chosen in this work. The PACIAE2.0b model contains 4 stages as follows:

1. In the parton initialization stage, a nucleus-nucleus collision is decomposed into binary nucleon-nucleon (NN) collisions according to the collision geometry and total NN cross section. Then the NN collision is decomposed into parton-parton collisions. The partons can be described by parton distribution function. Moreover, after the hadron-hadron (hh) collision the parton initial stage is considered as QGP (Quark Gluon Plasma) which consists of quarks, anti-quarks and gluons as well as a few hadronic remnants.

2. In the parton evolution (parton rescattering) stage, the scattering of partons is considered by using parton-parton interaction cross sections. The parton rescattering will be simulated until all parton-parton collisions are exhausted.

3. In the hadronization stage, the partonic matter is hadronized to hadron after parton rescattering by string fragmentation and/or coalescence model. In this stage, 2 partons coalesce a meson and 3 partons coalesce a baryon.

4. In the hadron evolution (hadron rescattering) stage, the formed hadrons scatter as the usual two-body collisions. While, the among $\pi, n, p, k, \rho(\omega), \Delta, \Lambda, \Sigma, \Psi, \Omega, J/\psi$ and their antiparticles are considered after hadron rescattering [9-12]. This particle list is then constructed by the above hadrons.

2.2. DCPC model

The final products of PACIAE are hadrons as mentioned in the previous subsection, but the objective of this work is to study the production of hypertriton which consists of $(p + n + \Lambda)$. Thus it is necessary to construct the hypertriton from the produced p, n and Λ.

In this subsection the dynamically constrained phase space coalescence model (DCPC) proposed in [15, 16] is introduced. The DCPC can be used to investigate the production of light nuclei and hypertriton in the framework of quantum statistical mechanics. Due to the uncertainty principle, the position $\vec{q} \equiv$ (x, y, z) and momentum $\vec{p} \equiv (p_x, p_y, p_z)$ of a particle cannot be exactly determined in the 6-dimension phase space, that is,

$$\Delta\vec{q}\Delta\vec{p} \sim h^3, \tag{1}$$

where h is the Planck's constant. It means that the particle locates somewhere with in a 6-dimension quantum box or state with a volume of $\Delta\vec{q}\Delta\vec{p}$. In another word, one may say that a particle state holds a volume of h^3 in the 6-dimension phase space. Therefore the yield of ${}^3_\Lambda H$

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in the DCPC is estimated to be

$$Y_{^3_\Lambda H} = \int ... \int \delta_{123} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2 d\vec{q}_3 d\vec{p}_3}{h^9}, \tag{2}$$

with

$$\delta_{123} = \begin{cases} 1 \text{ if } & 1 \equiv p,\ \ 2 \equiv n,\ \ 3 \equiv \Lambda, \\ & m_0 - \Delta m \leq m_{inv} \leq m_0 + \Delta m, \\ & q_{12} \leq D_0,\ \ q_{13} \leq D_0,\ \ q_{23} \leq D_0, \\ 0 \text{ otherwise}, & \end{cases} \tag{3}$$

where m_0 and D_0 represent the rest mass and diameter of $^3_\Lambda H$, respectively. Δm indicates the allowed mass uncertainty and $q_{ij} = |\vec{q}_i - \vec{q}_j|$ is the distance between particle i and j. The invariant mass, m_{inv}, in the DCPC is

$$m_{inv} = [(E_1 + E_2 + E_3)^2 - (\vec{p}_1 + \vec{p}_2 + \vec{p}_3)^2]^{1/2}, \tag{4}$$

where (E_1, E_2, E_3) and $(\vec{p}_1, \vec{p}_2, \vec{p}_3)$ are the energies and momenta of particles p, n and Λ, respectively.

The DCPC together with PACIAE will be used to study the production of hypertriton in Pb-Pb collisions at LHC energies.

3. Prediction of hypertriton production

In order to simulate inelastic Pb-Pb collisions using PACIAE model, suitable values of the model parameters K, $parj(1), parj(2)$ and $parj(3)$ are required. The meaning of each parameter is as follows:

- K is the string tension assumed to be ($\kappa \approx 1$ GeV/fm ≈ 0.2 GeV^2)
- $parj(1)$ is the suppression of diquark-antidiquark pair production compared with quark-antiquark production
- $parj(2)$ is the suppression of s quark pair production compared with u or d pair production
- $parj(3)$ is the extra suppression of strange diquark production compared with the normal suppression of s quark.

The above parameters may be fixed by comparing the PACIAE result with the ALICE experimental data on Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [17, 18]. Here the yields of proton (p) and (Λ) are considered because they are the components of hypertriton ($p+n+\Lambda$). In order to get the best fit, sets of the parameters are employed as the input for PACIAE. It is finally found that the parameter set of $K = 3, parj(1) = 0.13, parj(2) = 0.58$ and $parj(3) = 0.70$ give the best fit to both the Λ and p productions in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV.

The comparison between the PACIAE results with the mentioned parameters set and ALICE experimental data for Λ and p are displayed in figure 1. Note that the Λ and p are produced in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with mid-rapidity |y| <0.5, 0.6 $< p_T <$ 12 GeV/c (for Λ) and 0.3 $< p_T <$ 4.6 GeV/c (for p).

By using the fitted parameters, the hypertriton and antihypertriton productions in Pb-Pb collsions are simulated in PACIAE+DCPC models at the center-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV with 10%−50% centrality bins. The allowed mass uncertainties Δm are varied from 0.00005 to 0.1 GeV/c^2 and shown in table 1. Shown in the table are also the yields of hypertriton and antihypertriton at each allowed mass uncertainty.

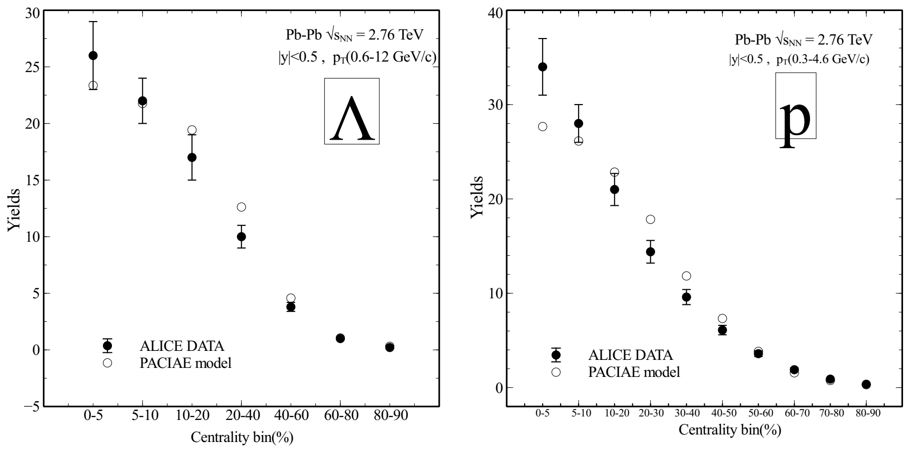

Figure 1. Comparison on the yields of Λ (left) and p (right) between ALICE experimental data and PACIAE.

Table 1. The yields of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with centralities 10%−50%.

Δm	${}^{3}_{\Lambda}H$		${}^{3}_{\Lambda}\overline{H}$	
	PACIAE+DCPC	ALICE [19]	PACIAE+DCPC	ALICE [19]
no limit	21.17	-	15.45	-
0.1	10.65	-	5.73	-
0.01	0.19	-	0.06	-
0.001	2.20×10^{-5}	-	0.68×10^{-5}	$0.85\pm0.25\times10^{-5}$
0.0008	1.05×10^{-5}	$1.31\pm0.37\times10^{-5}$	0.25×10^{-5}	-
0.0001	0	-	0	-
0.00015	0	-	0	-
0.00005	0	-	0	-

As reviewed in [19], the theoretical decay branching ratio of the ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ is 25%. Therefore, the PACIAE+DCPC results are weighted by multiplying 0.25, considering that the yield of ${}^{3}_{\Lambda}H$ at ALICE is measured in the decay channel ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$.

It is found in table 1 that the yield of hypertriton in the PACIAE+DCPC model at the allowed mass uncertainty Δm around 0.0008 GeV/c^2 is consistent with the experimental data while the yield of antihypertriton is in line with the experimental data with Δm around 0.001 GeV/c^2. However, the PACIAE+DCPC results in this work are very preliminary. To get more accurate results, one may need to use smaller Δm steps though it could be very time consuming.

As seen in table 1 the PACIAE+DCPC results at $\Delta m = 0.0008$ GeV/c^2 and $\Delta m = 0.001$ GeV/c^2 are respectively in line with ALICE experimental data for hypertriton and antihypertriton, thus these two Δm are applied to predict the productions of hypertriton and hypertriton in Pb-Pb collsions at $\sqrt{s_{NN}} = 0.9$, 5.02 and 7 TeV.

Table 2 shows that the hypertriton and antihypertriton yields at $\sqrt{s_{NN}} = 0.9$, 2.76, 5.02 and 7 TeV with centrality bins 5%−10% and 10%−50%. These results are plotted and shown in figure 2. At the same energy, both the hypertriton and antihypertriton yields decrease with increasing centrality due to the decrease of the yields of p and Λ with increasing centrality, as seen in figure 1. With the same centrality bin and same energy, the yield of hypertriton is higher than the one of antihypertriton, which is consistent with the ALICE experimental data at $\sqrt{s_{NN}}$

Table 2. The yield of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 0.9, 2.76, 5.02 and 7 TeV with centrality bins 5%−10% and 10%−50%.

	${}^{3}_{\Lambda}H$		${}^{3}_{\Lambda}\overline{H}$	
$\sqrt{s_{NN}}$ (TeV)	5%−10%	10%−50%	5%−10%	10%−50%
0.9	2.16×10^{-4}	5.47×10^{-5}	1.31×10^{-4}	3.00×10^{-5}
2.76	1.33×10^{-4}	4.21×10^{-5}	8.01×10^{-5}	2.73×10^{-5}
5.02	4.75×10^{-5}	3.43×10^{-5}	3.48×10^{-5}	1.96×10^{-5}
7	3.06×10^{-5}	1.99×10^{-5}	2.35×10^{-5}	1.59×10^{-5}

= 2.76 TeV as shown in table 1. At the same centrality bin, the yields of both hypertriton and antihypertriton decrease with increasing energy.

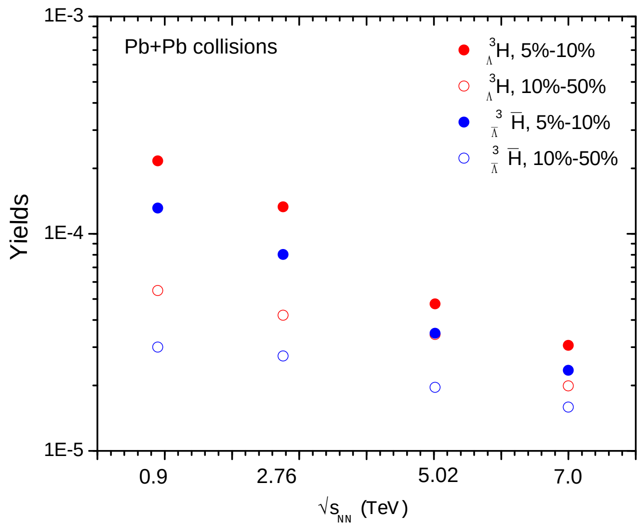

Figure 2. Plot of the yield of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 0.9, 2.76, 5.02 and 7 TeV with centrality bins 5%−10% and 10%−50%.

4. Conclusions

In this work the productions of hypertriton and antihypertriton in Pb-Pb collisions at $\sqrt{s_{NN}} = 0.9, 2.76, 5.02$ and 7 TeV are studied in the PACIAE plus DCPC model, where all the model parameters are pre-determined by fitting the model results of Λ and p productions to the ALICE data.

The theoretical results of the hypertriton and antihypertriton yields in Pb-Pb collsions at $\sqrt{s_{NN}}$ = 2.76 TeV with centrality 10%−50% at Δm = 0.0008 GeV/c^2 and Δm = 0.001 GeV/c^2 respectively are in line with ALICE experimental data.

Δm = 0.0008 GeV/c^2 and Δm = 0.001 GeV/c^2 are employed in the PACIAE plus DCPC model to predict the hypertriton and antihypertriton productions in Pb-Pb collisions at 0.9, 5.02 and 7 TeV with centrality bins of 0%−10% and 10%−50%. It is found that at the same energy, both the hypertriton and antihypertriton yields decrease with increasing centrality. With the same centrality bin and same energy, the yield of hypertriton is higher than the one of antihypertriton. At the same centrality bin, the yields of both hypertriton and antihypertriton decrease with increasing energy.

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