On pseudorapidity distribution in \( p\)-\( Pb \) and \( Xe\)–\( Xe \) collisions at high energy based on the three-source Landau hydrodynamic model

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Abstract: We used the three-source Landau hydrodynamic model to describe the pseudorapidity distributions of charged particles produced in \( p\)-\( Pb \) collisions and \( Xe\)–\( Xe \) collisions at LHC energies. The research results fit well with the experimental data which are measured by ALICE collaboration at LHC. The related parameters are obtained and analyzed. Moreover, in most cases, we consider that the central source undergoes the change of the hadronic gas to QGP liquid.

Keywords: Pseudorapidity distributions; Landau hydrodynamic model; Speed of sound

1. Introduction

There is a high interest in heavy-ion collisions where a new state of matter is considered to be created. This new matter refers to the quark–gluon plasma (QGP). It promotes the development of theoretical and experimental research of the high-energy heavy-ion collisions. And, it makes the high-energy heavy-ion collisions become an important field in modern nuclear physics. Since the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) run successfully, a large number of experimental data have been published. These new experimental data push the work of searching QGP to a big step forward. People expected the high-energy heavy-ion collisions would provide abundant information to study in the future.

With the rapid development of science and technology, collision energy has been greatly improved. Recently, ALICE collaboration has announced the experiment data of \( p\)-\( Pb \) collisions at \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV and \( Xe\)–\( Xe \) collisions at \( \sqrt{s_{\text{NN}}} = 5.44 \) TeV [1, 2]. These experiment data have aroused us great concern, and we believe that a lot of exciting research results will be reported by particle physicists.

In our previous work, we have built a new model which is based on the Landau hydrodynamic model, and we called it the three-source Landau hydrodynamic model. We have used the three-source Landau hydrodynamic model to systematically describe many (pseudo)rapidity distributions, such as the pseudorapidity distributions of charged particles produced in \( Au\)–\( Au \) collisions at \( \sqrt{s_{\text{NN}}} = 19.6, 62.4, 130 \) and 200 GeV, \( Cu\)–\( Cu \) collisions at \( \sqrt{s_{\text{NN}}} = 22.4, 62.4 \) and 200 GeV, \( Pb\)–\( Pb \) collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \) TeV [3], and the proton rapidity distributions in \( Au\)–\( Au \) collisions at \( \sqrt{s_{\text{NN}}} = 2.4, 3.1, 3.6, 4.1 \) and 200 GeV, \( Pb\)–\( Pb \) collisions at \( \sqrt{s_{\text{NN}}} = 8.8 \) GeV, and the net-proton rapidity distributions in \( Au\)–\( Au \) collisions at \( \sqrt{s_{\text{NN}}} = 5 \) and 200 GeV, \( Pb\)–\( Pb \) collisions at \( \sqrt{s_{\text{NN}}} = 16.8 \) and 17.3 GeV [4]. The energy range of our researches covers from AGS to RHIC. Research results showed that the calculate results of our new model fit well with all experimental data which are used to study. In this paper, we will continue using the new model to describe the pseudorapidity distributions of charged particles produced in \( p\)-\( Pb \) collisions and \( Xe\)–\( Xe \) collisions at LHC energies. With this work, we could conclude the new model whether suits for higher energy region than before researched or not. If the new model could apply to the high-energy region, we expect to extract the speed of sound parameter for each emission source.

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2. The model

As mentioned in Introduction, we use the new model [4] to describe the pseudorapidity distributions of charged particles produced in p–Pb collisions at $\sqrt{s_{\text{NN}}}=8.16$ TeV and Xe–Xe collisions at $\sqrt{s_{\text{NN}}}=5.44$ TeV. These experimental data are measured by ALICE collaboration [1, 2]. In order to have an overall understanding of the model and maintain the coherence and unity of this paper, we will give a short and clear description of our model.

Enlightened by the participant-spectator model [5] and the three-fireball model [6, 7], we could regard the pseudorapidity distributions of charged particles as the results of the joint contributions by three emission sources. The three emission sources are the central source, the target source, and the projectile source. These three emission sources locate in the mid-pseudorapidity region, the backward pseudorapidity region, and the forward pseudorapidity region, respectively [3, 4]. In addition, in the three emission sources which are our built, we think the target (projectile) source has a little contribution to the pseudorapidity distributions. And, the target (projectile) source is a revised term for the pseudorapidity distributions from the central source.

According to the Landau hydrodynamic model [8] and some relevant literature [9–11], we found that the rapidity distributions of charge particles can be described by a Gaussian form of the Landau solution:

$$\frac{dN_{\text{ch}}}{dy} = \frac{N_0}{\sqrt{2\pi}\sigma_X} \exp\left(-\frac{(y - y_X)^2}{2\sigma_X^2}\right)$$

(1)

In general, there are some differences between the rapidity ($y$) distribution and the pseudorapidity ($\eta$) distribution. However, we could use approximately $y \approx \eta$ at very high energy such as RHIC and LHC energies. So, the pseudorapidity distribution of charged particles produced in any one of the three emission sources [12–15] can be described by:

$$\frac{dN_{\text{ch}}}{d\eta} = \frac{N_0}{\sqrt{2\pi}\sigma_X} \exp\left(-\frac{(\eta - y_X)^2}{2\sigma_X^2}\right)$$

(2)

where $N_0$ is the normalization constant, $\sigma_X$ is the distribution width, and $y_X$ denote the peak position. Moreover, the $X$ indicates the central source (C), target source (T), and projectile source (P). The final experimental result can be expressed as a sum weighted by the three Gaussian form of the Landau solution:

$$\frac{dN_{\text{ch}}}{d\eta} = \frac{N_0}{\sqrt{2\pi}\sigma_X} \exp\left(-\frac{(\eta - y_X)^2}{2\sigma_X^2}\right) + k_T \exp\left(-\frac{(y - y_T)^2}{2\sigma_T^2}\right) + k_C \exp\left(-\frac{(y - y_C)^2}{2\sigma_C^2}\right),$$

(3)

where $k_X$ means the contribution ratio of each emission source, and $y_C = 0$. Equation (3) is the concrete expression for the three-source Landau hydrodynamic model.

According to the literature [11], we obtained the relationship between the width of pseudorapidity distributions and the speed of sound. The relation formula is:

$$\sigma_X = \sqrt{\frac{8}{3} \left[ 1 - c_s^4(X) \right] \ln \left( \frac{\sqrt{s_{\text{NN}}}}{2m_N} \right)},$$

(4)

where $m_N$ denotes the rest mass of a proton and $\sqrt{s_{\text{NN}}}$ means the center of mass energy. For this relationship, the squared speed of sound $c_s^4(X)$ can be expressed as:

$$c_s^4(X) = \frac{1}{3\sigma_X^2} \left[ -16 \ln^2 \left( \frac{\sqrt{s_{\text{NN}}}}{2m_N} \right) + 9\sigma_X^4 - 4 \left( \frac{\sqrt{s_{\text{NN}}}}{2m_N} \right)^2 \right].$$

(5)

We could figure out the value of the squared speed of sound from the above equation.

3. Results and discussion

Figure 1 shows the pseudorapidity distributions of charged particles produced in p–Pb collisions for seven kinds of centrality at $\sqrt{s_{\text{NN}}}=8.16$ TeV. In the seven figures, the black solid points represent the experimental data measured by ALICE collaboration obtained from the literature [1], and the red curves are our results calculated by the three-source Landau hydrodynamic model. For an asymmetric nuclear collision, we think the contribution ratio, distribution width and peak position for the central source, target source and projectile source are different. About the peak position of the three sources, we have $y_T < y_C < y_P$ and $y_C = 0$ at the pseudorapidity region. One can see that our calculated results accord with the experimental data. In the calculation, we extracted the free parameter values of the contribution ratio ($k_X$), distribution width ($\sigma_X$) and peak position ($y_X$). Moreover, based on Eq. (4), we obtained the values of $c_s^4(X)$. The values of free parameters, $c_s^4(X)$ and
\( \chi^2 \) per degree of freedom (\( \chi^2 / \text{dof} \)) are listed in Table 1. In the range of errors, the contribution ratio and distribution width for central source and target source (\( k_C, k_T, \sigma_C, \) and \( \sigma_T \)) show a slight fluctuation with the increase in centrality, and the values of them on the centrality percentage 80–100% are bigger than other centrality percentage. The peak position and distribution width for target source and projectile source (\( y_T, y_P, \sigma_T, \) and \( \sigma_P \)) are gradually becoming symmetry with the increase in centrality.

Figure 2 is similar to Fig. 1 but shows the results in Xe–Xe collisions at \( \sqrt{s_{\text{NN}}} = 5.44 \) TeV. The black solid points represent the experimental data measured by ALICE collaboration obtained from the literature [2]. The red curves are our results calculated by the three-source Landau hydrodynamic mode. For a symmetric nuclear collision, we think the values of contribution ratio and distribution width for target source and projectile source are equal (\( k_T = (1 - k_C) / 2 \) and \( \sigma_T = \sigma_P \)). We can see that our calculated results fit the experimental data well. We have extracted the values of free parameters and calculated the values of \( c_2^X(X) \) for three types of emission source. Table 2 presents the values of free parameters, \( c_2^X(X) \) and \( \chi^2 / \text{dof} \).
In the range of errors, $k_C$ decreased slightly with the increase in centrality, $\sigma_C$ and $\sigma_T$ ($\sigma_P = \sigma_T$) increased with the centrality.

From the literature [16], we learn about some new approaches to study the pseudorapidity distributions in high-energy collisions, such as the HRG approach and the Carruthers approach. Enlightened by literature [16], as a comparison, we use the Gaussian normal distribution function [16] to analyze the (pseudo)rapidity distributions of Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. In Fig. 2, the blue dotted lines are our results calculated by the Gaussian normal distribution function. For a symmetric nuclear collision, we think the value of $a_1$ is zero. We list the values of free parameters ($a_0$ and $a_2$) in Table 3. We noticed that the results fit well with the experimental data at the low centrality. But the trend of dotted lines is not suitable for experimental data at the high collision centrality region. This phenomenon presented the limitation of the Gaussian normal distribution function.

To see the relationship between $\sigma_X$ and centrality, we plot the $\sigma_X$ values listed in Tables 1 and 2 in Fig. 3. In the panel, the symbols represent the data listed in Tables 1 and 2, and the lines are linear fitting functions. The intercepts, slopes, and $\chi^2$/dof corresponding to the lines in Fig. 3 are listed in Table 4.

Base on Fig. 3, we can see clearly about the conclusions obtained from Figs. 1 and 2. In the range of errors, for the values of $\sigma_C$, there is a little difference between the p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV and the Xe–Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV. $\sigma_C$ of the Xe–Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV is smaller than the p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV at the collision centrality percentage 0–50%. At the centrality percentage 50–100%, the values of $\sigma_C$ are approximately the same. The values of $\sigma_T$ and $\sigma_P$ of the two collision systems are different. With the increased centrality percentage, the values of $\sigma_T$ and $\sigma_P$ of the Xe–Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV do not show obvious change. For the p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV, $\sigma_T$ does not show obvious change and $\sigma_P$ shows a slight decreases when the centrality percentage increases.

In addition, we study the relationship between $c^2(C)$ and centrality. In the range of errors, we can see clearly that all values of $c^2(C)$ for p-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV and Xe–Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV are between 0.4 and 0.5. Compared to our previous work, we obtained larger values of $c^2(C)$ in this work. The phenomenon may be caused by increased collision energy. This result is consistent with the conclusion of our previous work [3, 4]. According to the literature [17] and [18], we know that for zero-shear modulus and massless particles have a relation between $c^2$ and the spatial dimension ($D$). The relationship is $c^2 = 1/D$. In our previous work, we have discussed the
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means of $c_s^2 = 1/3$ and $c_s^2 = 1/2$. From the particular values of $c_s^2$, we could analyze the properties of the matter created in heavy-ion collisions. $c_s^2 = 1/3$ implies that the value of $D$ is 3; this result expresses the properties of the matter is the ideal hadronic gas [19–23]. $c_s^2 = 1/2$ means the value of $D$ is 2; this result shows the properties of the matter is the ideal QGP liquid [19]. In this work, we extracted the values of $c_s^2(C)$ between 0.4 and 0.5, and this implies that the central source experienced a complicated phase transition process. We consider that the central source undergoes the change of the hadronic gas to QGP liquid in most cases.

4. Conclusions

From the above discussions, we obtain the following conclusions:

We have used the three-source Landau hydrodynamic model to describe the pseudorapidity distributions of charged particles produced in $p$-Pb collisions and Xe–Xe collisions at LHC energies. The modeling results are in agreement with the experimental data. The research results indicate that our model still applies to higher energy collisions than in previous.

Our results calculated by the three-source Landau hydrodynamic model show that in the range of errors, the values of $\sigma_C$ for the $p$-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV are almost the same as the Xe–Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV, and $\sigma_C$ for the two collisions do not show obvious change with the centrality. With the increased centrality percentage, the values of $\sigma_T$ and $\sigma_P$ for the Xe–Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV do not show obvious change. For the $p$-Pb collision at $\sqrt{s_{NN}} = 8.16$ TeV, $\sigma_T$ does not show obvious change and $\sigma_P$ shows a slight decrease when the centrality percentage increases. The special change of $\sigma_P$ is caused by the very asymmetric collisions.

From the pseudorapidity distributions widths, we extracted the values of square speed of sound in the two collisions. The values of $c_s^2(C)$ are between 0.4 and 0.5. This result is consistent with our previous work.

| Figure | C(%) | $k_C$ | $y_T$ | $\sigma_C$ | $\sigma_{TP}$ | $c_s^2(C)$ | $c_s^2(T/P)$ | $\chi^2$/dof |
|--------|-------|-------|-------|------------|--------------|-------------|---------------|--------------|
| Fig. 2(a) | 0–2.5 | 0.822 ± 0.023 | -4.687 ± 0.237 | 3.432 ± 0.348 | 1.908 ± 0.098 | 0.444 ± 0.060 | 0.166 ± 0.016 | 3/4 |
| Fig. 2(b) | 2.5–5 | 0.823 ± 0.020 | -4.780 ± 0.240 | 3.435 ± 0.350 | 1.903 ± 0.092 | 0.445 ± 0.061 | 0.166 ± 0.015 | 2/4 |
| Fig. 2(c) | 5–7.5 | 0.820 ± 0.022 | -4.688 ± 0.235 | 3.445 ± 0.350 | 1.907 ± 0.094 | 0.447 ± 0.060 | 0.166 ± 0.016 | 6/4 |
| Fig. 2(d) | 7.5–10 | 0.818 ± 0.023 | -4.630 ± 0.220 | 3.478 ± 0.353 | 1.902 ± 0.092 | 0.452 ± 0.061 | 0.166 ± 0.015 | 3/4 |
| Fig. 2(e) | 10–20 | 0.819 ± 0.024 | -4.596 ± 0.219 | 3.538 ± 0.355 | 1.907 ± 0.097 | 0.463 ± 0.060 | 0.166 ± 0.016 | 4/4 |
| Fig. 2(f) | 20–30 | 0.826 ± 0.024 | -4.294 ± 0.224 | 3.689 ± 0.351 | 1.906 ± 0.096 | 0.474 ± 0.058 | 0.166 ± 0.016 | 6/4 |
| Fig. 2(g) | 30–40 | 0.792 ± 0.020 | -3.980 ± 0.225 | 3.689 ± 0.354 | 1.930 ± 0.100 | 0.488 ± 0.058 | 0.170 ± 0.017 | 7/4 |
| Fig. 2(h) | 40–50 | 0.772 ± 0.018 | -3.887 ± 0.232 | 3.703 ± 0.360 | 1.948 ± 0.103 | 0.490 ± 0.058 | 0.173 ± 0.017 | 6/4 |
| Fig. 2(i) | 50–60 | 0.762 ± 0.020 | -3.806 ± 0.222 | 3.722 ± 0.362 | 1.925 ± 0.095 | 0.493 ± 0.058 | 0.169 ± 0.016 | 8/4 |
| Fig. 2(j) | 60–70 | 0.742 ± 0.018 | -3.925 ± 0.225 | 3.705 ± 0.358 | 1.917 ± 0.098 | 0.490 ± 0.058 | 0.168 ± 0.016 | 9/4 |
| Fig. 2(k) | 70–80 | 0.735 ± 0.020 | -4.025 ± 0.235 | 3.735 ± 0.360 | 1.920 ± 0.100 | 0.495 ± 0.058 | 0.168 ± 0.016 | 8/4 |
| 2(l) | 80–90 | 0.730 ± 0.023 | -4.302 ± 0.242 | 3.702 ± 0.358 | 1.926 ± 0.103 | 0.490 ± 0.058 | 0.169 ± 0.017 | 9/4 |
Fig. 3 The relationship of $\sigma_X$ and centrality: (a) $\sigma_{C} - C$, (b) $\sigma_{T/P} - C$, (c) $c^2_s(C) - C$, (d) $c^2_s(T/P) - C$

| Figure | Collision | Type       | Intercept  | Slope          | $\chi^2$/dof |
|--------|-----------|------------|------------|----------------|--------------|
| 3(a)   | 8.16 TeV p-Pb | $\sigma_{C}-C$ | 3.5932 ± 0.0111 | 0.0023 ± 0.0002 | 0.016/2 |
|        | 5.44 TeV Xe–Xe | $\sigma_{C}-C$ | 3.5118 ± 0.0473 | 0.0032 ± 0.0011 | 0.933/2 |
| 3(b)   | 8.16 TeV p-Pb | $\sigma_{T}-C$ | 0.7916 ± 0.0088 | 0.0009 ± 0.0002 | 0.199/2 |
|        | 5.44 TeV Xe–Xe | $\sigma_{T/P}-C$ | 1.9065 ± 0.0050 | 0.0003 ± 0.0001 | 0.128/2 |
| 3(c)   | 8.16 TeV p-Pb | $c^2_s(C)-C$ | 0.4574 ± 0.0020 | 0.0004 ± 0.0000 | 0.017/2 |
|        | 5.44 TeV Xe–Xe | $c^2_s(C/T/P)-C$ | 0.4502 ± 0.0041 | 0.0006 ± 0.0001 | 0.259/2 |
| 3(d)   | 8.16 TeV p-Pb | $c^2_s(T)-C$ | 0.0281 ± 0.0007 | 0.0001 ± 0.0000 | 0.196/2 |
|        | 5.44 TeV Xe–Xe | $c^2_s(T/P)-C$ | 0.1027 ± 0.0045 | −0.0006 ± 0.0001 | 4.273/2 |

Table 4 Values of intercepts, slopes, and $\chi^2$/dof corresponding to the lines in Figs. 3
Perhaps, this corroborates that QGP is probably produced in high-energy nuclear collisions.

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Data availability All data are quoted from the mentioned references. As a phenomenological work, this paper does not report new data.

Compliance with ethical standards Conflict of interest The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] ALICE Collaboration Eur. Phys. J. C 79 4 (2019)
[2] ALICE Collaboration Phys. Lett. B 790 35 (2019)
[3] L. N. Gao and F. H. Liu Adv. High Energy Phys. 2015 184713 (2015)
[4] L. N. Gao, F. H. Liu, and Y. Sun et al. Eur. Phys. J. A 53 61 (2017)
[5] R. Snellings New J. Phys. 13 055008 (2011)
[6] L. S. Liu and T. C. Meng Phys. Rev. D 27 2640 (1983)
[7] K. C. Chou, L. S. Liu and T. C. Meng Phys. Rev. D 28 1080 (1983)
[8] L. D. Landau Izv. Akad. Nauk SSSR: Ser. Fiz. 17 5 (1953)
[9] P. Carruthers and M. Duong-van Phys. Lett. B 41 597 (1972)
[10] P. Carruthers and M. Duong-van Phys. Rev. D 8 859 (1973)
[11] C. Y. Wong Phys. Rev. C 78 054902 (2008)
[12] Y. B. Ivanov Phys. Lett. B 721 123 (2013)
[13] Y. B. Ivanov Phys. Rev. C 87 064904 (2013)
[14] G. Wolschin Prog. Part. Nucl. Phys. 59 374 (2007)
[15] G. Wolschin J. Phys. G 40 045104 (2013)
[16] A. N. Tawfik, M. Hanafy and W. Scheinast arXiv:1911.01675 (2019)
[17] K. Y. Kim and I. Zahed J. High Energy Phys. 2008 075 (2008)
[18] E. I. Buchbinder, A. Buchel and S. E. Vázquez J. High Energy Phys. 2008 090 (2008)
[19] A. Bazavov, T. Bhattacharya and C. DeTar et al. Phys. Rev. D 90 094503 (2014)
[20] P. Castorina, J. Cleymans, and D. E. Miller et al. Eur. Phys. J. C 66 207 (2010)
[21] V. Roy and A. K. Chaudhuri J. Phys. G: Nucl. Part. Phys. 37 035105 (2010)
[22] A. Cherman, T. D. Cohen and A. Nellore Phys. Rev. D 80 066003 (2009)
[23] U. Gürsöy, E. Kiritsis and L. Mazzanti et al. Phys. Rev. L 101 181601 (2008)

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