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Transverse Mass Distributions of Strange Particles Produced in Pb-Pb Collisions at High Energies*

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Abstract: Transverse mass distributions of Λ, $\bar{\Lambda}$, and Ξ^- produced in Pb-Pb reactions at 40 and 158 AGeV are described by an expansive three-fireball model. A transverse expansion is observed in our calculation. The calculated results, by the expansive three-fireball model, are in agreement with the experimental data of NA49 Collaboration.

Key words: transverse mass; Pb-Pb collision; expansive three-fireball model

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1 Introduction

Heavy ion collisions at high energies have been interesting subjects in recent years because they can provide evidence for the production of Quark-Gluon Plasma (QGP) and study the mechanism of nuclear reactions[1-6]. In high-energy heavy-ion collisions, many strange particles including Λ, Ξ and their antiparticles are produced in final state[7]. It is highly important for us to study these strange particles because they have been proved to be a powerful tool for study of reaction dynamics in high energy heavy ion collisions and the production of QGP in the past years[8].

The transverse mass distributions (m_T) of strange particles produced in relativistic heavy ion collisions at high energies have been measured in experiment. Many international collaborations have reported the experimental data of transverse mass distributions by now. For example, NA57 Collaboration[9], NA49 Collaboration[10-12], E917 Collaboration[1] etc.. Meanwhile, much theoretical work have been done to explain these experimental data for the m_T distributions, such as the 3-fluid model[13], the blast-wave model[14].

Recently, the NA49 Collaboration[12] presented the experimental data of m_T distributions of Λ, $\bar{\Lambda}$, and Ξ^- produced in Pb-Pb collisions at 40 and 158 AGeV measured at the CERN Super Proton Synchrotron (CERN-SPS). It provides a chance to explain these experimental data by using theoretical model.

The fireball model in high-energy nucleus-nucleus collisions has been supposed for more than 30 a. There are the one-fireball model[15], the three-fireball model[16-20], the four-fireball model[21], etc.. Actually, the three-fireball model and the four-fireball model are the extension of the one-fireball model. In present work, we use the three fireballs with a transverse expansion[22] to describe the transverse mass distributions of strange particles in heavy-ion collisions at high energies. To

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avoid the complex calculation in the analytic method, we will use the Monte Carlo method to calculate the transverse mass spectra and then compare with the NA49 experimental data[12].

2 The model

According to the three-fireball model in high-energy hadron hadron collisions[16—20], LIU et al. have developed an expansive three-fireball model to describe the (pseudo) rapidity distributions of charged particles produced in nucleus-nucleus collisions over an energy range from 1 *A*GeV to 100 *A*TeV[22]. In a high-energy hadron-hadron collision, a projectile fireball, a central fireball, and a target fireball are formed[16—20]. A lot of projectile fireballs, central fireballs and target fireballs are formed in heavy ion collisions at high energies[16—20]. In the rapidity space, different fireballs stay at different rapidity region. Generally speaking, the projectile fireballs, the central fireballs and the target fireballs are distributed in the high rapidity region, the middle region and the low rapidity region, respectively. We regard the projectile fireballs formed in high-energy heavy-ion collisions as a big projectile fireball (P'), and we regard the central fireballs and target fireballs as a big central fireball (C') and a big target fireball (T'), respectively.

In the fireball rest frame, the particles from each fireball (P', C', or T') is assumed to emit isotropically. Let the beam direction be the *oz* axis. As in Maxwell's ideal gas model, the three components (P_x, P_y and P_z) of particle momentum in the fireball rest frame are assumed to obey Gaussian distribution having the same width σ. Considering the expansions of the fireballs in the transverse directions due to interactions among them, the final state transverse momentum in the fireball rest frame can be written as[22]

$$p'_{\mathrm{T}} = k p_{\mathrm{T}}, \tag{1}$$

where k denotes the transverse expansive strength. $k>1$ means that there is an transverse expansion and $k=1$ means that there is no expansion.

The final state transverse mass in the center-of-mass frame or the laboratory frame can be written as

$$m_{\mathrm{T}} = \sqrt{p'^{2}_{\mathrm{T}} + m_0^1}\ , \tag{2}$$

because the transverse mass is invariant in the fireball frame, the laboratory frame and the center-of-mass frame. The m_0 in expression (2) is the rest mass of a particle.

In the Monte Carlo method, let r_1, r_2, r_3 and r_4 stand for the even random variables distributed in [0, 1]. We have

$$p_x = \sqrt{-2\ln r_1}\cos(2\pi r_2)\sigma \tag{3}$$

and

$$p_y = \sqrt{-2\ln r_3}\cos(2\pi r_4)\sigma. \tag{4}$$

According to Eqs. (1)—(4), the transverse mass can be written as

$$m_{\mathrm{T}} = \Big\{ k^2\sigma^2[(-2\ln r_1)\cos^2(2\pi r_2) + (-2\ln r_3)\cos^2(2\pi r_4)] + m_0^2 \Big\}^{1/2}. \tag{5}$$

From the above discussions, we can use the formula (5) to calculate the transverse mass distributions by the Monte Carlo method. In the formula (5), there are two free parameters k and σ included in the calculations of transverse mass distributions. The σ is the parameter which describes the excitation degree of emission source. In this paper, we assume that three fireballs have the same excitation degree. The transverse mass distributions, $(1/m_{\mathrm{T}})\, \mathrm{d}^2N/\mathrm{d}m_{\mathrm{T}}\mathrm{d}y$, are finally given by the statistical method, where N and y denote particle number and rapidity respectively.

According to Refs. [23—25], we know that $T=\sigma^2/\gamma m_0$, where T, γ and m_0 are the temperature of the particle emission source, the Lorentz factor, and the static mass of produced particles. Therefore, we can use the three-fireball model to investigate and calculate the temperature of the interacting system. In the calculations, we take $\gamma\approx1$. It is difficult for us to give a precise Lorentz factor for produced particles in the present work. The obtained T values are given in Table 1.

Table 1 Parameter values and χ^2 dof^{-1} values for the fits in Figs. 1—6

Particle	Energy /AGeV	Centrality (%)	k	σ /(GeV/c)	T /GeV	χ^2 dof^{-1}
Λ	40	0—5	1.28	0.54	0.26	0.246
		5—12.5	1.28	0.53	0.25	0.055
		12.5—23.5	1.3	0.53	0.25	0.545
		23.5—33.5	1.26	0.505	0.23	0.199
		33.5—43.5	1.24	0.495	0.22	0.124
	158	0—5	1.18	0.62	0.34	0.339
		5—12.5	1.25	0.57	0.29	0.0198
		12.5—23.5	1.23	0.57	0.29	0.145
		23.5—33.5	1.25	0.57	0.29	0.121
		33.5—43.5	1.18	0.54	0.26	0.274
$\bar{\Lambda}$	40	0—5	1.27	0.60	0.32	0.047
		5—12.5	1.25	0.58	0.30	0.02
		12.5—23.5	1.24	0.55	0.27	0.33
		23.5—33.5	1.15	0.59	0.31	0.343
	158	0—5	1.20	0.75	0.50	0.056
		5—12.5	1.27	0.64	0.37	0.0175
		12.5—23.5	1.18	0.59	0.31	0.108
		23.5—33.5	1.20	0.56	0.28	0.202
		33.5—43.5	1.15	0.54	0.26	0.296
Ξ^-	40	0—12.5	1.25	0.54	0.22	0.079
		12.5—33.5	1.25	0.54	0.22	0.364
	158	0—23.5	1.32	0.57	0.25	0.357
		0—12.5	1.16	0.59	0.26	0.175
		12.5—33.5	1.23	0.59	0.26	0.079
		33.5—100	1.20	0.59	0.26	0.584

3 Comparison with Experimental Data

The transverse mass distributions of Λ hyperon produced in Pb-Pb reactions at 40 AGeV, for five classes of centrality in the rapidity interval $|y|<0.4$, are shown in Fig. 1. The values of k and σ, obtained by fitting the experimental data, are shown in Table 1. In the selection of parameter values, the χ^2-testing method is used and the values of χ^2/degree of freedom (dof) are displayed in Table 1. One can see that the three fireballs with a relative strong transverse expansion ($k>1$) can describe the transverse mass distributions of Λ hyperon in 40 AGeV Pb-Pb collisions for different centralities.

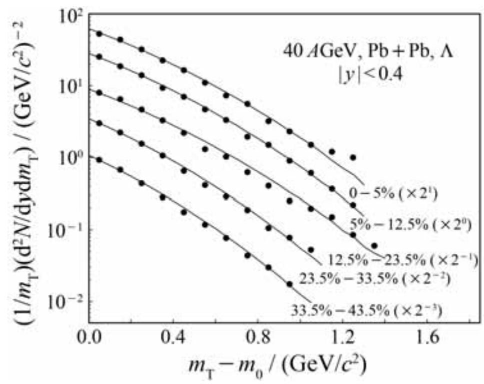

Fig. 1 The transverse mass distributions of Λ produced in Pb-Pb collisions at 40 AGeV, for the five classes of centrality in the rapidity interval $|y|<0.4$. The full circles represent the experimental data of the NA49 Collaboration[12] and the curves show our calculated results. From 0—5% to 33.5%—43.5% of the centrality, the spectra are scaled by successive powers of 2 as indicated for clarity.

Fig. 2 shows the transverse mass distributions of $\bar{\Lambda}$ produced in Pb-Pb collisions at 40 AGeV, for

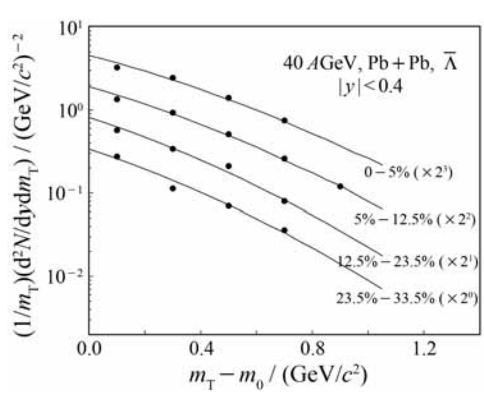

Fig. 2 The transverse mass distributions of $\bar{\Lambda}$ produced in Pb-Pb collisions at 40 AGeV for four classes of centrality in the rapidity interval $|y|<0.4$. The full circles and the curves denote the experimental data of NA49 Collaboration[12] and our results, respectively. From 23.5%—33.5% to 0—5%, the spectra are multiplied by the factor 2 for clarity.

four classes of centrality in the rapidity interval $|y|<0.4$. The method of χ^2-testing is used in the selection of parameter values. The values of k, σ, and χ^2/dof are shown in Table 1. The k and σ values are given by fitting the experimental data. We can see that our calculated results are in agreement with the experimental data in high energy heavy ion collisions.

In Fig. 3, the transverse mass distributions of Ξ^- produced in Pb-Pb collisions at 40 AGeV, for two classes of centrality in the rapidity interval $|y|<0.5$, are given. In the selection of parameter values, the method of χ^2-testing is used and the values of k, σ, and χ^2/dof are shown in Table 1. One see again that our calculated results are in agreement with the experimental data in Pb-Pb collisions at 40 AGeV.

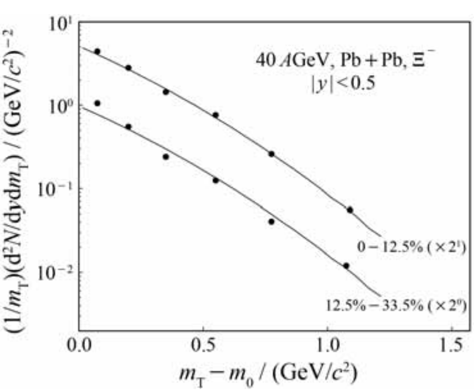

Fig. 3 The transverse mass distributions of Ξ^- produced in Pb-Pb collisions at 40 AGeV, for two classes of centrality in the rapidity interval $|y|<0.5$. The circles denote the experimental data of NA49 Collaboration[12], and the curves indicate our results. From bottom to top, the spectra are multiplied by the factor 2 for clarity.

In Figs. 4—6, the transverse mass distributions of Λ, $\bar{\Lambda}$, and Ξ^- produced in Pb-Pb reactions at 158 AGeV, for different centrality bins at mid-rapidity($\Lambda/\bar{\Lambda}$: $|y|<0.4$, Ξ^-: $|y|<0.5$), are given respectively. The values of parameters obtained by fitting the experimental data are shown in Table 1. In the selection of parameter values, the method of χ^2-testing is used and the values of

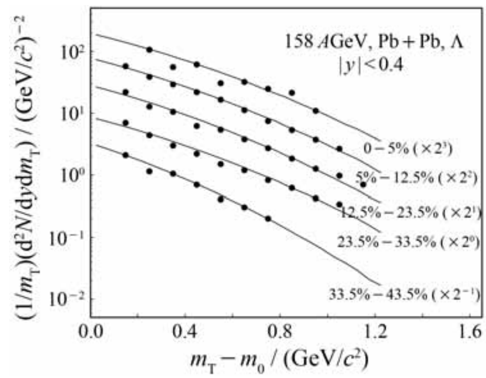

Fig. 4 The transverse mass distributions of Λ in 158 AGeV Pb-Pb collisions, for five classes of centrality in the rapidity interval $|y|<0.4$. The circles and the curves denote the experimental data of the NA49 Collaboration[12] and our results respectively. The spectra are scaled as indicated for clarity.

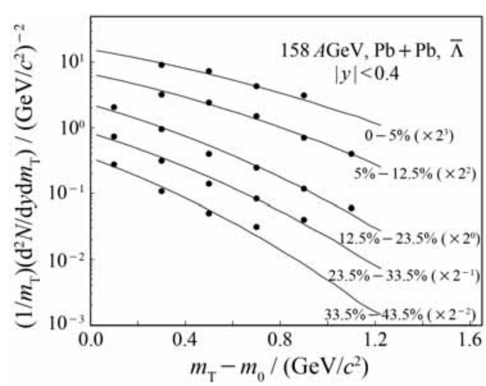

Fig. 5 As for Fig. 4, but showing the results for $\bar{\Lambda}$. The spectra are scaled as indicated for clarity.

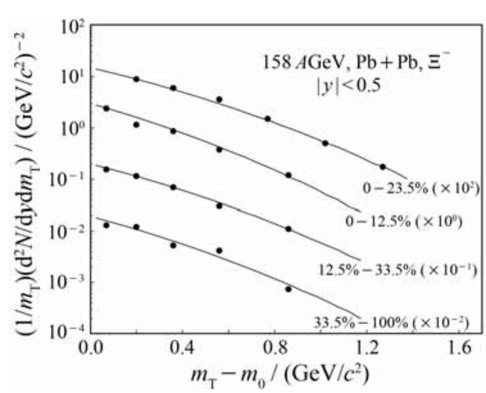

Fig. 6 The transverse mass distributions of Ξ^- produced in Pb-Pb collisions at 158 AGeV, for four classes of centrality in the rapidity interval $|y|<0.5$. The circles denote the experimental data of NA49 Collaboration[12], and the curves show our calculated results. The spectra are scaled as indicated for clarity.

χ^2/dof are shown in Table 1. We can see that the three fireballs with a relative strong expansion in the transverse direction describe well the experimental data of transverse mass distributions in Pb-Pb collisions at 158 *A*GeV.

4 Conclusions and Discussions

We have calculated the transverse mass distributions of Λ, $\overline{\Lambda}$, and Ξ^- produced in 40 and 158 *A*GeV Pb-Pb collisions in different centrality bins at midrapi-dity ($\Lambda/\overline{\Lambda}$: $|y|<0.4$, Ξ^-: $|y|<0.5$) using the Monte Carlo method in the framework of the expansive three-fireball model[22]. One have seen that our calculated results are in agreement with the experimental data in heavy-ion collisions at high energies.

In fact, the fireballs formed in the nucleus-nucleus collisions at high energies have the expansion both in the transverse direction and in the longitudinal direction. We do not need to take into account the expansion in the longitudinal direction in the study of transverse mass distributions. From Table 1, we can see that the fireballs have a relative strong transverse expansion.

The parameters k and σ in Eq. (5) denote the transverse expansive strength and excitation degree of the emission source, respectively. $k>1$ means a relative strong transverse expansion and $k=1$ means that there is no expansion. The physical condition requires $k\geqslant 1$. For the different particles produced in a fixed incident energy, the k and σ values are not same. We thought the interacting mechanism would be responsible for the different k values among the different particles produced in the fixed incident energy and the σ values increase slightly with the particle mass increasing. In the case of the particle produced in the fixed incident energy for the different centralities, such as Λ hyperon produced at 40 *A*GeV for five different centralities, the different centralites correspond to the different k and σ values due to the different collision intensity. Generally, a stronger collision corresponds to a higher excitation degree and a greater σ value corresponds to a higher degree of excitation. Therefore, there is a bigger σ value when the collision is central and there is a smaller σ value when the collision is noncentral. Considering the particle produced in various incident energy, the σ value increases with increasing the incident energy because a higher incident energy correspond to a harder collision.

We would like to point out that we have neglected the effect of leading particles. If we consider the effect of leading particles, the three fireballs will have different excitation degrees due to the interactions between the leading particles and the three fireballs[18]. In our previous work[26] and Ref. [27], a multisource ideal gas model was introduced to describe the transverse mass spectra of particles produced in high energy nucleus-nucleus collisions. Generally speaking, the three-fireball model can be included in the framework of the multisource ideal gas model. The present work shows that the three-fireball model[22] by considering the transverse and longitudinal expansion of the emission sources gives a good description of the strange particle transverse mass distributions in Pb-Pb collisions at 40 and 158 *A*GeV. We shall be interested to test the expansive three-fireball model in the future by using the transverse mass distributions of other particles produced in nucleus-nucleus at other energies[28-30].

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高能 Pb-Pb 碰撞中产生的奇异粒子的横质量分布*

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摘 要：基于三火球模型，用蒙特卡罗方法计算了 40 和 158 *A*GeV 能量下 Pb-Pb 碰撞中产生的 Λ，$\overline{\Lambda}$ 和 Ξ^- 强子的横质量分布。在计算中发现射弹核火球、中心火球和靶核火球在横向有明显的扩展，并且模型计算的结果与 NA49 合作组的实验结果相一致。

关 键 词：横质量；Pb-Pb 碰撞；扩展的三火球模型

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