Particle decay from statistical thermal model in high energy nucleus-nucleus collision

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Abstract

In high energy nucleus-nucleus collision, it is not easy to measure the weak decay and difficult to measure the resonance strong decay components of the final measured hadrons and the corresponding effects on some physical observables. To provide a reference from statistical thermal model, we performed a systematic analysis, using a statistical model (THERMUS), for Au + Au collisions. It is found the primary fraction of final hadrons decrease with increasing collision energy and somehow saturates around $\sqrt{s_{NN}} = 10$ GeV, indicating a limiting temperature in hadronic interactions. Meanwhile, the resonance strong decay fraction increases with increasing collision energy and saturates around $\sqrt{s_{NN}} = 20$ GeV. The energy dependence of strong or weak decay will show non-primary behavior, which should be considered in the study of real QCD signal. These dependencies are different for some particle ratios and almost the same for $K^+/\pi^+$ ratios with diluted effect.

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Ultra-relativistic nucleus-nucleus collisions can create a new state of matter, the quark-gluon plasma (QGP) in laboratories. The phase structure of strong interactions, where quarks and gluons are deconfined, can be studied by quantum chromodynamics (QCD). After this strongly coupled QGP was observed at the Relativistic heavy-ion Collider (RHIC) [1], attempts are being made to vary the colliding beam energy and to research the thermodynamics properties of QCD matter expressed in terms of a temperature vs baryo-chemical potential ($T_{ch} - \mu_B$) phase diagram, which lies at the heart of what the RHIC Beam Energy Scan (BES) program is all about [2, 3].

Thermodynamic properties of the QCD phase diagram can be decoded via analysis of particle production in heavy-ion collisions. This is achieved by using statistical thermal model, in which the production yields of different particle species contain characteristic features to determine the $T_{ch}$ and $\mu_B$ of the system at freeze-out. During the system evolution, there are two types of freeze-out which are commonly discussed: chemical freeze-out and kinetic freeze-out. Chemical freeze-out is typically supposed to happen when inelastic scattering stops, and the particle identities are set until they decay [4]. After chemical freeze-out, elastic interactions among the particles are still ongoing which leads to changes in the momentum of the particles. When the average inter-particle distance becomes large enough to make the elastic interactions stop, the system is said to have reached kinetic freeze-out. At this stage, the transverse momentum spectra of the produced particles becomes fixed. It is a surprising success that statistical thermal model can reproduce essential features of particle production in nucleus-nucleus collisions [5–8], suggesting that statistical production is a general property of the hadronization process.

It must be noted that the chemical freeze-out, i.e. from hadrons and especially, hadronic resonances, happens before they decay, including strong and electromagnetic decays of high-mass resonance, and weak decay from heavy flavor hadrons. In experiment, contamination of hadrons from strong decay $h_s$ is hard to measure due to their short lifetime. Contamination of hadrons from weak decay $h_w$ can be extracted by DCA(distance of closest approach) distribution [9]. Energy dependence of $h_p$ (hadrons created before particle decay), $h_s$, and $h_w$ might be different. The $h_s$ and $h_w$ of $\sqrt{s_{NN}}$ will show some non-primary behavior, which are not real QCD phase diagram signals we care about. These effects of $h_s$ and $h_w$ should be removed from physical quantitative observables, such as particle spectra and particle ratios.

To study energy dependence of $h_s$ and $h_w$, a statistic thermal model will be used. At the
stage of chemical freeze-out, the particle abundance of species $i$ can be parametrized by

$$\frac{N_i}{V} = \frac{g_i}{2\pi^2} \sum_{k=1}^{\infty} \left( \mp \right)^{k+1} \frac{m_i^2 T_{ch}^2}{k} K_2 \left( \frac{k m_i}{T_{ch}} \right) e^{k \mu_i / T_{ch}}$$

(1)

where

$$\mu_i = \mu_B B_i + \mu_Q Q_i + \mu_S S_i$$

(2)

and $g_i$ is the spin-iso-spin degeneracy factor; $T_{ch}$ is the chemical freeze-out temperature; $B_i$, $S_i$, $Q_i$ are the baryon number, strangeness, and charge, respectively, of hadron species $i$; $\mu_B$, $\mu_S$, and $\mu_Q$ are the corresponding chemical potentials for these conserved quantum numbers. The code THERMUS [10] is utilized to perform a thermal calculation of particle yields. Within the model, there is a freedom regarding the ensemble with which to treat conserved numbers $B$, $S$, and $Q$ in strong interactions. The chemical potentials for each of these quantum numbers allow fluctuations about conserved averages, which is a reasonable approximation only when the number of particles carrying the quantum number concerned is large. Three ensembles can be employed in the model. Those are the grand-canonical ensemble (GCE), canonical ensemble (CE), and mix-strangeness canonical ensemble (SCE). The GCE is the most widely used in the application to heavy-ion collisions. In GCE, the Boltzmann approximation ($k = 1$ in Eq. [1]) is reasonable for all particles except the pions, so

$$N_i = \frac{g_i V}{2\pi^2} m_i^2 T K_2 \left( \frac{m_i}{T_{ch}} \right) e^{\beta \mu_i}$$

(3)

For this approximation analysis, the deviation of quantum statistical effect for pions is at the level of 10%, while, for kaons, the deviation peaks at between 1 and 2%. For all other mesons, the deviation is less than the 1% level. For baryons, the deviation is extremely small.

The energy dependence of chemical freeze-out parameters $T_{ch}$ and $\mu_B$ are obtained from statistical hadronization analysis of hadron yields [11],

$$T_{ch} = \frac{T_{ch}^{\lim}}{1 + \exp \left( 2.60 - \ln(\sqrt{s_{NN}}) / 0.45 \right)}$$

(4)

$$\mu_B = \frac{\mu_B^{\lim}}{1 + 0.288 \sqrt{s_{NN}}}$$

(5)
FIG. 1. Energy dependence of $\pi^+$ and $\pi^-$ fractions for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons.

where $T_{\text{ch}}^{\text{lim}} = 158.4 \pm 1.4$ MeV, $\mu_B^{\text{lim}} = 1307.5$ MeV. With these thermal parameters on energy, we can get the energy dependence of $h_p$, $h_s$, and $h_w$.

Figure 1 shows energy dependence of $\pi^+$ and $\pi^-$ fractions for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons. Those are $h_p/(h_p + h_s + h + w)$, $h_s/(h_p + h_s + h + w)$, and $h_w/(h_p + h_s + h + w)$. It can be found that energy dependence of these factions are different for $\pi^+$ and $\pi^-$. Fractions of $h_p$ for $\pi^+$ and $\pi^-$ are almost the same, decrease from 65% to 28% with increasing collision energy. In Boltzmann approximation, the particle ratio $\pi^-/\pi^+$ is related to the iso-spin effect as

$$
\frac{h_p(\pi^-)}{h_p(\pi^+)} = \exp\left(-\frac{2\mu_Q}{T_{\text{ch}}}\right)
$$

The quantum statistics effect is less than 5% with $T_{\text{ch}} < 180$ MeV and $\mu_Q/T_{\text{ch}} > -0.4$. In nucleus-nucleus collision, $h_p(\pi^-)/h_p(\pi^+)$ is greater than 1 and decrease with $\sqrt{s_{\text{NN}}}$ and saturate to 1, which can be found in figure 2. That is due to $\mu_Q$ is less than 0 and increase to zero with increasing $\sqrt{s_{\text{NN}}}$. $h_s(\pi^\pm)$ are mainly from $\Delta$ resonances at low collision energies. Ratio of pions from $\Delta$ decay can be calculated by
FIG. 2. Energy dependence of particle ratios $\pi^-/\pi^+$ from the stage at primary production, after strong decay from high-mass resonance, and after weak decay from heavy flavor hadrons. Experimental results from AGS [12–18], SPS [19–22], and RHIC [23–26] of the most central collision are shown for comparison.

\[
\frac{h_s(\pi^- \leftarrow \Delta)}{h_s(\pi^+ \leftarrow \Delta)} = \exp \left( \frac{-2c_\Delta \mu_Q - 2\mu_B}{T_{ch}} \right) \approx \exp \left( \frac{-2\mu_B}{T_{ch}} \right) < 1
\]

where $c_\Delta > 1$ is effective charge of strong decay which contains the contribution of multicharged $\Delta$. The contribution from $\Delta$ for $\pi^-$ is smaller than that for $\pi^+$. The contribution from short lived mesons, such as $\eta, \rho$ become significant with increasing energy, which gives the same contribution to the yields of $\pi^+$ and $\pi^-$. With these two kinds of strong decay, the fraction of $h_p(\pi^-)$ is small than that of $h_p(\pi^+)$ and the particle ratio $\pi^-/\pi^+$ is suppressed after strong decay. As a result, we cannot use Eq. 6 with the ratio corrected by weak decay to extract iso-spin effect in nucleus-nucleus collision, which will underestimate real iso-spin effect. Components of $h_s(\pi^\pm)$ increase with energy and saturate at the value of 57% around $\sqrt{s_{NN}} = 10$ GeV. $h_w(\pi^\pm)$ are mainly from the channels below.
\[ K_S^0 \rightarrow \pi^+ + \pi^- \quad \text{B.R.} = 69.2\% \]
\[ \Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^\pm \quad \text{B.R.} = 63.9\% \]
\[ \Sigma^+(\bar{\Sigma}^-) \rightarrow n(\bar{n}) + \pi^\pm \quad \text{B.R.} = 48.31\% \]
\[ \Sigma^-(\bar{\Sigma}^+) \rightarrow n(\bar{n}) + \pi^\mp \quad \text{B.R.} = 99.85\% \]

The ratio of pions from weak decay can be calculated by

\[ \frac{h_w(\pi^- \leftarrow \Lambda)}{h_w(\pi^+ \leftarrow \Lambda)} = \exp \frac{2\mu_B - 2\mu_S}{T_{ch}} > 1 \tag{8} \]
\[ \frac{h_w(\pi^- \leftarrow \Sigma^-/\Sigma^-)}{h_w(\pi^+ \leftarrow \Sigma^+/\Sigma^-)} \approx 1 + \frac{51.54\% \times \left(\exp \frac{2\mu_B - 2\mu_S}{T_{ch}} - 1\right)}{48.31\% \times \exp \frac{2\mu_B - 2\mu_S}{T_{ch}} + 99.85\%} > 1 \tag{9} \]

(10)

the value 51.54% is from the difference of branch ratio between \( \Sigma^+ \) and \( \Sigma^- \) decay to pions. The same yield of \( \pi^+ \) and \( \pi^- \) is created in \( K_S^0 \) weak decay. So, more \( \pi^- \)s are created in weak decay than \( \pi^+ \)s especially at low energy, which will enhance the \( \pi^-/\pi^+ \) after weak decay. The \( h_w(\pi^+) \) reach maximum around \( \sqrt{s_{NN}} = 8 \) GeV and saturates to the value of 15%.

Experimental results from AGS [12–18], SPS [19–22], and RHIC [23–26] of the most central collision are also shown in figure 2 and are found to be consistent with the results after strong decay in the thermal model.

Figure 3 shows the energy dependence of \( K^+ \) and \( K^- \) fractions for primary production and strong decay. The weak decay channel for \( K^+ \) and \( K^- \) is \( \Omega^- (\bar{\Omega}^+) \rightarrow \Lambda(\bar{\Lambda} + K^\pm) \), which could be negligible due to the low multiplicity of \( \Omega \). Energy dependence of \( h_p \) and \( h_s \) for \( K^\pm \) are opposite, \( h_p \) decrease and \( h_s \) increase with increasing collision energy. In figure 4 we can find that the yield of \( K^+ \) from primary is larger than \( K^- \), since some of constituent \( u \) quarks are from initial nucleon for \( K^+ \) but all constituent quarks (\( \bar{u} \) and \( s \)) are from pair productions for \( K^- \). The particle ratio \( K^-/K^+ \) from primary production can be written as

\[ \frac{h_p(K^-)}{h_p(K^+)} = \exp \frac{-2\mu_S - 2\mu_Q}{T_{ch}} \tag{11} \]

this ratio is less than unity due to \( \mu_S > -\mu_Q \). At large \( \sqrt{s_{NN}} \), \( \mu_S \) and \( \mu_Q \) tend to be zero, the ratio is approaching unity. Strong decay for kaon is mainly from hidden strange mesons and open strange meson. The first kind of meson decay gives the same contribution to the yields
FIG. 3. Energy dependence of $K^+$ and $K^-$ fractions for primary production and strong decay from high-mass resonance.

of $K^+$ and $K^-$, which will dilute the $K^−/K^+$ ratio. The second will remain unchanged in the ratio because strangeness is conserved in strong interaction. These two effects will slightly enhance the $K^−/K^+$ ratio after strong decay.

Energy dependence of $p$ and $\bar{p}$ fractions for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons are shown in figure 3. The $h_s$ for $p(\bar{p})$ decrease with increasing energy and saturate to the value of 22%. Strong decay for (anti-)proton is mainly from $\Delta$ resonance, which increase with energy and reach maximum around $\sqrt{s_{NN}} = 10$ GeV for $p$ and saturate to the value of 45%. The energy dependence of $h_w$ for $p$ and $\bar{p}$ are different. $h_w(\bar{p})$ increase with energy and reach maximum around $\sqrt{s_{NN}} = 6$ GeV, while $h_w(p)$ increase with energy. Both of them saturate at higher energy to the value of 33%. In figure 6 particle ratio $\bar{p}/p$ of primary production, after strong decay, and after weak decay are shown. The ratio $h_p(\bar{p})/h_p(p)$ can be written as

$$\frac{h_p(\bar{p})}{h_p(p)} = \exp -\frac{2\mu_B - 2\mu_Q}{T_{ch}} \approx \exp -\frac{2\mu_B}{T_{ch}} < 1$$

(12)

Particle ratio $\bar{p}/p$ of $h_p + h_s$ is almost the same as the ratio of primary production due
FIG. 4. Energy dependence of particle ratios $K^-/K^+$ from the stage at primary production, after strong decay from high-mass resonance. Experimental results from AGS [12–18], SPS [19–22], and RHIC [23–26] of the most central collision are shown for comparison.

To strangeness is conserved in strong interaction and the little contribution from strange resonance baryon decay to proton.

The $p(\bar{p})$ of weak decay are from the channels below

\[ \Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^\pm \quad \text{B.R.} = 63.9\% \]
\[ \Sigma^+(\bar{\Sigma}^-) \rightarrow p(\bar{p}) + \pi^0 \quad \text{B.R.} = 51.6\% \]
\[ \Xi^0(\bar{\Xi}^0) \rightarrow \Lambda(\bar{\Lambda}) + \pi^0 \rightarrow p(\bar{p}) + \pi^0 + \pi^\mp \quad \text{B.R.} = 63.6\% \]
\[ \Xi^-(\bar{\Xi}^+) \rightarrow \Lambda(\bar{\Lambda}) + \pi^- \rightarrow p(\bar{p}) + \pi^- + \pi^\mp \quad \text{B.R.} = 63.8\% \]
FIG. 5. Energy dependence of \( p \) and \( \bar{p} \) fractions for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons.

The ratios of \( p(\bar{p}) \) in weak decay can be calculated by

\[
\frac{h_w(\bar{p} \leftarrow \bar{\Lambda})}{h_w(p \leftarrow \Lambda)} = \exp \frac{2\mu_S - 2\mu_B}{T_{ch}} > \frac{h_p(\bar{p})}{h_p(p)} \quad (13)
\]

\[
\frac{h_w(\bar{p} \leftarrow \bar{\Sigma}^-)}{h_w(p \leftarrow \Sigma^+)} = \exp \frac{-2\mu_Q - 2\mu_S - 2\mu_B}{T_{ch}} > \frac{h_p(\bar{p})}{h_p(p)} \quad (14)
\]

\[
\frac{h_w(\bar{p} \leftarrow \bar{\Xi}^0)}{h_w(p \leftarrow \Xi^0)} = \exp \frac{4\mu_S - 2\mu_B}{T_{ch}} > \frac{h_p(\bar{p})}{h_p(p)} \quad (15)
\]

\[
\frac{h_w(\bar{p} \leftarrow \bar{\Xi}^+)}{h_w(p \leftarrow \Xi^-)} = \exp \frac{2\mu_Q + 4\mu_S - 2\mu_B}{T_{ch}} > \frac{h_p(\bar{p})}{h_p(p)} \quad (16)
\]

so particle ratio \( \bar{p}/p \) will be enhanced by weak decay. Experimental results from SPS \([19-22]\), which are corrected by weak decay, and RHIC \([23-26]\) of inclusive production at the most central collision are also shown in figure 6 and are found to be consistent with the corresponding thermal model lines.

Figure 7 shows energy dependence of \( \Lambda \) and \( \bar{\Lambda} \) fractions for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons. The behavior is similar to that of the (anti-)proton. The \( h_s \) decrease with increasing energy and saturate to one fifth. The strong decay increase with energy and reach maximum around \( \sqrt{s_{NN}} = 10 \)
FIG. 6. Energy dependence of particle ratios $\bar{p}/p$ from the stage at primary production, after strong decay from high-mass resonance. Experimental results from SPS [19–22] and RHIC [23–26] of the most central collision are shown for comparison.

GeV and saturate to the value of 55%. The energy dependence of $h_w$ for $\Lambda$ and $\bar{\Lambda}$ are different. $h_w(\Lambda)$ increase with energy and reach maximum around $\sqrt{s_{\text{NN}}} = 5$ GeV, while $h_w(p)$ increases with energy. Both of them saturate at higher energy to the value of one fourth.

Figure 8 and 9 show energy dependence of particle ratio $K^+/\pi^+$ and $K^-/\pi^-$ with experimental results from AGS [12–18], SPS [19–22], and RHIC [23–26] of the most central collision. $K^+/\pi^+$ ratio is roughly proportional to the total strangeness to entropy ratio, which is assumed to be preserved from the early stage until freeze-out [19]. The peak position (usually called the “horn”) of the $K^+/\pi^+$ ratio in the energy dependence has been considered as an indication of QGP formation. It can be found the horn does not change significantly after strong and weak decay but with diluting effect. $K^-/\pi^-$ ratio increase with $\sqrt{s_{\text{NN}}}$, corresponding to decreasing $\mu_S$ on $\sqrt{s_{\text{NN}}}$.

In summary, we concentrated on the use of statistical thermal model (THERMUS) to understand the effects of strong and weak decay for different particle species which are dif-
FIG. 7. Energy dependence of $\Lambda$ and $\bar{\Lambda}$ fractions for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons.

Ficult to measure in nucleus-nucleus collision. The fractions of primary production for final hadrons decrease with increasing collision energy and somehow saturates near $\sqrt{s_{NN}} = 10$ GeV. The appearance of this behavior can be related to specific dependence of $T_{ch}$ on the collision energy. At low energy, most of the hadrons are from primary production, while the decay components will dominate at high energy. The saturation of the primary production fraction on collision energy indicates the limitation chemical freeze-out temperature in hadronic interactions. The position of this saturation for some hadrons deviate $\sqrt{s_{NN}} = 10$ GeV is due to the contribution of quarks that are present in the colliding particles or target and projectile. The fraction of strong decay for final hadrons increase with increasing collision energy and somehow saturates near $\sqrt{s_{NN}} = 20$ GeV, which might be an effect on the dependence of chemical potential ($\mu_B$ and $\mu_S$) on collision energy. The production of resonance is suppressed at large $\mu_B$ or $\mu_S$, i.e. low collision energy but enhanced at high collision energy. Weak decay fractions for hadron and anti-hadrons have different behavior, which may be due to the energy dependence of baryon density. Energy dependence of $h_s$ and $h_w$ will show different behavior as that of primary production at chemical freeze-out, which
FIG. 8. Energy dependence of $K^+/\pi^+$ ratio for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons. Experimental results from AGS [12–18], SPS [19–22], and RHIC [23–26] of the most central collision are shown for comparison.

is of real QCD phase diagram signals we care about. The iso-spin effect $\mu_Q/T_{ch}$ extracted from $\pi^+/\pi^-$ ratios in the experiment with the ratios corrected by weak decay are smaller than the real effect. The $K^-/K^+$ is enhanced after strong decay, while $\bar{p}/p$ does not change after strong decay and enhance after weak decay. Because we cannot exhaust all the physical observables, some of those are chosen for discussions. For an example, the position of the horn extracted from $K^+/\pi^+$ ratio does not vary after strong or weak decay. In this paper, we do not care about the $p_T$ or phase space of $h_s$ and $h_w$, which will show different behavior. As we know, the decay effect is dominant for low $p_T$ particles, while the high $p_T$ particles are mainly from primary production. For future study, extended thermal statistical model, which contain the phase space information of produced particles should be utilized.

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FIG. 9. Energy dependence of $K^-/\pi^-$ ratio for primary production, strong decay from high-mass resonance, and weak decay from heavy flavor hadrons. Experimental results from AGS [12–18], SPS [19–22], and RHIC [23–26] of the most central collision are shown for comparison.

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[1] J. Adams et al., Nuclear Physics A 757, 102 (2005).
[2] M. A. Stephanov, Prog. Theor. Phys. Suppl. 153, 139 (2004).
[3] B. Mohanty, Nuclear Physics A 830, 899c (2009).
[4] R. Vogt, Ultrarelativistic Heavy-Ion Collisions (Elsevier Science Ltd, 2007).
[5] J. Cleymans, B. Kämpfer, and S. Wheaton, Phys. Rev. C 65, 027901 (2002).
[6] F. Becattini, J. Manninen, and M. Gaźdicki, Phys. Rev. C 73, 044905 (2006).
[7] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Nuclear Physics A 789, 334 (2007).
[8] J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton, Phys. Rev. C 73, 034905 (2006).
[9] B. Abelev et al. (ALICE Collaboration), Phys. Rev. C 88, 044910 (2013).
[10] S. Wheaton, J. Cleymans, and M. Hauer, Computer Physics Communications 180, 84 (2009).
[11] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, (2017), arXiv:1710.09425 [nucl-th].

[12] Y. Akiba et al., Nuclear Physics A 610, 139 (1996).

[13] L. Ahle et al. (E802 Collaboration), Phys. Rev. C 57, R466 (1998).

[14] L. Ahle et al. (E866 Collaboration, E917 Collaboration), Physics Letters B 476, 1 (2000).

[15] J. Barrette et al. (E877 Collaboration), Phys. Rev. C 62, 024901 (2000).

[16] L. Ahle et al. (E802 Collaboration), Phys. Rev. C 60, 064901 (1999).

[17] L. Ahle et al. (E866 Collaboration, E917 Collaboration), Physics Letters B 490, 53 (2000).

[18] J. L. Klay et al. (E895 Collaboration), Phys. Rev. Lett. 88, 102301 (2002).

[19] C. Alt et al. (NA49 Collaboration), Phys. Rev. C 77, 024903 (2008).

[20] C. Alt et al. (NA49 Collaboration), Phys. Rev. C 73, 044910 (2006).

[21] T. Anticic et al. (NA49 Collaboration), Phys. Rev. C 69, 024902 (2004).

[22] S. V. Afanasiev et al. (The NA49 Collaboration), Phys. Rev. C 66, 054902 (2002).

[23] L. Adamczyk et al. (STAR Collaboration), Phys. Rev. C 96, 044904 (2017).

[24] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 81, 024911 (2010).

[25] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009).

[26] J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 92, 112301 (2004).