

Net Charge Fluctuations and Chemical Freeze-out Conditions

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Abstract

Different freeze-out conditions such as energy per particle density, baryon and anti-baryon density, normalized entropy density and constant trace anomaly are analyzed. These criteria for chemical freeze-out are calculated in framework of the hadron resonance gas (HRG) model. A systematic comparison with recent experimental data is presented. The Dependence of particle ratios on beam energy is extracted. The net charge fluctuations ν_{dyn} for different species K/ π , P/ π , and K/P are studied and compared with STAR measurements from Au+Au collisions at $\sqrt{s_{\text{NN}}}=7.7-200$ GeV. We find a satisfied agreement with the experimental results and furthermore conclude that the HRG model is suitable to explain the dynamical net charge fluctuations.

Keywords: Baryon density, normalized entropy, Constant trace anomaly, hadron resonance gas (HRG) .

1. Introduction

Hadronic matter is studied in heavy-ion experiments under extreme conditions of high temperature, density or both of them [1]. In a few microseconds from Big Bang, the new state of matter, quark-gluon plasma (QGP), should be created [2]. On other hand, quantum chromodynamics (QCD) predicts that strongly interacting matter undergoes a phase transition from the hadronic state to a system of deconfined quarks and gluons; QGP [3]. The particle yields is considered one of the most important results obtained from relativistic heavy-ion collisions at different beam energies and can be described by thermal-statistical models [4-18]. It is supposed that, the chemical equilibrium has only two parameters; the temperature (T) and baryon chemical potential μ_b [19-27]. After hadronization, the particles interact strongly with each others at distances is of order 1 fm, and later on the system would reach a state of chemical equilibrium referring to the composition of the fireball [28]. Hence, the chemical equilibrium means that the rate of creation and annihilation will be exactly equal. This evolution process continues until the hadron gas cools down, i.e. chemical freeze-out. The chemical freeze-out is the point at which the inelastic collisions cease and all particle ratios are frozen.

A second form of particle equilibrium is the thermal freeze-out, where the produced particles (their number is fixed in stage of chemical freeze-out) continue interacting, elastically. The fireball continues expanding and cooling until these interactions cease. By observing the particle abundances which reflect the properties of the system at chemical freeze-out, one finds that at Super Proton Synchrotron SPS energies the particle distribution becomes characteristic at $T=170$ MeV

[29]. By observing the particle momentum distributions which characterize the system at thermal freeze-out, one can conclude that the thermal freeze-out occurs later at $T=130$ MeV at same SPS energies.

The hadron Resonance Gas (HRG) model seems to give a good description for the thermal evolution of the thermodynamic quantities in the hadronic matter [7-10] and has been successfully utilized to characterize the conditions deriving the chemical freeze-out [28-31]. Also the partition function used in heavy-ion collisions has shown an agreement with the results obtained from lattice QCD in the hadronic phase [30]. It is found with increasing the collision energy, the chemical freeze-out temperature, T , increases while the corresponding baryon chemical potential, μ_b , decreases. In lattice QCD [31,32], the phase diagram is studied from low energy Schwerionensynchrotron SIS to high energy, Relativistic Heavy Ion Collider, RHIC with a critical temperature $T=170$ MeV at vanishing chemical baryon potential. The study of the freeze-out conditions is essential in extracting the particle spectra and particle excitation function, since we can know the number of resonances, their widths, and the treatment of weak decays [19].

Different freeze-out conditions are studied, e.g.

$$\frac{E}{N} \approx 1 \text{ GeV} [33,34] \text{ and a baryon and anti-baryon}$$

densities, $n_B + n_{\bar{B}} \approx 0.12 \text{ fm}^{-3}$ [29], normalized entropy, $s/T^3=7$ and the trace anomaly $(\epsilon - 3p)/T_4 = 7/2$ [2,35-38]. We compare the HRG calculations with data from SIS [33,34-40], Alternating Gradient Synchrotron AGS, SPS [39-41] and RHIC [42-47].

The present paper is organized as follows;

section II is devoted to study the HRG model, the thermodynamical quantities, e.g. number density and pressure are derived using the grand canonical partition function. The parameterization of the baryonic chemical potential on the dependence of $\sqrt{s_{NN}}$ is showed. In Section III, the net charge fluctuations as a signal of QGP are calculated. The particle ratios are studied at different energies. In Section IV, the results from different freeze-out conditions, particle ratios and net charge fluctuations for K/π , P/π , and K/P are presented. In Section V, summary and conclusion are outlined.

2. Formalism

The thermodynamics can be extracted simply from the partition function $Z(T,V)$. The grand

$$\ln Z(T, V, \vec{\mu}) = \sum_i \ln Z_i(T, V, \vec{\mu}_i) \tag{2}$$

where

$$\vec{\mu}_i = (\mu_B, \mu_S, \mu_Q)$$

are the chemical potentials related to baryon

$$\ln Z_i(T, V, \vec{\mu}_i) = \frac{Vg_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln [1 \pm \lambda_i \exp(-\beta \epsilon_i)] \tag{3}$$

where +ive and -ive sign stand for bosons and fermions, respectively, $\epsilon_i = \sqrt{p^2 + m_i^2}$ and the

fugacity factor λ_i [29] is given by

$$\lambda_i(T, \vec{\mu}) = \exp\left(\frac{B_i \mu_B + S_i \mu_S + Q_i \mu_Q}{T}\right) \tag{4}$$

Expressing the partition function (3) in terms of Bessel function [29], one get

$$\ln Z_i(T, V, \vec{\mu}_i) = \frac{VTg_i}{2\pi^2} \sum_{k=1}^\infty \frac{\pm^{k+1}}{k^2} \lambda_i^k m_i^2 K_2\left(\frac{km_i}{T}\right) \tag{5}$$

where K_2 is the second order modified Bessel function.

The number density of particles per unit volume is obtained from (5) as the following [29]

$$n_i(T, \vec{\mu}_i) = \frac{\langle N_i \rangle}{V} = \frac{Tg_i}{2\pi^2} \sum_{k=1}^\infty \frac{\pm^{k+1}}{k^2} \lambda_i^k m_i^2 K_2\left(\frac{km_i}{T}\right) \tag{6}$$

At finite temperature T and baryon chemical potential μ_i , the pressure of the i-th hadron or resonance is given as [29]

$$p(T, \mu_i) = \pm \frac{g_i}{2\pi^2} T \int_0^\infty k^2 dk \ln(1 \pm [(\mu_i - \epsilon_i)/T]) \tag{7}$$

In order to calculate all particle ratio, the parametes we need are the chemical potentials, temperature, degeneracy factor and volume. We will calculte the chemical potential and temperature from Tawfik [1,2-7-10] realtion that related them to the energy as the following

$$\mu_B = \frac{a}{1 + b\sqrt{s_{NN}}} \tag{8}$$

canonical partition function [29] is given by

$$Z^{GC}(T, V, \mu_Q) = \text{Tr} \left[\text{EXP} - \beta \left(H - \sum_i \mu_Q Q_i \right) \right] \tag{1}$$

where H is the Hamiltonian of the system, Q_i are

the conserved charges and μ_Q are the chemical potentials and $\beta = \frac{1}{T}$. The Hamiltonian is used in

the partition function because it contains all relevant degrees off freedom of the confiend and the strongly interacting medium implicitly includes other types of interactions that results in resonances formation.

Therefore the partition function (1) of a hadron resonance gas can be written as [29]

number, strangness and electric charge, respectively.

where $\sqrt{s_{NN}}$ is in GeV, $a=1.245\pm 0.094$ GeV and $b=0.264\pm 0.028$ GeV⁻¹. Also the dependence of the chemical freeze-out temperature T_{ch} on $\sqrt{s_{NN}}$ can be parametrized as [34]

$$T_{ch} = T_{lim} \left(\frac{1}{1 + \exp\left[\frac{1.172 - \ln(\sqrt{s_{NN}})}{0.45}\right]} \right) \tag{9}$$

where the limiting temperature is, $T_{lim} = 164MeV$.

Another relation suggested by Cleymans [34] shows that the baryonic potential can be fitted to the beam energy using the following formula

$$\mu_B(s) \approx \frac{a}{1 + \frac{\sqrt{s}}{b}} \tag{10}$$

3. Net charge fluctuation

Phase transition has well known signatures such as fluctuations of the net charge. A significant fluctuation occurs when the QGP undergoes phase transition to the hadronic one [46-47]. The Relativistic Heavy Ion Collider (RHIC) start to search for the QCD critical point by making an energy scan of Au+Au collisions from low collision energy ($\sqrt{s_{NN}}=7.7$ GeV) up to high energies ($\sqrt{s_{NN}}=200$ GeV). The net charge fluctuations as a signal of quark-gluon plasma (QGP) are calculated in terms of the parameter ν_{dyn} .

The definition of $\nu_{dyn,k/\pi}$ which describes fluctuations in K/π ratio is given by [46]

$$\nu_{dyn,k/\pi}$$

$$= \frac{\langle N_K(N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_\pi(N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2 \frac{\langle N_K N_\pi \rangle}{\langle N_K \rangle \langle N_\pi \rangle} \quad (11)$$

We calculated the charge dependence of the dynamical K/ π , P/ π , and K/P fluctuations and make comparison with STAR experiment results. The charge dependence of the dynamical K/ π , P/ π , and K/P fluctuations are calculated and compared with STAR results [46].

Similarly, formula for P/ π , and K/P ratios can be constructed as in Eq.(11). For more details readers are advised to consult Refs. [49-50].

4. Results and discussion

The dependence of freeze-out temperature T on the baryon chemical potential μ_b at different freeze-out conditions is given in Fig (1) In Fig (1a), he temperature is plotted versus μ_b at fixed E/N = 1.02 GeV.

Fig (1b) shows the (T- μ_b) dependence in case of , $s/T^3 = 7$ where s is the entropy. Fig (1c) shows the (T- μ_b) dependence using the following condition ; $n_B + n_{\bar{B}} = 0.12 \text{ fm}^{-3}$; where n_B and $n_{\bar{B}}$ are the sum of baryon and anti-baryon densities respectively. Finally, fig (1d) shows the (T- μ_b) dependence in case of using the QCD trace anomaly condition which is defined as $(\epsilon - 3p)/T_4 = 7/2$. From figs (1), one can notice that; at vanishing chemical potential, the freeze-out temperature T_f is taking the values ; $164 \leq T_f \leq 169$ MeV; and this value is close to that of undergoes phase transition as known from lattice gauge theory that give an upper limit of about 170 MeV [29-51]. Also there is a great discrepancy at higher μ_b values ($\mu_b \geq 650$ MeV).

In Figs (2a-2i), the calculated charge dependence of the dynamical K/ π , P/ π , and K/P fluctuations compared to with STAR experiment results.

Fig (2a) , (2b), and (2c) shows $v_{\text{dyn},k/\pi}$ as a function of the energy compared to STAR data measured in central 0-5% Au+Au collisions at $\sqrt{s_{NN}}=7.7-200$ GeV. The total dynamical

fluctuation $\frac{K}{\pi}$ are setted as $\frac{K}{\pi} = \frac{K^+ + K^-}{\pi^+ + \pi^-}$ as shown

in fig (2a) where the volume of the fire ball is taken as $770.72 \pm 77 \text{ fm}^3$. Only the $v_{\text{dyn},k/\pi}$ in case of

$\frac{K}{\pi} = \frac{K^+ + K^-}{\pi^+ + \pi^-}$ have positive values. In fig (2b),

The total dynamical fluctuation $\frac{K}{\pi}$ are setted

as $\frac{K}{\pi} = \frac{K^+}{\pi^+} + \frac{K^-}{\pi^-}$, where we take the average of the same sign and the volume of the fire ball is taken as

$1.43 \pm 0.143 \text{ fm}^3$. In fig (2c), the average of the

opposite sign is considered where $\frac{K}{\pi} = \frac{K^+}{\pi^-} + \frac{K^-}{\pi^+}$

and the volume of the fire ball is taken as; $1.82 \pm 0.182 \text{ fm}^3$. One can see that we have a satisfied

agreement with the experimental data in case of the

different $\frac{K}{\pi}$ dynamical fluctuations.

Fig (2d), (2e), and (2f) shows $v_{\text{dyn},P/\pi}$ as a function of the energy in comparison with STAR experiment measured in central 0-5% Au+Au collisions at $\sqrt{s_{NN}}=7.7-200$ GeV. The total

dynamical fluctuation $\frac{P}{\pi}$ are setted as

$\frac{P}{\pi} = \frac{P^+ + P^-}{\pi^+ + \pi^-}$ as shown in fig (2d) where the volume of the fire ball is taken as 2.052 ± 0.2052

fm^3 . In fig (2e), the total dynamical fluctuation $\frac{P}{\pi}$

are setted as $\frac{P}{\pi} = \frac{P^+}{\pi^+} + \frac{P^-}{\pi^-}$, where we take the average of the same sign and the volume of the fire ball is taken as

$1.56 \pm 0.156 \text{ fm}^3$. In fig (2f), the average of the opposite sign is considered where

$\frac{P}{\pi} = \frac{P^+}{\pi^-} + \frac{P^-}{\pi^+}$ and the volume of the fire ball is taken as

$1.69 \pm 0.169 \text{ fm}^3$. One can see that we have a satisfied agreement with the experimental data in

case of the different $\frac{P}{\pi}$ dynamical fluctuations.

Fig (2g), (2h), and (2i) shows $v_{\text{dyn},K/P}$ as a function of the energy in comparison with STAR experiment measured in central 0-5% Au+Au collisions at $\sqrt{s_{NN}}=7.7-200$ GeV. The total

dynamical fluctuation $\frac{K}{P}$ are setted

as $\frac{K}{P} = \frac{K^+ + K^-}{P^+ + P^-}$ as shown in fig (2g) where the volume of the fire ball is taken as $2.1 \pm 0.21 \text{ fm}^3$. In

fig (2h), The total dynamical fluctuation $\frac{K}{P}$ are

written as $\frac{K}{P} = \frac{K^+}{P^+} + \frac{K^-}{P^-}$, where we take the average of the same sign and the volume of the fire ball is taken as

$1.3 \pm 0.13 \text{ fm}^3$. In fig (2i), the average of

the opposite sign is considered where $\frac{K}{P} = \frac{K^+}{P^-} + \frac{K^-}{P^+}$

and the volume of the fire ball is taken as $1.3 \pm 0.13 \text{ fm}^3$. One can see that we have a satisfied agreement with the experimental data in case of the

different $\frac{K}{P}$ dynamical fluctuations.

In figs (3a-3f), we have shown the energy

dependence of the particle ratios $\frac{\pi^-}{\pi^+}$, $\frac{K^-}{K^+}$, $\frac{K^-}{\pi^-}$, $\frac{P^-}{P^+}$, $\frac{\Lambda^-}{\Lambda^+}$, and $\frac{\Omega^-}{\Omega^+} \times 10$ respectively in comparison with the available experimental results [38].

From these figures, one can see that $\frac{\pi^-}{\pi^+}$ ratio decreases with increasing the collision energy while

$\frac{K^-}{K^+}$, $\frac{K^-}{\pi^-}$, $\frac{P^-}{P^+}$, and $\frac{\Lambda^-}{\Lambda^+}$ ratios increases with

increasing the collision energy. In case of $\frac{\Omega}{\pi^-}$ ratio (where, in this case the values are multiplied with scale factor 10), one can notice that, this ratio increases with the collision energy until sharp peak (at $\sqrt{s_{NN}} = 25$ GeV) and then began to decrease. This behaviour is call as the horn.

In fig (3g), (3h), and (3i), we have calculated

$\frac{\pi^-}{\pi^+}, \frac{k^-}{k^+}, \frac{\bar{p}}{p}, \frac{\bar{\lambda}}{\lambda}, \frac{\bar{\Xi}}{\Xi}$ ratios at STAR beam energies 62, 130, and 200 GeV. One can see a satisfied agreement with the experimental data in case of the all considered particle ratios.

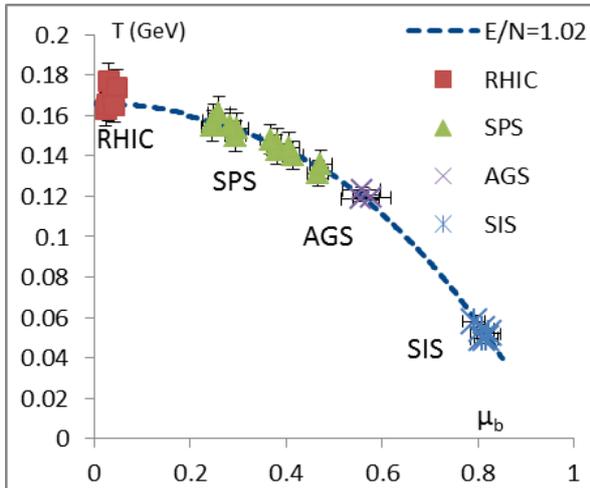


Fig (1a) (T- μ_b) relation at fixed $E/N=1.02$ GeV compared with data from SIS(lowenergy) to RHIC(High energy) [48].

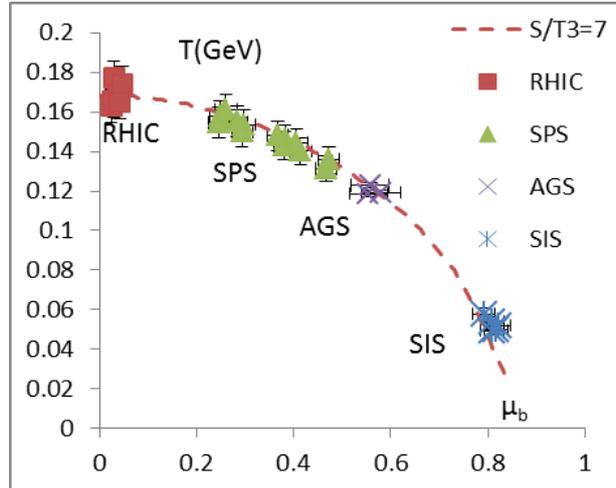


Fig (1b) (T- μ_b) relation at fixed entropy density over T^3 compared with data from SIS(lowenergy) to RHIC(High energy)[48].

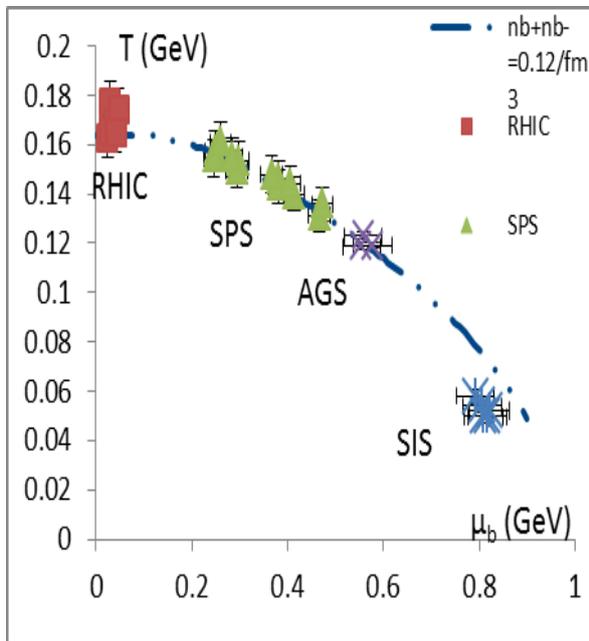


Fig (1c) (T- μ_b) relation at fixed value for the sum of baryon and anti-baryon densities compared with data from SIS(lowenergy) to RHIC(High energy) [48].

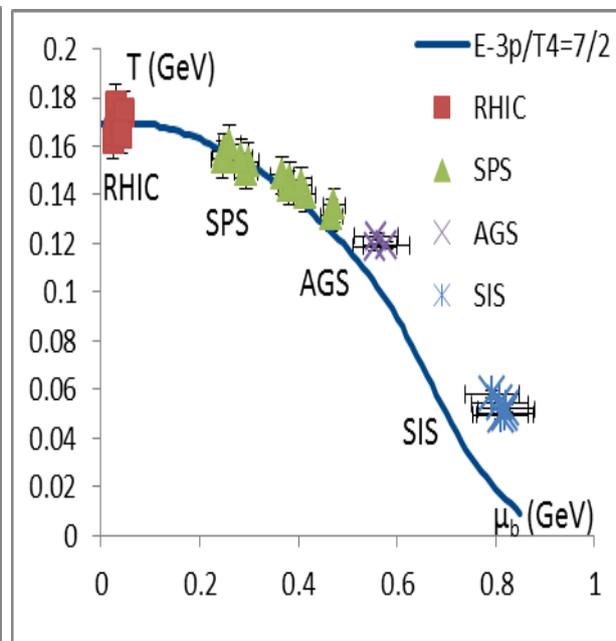


Fig (1d) (T- μ_b) relation at Constant Trace Anomaly as compared with data from SIS(lowenergy) to RHIC(High energy)[48].

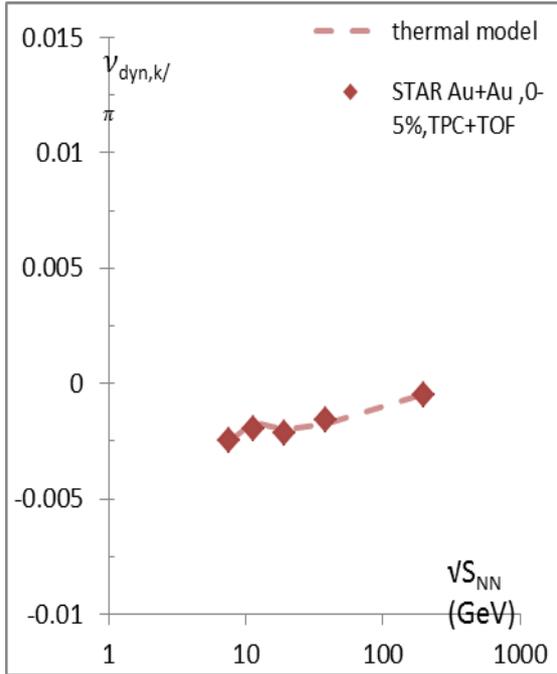


Fig (2a) The calculated $v_{dyn,k/\pi}$ ($\frac{K}{\pi} = \frac{K^+ + K^-}{\pi^+ + \pi^-}$) in comparison with STAR experiment [46].

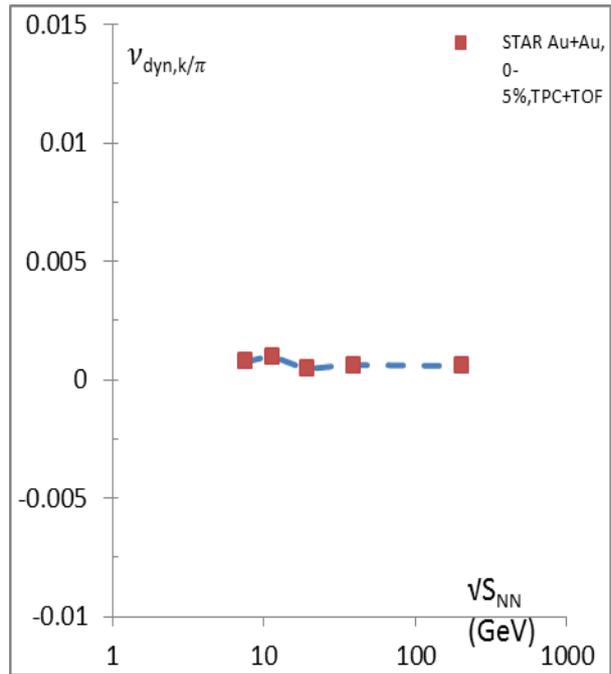


Fig (2b) The calculated $v_{dyn,k/\pi}$ for the average of the same sign ($\frac{K}{\pi} = \frac{K^+}{\pi^+} + \frac{K^-}{\pi^-}$) in comparison with STAR experiment [46].

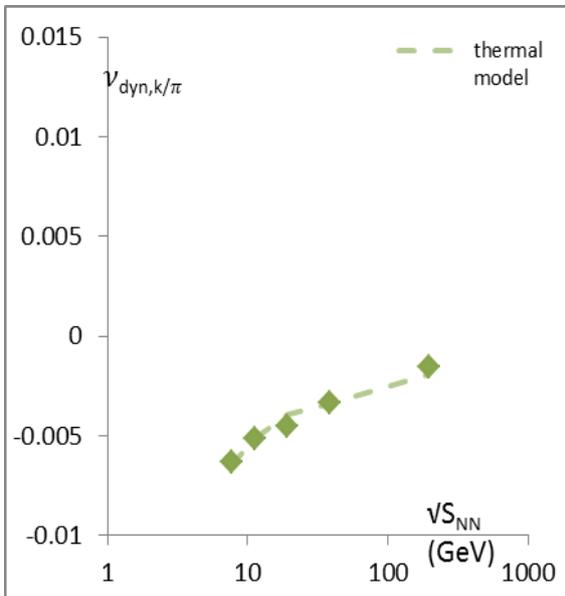


Fig (2c) The calculated $v_{dyn,k/\pi}$ for the average of the opposite sign ($\frac{K}{\pi} = \frac{K^+}{\pi^-} + \frac{K^-}{\pi^+}$) in comparison with STAR experiment [46].

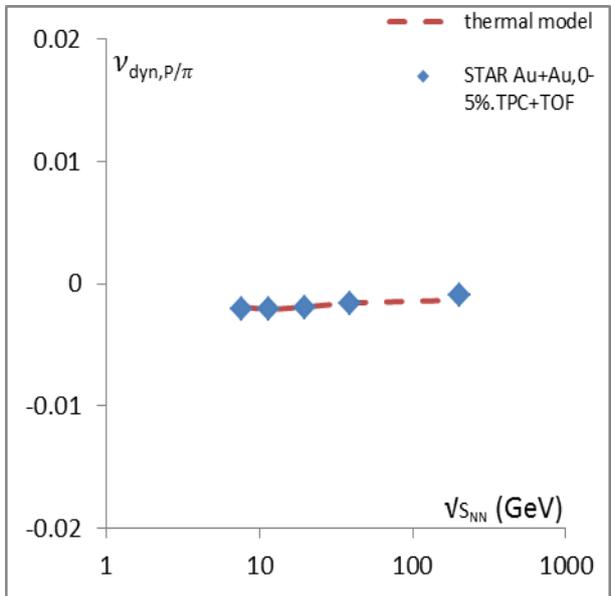


Fig (2d) The calculated $v_{dyn,k/\pi}$ ($\frac{P}{\pi} = \frac{P^+ + P^-}{\pi^+ + \pi^-}$) in comparison with STAR experiment [46].

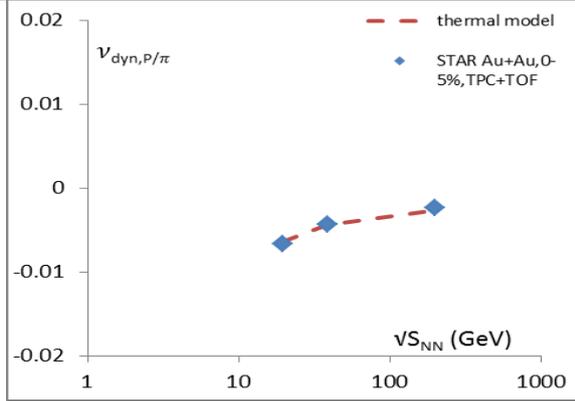


Fig (2e) The calculated $v_{dyn,k/\pi}$ for the average of the same sign $(\frac{P}{\pi} = \frac{P^+}{\pi^+} + \frac{P^-}{\pi^-})$ in comparison with STAR experiment [46].

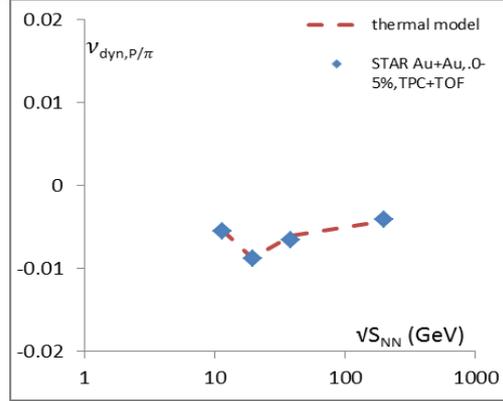


Fig (2f) The calculated $v_{dyn,k/\pi}$ for the average of the opposite sign $(\frac{P}{\pi} = \frac{P^+}{\pi^-} + \frac{P^-}{\pi^+})$ in comparison with STAR experiment [46].

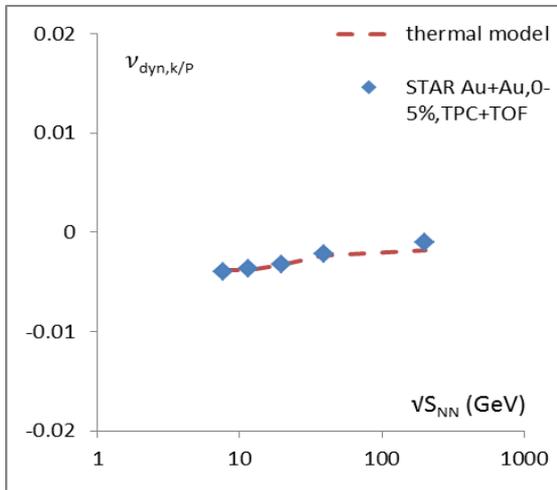


Fig (2g) The calculated $v_{dyn,k/\pi}$ $(\frac{k}{P} = \frac{k^+}{P^+} + \frac{k^-}{P^-})$ in comparison with STAR experiment [46]

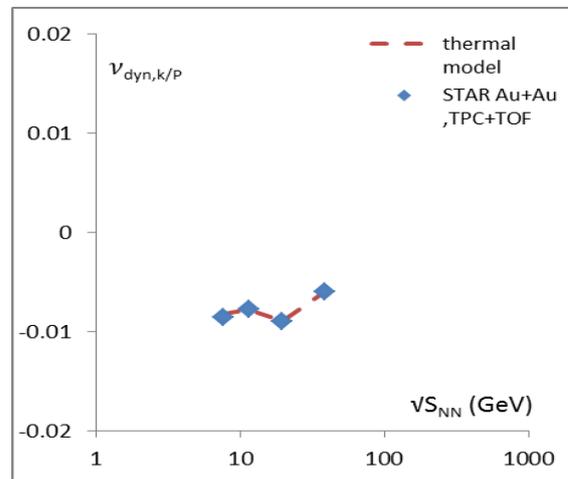


Fig (2h) The calculated $v_{dyn,k/\pi}$ for the average of the same sign $(\frac{K}{P} = \frac{K^+}{P^+} + \frac{K^-}{P^-})$ in comparison with STAR experiment [46].

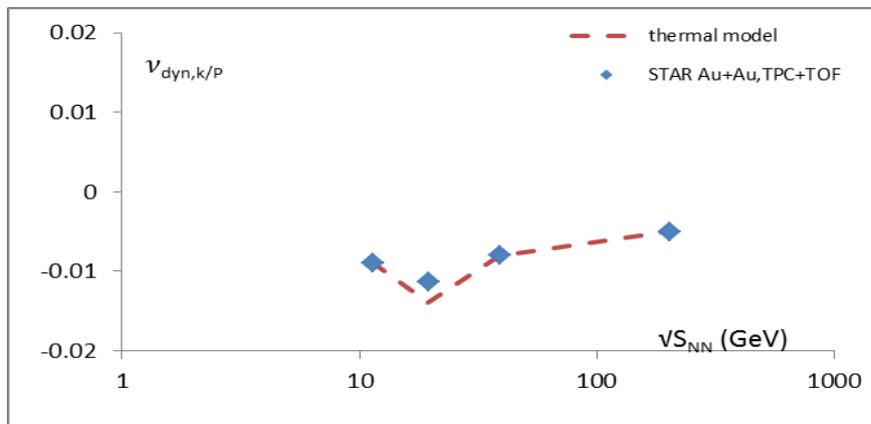


Fig (2i) The calculated $v_{dyn,k/\pi}$ for the average of the opposite sign $(\frac{K}{P} = \frac{K^+}{P^-} + \frac{K^-}{P^+})$ in comparison with STAR experiment [46].

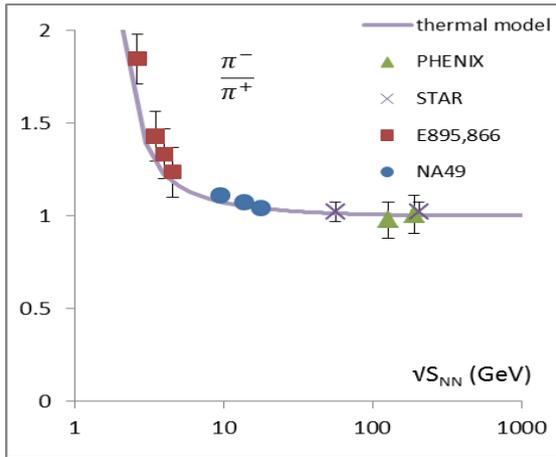


Fig (3a) The energy dependence of particle ratios for $\frac{\pi^-}{\pi^+}$ in comparison with different experimental results [38].

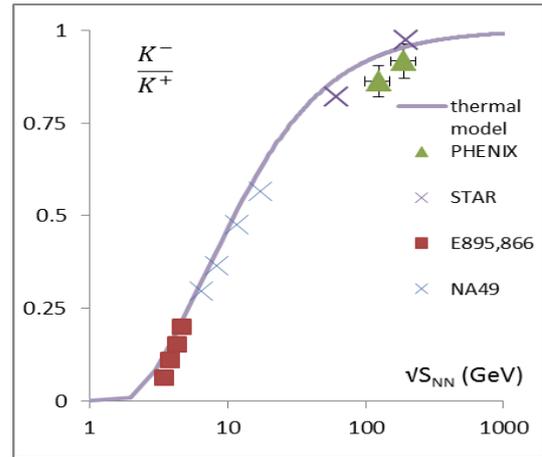


Fig (3b) The energy dependence of particle ratios for $\frac{K^-}{K^+}$ in comparison with different experimental results [38].

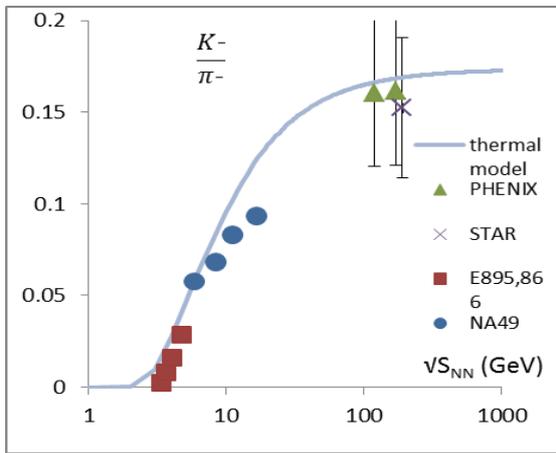


Fig (3c) The energy dependence of particle ratios for $\frac{K^-}{\pi^-}$ in comparison with different experimental results [38].

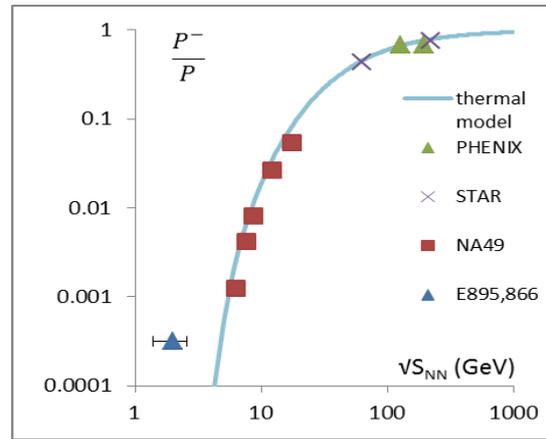


Fig (3d) The energy dependence of particle ratios for $\frac{P^-}{P}$ in comparison with different experimental results [38].

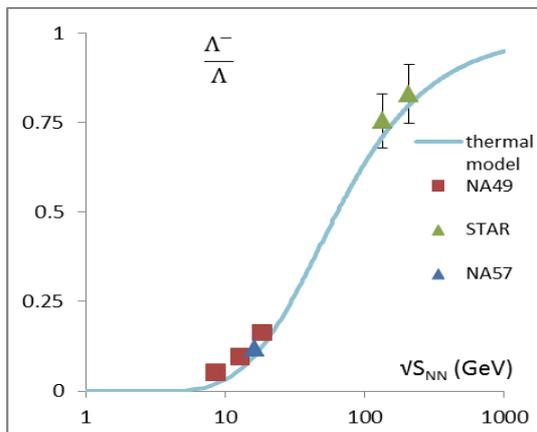


Fig (3e) The energy dependence of particle ratios for $\frac{\Lambda^-}{\Lambda}$ in comparison with different experimental results [38].

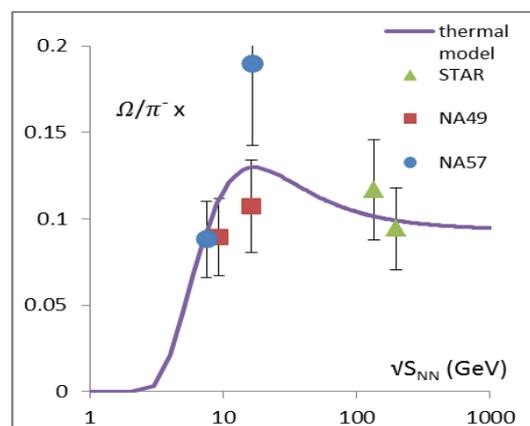


Fig (3f) The energy dependence of particle ratios for $\frac{\Omega}{\pi^-}$ in comparison with different experimental results [38].

From these figures, one can see that $\frac{\pi^-}{\pi^+}$ ratio

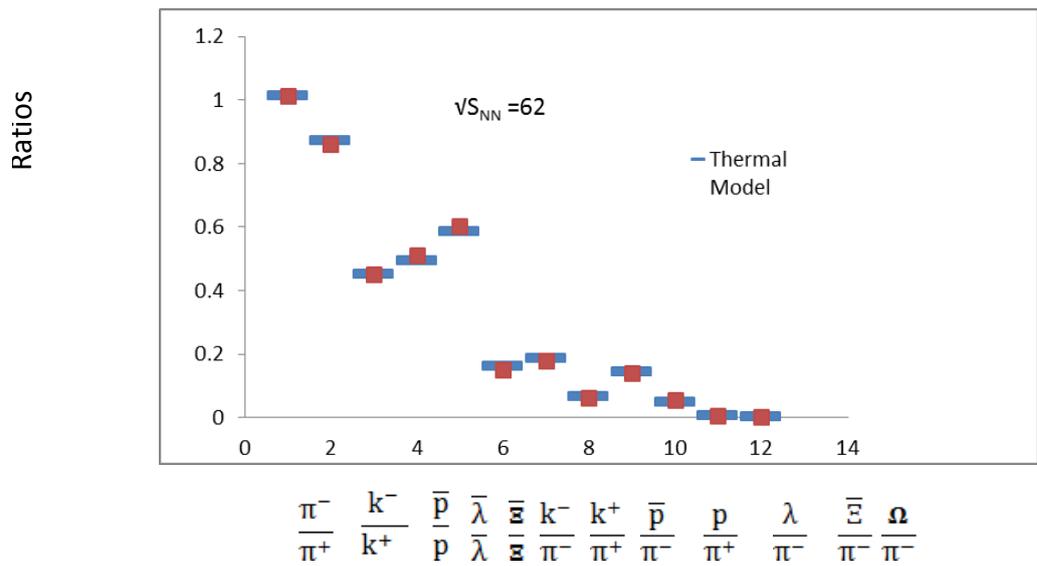


Fig (3g) Calculated Particle ratios at $\sqrt{s_{NN}}=62$ GeV in comparison with STAR experiment [29].

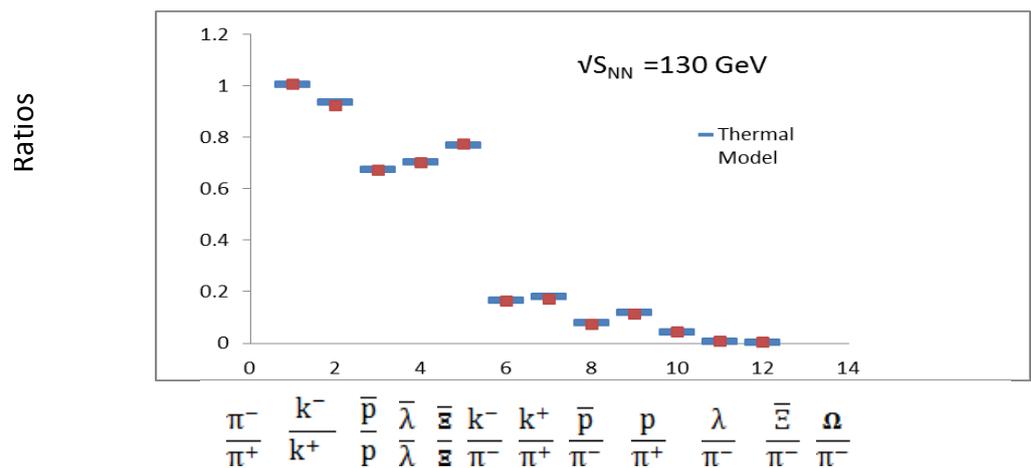


Fig (3h) Calculated Particle ratios at $\sqrt{s_{NN}}=130$ GeV in comparison with STAR experiment [29].

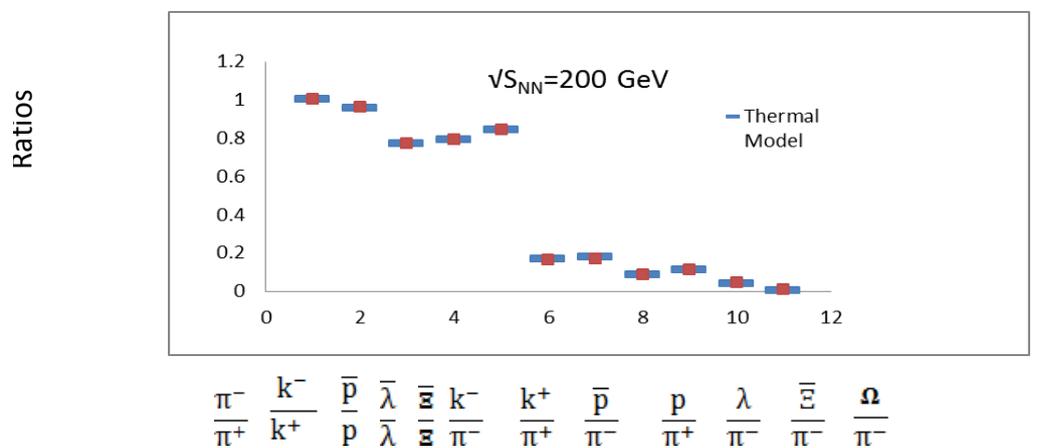


Fig (3i) Calculated Particle ratios at $\sqrt{s_{NN}}=200$ GeV in comparison with STAR experiment [29].

5. Conclusion

In this paper, the four different freeze-out conditions which mentioned above have been calculated and compared with the available experimental data. One can see that, the freeze-out temperature is approximately of $164 \leq T_f \leq 169$ MeV, which is close to the one expected for phase transition, which is about 170 MeV [51] as indicated by lattice gauge theory.

Also, The net charge fluctuations as a signal of quark-gluon plasma (QGP) are calculated in terms of the parameter ν_{dyn} . We calculated the charge dependence of the dynamical K/π , P/π , and K/P fluctuations. Only the $\nu_{\text{dyn},k/\pi}$ in case of $\frac{K^-}{\pi^-} = \frac{K^+ + K^0}{\pi^+ + \pi^0}$ have positive values.

The energy dependence of the particle ratios $\frac{K^-}{\pi^-}$, $\frac{K^+}{\pi^+}$, $\frac{K^0}{\pi^0}$, $\frac{P^-}{\pi^-}$, $\frac{P^+}{\pi^+}$, $\frac{\Lambda^-}{\pi^-}$, and $10 \times \frac{\Omega^-}{\pi^-}$ are calculated in comparison to the available results from different experiments. The particle ratios $\frac{k^-}{k^+}$, $\frac{\bar{p}}{p}$, $\frac{\bar{\lambda}}{\lambda}$, $\frac{\bar{\Xi}}{\Xi}$, $\frac{k^-}{\pi^-}$, $\frac{k^+}{\pi^+}$, $\frac{\bar{p}}{\pi^-}$, $\frac{p}{\pi^+}$, $\frac{\lambda}{\pi^-}$, $\frac{\bar{\Xi}}{\pi^-}$, and $\frac{\Omega}{\pi^-}$ are calculated at STAR beam energies 62, 130, and 200 GeV.

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