Cumulants of net-strangeness multiplicity distributions at RHIC energies

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The higher order cumulants of net-proton number, net-charge, and net-strangeness multiplicity distributions are widely studied to search for the Quantum-Chromodynamics(QCD) critical point and extract the chemical freeze-out parameters in heavy-ion collisions. In this context, the event-by-event fluctuations of the net-strangeness multiplicity distributions play important roles in extracting the chemical freeze-out parameter in the strangeness sector. Due to having difficulties in detecting all strange hadrons event-by-event, the kaon (K) and lambda(Λ) particles serve as a proxy for the strangeness related observable in heavy-ion collisions. We have studied the net-K, net-Λ, and net-(K+Λ) multiplicity distributions and calculated their different order of cumulants using the UrQMD model and Hadron Resonance Gas (HRG) calculation. It is found that resonance decay contributes to the net-strangeness cumulants. Furthermore, we compare the freeze-out parameters used in the HRG calculation to match the STAR published net-kaon and net-lambda higher order cumulants with that extracted from the strange particle yield data and find consistency between these two methods.

I. INTRODUCTION

A deconfined phase of QCD matter—known as the Quark-Gluon Plasma—is created by colliding heavy-ions at Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC). The main goal of the RHIC Beam Energy Scan (BES) program is to search for the QCD Critical Point and gauge the QCD phase diagram in temperature (T) and baryon chemical potential ($\mu_B$) plane. In BES phase-I, the STAR experiment reported several measurements on the higher order cumulants of net-charge [1], net-proton number [2, 3, 5], net-kaon [6], and net-lambda [7] multiplicity distributions as well. These cumulants are associated with their respective conserved charge susceptibilities, and hence these are related to thermodynamic quantities, like T and $\mu_B$, in heavy-ion collisions.

The net-proton number cumulant measurements are proposed as the proxy of net-baryon number susceptibility; hence it is used to search for the location of the QCD critical point [4] in heavy-ion collision. Refs [2, 3, 5] have reported several net-proton cumulant measurements. In addition, one can extract the Chemical Freeze-Out (CFO) temperature and $\mu_B$ in the heavy-ion collisions with the help of these cumulants [14, 16].

On the other hand, the cumulants of net-kaon and net-lambda multiplicity distribution act as a proxy for the strangeness-related cumulants and help to extract the CFO parameters from the strangeness sector, especially strangeness chemical potential ($\mu_S$) and the respective temperature. The standard practice is to extract these parameters using the strange hadron yields [17, 20] and also the higher order cumulants of net-strangeness multiplicity distributions. The inclusion of different resonances in the thermal model fit influences the CFO parameter [11]. The freeze-out temperature increases with the inclusion of heavier hadrons [8, 17]. Furthermore, the strange meson freezes out earlier than lighter hadrons at the highest RHIC energy, as studied in Ref.[12, 13]. Hence it is important to know the other strange baryons’ freeze temperature and their chemical potential in heavy-ion collisions.

In this paper, we study the cumulants of net-kaon, net-lambda, and net-(kaon+lambda) multiplicity distributions using the UrQMD model and the centrality variation for the STAR energies. To estimate the degree of thermalization, we have compared the most central results from UrQMD with the Hadron Resonance Gas (HRG) calculation. These results would set a baseline for the ongoing measurements in the STAR experiment. The CFO parameters extracted from the thermal model fit of the particle yields are used in the HRG calculations to match the net-kaon and net-lambda higher order cumulant data from the STAR results [20]. A one-to-one comparison between UrQMD and HRG results for the net-(kaon+lambda) elucidate the necessity to consider the contribution of the feed-down from the decay of higher mass resonance into the thermal model to explain the net-strangeness observable at RHIC energies.

This paper is organized as follows. In section II A the definition of net-(kaon+lambda) and their cumulants are introduced. A brief introduction of the UrQMD model and HRG calculation are mentioned in Section II B and II C respectively. The net-kaon, net-lambda, and net-(kaon+lambda) cumulants and their ratios are discussed in Section III A. The comparison between the UrQMD and HRG calculations for the net-K and net-Λ multiplicity distributions is discussed in Section III B. The strangeness production and resonance decay effects are discussed in section III C. Finally, we summarize our
II. OBSERVABLES AND MODELS

A. Cumulants of Net-(kaon+lambda) multiplicity distributions

We define the number of net-(kaon+lambda) (in short net-(K+Λ)) as,

\[ N_{K+\Lambda} = (N_{K^+} + N_{\Lambda}) - (N_{K^-} + N_{\Lambda}). \]  (1)

Here \( N_x \) is the number of \( x \) particle in an event within a given phase space window, where \( x \) is \( K^+(us), K^-((us), \Lambda(usd), \) or \( \Lambda(uds) \). Here the \( (N_{K^+} + N_{\Lambda}) \) and \( (N_{K^-} + N_{\Lambda}) \) represent the total positive and negative strangeness quantum numbers in an event, respectively. In heavy-ion collisions, the initial \( N_{K+\Lambda} \) is zero. Note here that the STAR net-kaon and net-lambda publications are reported with \( (N_{K^+} - N_{K^-}) \) in net-kaon and \( (N_{\Lambda} - N_{\bar{\Lambda}}) \) in net-lambda measurements, respectively.

The \( \langle N \rangle \) is the ensemble average of multiplicity in a given centrality class. The deviation of \( \delta N = N - \langle N \rangle \). The \( n^{th} \) order of diagonal cumulants \( \langle C_n \rangle \) can be defined as,

\[ C_1 = \langle N \rangle, \] (2)
\[ C_2 = \langle (\delta N)^2 \rangle, \] (3)
\[ C_3 = \langle (\delta N)^3 \rangle, \] (4)
\[ C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2. \] (5)

A detailed discussion regarding the cumulant generating function and relationships between moments, central moments, and cumulants can be found in Ref. [13]. In this paper, we discuss different orders of cumulants and their ratios for the net-(K+Λ), net-K, and net-(Λ) multiplicity distributions. The connection between these cumulants and the thermodynamics susceptibilities is discussed in Section II C.

B. UrQMD model

The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) [21, 22] model is a microscopic transport model. In this space-time evolution model, the propagation, re-scattering among hadrons, and string excitation are included, whereas no in-medium modifications effects are implemented. Hence, this model is used to study the baseline measurement in heavy-ion collisions for various observables [23, 24].

In the present work, the Au+Au collision events are simulated at \( \sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4, \) and \( 200 \) GeV with minimum-bias configuration (impact parameter, \( b = 0 \) to \( 14 \) fm). The different particles with their PDG particle identification in an event are analyzed using the same phase space window similar to the STAR experiment. The centrality selections are performed based on the charged particle multiplicity distribution at the mid rapidity, following the STAR experiment specifications. The net-K, net-Λ, and net-(K+Λ) multiplicity distributions are calculation within \( 0.4 < p_T < 1.6\) GeV/c and rapidity window \( |y| < 0.5 \). The cumulants and their ratios are calculated as mentioned in Section II A.

C. HRG calculation

The HRG model considers the medium as an ensemble of non-interacting hadrons and their resonances. The partition function can be written as,

\[ \ln Z_{id}^\text{id} = \sum_i \ln Z_i^\text{id}, \] (6)

where the sum runs over all the hadrons and resonances. For the \( i^{th} \) hadron,

\[ \ln Z_i^\text{id} = \pm \frac{V_i g_i}{2\pi^2} \int_0^\infty p^2 dp \ln \left[ 1 \pm \exp \left( -\frac{(E_i - \mu_i)}{T} \right) \right] \] (7)

where \( V, T \) and \( g_i \) is the system volume, temperature and degeneracy factor of the \( i^{th} \) hadron. \( E_i = \sqrt{p^2 + m_i^2} \) is the single particle energy. \( \mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q \) is the chemical potential, where \( B_i, S_i, \) and \( Q_i \) are respectively the baryon number, strangeness, and charge of the particle. The \( \mu_B, \mu_S, \) and \( \mu_Q \) are the baryon, strangeness, and charge chemical potentials, respectively.

The pressure of a single hadron is defined as,

\[ P_i^\text{id} = \frac{T}{V} \ln Z_i^\text{id} \]
\[ = \frac{g_i T}{2\pi^2} \int_0^\infty p^2 dp \ln \left[ 1 \pm \exp \left( -\frac{(E_i - \mu_i)}{T} \right) \right] \] (8)

The \( n^{th} \) order susceptibility is defined as,

\[ \chi_n^\text{x} = \frac{1}{V T^3} \frac{\partial^n \ln Z}{\partial \left( \frac{\mu_x}{T} \right)^n} \] (9)

where \( \mu_x \) is the chemical potential for conserved charge \( x \). Derivatives of the grand canonical partition function \( (Z) \) with respect to the chemical potential define susceptibilities which experimentally become available through the event by event analysis of fluctuations of conserved charges such as baryon number, electric charge, strangeness and others. For our present purpose \( x = S \) (strangeness).

The \( 1^{st} \) order susceptibility can be expressed as,

\[ \chi_1^\text{x} = \sum_i \frac{g_i x_i}{2\pi^2 T^3} \int_0^\infty f_i p^2 dp. \] (10)

Here,

\[ f_i = \frac{1}{\exp \left[ (E_i - \mu_i)/T \right] \pm 1} \] (11)
In this work, the particle species under consideration \((K, \Lambda)\) can be approximated with the corresponding Boltzman distribution as they have much higher masses than the corresponding temperature of the freeze-out surface. Then one can write,

\[
 f_i = \exp \left[ - (E_i - \mu_i) / T \right].
\]

One can find the higher order susceptibilities by taking derivative of Eq.(10) with the corresponding chemical potential.

D. Connection with experimental observable

In heavy-ion experiments, the event-by-event net-charge multiplicity distributions are measured within a finite acceptance. The cumulants \((C_n)\) discussed in Section IV.A are related to the different order of susceptibilities by the following relation,

\[
 VT^3 \chi^n = C_n
\]

The ratios of these cumulants are taken to cancel the volume term in the above expression. The mean \((\langle N \rangle)\), variance \((\sigma^2_q)\), skewness \((S_q)\) and kurtosis \((\kappa_q)\) are also related with different cumulants as follows.

\[
\begin{align*}
\sigma^2_q / M_q &= C_2 / C_1 = \chi^2_q / \chi^1_q \\
S_q \sigma_q &= C_3 / C_2 = \chi^3_q / \chi^2_q \\
\kappa_q \sigma^2_q &= C_4 / C_2 = \chi^4_q / \chi^2_q
\end{align*}
\]

III. RESULTS AND DISCUSSION

A. Cumulants of Net-K, net-\(\Lambda\), and net-(K+\(\Lambda\)) in UrQMD

The \(K^-/K^+\) yield ratio increases with collision energy and approaches to unity at higher collision energy due to the interplay between associated production (NN \(\rightarrow\) KYN, \(\pi N \rightarrow\) KY) and pair production (NN \(\rightarrow\) NNK\(^+\)K\(^-\)). The \(\Lambda/\bar{\Lambda}\) yield ratio also shows the same trend as a function of collision energy. The recent net-K and net-\(\Lambda\) measurements show that the \(C_1\) of these multiplicity distributions are positive and increase with centrality and also collision energy. In this paper, we calculate the \(C_n\) of net-K, net-\(\Lambda\), and net-(K+\(\Lambda\)) multiplicity distributions for seven collision energies using the UrQMD model.

The variation of \(C_1\), \(C_2\), \(C_3\), and \(C_4\) as a function of centrality for the net-K, net-\(\Lambda\), and net-(K+\(\Lambda\)) multiplicity distributions using the UrQMD model are shown in Fig. 1 for various collision energies. The collision centralities are represented by the average number of participating nucleons \((\langle N_{\text{part}} \rangle)\). For individual particle species, the variation is similar to multiplicity. The dominance of particle \((K^+, \Lambda)\) over the anti-particle increases with \(\langle N_{\text{part}} \rangle\) for all the \(\sqrt{s_{\text{NN}}}\). The abundance of particles and anti-particle becomes similar as the collision energy increases. We have observed this behavior in all four cumulants. At lower \(\sqrt{s_{\text{NN}}}\), baryon stopping creates a medium with high baryon density, which effectively produces more \(K^+, \Lambda\) than the corresponding anti-particle.

On the contrary, the mean value \((C_1)\) of net-(K+\(\Lambda\)) is negative at lower energy, whereas it becomes positive at \(\sqrt{s_{\text{NN}}} = 200\) GeV in Au+Au collisions in UrQMD. Here we reiterate the combined quantity, \(N_{K+\Lambda} = (N_{K^+} + N_{\Lambda}) - (N_{K^-} + N_{\bar{\Lambda}})\). We can understand this trend as the following. More baryons are produced at the lower collision energy due to the higher baryon deposition. The \(\Lambda\) particle, being the lightest strange baryon, dominates the net-(K+\(\Lambda\)) and gives rise to this negative value. This negative trend decreases as the collision energy increases and particle-anti-particle yields become similar.

The \(C_2\) of net-(K+\(\Lambda\)) is greater than that of net-K and net-\(\Lambda\) at all collision energies; that indicates a large number of total strange multiplicity in net-(K+\(\Lambda\)) case than the individual net-K and net-\(\Lambda\) and hence the fluctuation is larger for net-(K+\(\Lambda\)). The behavior of \(C_3\) is similar to \(C_1\) since the mean of distribution mainly contributes to its skewness. Here more negative net-strangeness number (more s-quarks) is seen at lower collision energies than at the top collision energy. The \(C_4\) as a function of centrality shows no noticeable difference between net-K, net-\(\Lambda\), and net-(K+\(\Lambda\)), implying that the kurtosis of these distributions does not change significantly.

Figure 2 shows the three cumulant ratios \(C_1/C_2\), \(C_3/C_2\), and \(C_4/C_2\) for the net-K, net-\(\Lambda\), and net-(K+\(\Lambda\)) multiplicity distributions from \(\sqrt{s_{\text{NN}}}=7.7\) to 200 GeV. The \(C_1/C_2\) for net-kaon and net-\(\Lambda\) is always positive as a function of centrality. Contrarily, this is negative up to \(\sqrt{s_{\text{NN}}}=39\) GeV for net-(K+\(\Lambda\)). Negative \(C_1\) is responsible for the negative value of this ratio. A similar trend is observed in the case of \(C_3/C_2\). The negative \(C_1\) and \(C_3\) are responsible for making these ratios negative for net-(K+\(\Lambda\)). The \(C_4/C_2\) is almost the same for three cases at all energies and remains around unity.

B. Comparison with HRG

A comparison among the UrQMD results and HRG calculation is important to understand the underlying hadronic scattering contribution to these observables and set a baseline for heavy-ion collision experiments. To study the degree of thermalization, we have used the HRG model calculated at the chemical freeze-out boundary. Ref. [19] has shown that various cumulants (up to \(3^3\)) of different species can describe the susceptibilities calculated in the HRG using a grand canonical ensemble above certain colliding energy; this may suggest that the non-applicability of thermalization to the fireball created in heavy-ion collisions.

Figure 3 shows the values of \(\mu_B / T\) and \(\mu_S / T\) as a function of \(\sqrt{s_{\text{NN}}}\). These values are the input parameters for
the HRG calculation. These parameters have been evaluated with the results from the thermal model, assuming a grand-canonical ensemble, fitting to the yields of particles including $\pi$, K, p, $\Lambda$, $\Xi$ and $\Omega$ [25-28]. These parameters are consistent with those extracted by the STAR collaboration [17, 20].

With these parameters in hand, we shall first compare ratios corresponding to the individual species. It was earlier found in Ref. [32-34], that for the individual species, the ratios of cumulants up to 3rd order, the decay feed-down does not affect the result significantly. We have shown the comparison between the STAR data and
HRG calculations for $S\sigma$ of net-K and net-Λ multiplicity distributions in Fig. 4. The HRG calculations, with $\mu_S/T$ and $\mu_B/T$ values in Fig. 3, are done both with and without acceptance cut as used in the data and show that the effect of acceptance cut used in the STAR experiment has a negligible effect. The HRG calculations can explain the data both for the net-K and net-Λ $S\sigma$ results. Note here that no decay contributions are included in these HRG calculations.

The comparison between the UrQMD model and HRG calculations shows that the net-K $S\sigma$ results are comparable and also match the data. The net-Λ $S\sigma$ results have an apparent difference between the UrQMD and HRG calculations. The UrQMD result for net-Λ deviates from the data at all energies. The higher mass resonances decay channels are included in the UrQMD events. This difference in net-Λ $S\sigma$ results from UrQMD could be due to the difference in the Λ, higher resonance (anti-)particle production yields in UrQMD, and the RHIC energies [22].

With a general agreement among UrQMD results, data, and HRG calculations, it would be interesting to compare results for the net-(K+Λ) multiplicity distribution. As no experimental data is available yet for this combination, we have compared the UrQMD results with those from the HRG model. In Fig. 5, the energy dependence of the net-(K+Λ) $C_1/C_2$, $C_3/C_2$, and $C_4/C_2$ for 0-5% central Au+Au collisions in the UrQMD model and HRG calculations are compared. The $C_1/C_2$ and $C_3/C_2$ show an opposite trend at lower collision energy between the UrQMD and the thermal model predictions. The HRG calculations have been performed with the chemical freeze-out parametrization from Ref. [25, 26, 28]. This disagreement is prominent at lower collision energy. This difference arises from higher mass resonance decay in the UrQMD model, whereas no such decay feed-down is included in the HRG calculations. A detailed discussion on the importance of higher mass resonance decay contributions can be found in Section III C. The $C_4/C_2$ of HRG calculation is unity at all energies and consistent.
FIG. 5. The energy dependence of $C_1/C_2$, $C_3/C_2$, and $C_4/C_2$ for 0-5% centrality for the UrQMD model (circles) and the HRG calculation (red line).

with the UrQMD models. It shows that $C_4/C_2$ is less sensitive to the resonance contributions.

C. Strangeness production in HRG

In heavy-ion collisions, the strange particles’ yields contain the contribution from the decay feed-down of higher mass resonances [17, 20]. In the thermal model, it is important to include all higher mass resonance decay channels to capture the bulk description of the chemical freeze-out surface properly. Inclusion of these decays for higher order susceptibility calculations needs to consider the probabilistic nature of decay channels through their branching fractions [29–32]. Including these decay products in the yield calculations are trivial as those are the 1st cumulant (mean). The (anti-)Λ(1115) has the contributions from the higher mass strange baryons, e.g., Σ(1385), Λ(1405), Λ(1520), and other heavy resonances. kaons(493) have contributions mostly from the higher mass meson resonances like $K^*(892)$, $K(1270)$, $\phi(1020)$, etc. However, for kaons, the inclusion of all resonances becomes complex as many resonances decay into both $K^+$ and $K^-$. In this work, we have not included any decay channel from the higher resonances for the susceptibility calculation in the HRG.

To quantify the relevance of decay from the higher mass resonances, we have plotted the ratio of the mean value of the net-(K+Λ) with that of the total in Fig. 6. The model calculations are performed following the freeze-out parameters from Ref.[25, 27]. These parameters were extracted with the mean value of yields and successfully explained the hadronic yield ratios. By including decays from higher mass resonances, the model agrees with the data, whereas the ratio increases with decreasing beam energy if we exclude the decay contribution. Hence, for a reasonable estimate of the parametrization and to explain the data, it is necessary to include the higher mass resonance decay in the calculation of the net-strangeness observable.

Although the strangeness neutrality demands the net-strangeness to be zero in the total system and distributed among the final particle species in the whole phase space. Here, we investigate only the charged kaon(493) and Λ(1115). With increasing $\mu_B$ at lower collision energies, strange baryons dominate, and the strangeness gets distributed mainly among the hyperons. The Λ being the lightest one contributes the most significant part. The decay from higher mass resonances increases the yield of Λ and produces a net negative strangeness at lower collision energies. With only the primary abundance, the net strangeness remains positive in our observable, as the lightest kaons dominate the sum and deliver a positive strangeness. Such behaviors can be seen in the UrQMD model calculation as it includes all resonance decays in an event, as discussed in Section III B.
IV. SUMMARY AND OUTLOOK

In heavy-ion collision experiments, observables related to net-K and net-Λ act as a proxy for the strangeness. Although the individual results for net-K and net-Λ are available from STAR BES, results for the combined study for the net-(K+Λ) are yet to be performed. In this work, we have studied the cumulants of net-K, net-Λ, and net-(K+Λ) multiplicity distributions for the RHIC BES energy range using the UrQMD model. These studies serve as a baseline for the cumulants measurement of the net-(K+Λ) multiplicity distributions.

In UrQMD, the $C_1$ and $C_3$ of net-(K+Λ) are negative at lower energies and become positive at higher collision energies within the given acceptance window mentioned in this paper. At lower $\sqrt{s_{NN}}$, the finite baryon density favors the dominance of hyperons over strange mesons, which produces this negative strangeness. This effect diminishes as the collision energy increases and kaon become more abundant than the hyperons. On the contrary, the higher order cumulant $C_4$ has no significant variation between net-K, net-Λ, and net-(K+Λ) multiplicity distributions.

As a benchmark, we have compared our UrQMD calculations of various cumulants with available STAR data of net-K and net-Λ for the most central collision, where a good agreement is apparent. Furthermore, we have compared the UrQMD results with the HRG calculation to study the thermalization contribution to these observables. The HRG calculations have been performed at the standard chemical freeze-out parametrization. We have chosen ratios of various cumulants to nullify the volume systematics. Although there is good agreement among data, UrQMD calculations and model(HRG) predictions for the individual net-K, net-Λ, and net-(K+Λ) are yet to be performed. In this work, we have studied the cumulants of net-K, net-Λ, and net-(K+Λ) for the most central collision, where a

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