Statistical Models and STAR’s Strange Data

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Abstract. The yields of strange hadrons have been measured as a function of centrality in Au + Au and in p + p collisions at $\sqrt{s_{NN}} = 200$ GeV in STAR. The system size and energy dependence are studied and compared for p+p and Au + Au collisions. Thermal models are fitted to the ratios of various strange particles to investigate the particle production and to determine the strangeness enhancement. The temperatures ($T$) and the strangeness enhancement factors ($\gamma_s$) of the systems determined from the fits are presented.

Keywords: list of keywords, relevant to the article
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1. Introduction

It was pointed out by Fermi and later by Hagedorn that particle production in heavy ion collisions can be described with the considerations of phase space [1]. The question that is being discussed is whether phase space arguments can also describe the centrality dependence of strangeness production. The differences in the production of bulk matter ($p_T < 1$ GeV) and non-bulk matter ($p_T > 1$ GeV) are investigated with statistical models which are also used to estimate the equilibrium properties and the trends of particle yields and ratios. The quality of the statistical fits and the implications of the resulting fit parameters such as $T$, $\gamma_s$ and $\mu_B$ are discussed.

2. Statistical Models

Assuming QGP formation in heavy ion collisions at RHIC energies, it is expected that the thermal nature of the partonic medium could be preserved during hadronization [2]. The particle yields measured in the final state then resemble a population in thermal equilibrium. Thermal models are used to predict the equilibrium properties of a macroscopic system from the measured yields of the constituent particles. It is commonly agreed that light (u and d) quarks are more likely to reach equilibrium...
in the medium than the strange quarks due to the relatively larger strange quark mass ($m_s \sim T_c$). The strangeness saturation factor, $\gamma_s$, is introduced to account for the amount of strangeness chemical equilibration [3]. One of the parameters of the statistical fits, which is the more generic term of the strangeness saturation factor ($\gamma_s$), is the phase space occupancy ($\gamma_s$). This term is used to regulate the sum of particle and anti-particle pairs produced in the medium.

With the given ratios of particles, it is possible to deduce the temperature $T$, the volume $V$, the baryonic chemical potential $\mu_B$, strangeness chemical potential $\mu_S$ and charge chemical potential $\mu_Q$ [2, 4, 5]. Chemical potentials describe the particle anti-particle difference and require that the variables are conserved only on average in the whole system (Grand Canonical (GC) ensemble). The GC ensemble can be used to describe large systems such as central Au + Au collisions, while the Canonical ensemble is used for small system such as $p + p$ collisions when all quantum numbers must be conserved exactly.

The predicting power of statistical models for $T$, $\mu_B$, $\mu_S$, and $\gamma_S$ require the utilization of measured particle ratios. With the ratios, all degeneracy factors of the fireball cancel, leaving just the relative fugacities. Some examples are given in Equation 1 and Equation 2.

\[
\frac{\bar{p}}{p} = \lambda_u^{-4} \lambda_d^{-2} = \exp(-\frac{4\mu_u + 2\mu_d}{T}),
\]

\[
\frac{\Lambda}{p} = \lambda_s \lambda_u^{-1} = \exp(\frac{\mu_s - \mu_u}{T})
\]

where the fugacity of a hadron is defined by the product of its valance quark fugacities (e.g., $\lambda_s = \lambda_u \lambda_d$, $\lambda_n = \lambda_u \lambda_d^2$ and $\lambda_A = \lambda_u \lambda_d \lambda_s$).

3. Statistical Model Comparisons

Several statistical model computational codes are available. A comparison of the parameters of these codes is presented in Table 1. In order to make any comparisons of the the fits, the requirements of the models are fixed to be same. For example, $\gamma_q$ (light-quark phase space occupancy) is fixed to 1 in SHARE [6] and only the Grand

| Models Used      | Ensemble       | Parameters                        |
|------------------|----------------|-----------------------------------|
| 4 Parameter Fit  | Grand Canonical| $T$, $\mu_q$, $\mu_s$, and $\gamma_s$ |
| SHARE V1.2       | Grand Canonical| $T$, $\lambda_q$, $\lambda_s$, $\gamma_q$, $\gamma_s$, $\mu_{T3}$, $N$, $\lambda_c$ and $\gamma_c$ |
| THERMUS V2       | Canonical      | $T$, $B$, $S$, $Q$, $\gamma_s$ and $R$ |
|                  | Grand Canonical| $T$, $\mu_B$, $\mu_s$, $\mu_Q$, $\mu_c$, $\gamma_s$, $\gamma_c$ and $R$ |
Canonical ensemble is used in THERMUS[7]. Also, since the default contribution of the feed-down from weak decays on particle ratios is handled differently in each code, either all the feed-down is removed or is included in all models in the same amounts.

4. Statistical Model Fits

Predictions of a thermal model are compared to the measured particle ratios from \( p + p \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV in Figure 1a. The resulting fit parameters are \( T_{ch} = 171 \pm 9 \) MeV, \( \gamma_s = 0.53 \pm 0.04 \) and the radius of the source, \( r \), is \( 3.49 \pm 0.97 \) fm. The quantum numbers baryon (B) and charge (Q) are fixed to 2 while net strangeness (S) is fixed to 0. The short lines represent the thermal model fits from a canonical calculation performed by Thermus V2.0. The closed circles represent the particle ratios measured in p+p collisions. The model accurately describes both the stable particle and resonance ratios in p+p collisions. The \( 1 \sigma \) error on the ratios and the differences between the model predictions and the data are included in the plot. The differences do not exceed \( 2 \sigma \).

Fig. 1. (a) Particle ratios in \( \sqrt{s_{NN}} = 200 \) GeV \( p + p \) collisions in comparison to canonical thermal model predictions (short lines) from Thermus V2.0[7]. The fit parameters are \( T_{ch} = 171 \pm 9 \) MeV, \( \gamma_s = 0.53 \pm 0.04 \) and \( r = 3.49 \pm 0.97 \) fm. B and Q are fixed to 2 while S is fixed to 0. (b) Particle ratios in the \( \sqrt{s_{NN}} = 200 \) GeV most central Au+Au collisions in comparison to a grand canonical thermal model prediction. The fit parameters are \( T_{ch} = 168 \pm 6 \) MeV, \( \gamma_s = 0.92 \pm 0.06 \), \( \mu_B = (4.52 \pm 0.98) \times 10^{-2} \) GeV, \( \mu_S = (2.23 \pm 0.74) \times 10^{-2} \) GeV, \( \mu_Q = (-2.05 \pm 0.77) \times 10^{-2} \) GeV, and \( r = 15 \pm 10 \) fm. See text for details.
Figure 1-b presents the particle ratios and Thermus V2.0 predictions for the most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The measured ratios are used to predict the free parameters by using a grand canonical approach. The fit parameters are $T_{ch} = 168 \pm 6$ MeV, $\gamma_s = 0.92 \pm 0.06$, $\mu_B = (4.52 \pm 0.98) \times 10^{-2}$ GeV, $\mu_S = (2.23 \pm 0.74) \times 10^{-2}$ GeV, $\mu_Q = (-2.05 \pm 0.77) \times 10^{-2}$ GeV, and $r = 15 \pm 10$ fm. The model describes all but two particle ratios within 1σ standard deviation. Except for the $\Lambda(1520)/\Lambda$ ratio, the other measured resonance ratios ($\phi/K^*$, $\Sigma^*(1385)/\Lambda$) are within a 1σ error of the model fits. Due to the very short lifetime ($\tau < \tau_{fireball} \sim 10$ fm) of most resonances, a large fraction of their decays occur before the thermal freeze-out. Elastic interactions of resonance decay products with particles in the medium alters the momenta of these particles. This results in a loss of the signal reconstructed for resonances (due to re-scattering). However, secondary interactions (regeneration) can increase the resonance yield. The effects of regeneration and re-scattering are not included in this thermal model which might explain why the experimental values differ from the statistical model calculations for the $\Lambda(1520)/\Lambda$ ratio. It is expected that there should be no re-scattering and regeneration effects on the $\phi$ meson due to its long life time. Since the model predicts the ratios for $\Sigma^*(1385)$ and $K^*$ correctly, re-scattering appears to be balanced with the regeneration effects.

In Au + Au collisions the free fit parameter corresponding to strangeness saturation, $\gamma_s$, is higher than in $p + p$ collisions, while $T$ is the same within the errors. In Figure 2-a, the energy and system size dependence of the measured $K/\pi$ ratios are presented [8]. An enhancement is observed in the $K/\pi$ ratios in central Au+Au collisions relative to $p + p$ collisions implying an increase in strangeness production resulting in larger values of $\gamma_s$. The higher $\gamma_s$ in Au + Au relative to $p + p$ collisions is in agreement with the $K/\pi$ ratio observations. Due to this increase of strangeness production from $p + p$ to Au + Au collisions, particle ratios are selected such that $\mu_s$ cancels out (e.g., $\Sigma^*(1385)/\Lambda$ ratio). The small value of the chemical potential, $\mu_B$, can be explained by the proximity of the measured anti-particle to particle ratios (e.g., $\Sigma^*(1385)/\Sigma^*(1385)$ [9]) to unity and it reflects the near zero net baryon number at mid-rapidity of Au + Au collisions.

For comparisons with heavy-ion systems, Figure 2-a shows the energy and system dependence of the $K/\pi$ ratios at mid-rapidity. Triangles correspond to data from heavy ion collisions and circles to $p + p$ collisions at the given energies [10, 11]. An enhancement in the $K/\pi$ ratios of about 50% is observed at RHIC energies in central Au+Au collisions relative to $p + p$ collisions extrapolated to similar energies. A similar magnitude of enhancement in $K^-/\pi$ has already been observed at the lower energies of the AGS and SPS [12, 13].

The energy dependence of the $\Lambda$ and $\bar{\Lambda}$ yields at mid-rapidity from Au + Au collisions at RHIC and Pb+Pb collisions at SPS as a function of $\sqrt{s_{NN}}$ is presented in Figure 2-b [13]. From SPS to RHIC energies, strange baryon production is approximately constant at mid-rapidity, whereas the $\bar{\Lambda}$ rises steeply, reaching 80% of the $\Lambda$ yield at RHIC top energies. The other hyperons, $\Xi$ and $\Omega$, follow similar trends. Since most of the strange baryons produced also include light up and down
quarks, strange baryon production at low energies is dominated by valence quark transport from the colliding system, but at RHIC it is dominated by pair production. This also implies that at RHIC energies, most of the incoming baryons continue moving with large rapidity and do not cause any increase in the baryon number in the mid-rapidity regions.

5. Statistical Coalescence?

Nuclear modification factors for strange particles in Au+Au collisions are presented in Figure 3-a. At high $p_T$, the ratios exhibit a suppression from binary scaling, attributed to fast moving partons losing energy as they traverse a dense medium. Hadron production at high $p_T$ does not follow binary scaling and is roughly consistent with participant scaling \[15\]. The clear differences between baryons and mesons, is believed to be due to hadron production through quark coalescence at intermediate $p_T$ \[16\]. For baryons and mesons, the suppression sets in at a different $p_T$. Motivated by the coalescence picture, Figure 3-b shows the $R_{CP}$ ratio vs $p_T/n$ for $\sqrt{s_{NN}} = 200$ GeV, where $n$ is the number of valence quarks. Thus $p_T/n$ represent the $p_T$ of a valence quark. The baryon and meson difference sets in at the same quark $p_T$, in agreement with the coalescence picture. This is also observed for $\sqrt{s_{NN}} = 62.4$ GeV collisions \[14\].

Separation of the mesons and baryons is observed when the $p_T$ of the quark of the meson or the baryon is in the range of 0.8-1.2 GeV which corresponds to a baryon $p_T$ range of 2.4-3.6 GeV and a meson $p_T$ range of 1.6-2.4 GeV. If the
Fig. 3. (a) $R_{CP}$ vs $p_T$ in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. (b) $R_{CP}$ vs $p_T/n$ in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV for $n = 3$ for baryons and $n = 2$ for mesons. $R_{CP}$ is calculated from 0-5% and 40-60% central $Au + Au$ collisions.

A comparison of the $T$ and the $\gamma_s$ fit parameters are presented in Figure 4. The $p_T$ integrated particle ratios that are used in the fits for Figure 4-a (closed circles) can be found in Reference [17]. A 40% feed-down correction is applied to the proton yields determined from the $\Lambda$ yields for the weak feed-down corrected fits (open circles). The effect of the weak feed-down correction can be seen as
an increase in the $\gamma_s$ and a reduction in the $T$. For any conclusion made using the statistical model fits, it is essential to remember that proper weak feed-down contributions plays a major role in the final fit parameters.

**Fig. 4.** (a) The $\gamma_s$ and the $T$ fit parameters of the integrated ratios from the given statistical models in comparison to the ones corrected for the weak decay feed-down. Input ratios of the fits can be find in [17]. (b) The $\gamma_s$ and the $T$ fit parameters of the ratios from the quark $p_T$ range of 0.8-1.2 GeV.

The particle ratios presented in Table 2 are used in the fits of Figure 4b (open circles) for comparison with the $p_T$ integrated ratios (solid circles). Since there is no $K/\pi$ or $\Omega/\pi$ ratios, the fits are less well constrained leading to larger errors as can be seen on the solid circles in Figure 4b as compared to those on the open circles in Figure 4a. $T$ and $\gamma_s$ increase for the quark $p_T$ range of 0.8-1.2 GeV relative to those for the whole $p_T$ range. Particles produced in this $p_T$ range possibly come from a hotter source.

6. Conclusions

The STAR experiment has collected tremendous amounts of data to study strangeness production in heavy-ion collisions at a variety of energies. The strange anti-particle to particle ratios show that baryon transport is approximately independent of system size at RHIC energies. Particle ratios in general can be used to investigate the fireball properties with the help of statistical models. We used several models to investigate the particle production in $p + p$ and $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Comparisons of the various models and their corresponding fits are also discussed. In these fits and model comparisons, the importance of the weak decay feed-down corrections is highlighted. $T$ is similar for $p + p$ and $Au + Au$ collisions.
at the same energy. While $\gamma_s$ of $p + p$ collisions at RHIC is smaller than the one in Au + Au, it is similar to that of Pb + Pb at SPS.

Baryon and meson suppression sets in at same quark $p_T$. Since coalescence can partially explain the difference between baryons and mesons in $\sqrt{s_{NN}} = 200$ GeV collisions, the region where coalescence dominates the particle production can be investigated further with statistical models. Where quark coalescence seems to dominate (intermediate $p_T$) $T$ and $\gamma_s$ show an increase. This implies that particles in this range of $p_T$ come from a hotter source.

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