STRANGENESS PRODUCTION IN Au–Au COLLISIONS AT $\sqrt{s_{NN}} = 62.4$ GeV*

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We obtain strangeness production as function of centrality in a statistical hadronization model analysis of all experimental hadron production data in Au–Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Our analysis describes successfully the yield of strange and multi-strange hadrons recently published. We explore condition of hadronization as a function of centrality and find universality for the case of chemical non-equilibrium in the hadron phase space corresponding to quark-gluon plasma (QGP) in chemical equilibrium.

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1. Experimental data

The statistical hadronization model (SHM) is known to successfully describe hadron yields in a variety of experiments at different energies [1, 2]. Recently, new results on the yields of strange and multi-strange hadrons at $\sqrt{s_{NN}} = 62.4$ GeV have been published [3]. This data together with previously published non-strange particle yields [4] and ϕ meson measurement [5] provides a new opportunity to reevaluate hadronization conditions in $\sqrt{s_{NN}} = 62.4$ GeV collisions.

Heavier multistrange particles are more rarely produced and therefore to assure that statistical errors are small, they are often presented in wider centrality bins than non-strange particles. In order to study all particle yields as a function of centrality, we have to account for the different centrality

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binning. We associate each bin with average number of participants $N_{\rm part}$. Then, we fit hadron yield as a function of $N_{\rm part}$ using a power law,

$$f(N_{\rm part}) = a\, N_{\rm part}^b + c\,, \qquad (1)$$

where a, b and c are free parameters fitted and shown in Table I. We see, as expected, that particles are always more numerous than their respective anti-particles. However for the Ω, we had only three data points and three free parameters of the interpolating function from Eq. (1). Therefore, we fixed $c = 0$ and fitted the other two. This fit, with one degree of freedom, gave us a qualitatively similar function as for the other particles.

TABLE I

Particle yields power fit parameters (as defined by Eq. (1)) used to describe particle yields as function of centrality. For Ω, $c = 0$ is assumed.

	a	b	c
π^-	3.756×10^{-1}	1.098	-2.330×10^{-2}
π^+	3.788×10^{-1}	1.094	-5.768×10^{-2}
K^+	4.769×10^{-2}	1.141	-2.002×10^{-1}
K^-	4.188×10^{-2}	1.138	-1.165×10^{-1}
$K^0_{\rm s}$	5.068×10^{-2}	1.074	-2.341×10^{-1}
p^+	3.972×10^{-2}	1.125	-9.963×10^{-2}
p^-	3.404×10^{-2}	1.024	-8.573×10^{-2}
ϕ^0	4.162×10^{-3}	1.203	-1.311×10^{-3}
Λ	1.772×10^{-2}	1.154	-1.025×10^{-2}
$\overline{\Lambda}$	1.045×10^{-2}	1.125	1.764×10^{-2}
Ξ^-	1.434×10^{-3}	1.197	-1.415×10^{-2}
$\overline{\Xi}^+$	7.693×10^{-4}	1.231	-1.765×10^{-3}
Ω	1.266×10^{-5}	1.720	0
$\overline{\Omega}$	3.985×10^{-6}	1.879	0

2. SHM fit including multistrange hadrons

We performed a cross check of SHARE [1], the thermal model implementation we used, with three other codes currently in use by other groups using the compiled data in [2]. We tested our model on the data set from Au–Au collision at $\sqrt{s_{NN}} = 200$ GeV from STAR and obtained both yields and thermal parameters within 5% from the values in [2].

Rather than hadron ratios studied in [3], we decided to fit hadron yields, which require a common volume dV/dy of the source. We complemented the data set with identified hadrons ($\pi^\pm$, $K^\pm$, $p^\pm$) from [4] and ϕ yield from [5]. Furthermore, we require the conservation of charge per baryon $(Q - \overline{Q})/(B - \overline{B}) = 0.39 \pm 0.01$ and strangeness $(s - \overline{s})/(s + \overline{s}) = 0 \pm 0.05$ with a few percent error to account for the detector acceptance and efficiency.

As was also pointed out in [3], the experimental particle yields are subject to an important inconsistency: for all centralities, the yield of $K^0_{\rm s}$ is smaller than both K^+ and K^- (lowest of three corresponding lines in the left panel of figure 1). In general, at finite baryon density, we expect $K^+ < K^0 < K^-$. Interestingly, the missing $K^0_{\rm s}$ are associated with yields of Λ, $\overline{\Lambda}$ in that these three particle types had the largest contributions to the total χ^2 of the fit. The choice to include or exclude them from the fit did not change the values of the SHM parameters we obtained.

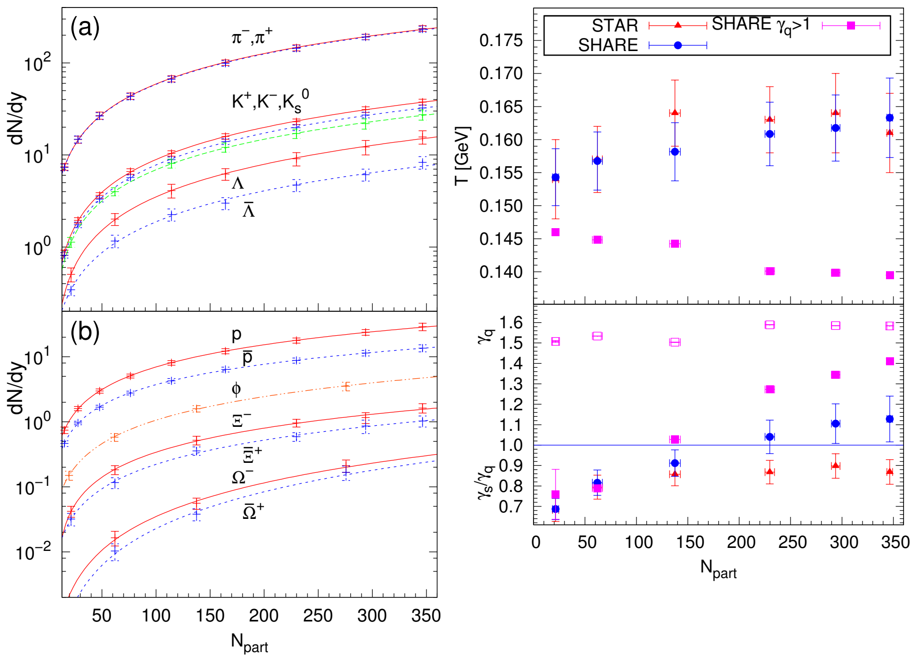

Fig. 1. Left panel: Particle yields as a function of number of participants with respective interpolating functions. Right panel: Top panel depicts chemical freeze-out temperature T as a function of the number of participants $N_{\rm part}$. Triangles (red) are a copy of the results in [3], circles (blue) describe our fit of the same data set in semi-equilibrium model with $\gamma_q \equiv 1$, $\gamma_s \neq 1$ and squares (purple) are non-equilibrium model $\gamma_i \neq 1$, $i = q, s$. Bottom panel shows the strangeness phase space occupancy compared to the light quark phase space occupancy ratio γ_s/γ_q for different models. Open squares (purple) show the values of γ_q for the non-equilibrium model.

It is interesting to note that the three neutral particle types have the same V-type charged particle decay and that there is an overlap in kinematic ID of the decay channels. For this reason, we fitted instead the yield of $\Lambda+\overline{\Lambda}+2\,K^0_{\rm s}$ which does not have this ambiguity. Considering the smallness of the required shift from more numerous $K^0_{\rm s}$ to Λ, $\overline{\Lambda}$ we also fitted the ratio $\overline{\Lambda}/\Lambda$. These two data points replace the three raw yields and proved to be consistent with all other particle yields. Assuming that other particles fix the source volume, this procedure incurs minimal loss of data information.

We expected that our SHM fit with $\gamma_q = 1$ should reproduce results of [3]. And indeed, we obtain compatible chemical freeze-out temperature T (top right panel of figure 1). However, we find that the strangeness phase space is strongly overpopulated, which is reflected by $\gamma_s > 1$ (bottom right panel of figure 1) contrary to results published by STAR. After we found this discrepancy, we learned from the authors that in [3] $\gamma_s < 1$ has been forced. This, of course, completely invalidates the conclusions of this work. This also resolves the myth that the yields of $\phi \propto \gamma_s^2$ are inconsistent with SHM.

As a next step, we considered the chemical non-equilibrium with $\gamma_i \neq 1$, $i = q, s$. This approach allows that aside of the strangeness phase space also the light $q = u, d$ quark phase space, when observed on hadron side, to be out of equilibrium. To preserve the number of degrees of freedom, we fitted the pressure $P \simeq 82$ MeV/fm^3, which is the value of critical hadronization pressure found in SHM fits to other experiments [7].

The chemical non-equilibrium SHM fit results in an even more pronounced strangeness yield enhancement, $\gamma_s \to 1.5$ at central rapidity, an over-population of the light quark phase space $\gamma_q \simeq 1.6$, and a lower freeze-out temperature $T \simeq 142$ MeV. Another important feature of this approach is that the parameter errors in the fit decreased dramatically compared to the semi-equilibrium model. In the right bottom panel of figure 1, the centrality dependence of these parameters is shown and the errors on γ_q and γ_s for chemical non-equilibrium are within the size of the symbols. We note that the SHM fits at all centralities have confidence level above 60%.

3. Hadronization conditions

In the non-equilibrium SHM approach there appears to be universal hadronization condition as function of centrality, which can be seen in figure 2 top two panels on the left. Apart from the constant pressure $P \simeq 82$ MeV/fm^3, obtained at other RHIC energies [7], which value was used in non-equilibrium fits and found consistent with the new data, the entropy density at hadronization stays at constant universal value $\sigma \simeq 3.3\,{\rm fm}^{-3}$. Similarly, the energy density is constant at $\varepsilon \simeq 0.48$ GeV/fm^3. A universal value of statistical properties at hadronization as function of centrality [8] supports the notion of a new phase of matter, the quark-gluon plasma undergoing a sudden break up transition to hadrons which free stream, as the chemical non-equilibrium model assumes. On the other hand, in the semi-equilibrium hadronization model, both entropy and energy density grow nearly proportional to the number of participants. There is no physical understanding of this behavior.

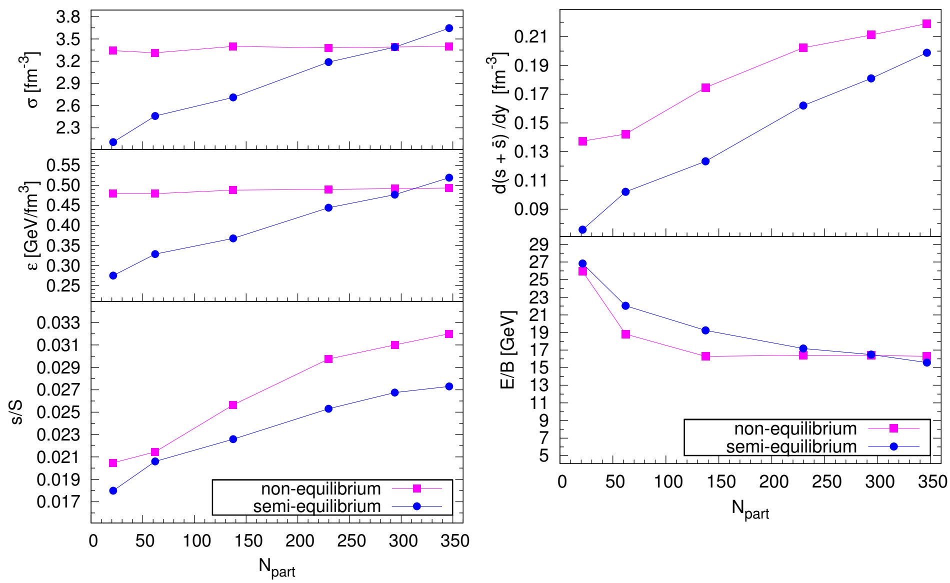

Fig. 2. Left panel: Going from top to bottom, centrality dependence of entropy density, energy density (σ and ε respectively) and strangeness per entropy ratio s/S. Right panel: Going from top to bottom, centrality dependence of the strangeness rapidity density and energy per baryon.

We see, in the left bottom panel of figure 2, that in SHM non-equilibrium fit, the ratio of strangeness s to entropy S approaches for most central collisions the QGP expectation $s/S = 0.031$. The relative yield of strangeness is systematically smaller in the SHM semi-equilibrium fit. In the right panel of figure 2, we see at the top that strangeness density increases with centrality, in agreement with the expectation that the largest system can approach the QGP yield. Moreover, we see that in the SHM non-equilibrium model, we always find a much greater strangeness yield compared to the SHM semi-equilibrium. The effect is quite large at small centrality, where the entropy contents differ most, see the left top panel.

Another interesting result in non-equilibrium SHM is the constancy for $N_{\rm part} > 130$ of hadronization energy per baryon E/B seen in the bottom right panel of figure 2. Moreover, we find that the fraction of the available energy in the collision is universal among other systems and collision energies. We find, $E/B_{\text{most central}} = 16.5$ GeV $\simeq 0.25 \times 62.4$ GeV $= \frac{1}{4}\sqrt{s_{NN}}$. This result is the same as at the lower SPS energies. It says that the stopping of baryon number is 4 times more effective than the stopping of energy. Only at small centralities the stopping of energy and baryon number seems to converge to a common value resulting in $E/B_{\text{most peripheral}} \to \frac{1}{2}\sqrt{s_{NN}}$.

4. Conclusions

We revisited the statistical hadronization fit of particle yields from Au–Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV recently updated with the yields of multi-strange hadrons. We obtained qualitatively different fit from the one published by the STAR Collaboration [3] which was done with the constraints $\gamma_q = 1$ and $\gamma_s < 1$ and which fails to resolve yields of all multistrange particles. They also show a very good confidence level at all centralities. Our results show that the hadron strangeness phase space is overpopulated $\gamma_s > 1$ from semi-central $N_{\text{part}} = 150$ to most central collisions $N_{\text{part}} = 350$. We allowed the light quark phase space, $\gamma_q \neq 1$, to be out of equilibrium as well and the new fit to the experimental data works for multistrange hadrons and has much smaller errors. However, given that K^0_{s} were inconsistent with the yields of charged hadrons, we did fit $\Lambda + \overline{\Lambda} + 2K^0_{\text{s}}$. We conclude that the non-equilibrium model shows appropriate and universal behavior of bulk physical properties (entropy, energy, strangeness and the stopped energy per baryon) as a function of centrality, *i.e.*, as a function of system size [7].

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