Volume Effects on Strangeness Production

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Abstract.
A study of the yields of strange particles produced in heavy-ion and elementary collisions is presented using preliminary results from the STAR experiment at RHIC. The strange particle production rates, relative to those of $p+p$, have been proposed as a means of determining an enhancement of strangeness production in heavy-ion collisions. Analysis of results from STAR show that this enhancement measure is reduced, or comparable, when contrasted to that at top CERN SPS energies. A smaller suppression in the $p+p$ yields at RHIC energies due to finite volume effects could be the cause of such a result. By studying the yields as a function of centrality we hope to establish how these effects vary with the volume of the source created.

1. Introduction

A vast amount of work has been done in implementing statistical models to aid our understanding of heavy-ion collisions, [1] and references therein. One of the most important features of these statistical models is that they assume a thermally and chemically equilibrated system at chemical freeze-out. They assume that the system consists of non-interacting hadrons and resonances but make no predictions about how the system arrived in such a state, or how long it exists in such fashion. Given these conditions the number density of a given particle can be calculated for a given chemical freeze-out temperature, $T_{ch}$, baryo-chemical potential, $\mu_B$, strangeness potential, $\mu_s$, and strangeness saturation factor, $\gamma_s$. Another important issue is that statistical models generally utilize Grand Canonical Ensemble statistics, which are only appropriate when the system becomes large. In small systems, or the (micro)Canonical regime, all quantum numbers have to be conserved explicitly; this means there not only has to be energy available for strangeness creation but also the phase space. This leads to an interesting effect on strange particle production; one of a suppression of strangeness in small systems due to a lack of available phase space. Once the volume is sufficiently large, this phase space suppression disappears and the amount of strange particle creation per unit volume becomes constant. Statistical models using the Grand Canonical approach may still appear to work for small systems but the fits do not represent true temperatures and chemical potentials. Hence, we need to establish at what collision energy and correlation volume, if any, such a Grand Canonical state occurs.

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Phase space suppression effects are measured experimentally as the yield per participant relative to the yield per participant in $p+p$ (or $p+Light$ nuclei), the volume of the system is believed to be directly proportional to the number of participants, $N_{part}$. Fig. 1(a) shows the predicted behaviour for $\Lambda$ and $\Xi^-$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 130$ GeV as a function of $N_{part}$, or volume [2]. No calculations are available for Au+Au data at 200 GeV. As can be seen the larger the number of strange quarks in the particle the greater the phase space suppression effect. It has also been demonstrated that increasing the collision energy decreases the suppression of a given species [2].

### 1.1. Enhancement Factors

At very low energies, such as those measured by the KAOS experiment at SIS, we can see the effects of canonical suppression even in the kaons [3, 4]. As the collision energy increases this kaon suppression dissipates and it has been shown that in Pb+Pb collisions of $\sqrt{s_{NN}} = 17.3$ GeV even the $\Lambda$ yield per participant appears to saturate [5]. It would seem therefore that the top energy CERN collision data show evidence of the applicability of the Grand Canonical Ensemble for particles up to the multi-strange baryons. The more recent data at $\sqrt{s_{NN}} = 8.8$ GeV [5], however, show enhancement factors for the $\Xi$ and $\Lambda$ that are approximately equal to the 17.3 GeV data. This result goes against our understanding of how canonical suppression is related to collision energy. Calculations have shown that the enhancement for $\Xi$ should be much higher at $\sqrt{s_{NN}} = 8.8$ GeV than at $\sqrt{s_{NN}} = 17.3$ GeV [2].
The predictions of Fig. 1(a) can be compared to Fig. 1(b) and (c), which shows preliminary calculations of the enhancement factors for strange hyperons from STAR [6, 7]. The difference in suppression from 130 to 200 GeV is expected to be small. We see that for this data set the hyperons show no sign of reaching a plateau, this could be an over-population of strangeness in the Λ channel. However, the $\gamma_s$ factor, calculated as a function of centrality from a statistical model [8], only approximately reaches unity for the most central data [7, 9]. This indicates that the created medium at RHIC is only just reaching the Grand Canonical Ensemble limit for the most central collisions. Figure 1(a) predicts the saturation levels of the different enhancement factors, the measured results are above those from theory. Fig. 1(b) and (c) also appear to show a smooth transition from $p + p$ to the most central Au+Au results, in contrast to the sharp rise at small $N_{\text{part}}$ predicted by theory. Improved measurements as a function of centrality will help clarify this issue.

There are several possible explanations for the discrepancies between the RHIC and SPS data and theory. One is that the freeze-out conditions of the sources are not those assumed in the calculations, the enhancement factors being very sensitive to this assumption. Another possibility is that the correlation volume is not linearly proportional to $N_{\text{part}}$.

2. Scaling Variables

No matter how the transition from phase space suppression to the Grand Canonical regime occurs in A+A collisions it is evident that there is an effect. A study of how the particle yields in Au+Au collisions depend on the centrality of the collision has therefore been made. Figure 2(a) shows the yields of various particles scaled by $N_{\text{part}}$ relative to the yield per $N_{\text{part}}$ in the most central Au+Au collisions. It can be seen that the anti-protons, which contain no strange quarks, scale linearly with $N_{\text{part}}$. As the strange quark content of the mesons and baryons increases this scaling steadily breaks. The Ω, which contains 3 s quarks, clearly has no such linear dependence on $N_{\text{part}}$. This led to the idea that strange quarks have a different scaling to the light u and d quarks. One possible scaling is with the total number of binary collisions, $N_{\text{bin}}$, in the collision. The individual particle scaling therefore becomes:

$$N_{\text{light}} * N_{\text{part}} / N_q + N_s * N_{\text{bin}} / N_q$$

(1)

where $N_{\text{light}}$ is the number of u and d quarks in the particle, $N_s$ is the number of strange quarks and $N_q$ is the total number of quarks in the hadron. Thus an anti-proton still scales with $N_{\text{part}}$, the $K_s^0$ now scales as $0.5 * N_{\text{part}} + 0.5 * N_{\text{bin}}$ and the Ω scales as $N_{\text{bin}}$. The results of such as scaling for the Au+Au 200 GeV data is shown in Fig. 2(b), it appears to be quite successful. This suggests that the relevant volume for strange particle production is not merely geometrical, and thus controlled by $N_{\text{part}}$, but is strongly affected by the number of hard processes in the collision. It should be noted
Figure 2. (a) Yield per $N_{\text{part}}$ (b) yields scaled as per Eqn. 4 for various particle species normalized to the measurement at $N_{\text{part}} = 352$, the most central Au+Au collisions at 200 GeV versus $N_{\text{part}}$.

that the $\phi$ is anomalous and is scaled in Fig. 2(b) by $N_{\text{part}}$ and not by $N_{\text{bin}}$. Perhaps this is indicative that the $\phi$, which contains an $s\bar{s}$ quark pair, is created via a different mechanism.

3. Summary

In summary we have shown that it is likely that the Grand Canonical regime is applicable for the most central Au+Au collisions at RHIC. The data shows that the correlation volume for strange particle production is not linearly correlated to $N_{\text{part}}$ but appears to be linked to $N_{\text{bin}}$. Further studies are needed to determine how the correlation volume can be mapped, if at all, onto a physically measurable quantity and a model developed that can explain both the SPS and RHIC data. The approach of the 200 GeV Au+Au data to the Grand Canonical regime does not seem to be well described by theory. The high statistics Au+Au data, already taken at 200 GeV, and the upcoming Cu+Cu run will allow us to map out the region around $N_{\text{part}} \sim 10$ in more detail. This region is critical for testing the parametric dependence of suppression on volume.

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