Bulk Matter Properties in RHIC Collisions

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Abstract. At this meeting I discussed selected bulk matter results from the RHIC experiments at Brookhaven National Laboratory. By studying the properties of the particles created we hope to gain information about the matter created in ultra-relativistic heavy-ion collisions and ultimately determine if the system ever consisted of liberated quarks and gluons.

1. Introduction
By colliding heavy-ions at the Relativistic Heavy Ion Collider (RHIC) we aim to create matter at sufficiently high temperatures and/or densities such that it becomes valid to discuss the physical interactions that occur in terms of partonic degrees of freedom. We cannot measure such a phase explicitly but must use indirect methods to deduce the early stages of the collisions by studying the yields and spectra of the produced hadrons. By making bulk measurements of the final state matter we hope to determine the temperature and density of the system produced and thus establish if suitable conditions have been produced for creating a partonic system.

There are several important stages in the evolution of a relativistic heavy-ion collision. In the early stages of the collision we try to create a temperature that exceeds $T_c$, the critical temperature at which a transition to partonic degrees of freedom occurs. The excited region then expands and cools until $T$ drops below $T_c$, at which point hadrons re-form. It is believed that there is a large amount of re-scattering both in the partonic and hadronic phases and that the system reaches a partial chemical equilibrium. Soon after $T_c$ the system passes through chemical freeze-out, $T_{ch}$. At this point inelastic scatterings cease and the stable hadronic ratios are frozen in. Finally kinetic freeze-out occurs when the system cools to below $T_k$ and elastic collisions also end. After this the particles stream freely to the detectors.

2. Chemical Freeze-out
Determining the chemistry of the particles emitted from the collision region can provide important information about the source created. A common way to deduce the chemistry is by comparing the measured ratios of various particles the calculations from a statistical hadronic model. In this way the chemical freeze-out temperature, $T_{ch}$, baryo-chemical potential, $\mu_B$, strangeness potential, $\mu_s$, and strangeness non-saturation factor $\gamma_s$ can be calculated. Further details can be obtained from [1] and references therein.

The $K^-/K^+$ ratio, which is effectively the $\bar{u}/u$ ratio as $\bar{s}/s=1$, reveals information about the systems’ baryon content, despite the kaon being a meson. Data from BRAHMS [2] shows
a strong correlation between the $K^-/K^+$ and the $\bar{p}/p$ ratios for various beam energies and rapidities. Both ratios indicate a falling net-baryon number with increasing collision energy and their correlation is in good agreement with the prediction from a statistical model assuming $T = 170$ MeV [3]. An overlap between the CERN measurements taken at mid-rapidity, and those of the forward rapidity BRAHMS measurements at $\sqrt{s_{NN}} = 130, 200$ GeV and the recent results at $\sqrt{s_{NN}} = 62.4$ GeV [4] is observed. This suggests that, chemically at least, the medium created at mid-rapidity at CERN energies occurs in the RHIC forward rapidities. This allows for the possibility of studying many different chemical environments by sitting at one collision energy and altering the rapidity region being measured. The results of a fit to the statistical model described in [5] gives a good representation of the preliminary data recorded at $\sqrt{s_{NN}} = 130, 200$, and 62.4 GeV, except for the short lived resonances [6]. It is believed that this discrepancy between the calculation and resonance measurements results from the measurable resonance yields being altered after chemical freeze-out due to re-scattering and/or regeneration in the hadronic phase [7]. The results of the fit give $T_{ch} = 160 \pm 5$ MeV, $\mu_B = 24 \pm 4$ MeV, $\mu_s = 1.4 \pm 1.6$ MeV, and $\gamma_s = 0.99 \pm 0.07$ for the most central data at $\sqrt{s_{NN}} = 200$ GeV. These results suggest that the Au+Au system at RHIC is very close to complete strangeness saturation with near zero baryon and strangeness chemical potentials. At $\sqrt{s_{NN}} = 62.4$ GeV the results yield similar values for $T_{ch}$, $\mu_s$, and $\gamma_s$ for the most central data. However a $\mu_B$ of approximately 60 MeV reflects a significant increase in the net baryon number.

Statistical models utilize Grand Canonical Ensemble statistics, appropriate only when the system is large. Small systems, lacking phase space for particle/quark creation, require the use of Canonical statistics. These phase space restrictions result in a suppression of strangeness; only once the correlation volume becomes sufficiently large does strange particle creation per unit volume become constant. It has been calculated that increasing the number of strange quarks in the particle and/or the lowering the collision energy results in a greater phase space suppression effect [8]. The correlation volume is believed to be directly proportional to $N_{part}$.

In Pb+Pb collisions of $\sqrt{s_{NN}} = 17.3$ GeV even the $\Lambda$ yield per participant (or wounded nucleon) appears to saturate [9]. It would seem therefore that the top energy CERN collision data are showing evidence of the applicability of the Grand Canonical Ensemble for all particles up to the multi-strange baryons. The more recent $\sqrt{s_{NN}} = 8.8$ GeV data, however, shows enhancement factors for the $\Xi$ and $\Lambda$ that are approximately equal to the 17.3 GeV data [9]. Calculations have shown that the enhancement for $\Xi$ should be much higher at 8.8 than at 17.3 GeV. Figure 1 shows the preliminary measured enhancement factors for strange hyperons from STAR. We see that for this data set the $\Lambda$ hyperons show no sign of reaching a plateau. As the SPS data appeared to saturate it is perhaps possible that the RHIC data shows an over population of strangeness in the $\Lambda$ channel. However, the $\gamma_s$ factor only just reaches unity for the most central data [6]. This indicates that the system at RHIC is only reaching the Grand Canonical Ensemble limit for the most central collisions. One possible explanation for these discrepancies between the data and theory could be 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 $N_{part}$.

It is predicted that the Grand Canonical regime should be reached by $N_{part} \sim 60$. If true, then for $N_{part} > 60$ the strange particle production per unit volume should be constant. Fig. 1 indicates that the strange baryon yields are never linear in $N_{part}$. 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, $N_{bin}$, in the collision. The individual particle scaling
3. Dynamics
The time between \( T_{ch} \) and \( T_k \) can have a significant effect on the system. The elastic scatterings of hadrons creates additional the transverse radial flow to that produced in the earlier partonic phase. We fit a hydrodynamically inspired model, known as the “blastwave” to try to extract the scale of the radial flow [10]. This model assumes a common velocity profile for all particles and a common kinetic freeze-out temperature, \( T_k \). The results are presented in Fig. 3. A combined fit to the preliminary \( \pi \), \( K \), and \( p \) spectra gives results of \( T_k = 89 \pm 10 \) MeV and \( < \beta > = 0.59 \pm 0.05 \) c. The \( \Xi \) and \( \Omega \) spectra however are not consistent with this result, the dashed curve is a fit to these baryons alone and gives \( T_k = 165 \) MeV \( \pm 40 \) MeV and \( < \beta > = 0.45 \pm 0.1 \) c. This suggests that the multi-strange baryons freeze-out thermally at an earlier time than the lighter particles, as might be expected as these particles are predicted to have a lower hadronic cross-section.

4. Summary and Conclusions
In summary I have shown that bulk properties of the particles created and their dynamics are key to understanding the source created in heavy-ion collisions.
The particle yields suggest a source that is in chemical equilibrium for the most central A+A collisions and that the Grand Canonical regime is applicable. The source created at RHIC displays strangeness saturation. The data show that the correlation volume for strange particle production is not linearly correlated to $N_{\text{part}}$ but might be linked to $N_{\text{bin}}$. Meanwhile, the dynamics of the particles, in the blastwave scenario, suggest a sequential freeze-out after hadronization that depends on the hadronic cross-sections. The multi-strange baryons freeze-out kinetically very close to the temperature at which chemical freeze-out occurs. While this result relies on the validity of the blastwave approach both this method and a full hydrodynamical model calculate that the source created must have a sizeable radial flow during the pre-hadronic stage.

The combined results of the RHIC project provide strong evidence of a system which, in the early phases, shows strong collective motion, is very dense, and has properties consistent with partonic degrees of freedom.

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