Evidence for chemical equilibration at RHIC

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Abstract.
This contribution focuses on the results of statistical model calculations at RHIC energies, including recently available experimental data. Previous calculations of particle yield ratios showed good agreement with measurements at SPS and lower energies, suggesting that the composite system possesses a high degree of chemical equilibrium at freeze-out. The effect of feeddown contamination on the model parameters is discussed, and the sensitivity of individual ratios to the model parameters \((T, \mu_B)\) is illustrated.

1. Introduction

Over the last few years, the study of thermalization in heavy-ion collisions using statistical models has been extended to SPS\(^1\)\(^2\)\(^3\) and RHIC\(^4\)\(^5\) energies, allowing the so-called “freeze-out curve”\(^6\) of hadronic matter to be extended close to the \(\mu_B = 0\) axis of the QCD phase diagram. This is an important development in the search for the quark gluon plasma because it allows a more direct comparison between lattice QCD calculations of the phase boundary temperature\(^7\), performed mostly at zero baryon density, and experiment-based methods for measuring the equilibrium temperature on the hadronic side of the phase boundary (if the system equilibrates).

The updated phase diagram presented at this conference by Braun-Munzinger\(^8\) suggests a scenario in which the final-state composition of the system, determined at chemical freeze-out, relies less on hadronic rescattering processes\(^9\) as the beam energy is increased. This effect arises due to two reasons: stronger transverse flow causes faster expansion of the system, allowing less time for inelastic interactions; and the hadronic phase is bounded above by the temperature of the phase boundary itself, meaning that the system cools very little between hadronization and freeze-out.

In our previous paper\(^4\), we showed that particle ratios at midrapidity measured during the RHIC run at \(\sqrt{s} = 130\) GeV are consistent with a system in chemical equilibrium, as described by a statistical model. The best-fit model parameters \((T = 174 \pm 7\) MeV, \(\mu_B = 46 \pm 6\) MeV\) differ by a factor 5 in baryon chemical potential \(\mu_B\) from the fit at maximum SPS energy\(^1\), while the temperature changes very little \((\text{SPS: } T = 168 \pm 3\) MeV, \(\mu_B = 266 \pm 5\) MeV\). The small change in temperature, together with the good agreement with lattice QCD predictions of \(T_c\)\(^10\) \((T_c = 170 - 190\) MeV\), suggests that the system is nearly borne into chemical equilibrium out of the phase transition\(^11\)\(^\pm\)\(^12\). We also presented predictions for particle ratios at full RHIC energy \(\sqrt{s} = 200\) GeV.

In this contribution, the model comparison for the RHIC run at \(\sqrt{s} = 130\) GeV is extended to include additional ratio measurements which have been recently published.
or presented, including at this conference. The treatment and effect of feeddown correction to particle densities in the model is discussed. Finally, the question of which ratios drive the model fit to the data is investigated. It is worth noting that the model parameter values \((T, \mu_B)\) obtained here for the best fit to the data have not changed from the fit performed with the data available at the time of our publication.

2. Overview of experimental results

The primary tool for investigating chemical equilibration in heavy-ion collisions is the experimental measurement of particle production, and in particular ratios of particle species. All four RHIC experiments have published or presented preliminary results on particle ratios. Some experimental observations are [3]:

- +/- ratios are approaching unity at midrapidity, indicating that quark coalescence and pair creation processes play a greater role in final-state particle yields. However, the midrapidity region is not yet baryon free at \(\sqrt{s} = 130\).
- No large trends have been reported in ratios as a function of \(p_t\) in the relevant \(p_t\) range.
- \(\sqrt{p/p}\) increases from \(\approx 0.4\) at \(y = 2\) to \(\approx 0.65\) at midrapidity, with a plateau width of 2 rapidity units. \(\pi^-/\pi^+\) shows no rapidity dependence over the same region.

Since the submission of our paper [4], several additional measurements of ratios have been presented for the RHIC 2000 data. The \(\phi/h^-\) ratio was measured by the STAR Collaboration [14] to be \(0.021 \pm 0.001_{\text{stat}} \pm 0.004_{\text{sys}}\). The PHENIX Collaboration presented [15] preliminary results for \(K^-/\pi^-\) at this conference (most central: \(K^-/\pi^- = 0.15 \pm 0.01_{\text{stat}} \pm 0.03_{\text{sys}}\)).

Also at this conference, an updated preliminary value for \(K^{*0}/h^-\) was presented [16] by the STAR Collaboration (\(|K^{*0}/h^-| = 0.032 \pm 0.003_{\text{stat}} \pm 0.008_{\text{sys}}\)). The new value differs from the previous value [17] by nearly a factor 2 due to improved statistics and a different treatment of the residual background.

3. Statistical model calculations

The statistical model employed in the present calculations was first described in [1]. In the model, particle densities are calculated as a grand canonical ensemble with the requirement that baryon, strangeness and isospin quantum numbers are conserved. All known particles and resonances up to 2 GeV are included in the calculation, and particles decay according to their branching ratios.

The best fit model parameters \((T, \mu_B)\) are determined by comparing model ratios to experimental values and finding the minimum \(\chi^2\). A \(\chi^2/\text{d.o.f.} \sim 1\) indicates a good fit. When both statistical and systematic errors have been presented for experimental values, the errors are added in quadrature.

In this work, the best fit parameters are determined to be \(T = 174 \pm 7\) MeV, \(\mu_B = 46 \pm 6\) MeV, with a \(\chi^2/\text{d.o.f.} \sim 0.35\). The parameters are the same as those in our paper [1], even though a new ratio is included and another significantly revised. The low \(\chi^2/\text{d.o.f.}\) can be attributed to the large systematic errors in the first measurements at RHIC; if the fit is performed with only statistical errors in the experimental values, \(\chi^2/\text{d.o.f.}\) increases to \(\sim 1.6\). The true \(\chi^2/\text{d.o.f.}\) lies between these two values.
Figure 1. Comparison between experimental data in Au+Au collisions at $\sqrt{s} = 130$ GeV and statistical model calculations of particle ratios. The parameters of the model are $T = 174$ MeV, $\mu_B = 46$ MeV, and were determined by finding the parameter set with minimum $\chi^2$. Experimental data are taken from [14, 15, 16, 18, 19, 20, 21, 22, 23, 24].

Figure 1 shows the model values for $T = 174$ MeV, $\mu_B = 46$ MeV, and the available data for the four experiments at RHIC. Note that many of the ratios are preliminary. Model predictions for ratios involving $h^-$ in the denominator have increased slightly due to the corrected treatment of negative hadrons. Now, as in the experimental values, only the primary negative hadrons ($p$, $\pi^-$, and $K^-$) are included.

In addition to the new and updated ratios mentioned in section 2, experimental values are taken from [18, 19, 20, 21, 22, 23, 24]; see the table of compiled ratios in our paper [4] for specific references. For the model calculations, a feeddown correction factor of 0.5 was applied for weak decays; see section 3.1 for a discussion of this factor.

Two observations can be made regarding Figure 1. First, the experimental value for $|K^{*0}|/h^-$ now lies under the model value but within error bars. The previous underprediction of $|K^{*0}|/h^-$ was a hot topic of discussion during this conference. Second, the good agreement between model and experiment for $\phi/h^-$ is a success of the statistical model; the model value can be treated as a prediction, since the model parameters here have not changed from our paper [4].

It should also be noted that preliminary values were shown at this conference by the STAR collaboration for $\Lambda/\pi^-$ and $\Xi^-/\pi^-$. The $\Lambda/\pi^-$ measurement agrees well with the prediction from present model calculations ($\Lambda/\pi^- : \text{expt} = 0.066 \pm 0.004_{\text{stat}} \pm 0.005_{\text{sys}}$; model = 0.059). However, $\Xi^-/\pi^-$ is underpredicted by a factor of 2 ($\Xi^-/\pi^- : \text{expt} = 0.014 \pm 0.001_{\text{stat}} \pm 0.003_{\text{sys}}$; model = 0.072). If the experimental value for $\Xi^-/\pi^-$ holds, the large disagreement with the statistical model would be an exciting result. However, we stress that the experimental results were presented as preliminary.
3.1. Influence of feeddown correction

As discussed in [1] primary particle multiplicities are affected by contributions from weak decays. In order to compare model calculations of particle production with experimental data, the “contamination” from these weak decays needs to be accounted for. This is done in the model by multiplying the branching ratios for weakly decaying particles (Λ, Ξ, Ω, etc.) by a correction factor.

Correction factors can be applied to particles individually in the model. However, in lieu of experimental values for these quantities, the default value used here and in our paper [4] is 0.5, which means e.g. that half of the protons arising from Λ decays are not removed from the proton multiplicity.

Figure 2 shows the location of minimum χ² on the $T - \mu_B$ diagram for three values of the weak decay correction factor. The lines surrounding each minimum are contours of constant χ². The temperature decreases as the contamination from weak decays increases, while $\mu_B$ changes very little. The decrease in $T$ can be explained by the direct relation between temperature and particle production in the statistical model. As the multiplicity of primary particles ($p$, $\bar{p}$, $n$, $\pi^\pm$, etc.) is increasingly contaminated, fewer true protons and pions need to be produced in order to agree with experimental values.

Of course, it is not realistic that all feeddown correction factors have the same value. The result of Figure 2 merely demonstrates that weak decay contamination has a nontrivial effect on the extracted model parameters, particularly the temperature.
3.2. Ratios which constrain model parameters

In this section we investigate the contribution of individual ratios to the good agreement between the statistical model and experimental data. The question arises as to which ratios are strongly dependent on the model parameters ($T, \mu_B$). A ratio’s sensitivity to these parameters comes from the mass and quantum numbers of the two particle species. This can be expressed in the Boltzmann approximation as:

$$\frac{n_1}{n_2} \sim \frac{g_1}{g_2} \left( \frac{m_1}{m_2} \right)^{3/2} \frac{e^{(\mu_1 - \mu_2)/T}}{e^{(\mu_2 - \mu_1)/T}}, \quad \mu_i = \mu_B B_i - \mu_S S_i - \mu_I I_i,$$

where $g_i$ is the spin-isospin degeneracy factor ($g_i = (2S_i + 1)(2I_i + 1)$), and $B$, $S$, and $I$ represent the baryon, strangeness and isospin quantum numbers, respectively. The chemical potential $\mu_i$ is the sum of the individual chemical potentials in the system.

Figure 3 shows the model calculation for each ratio included in Figure 1 as a function of $\mu_B$ for two values of the temperature. The range of values is chosen to include the fitted parameter values at $\sqrt{s} = 130$ GeV. The $\overline{p}/p$, $\Lambda/\Lambda$, and $K^-/K^+$ ratios are strongly dependent on $\mu_B$. In the case of $\overline{p}/p$, equation 1 becomes

$$\frac{n_\overline{p}}{n_p} \sim e^{-2\mu_B/T}$$

The $\mu_B$ dependence of anti-baryon/baryon ratios is strong whenever $\mu$ is much less than $T$; therefore, the dependence weakens for strange and multistrange baryons due to the additional $\mu_S$ term in the chemical potential.

Conversely, figure 4 shows the temperature dependence of each ratio for two values of $\mu_B$. The $\overline{p}/\pi^-$ ratio exhibits the strongest dependence on the temperature. The strong $T$ dependence of $\overline{p}/\pi^-$ is due to the large mass difference between the two species, which dominates for small values of $\mu$. This is also the primary reason why multi-strange baryon/meson ratios are sensitive to the temperature, which we demonstrated in our paper [4].

The $\Xi^+ / \Xi^-$ ratio’s dependence on temperature results from the large contribution of the $\mu_S$ term in the chemical potential ($S_{\Xi^-} = -2$). Equation 1 is expressed as:

$$\frac{n_{\Xi^+}}{n_{\Xi^-}} \sim \exp \left( \frac{-2\mu_B - 4\mu_S}{T} \right)$$

Note that strangeness conservation in the collision does not require that $\mu_S$ is zero.

4. Conclusions

In this contribution, the work of our previous paper [4] was extended to include new and updated ratios from the RHIC experiments. The best-fit parameters of the statistical model calculations do not change when including the new data. The strong agreement between model and data for the available ratios supports the notion of a system in chemical equilibrium at freeze-out.

Also, the uncorrected feeddown contamination from weak decays has a small but relevant effect on the values of the extracted parameters. The model temperature decreases as feeddown contamination of primary particles ($p, \pi, \text{etc.}$) increases because less primaries need to be produced by the model to account for the experimental value. Finally, $\mu_B$ was shown to be sensitive to anti-baryon/baryon ratios, primarily $\overline{p}/p$, and the $\overline{p}/\pi^-$ ratio shows a strong temperature dependence.

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Figure 3. Calculations with the statistical model showing the dependence on $\mu_B$ for each ratio in Figure 1 for two different values of the temperature. Experimental values, compiled when multiple measurements are available, are represented by horizontal lines; shaded areas indicate the experimental error.
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Figure 4. Calculations with the statistical model showing the temperature dependence of each ratio in Figure 1 for two different values of $\mu_B$. Experimental values, compiled when multiple measurements are available, are represented by horizontal lines; shaded areas indicate the experimental error.