Test of Chemical freeze-out at RHIC

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Abstract. We present the results of a systematic test applying statistical thermal model fits in a consistent way for different particle ratios, and different system sizes using the various particle yields measured in the STAR experiment. Comparison between central and peripheral Au+Au and Cu+Cu collisions with data from p+p collisions provides an interesting tool to verify the dependence with the system size. We also present a study of the rapidity dependence of the thermal fit parameters using available data from RHIC in the forward rapidity regions and also using different parameterization for the rapidity distribution of different particles.

1. Introduction

Statistical thermal model has been very successful in describing the various particle ratios measured in heavy ion collisions, from the SPS energies up to the highest RHIC energies. It is impressive that with a single chemical freeze-out Temperature these models can describe all the different particle ratios up to the heaviest strange hyperons. Thermal parameters obtained from the fits to the various data sets seems to be extremely well behaved in a wide range of energy and different collisions systems and parameters such as Temperature and Baryo-chemical potential has been well parameterized [1, 2] as a function of energy. In many ways, this remarkable success of describing the data with a few simple statistical parameters can be viewed as an indication that indeed the particles in these collisions were produced in a chemically equilibrated system. However, if this is the case, there must be a critical system size or collision energy where the statistical thermal model fails to describe the observed data, where equilibration is not achieved due to the insufficient number of particle interactions. In this context, it is important to perform a careful and systematic scan of the thermal model fits considering systems with different size and collision energies. This is now possible with the large amount of data accumulated at RHIC, and in particular, the high quality and high statistic data obtained by the STAR experiment with its large acceptance detectors and extended particle identification capability. A detailed description of the STAR detector system and the different analysis techniques used to obtain the yields can be found elsewhere [3, 4, 5].

We present a study of the system size dependence of the hadronic freeze-out parameters by comparing the results from different event centrality classes of Au+Au
and Cu+Cu collisions at $\sqrt{S_{NN}} = 200$ GeV measured by the STAR experiment. Due to the fact that we are using data from the same detector system many of the systematic errors were canceled and the relative error of the particle ratios used in the fit were reduced. For the statistical thermal fit, we used the THERMUS code from Cleymans et al. [6], that allows for fits to the data using a Grand-Canonical ensemble approach, with the inclusion of a strangeness saturation parameter $\gamma_S$ and also a Semi-Canonical approach where the strangeness production was treated canonically while the light quark particles were still considered using a Grand-Canonical approach. In this study, we have used particle ratios that include the Pions, Protons, Kaons, $\Lambda$, $\Xi$, $\Omega$ [7], the corresponding anti-particles and also the $\phi$ meson [8]. The Pion and Proton yields were corrected for the feed-down from the weak decays before the thermal fit. Variations in the thermal fit parameters due to uncertainties in the feed-down corrections were tested and found to add an extra uncertainty of less than 5% in the final uncertainties of these parameters.

2. System size dependence

Particle ratios from different event centrality classes were used to study the dependence of chemical freeze-out conditions with the system size. Figure 1 shows the results of the Temperature and Strangeness saturation parameter $\gamma_S$ as a function of the mean number of participants. For comparison, data from p+p collisions was also fitted and included in these plots. Temperature, Baryo-chemical potential ($\mu_B$) and Strangeness-chemical potential ($\mu_S$) show little variation with the system size. Even the p+p data yields reasonable fit with the thermal model with a Temperature equivalent to the Au+Au data, of approximately 160 MeV. However, the $\gamma_S$ parameter shows a strong deviation from unity for smaller systems including peripheral Au+Au and Cu+Cu events and p+p. This may be an indication that in these smaller systems, strangeness production is no longer well described with a simple Grand-Canonical approach.

To evaluate the effect of a limited system size in the strange particle production, we used a Semi-Canonical ensemble approach, where only the conservation of the strange sector was imposed within a canonical volume and the light quarks were considered still in the Grand-Canonical approach. Figure 2a shows the relative production of strange particles $K$, $\Lambda$, $\Xi$, $\Omega$ and the $\phi$ with respect to the pions yields, as a function of the radius of the canonical volume obtained using the THERMUS code. The Temperature and Baryo-chemical potential used to calculate these curves were fixed to be the same values obtained from the fit to the data. The solid points show the equivalent experimental particle ratios, for central Au+Au, peripheral Au+Au and p+p collisions. As expected, the $\phi$ meson with its hidden strangeness shows no variation with the canonical volume, and the $\Omega$ shows the highest sensitivity to the canonical volume. The most peripheral data in Au+Au seems to yield results already consistent with values that are no longer subject to the reduction of strangeness production due to this canonical effect.

The thermal fit results of the Temperature, $\mu_B$, $\mu_S$ and $\gamma_S$ seems to show no
difference between the Au+Au and Cu+Cu data. However, the relative yields per participant of strange particles and also of Pions, measured in Cu+Cu collisions was observed to be higher than the equivalent yields measured in Au+Au collisions for the same number of $\langle N_{\text{part}} \rangle$ [9]. This apparent discrepancy seems not to be reflected in the particle ratios, thus, no difference in the thermal parameters were observed between the results from Cu+Cu and Au+Au data. The volume of the system at chemical freeze-out was calculated using the thermal parameters obtained from the fits to the particle ratios and also using the absolute yields of Pions. Figure 2b shows the relative volume per participant of the system for Au+Au and Cu+Cu data, normalized by the results of p+p. In this plot, we can observe that the Cu+Cu data yields a higher freeze-out volume than the equivalent Au+Au data.

3. Rapidity Dependence of thermal parameters

Most of the results of statistical thermal fits applied to data from RHIC experiments correspond to particle ratios of $dN/dy$ at mid-rapidity, and not the integrated yield of particles in all rapidity range. To study the variation of the thermal fit parameters in the different rapidity range, we have used two different parameterizations of the rapidity distribution for the different particles to extrapolate the particle yields at the forward regions and obtain the thermal fit parameters. In a first attempt, we used a Gaussian shape to describe the various particle distributions, adjusting the yield and width of the distribution using the available data from STAR [10] and BRAHMS [11, 12] experiment. Particle ratios were built by extracting the corresponding $dN/dy$ for the different rapidity regions and also using the total integrated yield. In a second approach, we have used the well known HIJING Monte Carlo simulation code [13, 14] to generate the particle rapidity distributions. The yields of the rapidity distributions generated by
HIJING were scaled to fit the data points from STAR at mid rapidity. Once normalized, the shape of the rapidity distributions from HIJING seems to describe well the available data from the BRAHMS experiment in the forward rapidity region. In these fits, only particle ratios using Protons, Pions and Kaons, and its corresponding antiparticles were used. We noted that the main effect caused by the reduced number of particles in the thermal fit is the increase of the relative uncertainties in the final parameters and also, a reduction of the $\gamma_S$ parameter, from 1.0 to approximately 0.8.

Figure 3a shows an example of the rapidity distribution obtained using the Gaussian extrapolation and the HIJING shape for the ratio between anti-protons and pions. In this example, it is clear that there are some considerable difference between the Gaussian parameterizations and the HIJING prediction. The solid star symbol corresponds to the STAR mid-rapidity measurement and the solid circles correspond to the data from the BRAHMS experiment. Figure 3b shows the Temperature obtained from the Thermal fit to this extrapolated data, and also the result of the fit to the STAR and BRAHMS data. Both data, and the Gaussian parameterization show a constant Temperature up to higher values of rapidity. The result from the thermal fit to the HIJING parameterization show an increase of the Temperature for the forward region with values higher than 2 units of rapidity.

Figure 4a and 4b show the result of the Baryo-chemical potential $\mu_B$ and strangeness saturation parameter $\gamma_S$ as a function of rapidity. The Baryo-chemical potential shows an increase with rapidity reflecting the increase of the net baryon density of protons over antiprotons. The $\gamma_S$ parameter seems to show a constant value up to higher values of rapidity and when using the data and the Gaussian parameterization, but the results obtained using the HIJING extrapolations show a strong decrease of the
strangeness equilibration in the forward direction. Despite the variations in the different parameterizations, all results obtained here seems to show that in the RHIC data, thermal characteristics of the chemical freeze-out conditions are quite constant up to approximately two units of rapidity.
4. Conclusions

Results from a systematic study using RHIC data for different centrality classes and different rapidity regions show that chemical freeze-out parameters can fit well the observed particle ratios. The thermal parameter such as Temperature and Baryo-chemical potential show negligible variation with the system size, and for event classes with \( N_{\text{part}} > 100 \) the data is well described using a Grand-Canonical approach with the strangeness saturation parameter \( \gamma_S \) consistent with unity. Smaller systems, such as Cu+Cu and p+p, can still be well described but with a lower value of \( \gamma_S \). Using a strangeness canonical ensemble approach instead of the Grand-Canonical ensemble, we were also able to fit the data. The size of the canonical correlation volume for the Au+Au data is already consistent with a completely saturated strangeness production, where the values of the strange particle production no longer varies with the correlation volume. Fit to the p+p data resulted in a much smaller correlation volume, where canonical suppression is still a non-negligible effect into the production of strange particles. We also showed a first attempt to parameterize the rapidity dependence of the thermal fits to the RHIC data, where we observed that the Temperature and the \( \gamma_S \) parameter is constant up to higher values of rapidity, while the Baryo-chemical potential shows an increase with rapidity.

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