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Hadron production in Au–Au collisions at RHIC

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Abstract

We present an analysis of particle production yields measured in central Au–Au collisions at RHIC in the framework of the statistical thermal model. We demonstrate that the model extrapolated from previous analyses at SPS and AGS energy is in good agreement with the available experimental data at $\sqrt{s} = 130$ GeV implying a high degree of chemical equilibration. Performing a χ^2 fit to the data, the range of thermal parameters at chemical freezeout is determined. At present, the best agreement of the model and the data is obtained with the baryon chemical potential $\mu_B \simeq 46 \pm 5$ MeV and temperature $T \simeq 174 \pm 7$ MeV. More ratios, such as multistrange baryon to meson, would be required to further constrain the chemical freezeout conditions. Extrapolating thermal parameters to higher energy, the predictions of the model for particle production in Au–Au reactions at $\sqrt{s} = 200$ GeV are also given.

1. Introduction

The ultimate goal of ultrarelativistic nucleus–nucleus collisions is to study the properties of strongly interacting matter under extreme conditions of high energy density [1–3]. Hadron multiplicities and their correlations are observables which can provide information on the nature, composition, and size of the medium from which they are originating. Of particular interest is the extent to which the measured particle yields are showing equilibration. The level of equilibrium of secondaries in heavy ion collisions can be tested by analyzing the particle abundances [4–10] or their momentum spectra [5,12]. In the first case one establishes the chemical composition of the system, while in the second case additional information on dynamical evolution and collective flow can be extracted.

A detailed analysis of the experimental data at SPS energy has shown that hadronic yields and their ratios resemble those of a population in chemical equilibrium. Most particle multiplicities measured in nucleus–nucleus collisions at the SPS are well consistent with thermal model predictions [6,10,11]. Particle transverse mass distributions, on the other hand, exhibit slopes showing a structures typical of a thermal source undergoing transverse expansion [12,13]. The slope parameters and the spectra have been well described by the convolution of thermal and flow components within the framework of hydrodynamical models [14]. Thus, on the basis of these analyses one concludes that, at the SPS, chemical and thermal equilibrium was indeed achieved at some stage of the collision. The chemical freezeout temperature $T_f \simeq 168 \pm 2.4$ MeV found from a thermal analy-

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sis [6] of experimental data in Pb–Pb collisions at SPS is remarkably consistent within error with the critical temperature $T_c \simeq 170 \pm 8$ MeV obtained from lattice Monte Carlo simulations of QCD at vanishing baryon density [15,16]. Thus, the observed hadrons seem to be originating from a deconfined medium and the chemical composition of the system is most likely established during hadronization [2,3]. The observed coincidence of chemical and critical conditions in the QCD medium, if indeed valid, should also be seen in heavy ion collisions at higher collision energies, in particular at RHIC.

In this Letter, we present a thermal analysis of particle production measured in Au–Au reactions at $\sqrt{s} = 130$ GeV which were reported in [17–26]. We will focus on momentum integrated particle yields and their ratios, thereby studying the soft component of particle spectra which gives the major contribution to the overall multiplicity. We derive the chemical freezeout conditions at RHIC and discuss their uncertainties. We also propose an experimental observable which could further constrain the thermal parameters. Finally, we provide model predictions for particle production in Au–Au reactions at $\sqrt{s} = 130$ and 200 GeV.

2. Results

In the present analysis of RHIC data, [1] we adopt the statistical model which has been used previously in the analysis of particle production at SPS and AGS energies [6]. This model was formulated in the grand canonical ensemble with the baryon number, strangeness and electric charge conservation. The partition function contains the contributions from all mesons and baryons with masses up to 1.5 and 2.0 GeV, respectively. To account for repulsive interactions between hadrons at small distances, an eigenvolume was assigned to all particles. The eigenvolume parameter is assumed to be the same for all hadrons and is calculated with a hard core radius of 0.3 fm. Calculations of relevant observables such as particle densities are performed thermodynamically in a self-consistent manner. Thus all these quantities are derived directly from the partition function by taking appropriate derivatives.

Within this framework particle multiplicity ratios depend only on two independent parameters: the temperature T and the baryon chemical potential μ_B. All other fugacity parameters are determined by the initial conditions requiring strangeness neutrality and electric charge conservation. The contribution of resonance decays to the final particle yields of lighter mesons and baryons is also included in the analysis.

The above model is now applied to Au–Au collisions at $\sqrt{s} = 130$ GeV at RHIC. We use the results of the STAR [17–21], PHENIX [22,23], PHOBOS [24], and BRAHMS [25,26] collaborations for different particle multiplicity ratios listed in Table 1. All these ratios were obtained from measured particle yields integrated over transverse momentum. The pseudo-rapidity coverage was, however, limited to the central region, $-0.5 < \eta < 0.5$.

We adjust the free parameters T and μ_B to get the best description of the data. The calculations are performed under the condition of strangeness neutrality within the 1 unit of rapidity covered by the data. Furthermore, we assume that 50% of all weakly decaying baryons are reconstructed in the experiments. For the criterium of the best fit we use the value of χ^2. Fig. 1 shows the contours of constant χ^2 in the T–μ_B plane. The best fit corresponding to the minimum of $\chi^2 \simeq 5.7$ for 7 effective degrees of freedom gives $T \simeq 174 \pm 7$ MeV and $\mu_B \simeq 46 \pm 5$ MeV as the chemical freezeout parameters at this RHIC energy. The corresponding strange chemical potential is $\mu_s = 13.6$ MeV. Repeating the calculations assuming that as an upper limit 100% of all weakly decaying baryons are reconstructed leads to $T \simeq 169 \pm 7$ MeV and $\mu_B \simeq 48 \pm 4$ MeV. Since experiments presently do not correct for feed-down from weakly decaying baryons, see, e.g., the discussion in [19], the reconstruction efficiency will be large, but the sensitivity of the calculations to the actual value is small. In the absence of more detailed information we use 50% as reconstruction efficiency.

The energy per particle of 1.1 GeV obtained with these parameters is consistent with the unified freezeout conditions proposed in [9]. We note that these parameter values are close to those used for a prediction

[1] A summary of data of different collaborations is presented in [27].

Table 1
Comparison of experimental particle ratios and thermal model calculations for $T = 174$ MeV, $\mu_B = 46$ MeV at $\sqrt{s} = 130$ GeV. Also shown in parentheses are model predictions for particle ratios at $\sqrt{s} = 200$ GeV with $T = 177$ MeV, $\mu_B = 29$ MeV

Ratio	Model calculation $\sqrt{s} = 130$ (200) GeV	Exp. data $\sqrt{s} = 130$ GeV	Exp.	Ref.
$\bar{p}/p$	0.629 (0.752)	0.65 ± 0.07	STAR	[17]
		0.64 ± 0.07	PHENIX	[22]
		0.60 ± 0.07	PHOBOS	[24]
		0.64 ± 0.07	BRAHMS	[26]
$\bar{p}/\pi^-$	0.078 (0.089)	0.08 ± 0.01	STAR	[18]
π^-/π^+	1.007 (1.004)	1.00 ± 0.02	PHOBOS	[24]
		0.95 ± 0.06	BRAHMS	[25]
K^-/K^+	0.894 (0.932)	0.88 ± 0.05	STAR	[19]
		0.78 ± 0.13	PHENIX	[23]
		0.91 ± 0.09	PHOBOS	[24]
		0.89 ± 0.07	BRAHMS	[25]
K^-/π^-	0.145 (0.147)	0.149 ± 0.02	STAR	[19]
$K^{\star 0}/h^-$	0.037 (0.036)	0.06 ± 0.017	STAR	[20]
$\overline{K^{\star 0}}/h^-$	0.032 (0.033)	0.058 ± 0.017	STAR	[20]
$\overline{\Lambda}/\Lambda$	0.753 (0.842)	0.77 ± 0.07	STAR	[20]
$\overline{\Xi}/\Xi$	0.894 (0.942)	0.82 ± 0.08	STAR	[21]
Λ/h^-	0.040 (0.039)			
$\Lambda/K^{\star 0}$	1.086 (1.091)			
Ξ^-/Λ	0.123 (0.127)			
Ξ^-/K^-	49.8×10^{-3} (50.2×10^{-3})			
$\Xi^+/\overline{\Lambda}$	0.145 (0.142)			
Ξ^+/π^+	6.51×10^{-3} (7.01×10^{-3})			
Ω/Ξ	0.196 (0.197)			
Ω^+/Ω^-	0.898 (0.941)			
Ω^-/π^-	1.47×10^{-3} (1.50×10^{-3})			

of particle yields at full RHIC energy [28] of $T = 168$ MeV and $\mu_B = 10$ MeV.

In Fig. 2 we show the comparison of the thermal model results with experimental data. One sees in Fig. 2 and also in Table 1 that the overall agreement is very good. Most of the data are reproduced by the model within the experimental errors. The largest deviations are seen in the ratios of $\overline{K}^{*0}/h^-$ and

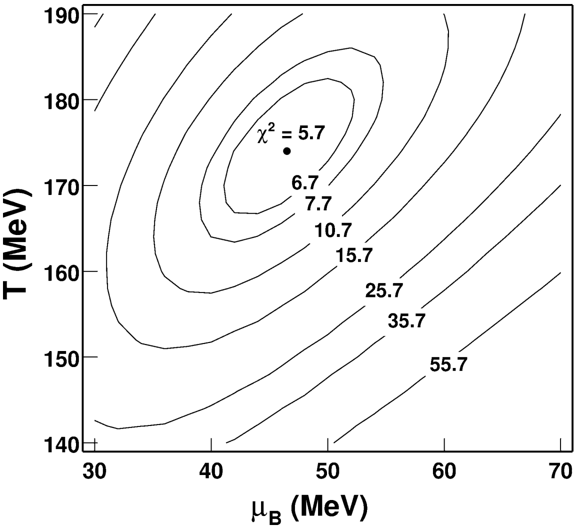

Fig. 1. Lines of constant χ^2 for the comparison of experimental particle ratios from RHIC experiments and model calculations for a wide range of thermal parameters (T, μ_B). The dot represents the parameter set with minimum χ^2 located at $T = 174$ MeV and $\mu_B = 46$ MeV.

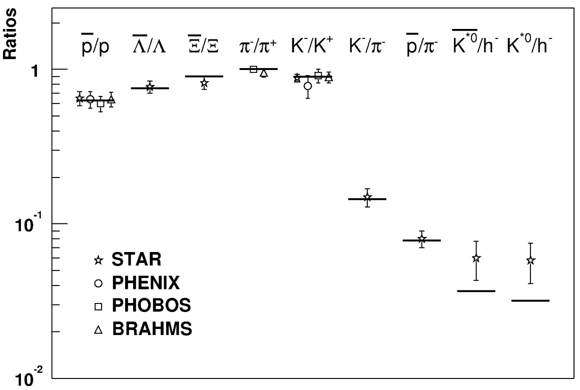

Fig. 2. Comparison between RHIC experimental particle ratios and statistical model calculations with $T = 174$ MeV and $\mu_B = 46$ MeV. Experimental data are taken from [17–26].

K^{*0}/h^- but still they are on the level of one standard deviation. In Table 1 the predictions of the model for different particle ratios which are still not known experimentally are also presented.[2] As is visible from Fig. 1, the minimum in the χ^2 surface is narrower in

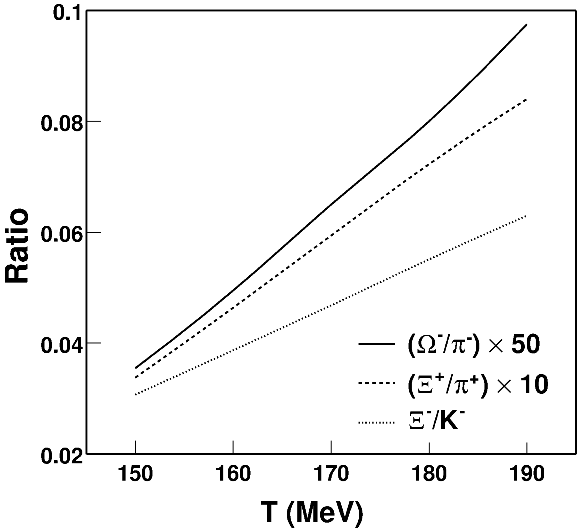

Fig. 3. Temperature dependence of different particle ratios calculated with $\mu_B = 50$ MeV.

μ_B direction while more freedom for variation is still possible in T direction (see also results presented in [10,27,29,30]). To further constrain the value of the freezeout temperature additional results for particle ratios are required. Of particular relevance would be the ratios of multistrange baryons to mesons which are strongly T dependent while being only weakly influenced by μ_B. In Fig. 3 we show the calculated temperature dependence of the Ω^-/π^-, Ξ^+/π^+ and Ξ^-/K^- ratios as possible observables which would constrain further the value of T.

Considering the best values of thermal parameters derived from the present analysis together with previous systematics on freezeout conditions in heavy ion collisions in the energy range from SIS up to SPS [9,31], one can make predictions for particle production in Au–Au reactions at $\sqrt{s} = 200$ GeV. Indeed in [32] it was shown that the energy dependence of the baryon chemical potential can be parameterized phenomenologically as $\mu_b \sim 1.3$ GeV $(1 + \sqrt{s}/4.5\ \text{GeV})^{-1}$. This prediction is consistent within error with our present result for RHIC energy. Using this parameterization one finds a decrease of baryon chemical potential from $\mu_B \simeq 46 \pm 5$

[2] These calculations are made assuming a 50% reconstruction efficiency for particles resulting from weak baryon decay. This may need to be adapted to specific experimental conditions when comparing ratios involving such particles to data.

MeV at $\sqrt{s} = 130$ GeV to $\mu_B \simeq 29 \pm 8$ MeV at $\sqrt{s} = 200$ GeV. The unified freezeout condition of fixed energy/particle $\simeq 1.1$ GeV provides a temperature increase to 177 ± 7 MeV in Au–Au reactions at $\sqrt{s} = 200$. The freezeout temperature is obviously bounded from above by the deconfinement phase transition temperature. The χ^2 fit provides only statistical indication of the most probable value of thermal parameters. In Table 1 we show the results of the statistical model for different particle ratios at the top RHIC energy. It is clear that the small baryon and corresponding strange chemical potentials imply that particle to antiparticle ratios are close to unity. Other ratios are also at values near the baryon-free limit.

Finally, we have to stress that at energies where baryon stopping is dominant, such as at the SPS, the comparison of the statistical model with experiment should be done with 4π particle yields [6,33]. This procedure strongly reduces the possible influence of dynamical effects on particle yields and guarantees that the conservation laws of quantum numbers are fulfilled. In the restricted acceptance near midrapidity one needs to account for additional uncertainties in the derivation of thermal conditions from the experimental data. It is not excluded that thermal parameters at midrapidity could deviate from their values in full phase space as already seen at the SPS energy [10]. On the other hand, if the energy is sufficiently high such that data exhibit boost-invariant rapidity plateaus, analysis near mid-rapidity should also be little influenced by dynamical effects such as, e.g., hydrodynamical flow [34]. The current energy seems already to be close to this regime.

3. Summary and conclusions

In conclusion, we have shown that the statistical model in complete equilibrium gives results consistent with the experimental data for particle production in Au–Au collisions at $\sqrt{s} = 130$ GeV. At this energy the chemical freezeout appears at $T = 174 \pm 7$ MeV and $\mu_B = 46 \pm 5$ MeV. The resulting temperature is only slightly higher than that previously found at the SPS where for Pb–Pb collisions $T = 168 \pm 5$ MeV. This relatively moderate increase of temperature could be expected since in the limit of vanishing baryon density the temperature should not exceed the critical value required for deconfinement. The substantial decrease of the baryon chemical potential from $\mu_B \simeq 270$ MeV at SPS to $\mu_B \simeq 45$ MeV at RHIC found in these calculations shows that at midrapidity we are dealing with a low net baryon density medium.

We have also discussed possible uncertainties of the results and proposed observables which could provide better constraints on thermal parameters. Finally, extrapolating the values of thermal parameters to a higher energy, we have made a prediction for particle production in Au–Au reactions at $\sqrt{s} = 200$ GeV.

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