Analysis of particle production in ultra-relativistic heavy ion collisions within a two-source statistical model

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(Dated: March 30, 2022)

The experimental data on hadron yields and ratios in central lead-lead and gold-gold collisions at 158 AGeV/c (SPS) and √s = 130 AGeV (RHIC), respectively, are analysed within a two-source statistical model of an ideal hadron gas. A comparison with the standard thermal model is given. The two sources, which can reach the chemical and thermal equilibrium separately and may have different temperatures, particle and strangeness densities, and other thermodynamic characteristics, represent the expanding system of colliding heavy ions, where the hot central fireball is embedded in a larger but cooler fireball. The volume of the central source increases with rising bombarding energy. Results of the two-source model fit to RHIC experimental data at midrapidity coincide with the results of the one-source thermal model fit, indicating the formation of an extended fireball, which is three times larger than the corresponding core at SPS.

PACS numbers: 25.75.-q, 24.10.Pa, 25.75.Dw

I. INTRODUCTION

Searching for the quark-gluon plasma (QGP) is one of the major objectives in the study of relativistic heavy ion collisions. The principal question is whether the strongly interacting nuclear, or rather parton, matter reaches the stage of chemical and thermal equilibrium. Although this idea was put forward by Fermi 50 years ago [1], up to now there is no unambiguous test to probe the degree of equilibration in the system. One of the possible approaches is to study the equilibration process within microscopic models [2, 3, 4, 5, 6, 7]. The more traditional way is to fit macroscopic observables, yields and transverse spectra of particles, obtained in experiments to the statistical model (SM) of a fully equilibrated hadron gas. The simplicity of the SM has led to a very abundant literature (see [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22] and references therein). As the experimental data became more precise, it has been understood that the ideal SM does not provide an adequate description of all hadron multiplicities [9]. Particularly, the yields of pions are usually underestimated while the abundances of strange particles are overpredicted. Besides, the calculated particle number density and the total energy density at the stage of chemical freeze-out are found to be too large [15]. Therefore, some modifications to the SM have been proposed. These improvements consider the following effects: (i) excluded volume effects that lead to a Van der Waals type equation of state (EOS) due to a non-zero "hard-core" radius of hadrons [13, 15, 16]; (ii) strangeness suppression, that enters into the distribution functions via the phenomenological factor γS < 1 [11, 12]; (iii) chemical non-equilibrium of light quarks [18]. It is worth noting that the assumption of a single expanding source remains the basic ad hoc hypothesis of these models. The scenario of several fireballs has not been employed except a particular case in which all fireballs have the same chemical potential and the same temperature [17, 23] but move with different collective velocities along the beam direction. In this special case the particle ratios are, however, not affected by superimposing a collective longitudinal kinetic energy and are, therefore, identical to the results of the single fireball scheme. Obviously, if the baryon density and/or the strangeness density are not the same everywhere in the reaction volume, the scenario with several independent sources cannot be reduced to the single source scenario. Our investigations of the two-source scenario have been inspired by the experimental observation of decreasing of antiproton to proton ratio with rising rapidity in the center-of-mass system [24] (the same is true for Λ/Λ ratio also) which results to low net baryon densities in the midrapidity range of relativistic heavy-ion collisions at SPS energies (158 AGeV/c) [25]. In the two-source model the total reaction volume is divided into two regions, the inner source and the outer
Each source is assumed to be in the chemical and thermal equilibrium, respectively, and allowed to have different temperature, baryon and strangeness densities, etc. This two-source scenario is also in accordance with microscopic model calculations. Such microscopic cascade calculations show that the central zone between the remnants of the colliding nuclei is more baryon dilute compared to the baryon-rich zones of the nuclei residues [5, 6]. Thus, global equilibrium is not reached by the whole system, but local equilibrium in the central zone and in the peripheral region may still occur separately.

The paper is organized as follows. Description of the two-source model is given in Sect. II. Sections III and IV present results of the model fit to the SPS and RHIC data, respectively. Comparison with the predictions of the standard thermal model is also given. Finally, conclusions are drawn in Sect. V.

II. TWO-SOURCE MODEL

Firstly, we briefly sketch some of the basic principles of the statistical model of an ideal hadron gas. In the framework of the grand canonical ensemble, the macroscopic characteristics of the system are derived via a set of distribution functions (we work with the system of units where \( c = \hbar = k_B = 1 \))

\[
f(p, m_i) = \left\{ \exp \left[ \frac{\left( \sqrt{p^2 + m_i^2} - \mu_B B_i - \mu_S S_i \right)}{T} \right] \pm 1 \right\}^{-1}, \tag{1}
\]

where \( p \) and \( m_i \) are the momentum and the mass of the hadron species \( i \), \( T \) is the temperature, \( \mu_B \) and \( \mu_S \) are the baryon chemical potential and strangeness chemical potential, \( B_i \) and \( S_i \) are the baryon charge and strangeness charge of hadron \( i \). The sign “+” in Eq. (1) stands for fermions and sign “−” stands for bosons. The particle number density \( n_i \), the energy density \( \varepsilon_i \) and the pressure \( P \) in the system read as

\[
n_i = \frac{N_i}{V} = \frac{g_i}{(2\pi)^3} \int_0^\infty f(p, m_i) d^3p, \tag{2}
\]

\[
\varepsilon_i \frac{E_i}{V} = \frac{g_i}{(2\pi)^3} \int_0^\infty \sqrt{p^2 + m_i^2} f(p, m_i) d^3p, \tag{3}
\]

\[
P = \sum_i \frac{g_i}{(2\pi)^3} \int_0^\infty \frac{p^2}{3(p^2 + m_i^2)^{1/2}} f(p, m_i) d^3p, \tag{4}
\]

with \( g_i \) being the degeneracy factor of hadron \( i \) and \( V \) the volume of the system. The entropy density \( s = S/V \) is determined via the Gibbs thermodynamic identity

\[
s = (\varepsilon + P - \mu_B \rho_B - \mu_S \rho_S) T^{-1}. \tag{5}
\]

Here \( \rho_B \) and \( \rho_S \) are the baryon density and strangeness density, respectively.

In the present paper we develop a two-source statistical model (TSM) of a hadron gas. The model divides the whole reaction zone into two regions: the outer region (source 1 or S1) and the inner region (source 2 or S2). Since these sources are assumed to be in local thermal and chemical equilibrium, they are allowed to possess different temperatures, net baryon densities, chemical potentials, etc. Furthermore, the strangeness density is no longer kept zero everywhere as in the SM. Only the total number of strangeness is required to be zero because of strangeness conservation in strong interactions.

The characteristics of a single fireball can be described by means of four independent parameters, such as volume \( V \), total energy \( E \), net baryon density \( \rho_B \) and net strangeness density \( \rho_S \). These parameters enable one to determine the fireball temperature \( T \), the strangeness and baryon chemical potentials \( \mu_S \) and \( \mu_B \). Since the total strangeness is zero in heavy-ion collisions, the number of free parameters in the SM of an ideal hadron gas is reduced to three, namely, \( V, E \) (or \( \varepsilon = E/V \)) and \( \rho_B = N_B/V \). In the two-source model the number of free parameters increases to seven. Although the net strangeness in each of the sources can be nonzero, they are linked via the condition of total strangeness conservation:

\[
N_{S1} + N_{S2} = 0. \tag{6}
\]

Our choice of the free parameters in the two sources is as follows: Besides temperature, volume, and net baryon density of the two sources, i.e. \( T_1, V_1, \rho_{B1} \) and \( T_2, V_2, \rho_{B2} \), the strangeness density in source 1, \( \rho_{S1} \), is considered as a free parameter.

III. HADRON PRODUCTION AT SPS

The baryon yield and ratios of hadrons at midrapidity in central Pb+Pb collisions at 158 AGeV are listed in Table I together with the results of the TSM fit. All hadrons including their resonances and possible anti-particles with masses less than 2 GeV/\( c^2 \) are included in the fitting procedure. No additional constraints such as strangeness suppression or excluded volume are assumed except the feeding-back effect from resonance decay. For the sake of comparison, we check our model by fitting the same set of experimental data with the single-source model. The results of the fit are also listed in Table I. As in the TSM case, these results are obtained including the feeding-back effect but without further corrections. Compared to the ideal SM, the TSM improves the agreement with the experimental data. The thermodynamic quantities obtained from the two fits to experimental data are shown in Table II. One can find the sizable differences in temperature and volume between the two sources. With 155 MeV the temperature in source 2 is significantly higher than that of 117 MeV in source 1. The volume of the hot source is about 0.7 \( V_0 \), where \( V_0 \) is the volume of a lead nucleus, while the volume of the cooler source is four times larger. This fact indicates that the two-source object can be interpreted as a hot,
small interaction cross section with hadrons, strangeness is mainly carried by kaons. Because of the particles must be produced in pairs. At SPS energies observation in strong interactions strange and anti-strange phenomenon is as follows: Due to the strangeness con-
crocoscopic point of view the possible explanation of the phenomenon is as follows: Due to the strangeness con-
ervation in strong interactions strange and anti-strange particles must be produced in pairs. At SPS energies strange

particles which carry s quarks, e.g., Λ and χ, thus leading to a negative strangeness density in the midrapidity range.

The energy density in S2 is about three times larger than that in S1. Such a low energy density in the outer source corresponds to the energy density at thermal freeze-out rather than at chemical freeze-out [5]. In other words, the solution for two sources can not be reduced to the one-source picture even in the case where exclusive midrapidity data have been used.

For further investigation we applied the two-source model to fit the set of experimental data used in Ref. [15], which are a combination of midrapidity and 4π-data. The data and the results of the TSM and SM fit are listed in Table III. Two important facts can be learned from this comparison. First of all, it is already known that the ideal SM (without strangeness suppression and excluded volume effects) underpredicts the number of negatively charged hadrons h− and overestimates the yield of φ mesons. The problem can be cured by increasing the volume V and decreasing the temperature T of the source [15]. However, the antibaryon to baryon ratios become then completely wrong. The TSM enables one to get both the correct multiplicities of h− and φ and the correct antibaryon/baryon ratios. Secondly, the temperatures of both sources remain almost unchanged when we have shifted from the data set of Table I to the data set of Table III, and the temperature of the central fireball is very close to the temperature of the entire system in the single-source model.

We have also fitted the hadron yields and ratios taken in the whole available rapidity range, see Table IV. Again, the thermodynamic characteristics in S2 are far from the averaged characteristics of the combined S1+S2 system. For instance, the entropy per baryon, S/A ≡ s/pB, equals 31 in source 1 but increases up to 373 in

TABLE I: Baryon yield and hadron ratios at midrapidity for central lead-lead collisions at SPS energies and predictions of the single-source and two-source statistical models of an ideal hadron gas.

|   | Data | SM | TSM | TSM−Data % | Ref. |
|---|---|---|---|---|---|
| N   | 372±10 | 371.9 | 372.1 | 0 | [26] |
| K+ / K− | 1.85±0.1 | 1.97 | 1.87 | 4 | [27] |
| η / p | 0.07±0.01 | 0.069 | 0.058 | -17 | [28] |
| Ξ / Ω | 0.249±0.019 | 0.231 | 0.247 | -1 | [29] |
| Λ / Ω | 0.383±0.081 | 0.427 | 0.405 | 6 | [29] |
| η / π | 0.128±0.012 | 0.130 | 0.137 | 7 | [30] |
| η / π | 0.081±0.013 | 0.133 | 0.108 | -33 | [31] |
| Ξ / Ω | 0.125±0.019 | 0.121 | 0.120 | -4 | [32] |
| Λ / Ω | 0.123±0.02 | 0.102 | 0.102 | -17 | [33] |
| Δ / h | 0.077±0.011 | 0.069 | 0.064 | -17 | [33] |
| Ω / Ξ | 0.219±0.045 | 0.131 | 0.104 | -53 | [33] |
| Ξ / Λ | 0.110±0.01 | 0.156 | 0.115 | 4 | [33] |
| χ^2/DOF | 46/9 | 16/5 |  |  |

TABLE II: Thermodynamic characteristics of two-source and single-source models.

|   | TSM (S1) | TSM (S2) | SM |
|---|---|---|---|
| T[MeV] | 117 | 156 | 188 |
| V[f m^3] | 7250(3700) | 1705(0.7100) | 4203 |
| ρB[f m^{-3}] | 0.048 | 0.014 | 0.088 |
| ρS[f m^{-3}] | 0.0018 | -0.0075 | 0.0 |
| ε[MeV/f m^3] | 104 | 314 | 436 |
| P[MeV/f m^3] | 14 | 52 | 67 |
| N_{B} | 348 | 55 | 408 |
| N_{n} | 0 | 30 | 36 |
| N_{B} - N_{n} | 348 | 25 | 372 |
| N_{S} | 34 | 42 | 117 |
| N_{n} | 21 | 55 | 117 |
| N_{S} - N_{n} | 13 | 13 | 0 |
| μ_{B}[MeV] | 460 | 45 | 213 |
| μ_{S}[MeV] | 68 | 17 | 22 |

TABLE III: The same as Table I but for the data set from Ref.[15].

|   | Data | SM | TSM | TSM–Data % | Ref. |
|---|---|---|---|---|---|
| N_{B} | 372±10 | 362.9 | 373.9 | 0.5 | [26] |
| h | 680±50 | 606 | 659 | -3.2 | [34] |
| K^0 | 68±10 | 61.6 | 64.4 | -5.5 | [34] |
| φ | 7.6±1.1 | 13.4 | 7.89 | 4 | [35] |
| p − p | 155±20 | 125 | 147 | -5 | [34] |
| K^+/K^- | 1.80±0.1 | 1.99 | 1.74 | -3 | [37] |
| η / p | 0.07±0.01 | 0.065 | 0.069 | -1.5 | [28] |
| Ξ / Ω | 0.249±0.019 | 0.220 | 0.229 | -8 | [29] |
| Ω / Ξ | 0.383±0.081 | 0.411 | 0.421 | 10 | [29] |
| χ^2/DOF | 41/6 | 3.1/2 |  |  |
| T[MeV] | 157 | 114 (S1) | 155 (S2) |  |  |
| V[f m^3] | 4160 | 17000 (S1) | 1920 (S2) |  |  |
| ε[MeV/f m^3] | 422 | 60 (S1) | 298 (S2) |  |  |
TABLE IV: The same as Table III but for the hadron yields and ratios in the whole rapidity range.

|          | Data | SM   | TSM  | TSM−Data % | Ref |
|----------|------|------|------|------------|-----|
| $N_B$    | 372±10 | 372.7 | 373.5 | 0.4 | [26] |
| $h$      | 680±50 | 684   | 673.4 | -1 | [34] |
| $K^0$    | 68±10  | 72.5  | 68.8  | 1  | [34] |
| $\phi$   | 7.6±1.1| 7.5   | 7.6   | 0  | [35] |
| $p−\bar{p}$ | 155±20 | 138   | 143   | -8 | [34] |
| $\pi^±/\pi^0$ | 1.10±0.05 | 1.0   | 1     | -10 | [36] |
| $K^+/K^−$ | 1.80±0.1 | 1.84 | 1.80   | 0  | [37] |
| $K^0/\pi^−$ | 0.125±0.019 | 0.121 | 0.118 | -5.5 | [32] |
| $\chi^2$/DOF | 1.3/5 | 0.6/1 |      |    |      |
| $T[MeV]$ | 126   | 117   | (S1)  |      |      |
| $V[fm^3]$ | 17400 | 18500 | (S1)  |      |      |
| $\varepsilon[MeV/fm^3]$ | 90.6 | 63  | (S1)  |      |      |

IV. HADRON PRODUCTION AT RHIC

Experimental data on hadron yields and ratios in the midrapidity range in central gold-gold collisions at $\sqrt{s} = 130$ AGeV became available recently [38, 39, 40, 41, 42, 43, 44, 45]. These data are listed in Table V together with the predictions of the SM and TSM. Surprisingly, now the two-source model divides the total volume in two parts with approximately equal sizes, temperatures, and other thermodynamic characteristics. The results of the SM fit and TSM fit are almost identical. It seems that the volume of the central fireball significantly increases by the transition from the SPS energies to the RHIC ones, and that hadrons detected in the midrapidity range are originated from a single thermalized source. Its volume is more than 5000 fm$^3$, that is about three times larger than the corresponding core volume in Pb+Pb collisions at the SPS, and the temperature reaches 186 MeV. Such a high temperature value is close to the value $T = 190$ MeV obtained in [42], while being 10 MeV higher than the temperature $T = 175$ MeV obtained in [22]. However, if the multiplicity of negatively charged hadrons, $h^−$, is excluded from the data set, the temperature of the modelled system drops to 176 MeV in our calculations. This important question should be clarified in future studies.

TABLE V: Hadron multiplicities and ratios at midrapidity for central gold-gold collisions at RHIC energy ($\sqrt{s} = 130$ AGeV) and predictions of the single-source and two-source statistical models of an ideal hadron gas.

|          | Data | SM   | TSM  | TSM−Data % | Ref |
|----------|------|------|------|------------|-----|
| $N_B$    | 343±11 | 340.6 | 340.6 | -7 | [38] |
| $h$      | 2050±250 | 2238 | 2239 | 9  | [38] |
| $p/p$    | 0.66±0.07 | 0.57 | 0.57  | -4 | [39] |
| $p/\pi^−$ | 0.08±0.01 | 0.087 | 0.087 | 8  | [40] |
| $K^+/K^−$ | 0.87±0.08 | 0.75 | 0.75  | -14 | [41] |
| $K^0/\pi^−$ | 0.149±0.02 | 0.153 | 0.153 | 3  | [41] |
| $K^0/\pi^−$ | 0.060±0.017 | 0.036 | 0.036 | -40 | [42] |
| $\chi^2$/DOF | 9.6/7 | 9.6/3 |      |    |      |
| $T[MeV]$ | 185.7 | 185.9 | (S1)  |      |      |
| $V[fm^3]$ | 5157  | 5208  | (S1)  |      |      |
| $\varepsilon[MeV/fm^3]$ | 1297  | 1305  | (S1)  |      |      |
| $\mu_B[MeV]$ | 52.6  | 53.3  | (S1)  |      |      |

We checked also that the incorporation of the excluded volume effects by assigning the hard-core radius $r = 0.4$ fm to all particles leads to an enlargement of the total volume but does not affect the temperature of the fireball.

Another interesting characteristics at the chemical freeze-out are the energy per particle and the entropy per baryon. In [17] the criterion $E/N ≈ 1$ GeV was introduced for all particles, baryons and mesons, in a broad range of bombarding energies spanning from a few GeV to several hundred GeV per nucleon up to several hundred GeV per nucleon in the center-of-mass system. The predictions of the SM and the TSM for the midrapidity range are as follows: $E/N = 1.1$ GeV, and $S/A ≡ s/\rho_B = 121$. The last value is about 20% below the value $s/\rho_B = 150$ predicted by the UrQMD calculations, but for Au+Au collisions at full RHIC energy, $\sqrt{s} = 200$ AGeV [46]. It would be interesting to perform these microscopic model calculations also at $\sqrt{s} = 130$ AGeV.

V. DISCUSSION AND CONCLUSIONS

In summary, the analysis of hadron multiplicities in central lead-lead and gold-gold collisions at 158 AGeV and $\sqrt{s} = 130$ AGeV, respectively, is presented within a two-source statistical model of an ideal hadron gas. The TSM fit to the experimental data taken at midrapidity at RHIC practically coincides with the standard single-source fit. This result supports the idea of a formation of an extended hot fireball in the central zone of heavy-ion collisions at RHIC energies. The temperature of the
central fireball varies from 176 MeV to 185 MeV, depending on the incorporation of the multiplicity of negatively charged hadrons, $h^{-}$, in the fitting data, whereas the excluded volume effects seem not to affect the fireball temperature. Further going studies are necessary to answer this question.

At SPS it is found that the properties of the system at chemical freeze-out can be well understood in terms of two sources, a central core and a surrounding halo, both being in local chemical and thermal equilibrium. Temperatures as well as baryon charge and strange charge of the two sources are different. The thermal characteristics of the central fireball, obtained from the TSM fit to hadron yields and ratios, depend only weakly on the considered rapidity interval of the data, i.e., midrapidity or the whole rapidity range.

It is worth mentioning that strangeness seems to be in equilibrium in both sources which is reflected by $\gamma_S \approx 1$ in our calculations. This observation is in line with the fact that there is no need to introduce a strangeness suppression factor into the standard SM if one fits the particle ratios from the midrapidity range of Pb+Pb collisions at SPS energies [16]. But the factor $\gamma_S < 1$ arises if one intends to fit $4\pi$-data [12, 15]. A possible explanation for this puzzle is a non-homogeneous distribution of the strange charge within the reaction volume. Therefore, the local, not global, equilibrium of strangeness can be reached separately in the central and in the outer part of the expanding fireball. Furthermore, in the standard SM the energy and hadron number densities are too high to treat the system at chemical freeze-out as a gas of point-like particles anymore. To resolve this problem the introduction of a repulsive hard-core potential for hadrons which leads to a Van der Waals type EOS might be important [15, 16].

In the case of two thermalized sources neither the energy density nor the hadron density is so large and the incorporation of excluded volume effects (at least for the halo) becomes less important.

Another interesting fact is that the temperature of source 2 at SPS energies is about 10 MeV lower than the temperature predicted by most of the single-source statistical models. In the SM such a low temperature can be obtained under the assumption of chemical nonequilibrium (overpopulation) of light $u$ and $d$ quarks [18]. In the latter case the system is not in a state with maximum entropy, i.e., it is probably produced directly from an exploding quark-gluon plasma (QGP) and does not undergo further chemical equilibration in the hadronic phase [18]. However, the ratios of heavy strange baryons, such as $\Omega/\Xi$ or $\Omega/\overline{\Xi}$, are still underpredicted. The TSM allows for another interpretation of the data. It is quite likely that hot nuclear matter, which forms the core, spends enough time in the hadronic phase to reach a chemically equilibrated state. In this case the system does not remember about the past, e.g., the QGP stage (see also [47]). This circumstance complicates the detection of the plasma. It would be very interesting to investigate the forthcoming data on Au+Au collisions at RHIC energies ($\sqrt{s} = 130$ and 200 AGeV) in the whole rapidity range within the TSM in order to check (i) the increase of the volume of the central fireball at the expenses of the halo; (ii) equilibration of strangeness in both sources; (iii) a possible change of the halo temperature.

Acknowledgments

We are grateful to L. Bravina for fruitful discussions. Z.D.L. acknowledges the hospitality of the Institute of Theoretical Physics, Tübingen University. The work was supported by the Deutsche Forschungsgemeinschaft (DFG), Bundesministerium für Bildung and Forschung (BMBF) under the contract No. 06TU986, and the National Science Foundation of China under the contracts No. 19975075 and No. 19775068.

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