Strangeness production in heavy ion collisions at SPS and RHIC within two-source statistical model

Z-D Lu†‡, Amand Faessler‡, C Fuchs‡, E E Zabrodin†§

† China Institute of Atomic Energy, Beijing 102413, China
‡ Institut für Theoretische Physik, Universität Tübingen, Tübingen, Germany
§ Institute for Nuclear Physics, Moscow State University, Moscow, Russia

Abstract. The experimental data on hadron yields and ratios in central Pb+Pb and Au+Au collisions at SPS and RHIC energies, respectively, are analysed within a two-source statistical model of an ideal hadron gas. These two sources 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.

1. Introduction. Two-source model

Searching for the quark-gluon plasma (QGP) is one of the main goals in the study of relativistic heavy ion collisions. The principal question is whether the strongly interacting 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 [2–5]. The more traditional way is to fit yields and transverse spectra of particles obtained in experiments to the statistical model (SM) of a fully equilibrated hadron gas (see [6–14] and references therein). In the model the macroscopic characteristics of the system, such as the particle number density, the energy density, etc., are derived via a set of distribution functions (we assume \( c = \hbar = k_B = 1 \))

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

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 strange charge of hadron \( i \). The sign “+” in Eq. (1) is for fermions and sign “−” for bosons.

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. Particularly, the yields of pions are usually underestimated while the abundances of strange particles are overpredicted. Therefore, some modifications to the SM have been proposed, such as excluded volume effects [8, 9]; strangeness suppression, \( \gamma_S < 1 \) [6, 7]; chemical non-equilibrium of light quarks [11]. The assumption of a single expanding source is the basic ad hoc hypothesis of these models. However, 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 are inspired by the experimental observation \[15\] and microscopic model predictions \[4\] of low net baryon densities in the midrapidity range of relativistic heavy-ion collisions at SPS energies. Thus, local equilibrium may occur separately in different zones of the fireball.

The proposed two-source statistical model (TSM) of a hadron gas \[16\] divides the whole reaction zone into two regions: the outer region (source 1 or S1) and the inner region (source 2 or S2). The two sources are allowed to possess different temperatures, net baryon and strangeness densities, etc. The characteristics of each of the fireballs can be described via the four independent parameters, such as volume \(V\), fireball temperature \(T\), net baryon density \(\rho_B\), and net strangeness density \(\rho_S\). Compared to the SM, the number of free parameters in the two-source model increases to seven: Although the net strangeness in each of the sources can be nonzero, they are linked via the the condition of total strangeness conservation \(N_{S1} + N_{S2} = 0\), i.e., either \(\rho_{S1}\) or \(\rho_{S2}\) may be considered as a free parameter.

2. Hadron production at SPS and RHIC

The baryon yield and ratios of hadrons at midrapidity in central Pb+Pb collisions at 158 AGeV are listed in Table 1 together with the results of the TSM and the SM fit. All hadrons 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. 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 1 also. One can see that the two-source object can be interpreted as a hot, relatively small core surrounded by a cooler and larger halo. The major part of baryons is contained in the outer source, while the inner source contains almost all antibaryons.

The strangeness density is negative in S2 and positive in S1, i.e., the inner source contains more \(s\)-quarks than \(\bar{s}\)-quarks. This finding is supported by microscopic model calculations \[4\]. The possible explanation of the phenomenon is as follows: strange and anti-strange particles must be produced in pairs. Because of the small interaction cross section with hadrons, \(K^+\) and \(K^0\) are leaving the central reaction zone easier than strange particles which carry \(s\) quarks, \(\Lambda\) and \(\bar{\Lambda}\), 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 \[3\]. In other words, the solution for two sources cannot be reduced to the one-source picture even in the case where exclusively midrapidity data have been used. Similar fit has been performed to solely 4\(\pi\)-data and to a mixture of 4\(\pi\)-data with midrapidity data. Results of all three fits favour the idea of the formation of a compact hot baryon-dilute central zone with the following averaged characteristics: temperature \(T = 157 \pm 2\) MeV, volume \(V = 0.6 \pm 0.1\) \(V_0\), where \(V_0\) is the volume of a lead nucleus, and baryon chemical potential \(\mu_B = 31 \pm 14\) MeV. The temperature of the halo is much lower, \(T_{S1} = 117 \pm 3\) MeV.

Experimental data on hadron yields and ratios in the midrapidity range in central Au+Au collisions at \(\sqrt{s} = 130\) AGeV are listed in Table 2 together with the predictions of the SM and TSM. Surprisingly, now the results of the SM fit and the 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 region are originated from a single thermalized source. Its volume is more than 5000 fm$^3$, i.e., three times larger than the core volume at SPS, and the temperature reaches 186 MeV. 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, that is extremely close to the value $T = 175$ MeV obtained in [14]. This important question should be clarified in future studies. We checked 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 volume but does not affect the temperature of the fireball.

Another useful characteristics at the chemical freeze-out are the energy per particle and the entropy per baryon. In [10] the criterion $E/N \approx 1$ GeV was introduced. The predictions of the SM and the TSM for the midrapidity range are as follows: $E/N = 1.1$ GeV, and $S/A = s/r_B = 121$. The last value is about 20% below the value $s/r_B = 150$ predicted by the UrQMD calculations, but the latter are for Au+Au collisions at $\sqrt{s} = 200$ AGeV [17]. It would be interesting to perform these microscopic model calculations also at $\sqrt{s} = 130$ AGeV.

3. Conclusions

In summary, the TSM fit to the experimental data taken at midrapidity at RHIC 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 in the fit, whereas the excluded volume effects seem not to affect the fireball temperature.

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,

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**Table 1.** 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 | Coll. | S1 | S2 | SM |
|------|----|-----|-------|----|----|----|
| $N_B$ (net) | 372$\pm$10 | 371.9 | 372.1 | NA49 | T[MeV] | 175 | 155 | 158 |
| $K^+/K^-$ | 1.85$\pm$0.1 | 1.97 | 1.87 | NA44 | V[fm$^3$] | 7250 | 1705 | 4203 |
| $\bar{p}/p$ | 0.07$\pm$0.01 | 0.069 | 0.058 | NA44 | $N_B$ | 348 | 55 | 408 |
| $\Xi/$ | 0.249$\pm$0.019 | 0.231 | 0.247 | WA97 | $N_B$ | 0 | 30 | 36 |
| $\bar{\Omega}/\Omega$ | 0.383$\pm$0.081 | 0.427 | 0.405 | WA97 | $N_S$ | 34 | 42 | 117 |
| $\Lambda/$ | 0.128$\pm$0.012 | 0.130 | 0.137 | WA97 | $N_S$ | 21 | 55 | 117 |
| $\eta/\pi^0$ | 0.081$\pm$0.013 | 0.133 | 0.108 | WA98 | $\mu_B[MeV]$ | 460 | 45 | 213 |
| $K^0_S/\pi^-$ | 0.125$\pm$0.019 | 0.121 | 0.120 | NA49 | $K^0_S/h^-$ | 0.123$\pm$0.02 | 0.102 | 0.102 | WA97 |
| $\Lambda/h^-$ | 0.077$\pm$0.011 | 0.069 | 0.064 | WA97 | $\Omega/\Xi$ | 0.219$\pm$0.045 | 0.131 | 0.104 | WA97 |
| $\Xi^-/\Lambda$ | 0.110$\pm$0.01 | 0.156 | 0.115 | WA97 | $\chi^2/DOF$ | 46/9 | 16/5 |
both being in local chemical and thermal equilibrium. Temperatures as well as baryon charge and strange charge of the two sources are different.

Strangeness seems to be in equilibrium in both sources. This observation is in line with the fact that $\gamma_S \approx 1$ if one fits the particle ratios from the midrapidity range to the SM, but $\gamma_S < 1$ if one intends to fit $4\pi$-data. A possible explanation for this puzzle is a non-homogeneous distribution of the strange charge within the reaction volume. It would be interesting to study the forthcoming $4\pi$-data on Au+Au collisions at RHIC energies in order to check (i) the increase of the volume of the central fireball w.r.t. the halo; (ii) equilibration of strangeness in both sources; (iii) a possible change of the halo temperature.

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