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Can thermal model explain $\overline{\Lambda}/\overline{p}$ puzzle?

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Abstract The abnormally high antilambda-to-antiproton ratio, which is close to 3.6 for central Au+Au collisions at 11.7 AGeV/c, was reported by the E917 Collaboration. Conventional thermal models and microscopic transport models generally predict that the ratio should be below unity. We show that this large value of the ratio can be reproduced within a two-source statistical model of an ideal hadron gas, which employs non-uniform distribution of net baryon charge and net strangeness within the reaction volume. The two sources are assumed to reach the chemical and thermal equilibrium separately and may have different temperatures, strangeness densities, etc. Other hadron yields and ratios measured for the reaction are reproduced quite well.

Key words ultrarelativistic heavy-ion collisions • statistical model of hadron gas • two-source model (TSM)

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Introduction

The use of statistical concepts to describe particle production in hadronic collisions has an extensive history. Fermi in his famous work [3] postulated the momentary stopping of two colliding hadrons within their overlapping volume, and assumed that due to strong interactions the vacuum boils up and we get a hot system of particles in thermal equilibrium at energy density $\varepsilon_F \sim s$ and temperature $T \sim s^{1/4}$. The particle multiplicity $\langle n \rangle \sim s^{1/4}$ is found to be in a good agreement with the cosmic ray data, but particle composition appeared to be completely wrong (almost three times more protons than pions). Landau [5] accepted the same initial conditions and assumed further that the expansion stage of this hot and dense matter is governed by relativistic hydrodynamics. When the substance cools down to the temperature about pion mass, $T \approx m_\pi$, the liquid decays into the gas of final particles. This model is able to explain various experimental results, such as particle multiplicities, independence of $\langle p_T \rangle$ from incident energy, its magnitude $\langle p_T \rangle \approx m_\pi$, the energy dependence of the multiplicity $\langle n \rangle \sim s^{1/4}$, the great predominance of pions among the produced particles, etc.

Nowadays sufficiently sophisticated statistical thermal models (see, e.g. [7, 8] and references therein) are widely used for the analysis of measured particle yields and energy spectra. They rely on the conventional evolution scenario that a rapidly expanding system experiences two freeze-out stages: the stage of chemical freeze-out, when all inelastic processes have to cease, and the subsequent thermal freeze-out, which occurs when the mean free path of hadrons exceeds the size of the system. Therefore, particle ratios and abundances are employed to reconstruct macroscopic characteristics of the system at chemical freeze-out, whereas the energy spectra are carrying information about the thermal freeze-out stage. Statistical models successfully describe in general the ratios and/or yields of hadron species produced in heavy-ion collisions at incident energies ranging from few GeV/nucleon up to $\sqrt{s} = 200$ AGeV. In this context, the abnormally high value of the ratio $\bar{\Lambda}/\bar{p} \sim 3.6$ measured in central gold-gold collisions at AGS energy [1] remains a puzzling fact. Note that in statistical models this ratio lies below unity. Also, bombarding energy is not high enough to invoke the hypothesis of the quark-gluon plasma (QGP) formation as a reasonable explanation of the antilambda enhancement. The aim of our paper is to show that high values of the $\bar{\Lambda}/\bar{p}$ ratio can be obtained within the so-called two-source model (TSM) proposed some time ago [6]. The basic idea of the TSM is as follows. The two sources, which are in chemical and thermal equilibrium separately, are allowed to have different temperatures as well as baryon and strangeness densities. It is easy to see that in case where chemical potentials and temperatures of the sources are the same, but collective velocities are different, the combined rapidity integrated abundances of hadrons are equal to those of a single static fireball. However, if the net baryon density and net strangeness density are not distributed uniformly within the whole volume of the reaction, the single fireball scenario is not applicable anymore. In the TSM, the expanding system can be well approximated by a hot central source surrounded by the larger and cooler halo. The 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. Except of $\bar{\Lambda}/\bar{p}$ ratio the TSM can explain, e.g., experimentally observed variation of antibaryon to baryon ratio with rising rapidity in the center-of-mass frame and increase of the strangeness suppression factor γ_S for the midrapidity data sample compared to the 4π data. The two-source picture is also in line with the microscopic model calculations [2]. Description of the two-source model is presented in details in the next section.

Two-source model

Since both core and halo are assumed to be in local thermodynamic equilibrium, one needs to know four parameters, e.g., temperature T, volume V, baryon chemical potential μ_B, and strangeness chemical potential μ_S (or, equivalently, energy density ε, volume V, net baryon density ρ_B, and net strangeness density ρ_S) to describe the macroscopic characteristics of each subsystem via a set of grand canonical distribution functions (in units $c = \hbar = k_B = 1$)

$$f(p, m_i) = \left[\exp\left(\frac{E_i - \mu_l}{T}\right) \pm 1\right]^{-1} \tag{1}$$

Here m_i, p, $E_i = \sqrt{p^2 + m_i^2}$, and μ_i are the mass, momentum, energy, and the chemical potential of the hadron species i, respectively. The sign $\pm$ in Eq. (1) is for fermions (bosons).

Compared to standard single-source model the number of free parameters for at least one of the sources increases by one: in the SM the strangeness chemical potential is determined from the requirement of zero net strangeness $N_S = 0$. In the TSM scenario only total net strangeness in both sources must be zero $N_S^{(S1)} + N_S^{(S2)} = 0$, therefore, the net strangeness (density) in one of the sources should be considered as an extra parameter. If the electrochemical potential and isospin chemical potential are disregarded, the chemical potential of the i-th hadrons depends only on the particle baryon B_i and strange S_i charges, $\mu_i = B_i\mu_B + S_i\mu_S$. Then, the particle number density n, the energy density ε, and the pressure P in the system read

$$n = \sum_i n_i = \sum_i \frac{g_i}{(2\pi)^3} \int_0^\infty f(p, m_i)\, d^3p \tag{2}$$

$$\varepsilon = \sum_i E_i = \sum_i \frac{g_i}{(2\pi)^3} \int_0^\infty E_i f(p, m_i)\, d^3p \tag{3}$$

$$P = \sum_i P_i = \sum_i \frac{g_i}{(2\pi)^3} \int_0^\infty \frac{p^2}{3E_i} f(p, m_i)\, d^3p \tag{4}$$

where g_i is the spin-isospin degeneracy. The entropy density s can be determined either via the equation

$$s = \sum_i s_i = -\sum_i \frac{g_i}{(2\pi)^3} \int_0^\infty f(p, m_i)\left[\ln f(p, m_i) - 1\right] d^3p \tag{5}$$

or directly from the Gibbs thermodynamic identity

$$Ts = \varepsilon + P - \mu_B\rho_B - \mu_S\rho_S \tag{6}$$

For convenience, we choose temperatures T_1 and T_2, net baryon densities $\rho_B^{(1)}$ and $\rho_B^{(2)}$, volumes V_1 and V_2, and net strangeness density of the halo $\rho_S^{(1)}$ as free parameters. The maximum likelihood estimate of their values is obtained by minimizing the chi-square quantity

$$\chi^2 = \sum_i \left(\frac{y_{\rm cal} - y_{\rm exp}}{\sigma}\right)_i^2 \tag{7}$$

where $y_{\rm cal}$, $y_{\rm exp}$, and σ are the calculated values (particle yields and ratios), the measured values, and the experimental errors, respectively. To calculate particle yields and macroscopic characteristics of each source, such as temperature, chemical potentials, etc., we employ the SHARE program [7]. Results of the fit to TSM are compared with those of the standard single fireball scenario, provided by the same model. It is important to stress here that only the 4π data were used for the analysis in order to check the TSM ability to reconstruct particle ratios in the middle of the system.

Table 1. Hadron yields and ratios for central heavy-ion collisions at 11.6 AGeV and 40 AGeV, and results of the fit to the two-source and the single-source statistical models of an ideal hadron gas

	Data	TSM	SM
Au+Au 11.6 AGeV			
N_B	363 ± 10	363.6	350.9
π^-/π^+	1.234 ± 0.126	1.21	1.20
	133.7 ± 9.9	132.3	121.5
K^+	23.7 ± 2.9	23.67	27.76
K^-	3.76 ± 0.47	3.77	5.20
Λ	20.34 ± 2.74	20.17	25.00
$\bar{p}$	0.0185 ± 0.002	0.0185	0.0173
Pb+Pb 40 AGeV			
N_B	349 ± 5	351.4	347.9
π^+	282 ± 15	264.9	250.8
K^+	56 ± 3	54.9	60.1
K^-	17.8 ± 0.9	18.8	22.1
Λ	45.6 ± 3.4	35.3	39.6
$\bar{\Lambda}$	0.71 ± 0.07	0.714	0.66

Results

The hadron yields and ratios in central Au+Au collisions at 11.6 AGeV and in central Pb+Pb collisions at 40 AGeV are listed in Table 1 together with the results of the one- and two-source fit. For the sake of simplicity no constraints such as strangeness suppression or excluded volume are assumed. Compared to the one-source model, the TSM improves agreement with the experimental data.

The thermodynamic quantities obtained from the two fits to experimental data are shown in Table 2. One can find the sizable differences in temperature and volume between the two sources. With 150–160 MeV the temperature in source 2 is significantly higher than that of about 100 MeV in source 1. The volume of the hot source is also smaller than the volume of the cooler one. This fact indicates that the two-source object, produced in heavy-ion collisions at incident energies 11.6 AGeV and 40 AGeV, can be interpreted as a hot, relatively small core surrounded by a cooler and larger halo.

The strangeness density is negative in S_2 and positive in S_1. It means that the inner source contains more s quarks than $\bar{s}$ quarks. This finding is supported by microscopic model calculations [2]. From the microscopic point of view, the possible explanation of the phenomenon is as follows: due to the strangeness conservation in strong interactions strange and antistrange particles must be produced in pairs. In a given range of bombarding energies strangeness is mainly carried by kaons and lambdas. Because of the small interaction cross section with hadrons, K^+ and K^0 are leaving the central reaction zone more easily than strange particles which carry s quarks, e.g., Λ and K, thus leading to a negative strangeness density in the midrapidity range. Similar results were obtained in [6], where a bit different SM of an ideal hadron gas was employed.

The main goal now is to get the anticipated ratio $\bar{\Lambda}/\bar{p}$ for the central source and to compare it to the experimental data taken at midrapidity. Note that neither this ratio nor the yields of both antilambdas and antiprotons simultaneously were used in the fitted data sets (see Table 1). Therefore, the $\bar{\Lambda}/\bar{p}$ ratio should be considered as a genuine prediction of the two-source model. The model favors for the core $\bar{\Lambda}/\bar{p} = 4.0$ for 11.6 AGeV (cf. experimental result $3.6^{+4.7}_{-1.8}$ [1]) and $\bar{\Lambda}/\bar{p} = 1.43$ for 40 AGeV (cf. experimental value 1.3 ± 0.2 [4]). To our best knowledge, this is the first time when the extremely large value of the $\bar{\Lambda}/\bar{p}$ ratio is reproduced by the statistical model.

Conclusions

It is shown that the properties of the system, produced in heavy-ion collisions at incident energies below 40 AGeV, 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.

Strangeness seems to be in equilibrium in both sources which is reflected by $\gamma_S \cong 1$ in our calculations. This observation is in line with the fact that there is no need to introduce a strangeness suppression factor into

Table 2. Temperature T, baryon chemical potential μ_B, strangeness chemical potential μ_S, net baryon density, and net strangeness density ρ_S obtained from the statistical model fit to experimental data on A+A collisions at 11.6 AGeV and 40 AGeV. Of each three numbers the upper one corresponds to the single-source model, the middle number to the central core, and the lower one to the halo in the two-source model

Reaction	T [MeV]	μ_B [MeV]	μ_S [MeV]	ρ_B [fm]	ρ_S [fm]
Au+Au, 11.6 AGeV	123 ± 6	558 ± 35	119 ± 21	0.159	0
	147.4 ± 5	470 ± 11	293 ± 4	0.248	–0.22
	91.0 ± 4	577 ± 52	68 ± 36	0.027	0.0009
Pb+Pb, 40 AGeV	146 ± 5	391 ± 31	89 ± 11	0.156	0
	160 ± 4	383 ± 62	148 ± 21	0.269	–0.063
	106 ± 10	449 ± 87	38 ± 70	0.024	0.0025

the standard SM if one fits the particle ratios from the midrapidity range. But the factor $\gamma_S < 1$ arises if one intends to fit 4π data. This feature can be explained by 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.

Large values of the $\bar{\Lambda}/\bar{p}$ ratio, measured near midrapidity, are successfully reproduced for the central sources in the TSM. Again, this puzzling fact is explained merely by the non-uniform distribution of the strangeness and baryon charge within the reaction volume.

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