Chemical freeze-out of strange particles and possible root of strangeness suppression

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Abstract – Two approaches to treat the chemical freeze-out of strange particles in the hadron resonance gas model are analyzed. The first one employs their non-equilibration via the usual \( \gamma_s \) factor and such a model describes the hadron multiplicities measured in nucleus-nucleus collisions at AGS, SPS and RHIC energies with \( \chi^2/\text{dof} \approx 1.15 \). Surprisingly, at low energies we find not the strangeness suppression, but its enhancement. Also we suggest an alternative approach to treat the strange particle freeze-out separately, but with the full chemical equilibration. This approach is based on the conservation laws which allow us to connect the freeze-outs of strange and non-strange hadrons. Within the suggested approach the same set of hadron multiplicities can be described better than within the conventional approach with \( \chi^2/\text{dof} \approx 1.06 \).

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Introduction. – Experimental data on multiplicities in heavy-ion collisions are traditionally described by the Hadron Resonance Gas Model (HRGM) [1–3]. Its core assumption is that the fireball produced in the collision reaches thermal equilibrium. Using this assumption it is possible to describe the hadronic multiplicities registered in experiment with the help of two parameters: the temperature \( T \) and the baryo-chemical potential \( \mu_B \). Parameters \( T \) and \( \mu_B \) obtained from multiplicities fit for different collision energies form the line of chemical freeze-out. In the simplest formulation of the HRGM it is assumed that on this line the inelastic collisions cease simultaneously for all sorts of particles, while to consider the observed deviation of strange particles from the complete chemical equilibrium the additional parameter \( \gamma_s \), the strangeness suppression factor, is introduced [4]. Although the concept of strangeness suppression proved to be important both in collisions of elementary particles [5] and in nucleus-nucleus collisions [5,6] the problem of its justification remains unsolved. Thus, up to now it is unclear what is the main physical reason which is responsible for chemical non-equilibration of strange hadrons, since all hadrons are in thermal equilibrium at chemical freeze-out and the hadrons built up from \( u \) and \( d \) quarks do not exhibit the chemical non-equilibration. Moreover, as pointed out in [2] the fit of hadron multiplicities with the strangeness suppression factor \( \gamma_s \) improves the quality of data description, but still the fit seldom attains a good quality, especially at low collision energies. The apparent failure of the \( \gamma_s \) fit is clearly seen for the ratios of multi-strange baryons \( \Xi \) and \( \Omega \) at the center-of-mass energy \( \sqrt{s_{NN}} = 8.76, 12.3 \) and 17.3 GeV [2]. Since the multi-strange baryons are most sensitive to the deviation from chemical equilibrium of strange quarks, but the \( \gamma_s \) fit does not improve their description sizably, we conclude that there is a different reason for the apparent deviation of strange hadrons from chemical equilibrium.

In contrast to the \( \gamma_s \) concept, here we suggest a modification of HRGM. Instead of a simultaneous chemical freeze-out for all hadrons we consider two different chemical freeze-outs: one for particles, containing strange charge, even hidden (we refer to it as strangeness freeze-out, i.e. SFO) and another one (FO) for all other hadrons which contains only \( u \) and \( d \) (anti)quarks. A partial justification for such a hypothesis is given in [7–9], where...
the early chemical and kinetic FO of Ω hyperons and J/ψ and φ mesons is discussed for the energies at and above the highest SPS energy.

One more important feature of the present approach is that FO and SFO parameters are connected by the conservation laws, namely: entropy conservation, baryon charge conservation, strangeness conservation and isospin projection conservation. These laws impose strong restrictions on the fitting parameters. Due to such restrictions, as we show in the theoretical part, introducing SFO adds only one free parameter for each energy of collision. Therefore, the number of fitting parameters for the SFO is the same as for the usual HRGM with the strangeness suppression factor $\gamma_s$. Another important feature of the present approach is that we employ the HRGM with multicomponent hard-core repulsion [10] which nowadays provides the best fit of hadronic multiplicity ratios [11] and for the first time it correctly reproduces the energy behavior of $K^+$ to $\pi^+$ and $\Lambda$ to $\pi^-$ ratios [3] without spoiling all other hadronic ratios.

Note that a similar idea for a separate strangeness FO was recently suggested in [12], but we point out that the approach presented here is much more elaborate than the one free parameter for each energy of collision. Therefore, the number of fitting parameters for the SFO is the same as for the usual HRGM with the strangeness suppression factor $\gamma_s$. Another important feature of the present approach is that we employ the HRGM with multicomponent hard-core repulsion [10] which nowadays provides the best fit of hadronic multiplicity ratios [11] and for the first time it correctly reproduces the energy behavior of $K^+$ to $\pi^+$ and $\Lambda$ to $\pi^-$ ratios [3] without spoiling all other hadronic ratios.

Note that a similar idea for a separate strangeness FO was recently suggested in [12], but we point out that the approach presented here is much more elaborate than the ideal gas treatment of [12].

A brief description of the model. –

1) $\gamma_s = 1$, no SFO. We consider a multicomponent HRGM, which is currently the best at describing the observed hadronic multiplicities. It is the same model as used in [3]. Hadron interaction is taken into account via hard-core radii, with the different values for pions, kaons, other mesons and baryons. Best-fit values for such radii $R_b = 0.2\text{ fm}$, $R_m = 0.4\text{ fm}$, $R_\pi = 0.1\text{ fm}$, $R_K = 0.38\text{ fm}$ were obtained in [3]. The main equations of the model are listed below, but more details of the model can be found in [3,11].

Consider the Boltzmann gas of $N$ hadron species in a volume $V$ that has the temperature $T$, the baryonic chemical potential $\mu_B$, the strange chemical potential $\mu_S$ and the chemical potential of the isospin third component $\mu_I$. The system pressure $p$ and the $K$-th charge density $n^K_i (i \in \{B,S,I\})$ of the $i$-th hadron sort are given by the expressions

$$
p = \frac{N}{T} \sum_{i=1}^{N} \xi_i, \quad n^K_i = \frac{Q^K_i \xi_i}{1 + \sum_{j=1}^{N} \xi_j}, \quad \xi = \left(\begin{array}{c} \xi_1 \\ \xi_2 \\ \vdots \\ \xi_N \end{array}\right), \quad (1)
$$

where $B$ denotes a symmetric matrix of the second virial coefficients with the elements $b_{ij} = \frac{2}{3} (R_i + R_j)^3$ and the variables $\xi_i$ are the solutions of the following system:

$$
\xi_i = \phi_i(T) \exp \left[ \frac{\mu_i}{T} - \sum_{j=1}^{N} 2\xi_j b_{ij} + \xi^T B \xi \left[ \sum_{j=1}^{N} \xi_j \right]^{-1} \right], \quad (2)
$$

$$
\phi_i(T) = \frac{g_i}{(2\pi)^3} \int \exp \left( -\frac{\sqrt{k^2 + m^2}}{T} \right) d^3 k, \quad (3)
$$

Here the full chemical potential of the $i$-th hadron sort $\mu_i \equiv Q^B_i \mu_B + Q^S_i \mu_S + Q^I_i \mu_I$ is expressed in terms of the corresponding charges $Q^K_i$ and their chemical potentials, $\phi_i(T)$ denotes the thermal particle density of the $i$-th hadron sort of mass $m_i$ and degeneracy $g_i$, and $\xi^T$ denotes the row of variables $\xi_i$. Therefore, the main fitting parameters are the temperature $T$, the baryonic chemical potential $\mu_B$ and the chemical potential of the third projection of isospin $\mu_I$, whereas the strange chemical potential $\mu_S$ is found from the vanishing strangeness condition.

Width correction is taken into account by averaging all expressions containing mass by Breit-Wigner distribution having a threshold. The effect of resonance decay $Y \rightarrow X$ on the final hadronic multiplicity is taken into account as $n_{Xn}(X) = \sum X BR(Y \rightarrow X) n(Y)$, where $BR(Y \rightarrow X) = 1$ for the sake of convenience. The masses, the widths and the strong decay branchings of all hadrons were taken from the particle tables used by the thermodynamic code THERMUS [13].

2) $\gamma_s$ is a fitting parameter. In this case we follow the conventional way of introducing $\gamma_s$ and replace $\phi_i$ in eq. (1) as

$$
\phi_i(T) \rightarrow \phi_i(T) \gamma_s^{s_i}, \quad (4)
$$

where $s_i$ is the number of strange valence quarks plus the number of strange valence antiquarks.

3) SFO. Let us consider two freeze-outs instead of one. The strangeness chemical freeze-out is assumed to occur for all strange particles at the temperature $T_{SFO}$, the baryonic chemical potential $\mu_{B_{SFO}}$, the isospin third projection chemical potential $\mu_{I_{SFO}}$, the three-dimensional space-time extent (effective volume) of the freeze-out hypersurface $V_{SFO}$. The freeze-out of hadrons which are built of the $u$ and $d$ quarks, i.e., FO, is assumed to be described by its own parameters $T_{FO}, \mu_{B_{FO}}, \mu_{I_{FO}}, V_{FO}$. Equations (1)–(3) for FO and SFO remain the same as for a simultaneous FO of all particles. In both cases $\mu_I$ is found from the zero net strangeness condition. The major difference of the SFO is in the conservation laws and the corresponding modification of the resonance decays. Thus, we assume that between two freeze-outs the system is sufficiently dilute and hence its evolution is governed by the continuous hydrodynamic evolution which conserves the entropy. Then equations for the entropy, the baryon charge and the isospin projection conservation connecting two freeze-outs are as follows:

$$
s_{FO} V_{FO} = s_{SFO} V_{SFO}, \quad (5)
$$

$$
n_{B_{FO}} V_{FO} = n_{B_{SFO}} V_{SFO}, \quad (6)
$$

$$
n_{I_{FO}} V_{FO} = n_{I_{SFO}} V_{SFO}. \quad (7)
$$

Getting rid of the effective volumes we obtain

$$
\frac{s}{n_{B_{FO}}} V_{FO} = \frac{s}{n_{B_{SFO}}} V_{SFO}, \quad \frac{n_{B_{FO}}}{n_{I_{FO}}} V_{FO} = \frac{n_{B_{SFO}}}{n_{I_{SFO}}} V_{SFO}. \quad (8)
$$

Therefore, the variables $\mu_{B_{SFO}}$ and $\mu_{I_{SFO}}$ are not free parameters, since they are found from the system (8) and
only $T_{SPO}$ should be fitted. Thus, for SFO the number of independent fitting parameters is the same as in the case of the $\gamma_s$ fit.

The number of resonances contributing due to decays are considered as follows:

$$\frac{N^{fin}(X)}{V_{FO}} = \sum_{Y \in FO} BR(Y \rightarrow X) n^{th}(Y)$$

$$+ \sum_{Y \in SFO} BR(Y \rightarrow X) n^{th}(Y) \frac{V_{SFO}}{V_{FO}}.$$ (9)

Technically this is done by multiplying all the thermal concentrations for SFO by $n_{fit}^{SFO}/n_{SFO}^{SFO} = V_{SFO}/V_{FO}$ and applying the conventional resonance decays.

Results.

Data sets and fit procedure. In our choice of the data sets we basically followed ref. [2]. Thus, at the AGS energy range of collisions ($\sqrt{s_{NN}} = 2.7$–$4.9$ GeV) the data are available for the kinetic beam energies from 2 to 10.7 AGeV. For the beam energies 2, 4, 6 and 8 AGeV there are only a few data points available: the yields for pions [14,15], for protons [16,17], for kaons [15] (except for 2 AGeV), for $\Lambda$ hyperons the integrated over $4\pi$ data are available [18]. For the beam energy 6 AGeV there exist the $\Xi^-$ hyperon data integrated over $4\pi$ geometry [19]. However, the data for the $\Lambda$ and $\Xi^-$ hyperons have to be corrected [2], and instead of the raw experimental data we used their corrected values of ref. [2]. For the highest AGS center-of-mass energy $\sqrt{s_{NN}} = 4.9$ GeV (or the beam energy 10.7 AGeV) in addition to the mentioned data for pions, (anti)protons and kaons there exist data for the $\phi$ meson [20], the $\Lambda$ hyperon [21] and the $\bar{\Lambda}$ hyperon [22]. Similarly to [3], here we analyzed only the NA49 mid-rapidity data [23–28]. Since the RHIC high-energy data of different collaborations agree with each other, we analyzed the STAR results for $\sqrt{s_{NN}} = 9.2$ GeV [29], $\sqrt{s_{NN}} = 62.4$ GeV [30], $\sqrt{s_{NN}} = 130$ GeV [31–34] and 200 GeV [34–36]. To simplify the numerical efforts and to avoid considering the effective volumes we fit particle ratios rather than the multiplicities. The best-fit criterion is a minimality of $\chi^2 = \sum_i \frac{(r_i^{\text{exp}} - r_i^{\text{theor}})^2}{\sigma_i^2}$, where $r_i^{\text{exp}}$ is an experimental value of the $i$-th particle ratio, $r_i^{\text{theor}}$ is our prediction and $\sigma_i$ is a total error of experimental value.

Fit with $\gamma_s$. The inclusion of $\gamma_s$ is expected to improve the description of ratios containing the strange particles. It may also give room in parameter space that will ultimately lead to improvement of ratios that contain no strange particles. In our investigation we pay a special attention to the $K^+/\pi^+$ ratio, because it is usually considered as the most problematic one for HRGM.

The behavior of fit parameters is shown in fig. 1 for $T$, $\mu_B$ and $\gamma_s$. The obtained values of the chemical FO temperatures and baryo-chemical potentials in the case with the $\gamma_s$ fit do not considerably differ from the case when $\gamma_s = 1$, while the behavior of $\gamma_s(\sqrt{s_{NN}})$ demonstrates entirely new results. Thus, at low energies for the $\gamma_s$ fit we found not a suppression, but a strangeness enhancement, i.e. $\gamma_s > 1$. These findings are in a drastic contrast to the results of the statistical hadronization model [5] for the fit of hadronic multiplicities, measured in nuclear collisions. The $\gamma_s$ values reported in [5] demonstrate a suppression, i.e. $\gamma_s < 1$, for all ASG and SPS energies. We, however, note that the fit quality of hadronic multiplicities reported in [5] is essentially worse, compared even to the present model without $\gamma_s$ fit, and, therefore, one cannot rely on the statistical hadronization model conclusions on the $\gamma_s$ values.

For 14 values of the collision energy $\sqrt{s_{NN}} = 2.7$, 3.3, 3.8, 4.3, 4.9, 6.3, 7.6, 8.8, 9.2, 12, 17, 62.4, 130, 200 GeV the best description with the $\gamma_s$ fit gives $\chi^2/\text{dof} = 63.4/55 = 1.15$, which is only a very slight improvement compared to the results $\chi^2/\text{dof} = 80.5/69 = 1.16$ found for a single chemical freeze-out with $\gamma_s = 1$. Note, however, that the value of $\chi^2$ itself, not divided by number of degrees of freedom, has improved notably. This fact motivates us to study which ratios are improved.
Fig. 2: (Colour on-line) Relative deviation of the theoretical description of ratios from the experimental value in units of the experimental error $\sigma$. The symbols on the OX-axis demonstrate the particle ratios. The OY-axis shows $|r_{\text{theor}} - r_{\text{exp}}|/\sigma_{\text{exp}}$, i.e. the modulus of relative deviation for $\sqrt{s_{NN}} = 6.3$, 12 and 17 GeV. Solid lines correspond to the model with a single FO of all hadrons and $\gamma_s = 1$, while the dashed lines correspond to the model with the $\gamma_s$ fit.

Fig. 3: (Colour on-line) Description of $K^+/\pi^+$ ratio. The solid line is the result of [3]. Crosses stand for the case with $\gamma_s$ fitted, while the horizontal bars correspond to SFO.

At AGS energies $\sqrt{s_{NN}} = 2.7$, 3.3, 3.8 and 4.3 GeV the number of available ratios is small (4, 5, 5, 5, respectively) and only kaons and $\Lambda$ contain strange quarks. Since the data description is rather good even within the ideal gas model [2], the inclusion of $\gamma_s$ into a fit does improve the fit quality, but it leads to the vast minima in the parameter space and large errors of $\gamma_s$. Moreover, at low energies the fit is unstable: two local minima with very close $\chi^2$ are often found. For instance, for $\sqrt{s_{NN}} = 3.8$ GeV we find $\gamma_s \simeq 1.6$ in the deepest minimum, while in another minimum, next to the deepest one, $\gamma_s \simeq 0.8$. An existence of two local minima with close values of $\chi^2$ at $\sqrt{s_{NN}} = 2.7 - 4.3$ GeV tells us that the $\gamma_s$ concept has to be improved further in order to resolve this problem.

At $\sqrt{s_{NN}} = 4.9$ GeV $\gamma_s$ does not improve ratios description, but its behavior is stable and hence $\gamma_s = 1$ within the error bars. At $\sqrt{s_{NN}} = 6.3 - 12$ GeV $K^+/\pi^+$ ratio is notably improved, while the description of other ones has improved only slightly or even became worse (see the typical examples in the upper and middle panels of fig. 2). At $\sqrt{s_{NN}} \geq 17$ GeV energies there is no special improvement. Conclusively, fitting $\gamma_s$ provides an opportunity to improve the strangeness horn description to $\chi^2/dof = 3.3/14$, i.e. better than it was done in [3] with $\chi^2/dof = 7.5/14$. The strangeness horn itself is shown in fig. 3. We would like to stress that even the highest point of the Horn is reproduced now, that makes our theoretical horn as sharp as an experimental one. However, the overall $\chi^2/dof \simeq 1.15$ obtained for the $\gamma_s$ fit is only slightly better compared to the result $\chi^2/dof \simeq 1.16$ found in [3]. Moreover, the $\gamma_s$ fit does not essentially improve the ratios with strange baryons and, hence, we consider an alternative approach.

Fit with SFO and no $\gamma_s$. In this case $\gamma_s = 1$ is fixed for all energies, but FO and SFO parameters are connected by conservation laws (8). Therefore for SFO at each collision energy there is only one fitting parameter, namely $T_{SFO}$. 
Strange particles freeze-out

Fig. 4: (Colour on-line) Parameters of chemical freeze-outs in the model with two freeze-outs. Upper panel: triangles correspond to SFO, their coordinates are \((\mu_{B,SFO} , T_{SFO})\), while circles correspond to FO and their coordinates are \((\mu_{B,FO} , T_{FO})\). The curves correspond to isentropic trajectories \(s/\rho_B = \text{const}\) connecting the two freeze-outs. Lower panel: \(\sqrt{s_{NN}}\) dependence of the ratio of SFO temperature to FO temperature.

while other parameters are found from the system \((8)\). Like in the previous case we study two things: behavior of parameters and what ratios are improved. First of all, we found out that for the SFO case \(\chi^2/\text{dof} = 58.5/55 \simeq 1.06\), which means that the \(\chi^2/\text{dof}\) improvement due to the SFO introduction (global \(\chi^2/\text{dof} : 1.16 \to 1.06\)) is better than its improvement due to \(\gamma_s\) fitting (global \(\chi^2/\text{dof} : 1.16 \to 1.15\)). For low energies the situation is similar to the previous case. At \(\sqrt{s_{NN}} = 2.7, 3.3, 3.8, 4.3\) and \(4.9\) GeV the original description obtained within the multicomponent model \([3]\) is very good and hence it is not improved significantly, but, at least, it is not worse than the description obtained by the \(\gamma_s\) fit. Similar results are found at highest RHIC energies \(\sqrt{s_{NN}} > 62.4\) GeV. From fig. 4 one can clearly see that within these two energy domains the SFO

Fig. 5: (Colour on-line) The same as in fig. 2. Solid lines correspond to the model without SFO and \(\gamma_s = 1\), dashed lines correspond to the model with SFO.

22002-p5
Due to the SFO fit the six out of seven problematic ratios improve the fit quality. Figure 5 clearly demonstrates that improves all the ratios with more than one σ deviation. For \( \sqrt{s_{NN}} = 6.3 \) GeV the SFO greatly improves \( \Lambda/\pi^- \) and \( \bar{p}/p \) ratios. For \( \sqrt{s_{NN}} = 12 \) GeV four ratios out of eight with more than one σ deviation, namely \( K^+/\pi^+, \Lambda/\Lambda, \Lambda/\pi^- \) and \( \Xi^+/\Xi^- \) are sizably improved. The data measured at \( \sqrt{s_{NN}} = 17 \) GeV were not improved by the γs fit at all, while the SFO approach allows us to greatly improve the fit quality. Figure 5 clearly demonstrates that due to the SFO fit the six out of seven problematic ratios of the γs = 1 fit moved from the region of deviation exceeding σ to the region of deviations being smaller than σ. The most remarkable of them are \( \bar{p}/\pi^-, \Lambda/\Lambda, \Xi^-/\Xi^- \) and \( \Omega/\Omega \). Thus, a separation of FO and SFO relaxes the strong connection between the non-strange and strange baryons and allows us for the first time not only to correctly describe the ratios of strange antibaryons to the same strange baryons, but also it allows us to successfully reproduce the antiproton to pion ratio. As is seen from fig. 3 the SFO fit quality is worse compared to the strangeness horn fit by γs, but overall it is very good with \( \chi^2/d\sigma = 6.3/14 \).

Conclusions. – In this paper we performed a high-quality fit of the hadronic multiplicity ratios measured at AGS, SPS and RHIC energies. In contrast to earlier beliefs established on the low-quality fit [5], we find that within the error bars in heavy-ion collisions there is a sizable enhancement of strangeness, i.e. \( \gamma_s > 1 \), at \( \sqrt{s_{NN}} = 2.7, 3.3, 3.8, 4.9, 6.3, 9.2 \) GeV. However, the effect of apparent strangeness enhancement can be successfully explained by the approach of separate chemical freeze-out of all strange hadrons. This approach is based on two traditional assumptions, i.e. the assumption of local chemical equilibrium of non-strange and strange hadrons and the assumption of isentropic expansion between FO and SFO. Our analysis shows that for the same number of fitting parameters the SFO approach is working not worse than the γs approach, but for \( \sqrt{s_{NN}} = 6.3 \), 12 and 17 GeV it tremendously improves the fit quality. At these energies we see that \( \bar{p}/\pi^-, \Lambda/\Lambda, \Xi^-/\Xi^- \) and \( \Omega/\Omega \) ratios are much better described than within the γs approach, since a separation of FO and SFO relaxes the strong connection between the non-strange and strange baryons. These results allow us to conclude that an apparent strangeness enhancement is due to the separate strangeness chemical freeze-out.

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