

Transverse-momentum spectra of strange particles produced in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV in the chemical non-equilibrium model

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Abstract. It is first shown that recent problems in heavy-ion collisions at the LHC energies, connected with thermal description of the proton yield and the pion spectra at low transverse-momenta, can be simultaneously explained within a chemical non-equilibrium statistical hadronization framework. Then the predictions of this approach for the production of strange particles are presented.

1. Introduction

Statistical hadronization model (SHM) of hadron production has become one of the cornerstones of our understanding of ultra relativistic heavy-ion collisions and also of more elementary hadronic processes including e^+e^- annihilation. In this situation, the data from the Large Hadron Collider (LHC) collected in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV came as a big surprise: the measured proton abundances do not agree with the most common version of the thermal model based on the grand-canonical ensemble [1, 2]. Possible explanations of this situation refer, for example, to hadronic rescattering present in the final stage [3] or to hadronization and subsequent freeze-out taking place off chemical equilibrium [4, 5]. The latter approach will be denoted below as NEQ SHM in contrast to the standard thermal framework to which we refer as to EQ SHM.

Besides the proton anomaly, the same LHC data exhibits another interesting feature, namely, the low-transverse-momentum pion spectra show enhancement by about 25%-50% with respect to the predictions of various thermal and hydrodynamic models. It turns out that the two problems may be solved simultaneously within the chemical non-equilibrium model. In this conference proceedings I review some of the findings which lead to this conclusion and present the NEQ SHM results for the strange particles [6, 7, 8].

2. Model assumptions

In this work I use the single-freeze out model [10, 11, 12] in the Monte-Carlo implementation given by the THERMINATOR code [13, 14]. The hadron spectra are calculated from the Cooper-Frye formula

$$\frac{dN}{dyd^2p_T} = \int d\Sigma_\mu p^\mu f(p \cdot u), \quad (1)$$

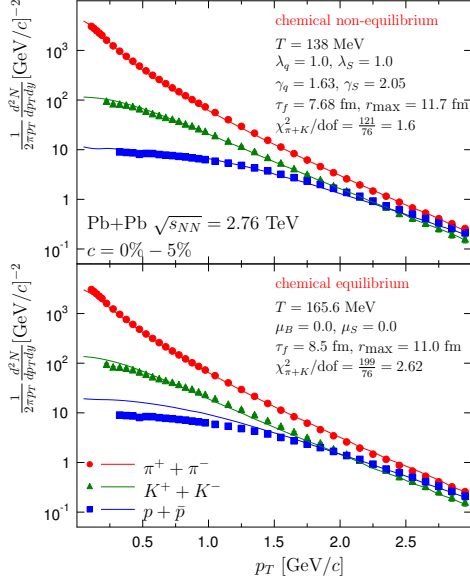


Figure 1. Comparison of the ALICE data [9] with the predictions of NEQ SHM and EQ SHM models.

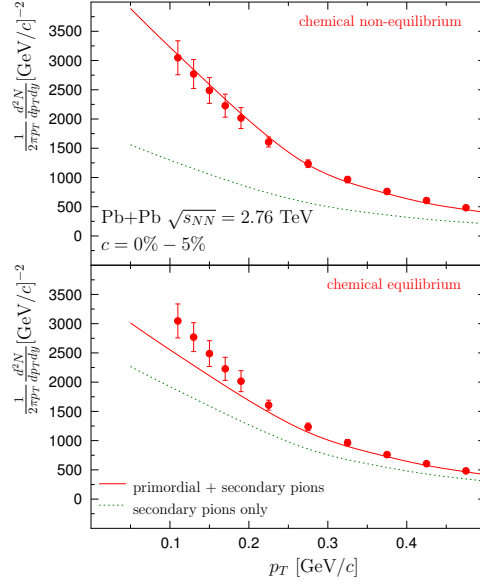


Figure 2. Same as Fig. 1 but with a linear vertical scale and low p_T region.

where the freeze-out hyper-surface is defined by the conditions

$$t^2 = \tau_f^2 + x^2 + y^2 + z^2, \quad x^2 + y^2 \leq r_{\max}^2. \quad (2)$$

The hydrodynamic flow at freeze-out has the Hubble form $u^\mu = x^\mu / \tau_f$.

There are only two independent parameters in the model: the product $\pi\tau_f r_{\max}^2$ that defines the volume (per unit rapidity), and the ratio r_{\max}/τ_f that determines the shape (slope) of the spectra for a given centrality class. The phase-space distributions include all well established resonances from PDG. The primordial distributions in the local rest frame have the form

$$f_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\Upsilon_i^{-1} \exp(\sqrt{m^2 + p^2}/T) \pm 1}, \quad (3)$$

where the parameterization of the fugacity Υ_i is defined as in SHARE [15]

$$\Upsilon_i = (\lambda_q \gamma_q)^{N_q^i} (\lambda_s \gamma_s)^{N_s^i} (\lambda_{\bar{q}} \gamma_{\bar{q}})^{N_{\bar{q}}^i} (\lambda_{\bar{s}} \gamma_{\bar{s}})^{N_{\bar{s}}^i}. \quad (4)$$

Here $\lambda_q = \lambda_{\bar{q}}^{-1}$, $\lambda_s = \lambda_{\bar{s}}^{-1}$, $\gamma_q = \gamma_{\bar{q}}$, $\gamma_s = \gamma_{\bar{s}}$, and N_q^i and N_s^i are the numbers of light (u, d) and strange (s) quarks in the i th hadron, while $N_{\bar{q}}^i$ and $N_{\bar{s}}^i$ are the numbers of the antiquarks in the same hadron. Using the Gell-Mann–Nishijima formulas one finds $\lambda_q = \exp(\mu_B/3T)$ and $\lambda_s = \exp((-3\mu_S + \mu_B)/3T)$, which gives

$$\Upsilon_i = \gamma_q^{N_q^i + N_{\bar{q}}^i} \gamma_s^{N_s^i + N_{\bar{s}}^i} \exp\left(\frac{\mu_B B_i + \mu_S S_i}{T}\right), \quad (5)$$

where B_i and S_i are the baryon number and strangeness of the i th hadron. At the LHC, in the central rapidity region the baryon number density and strangeness are negligible, hence

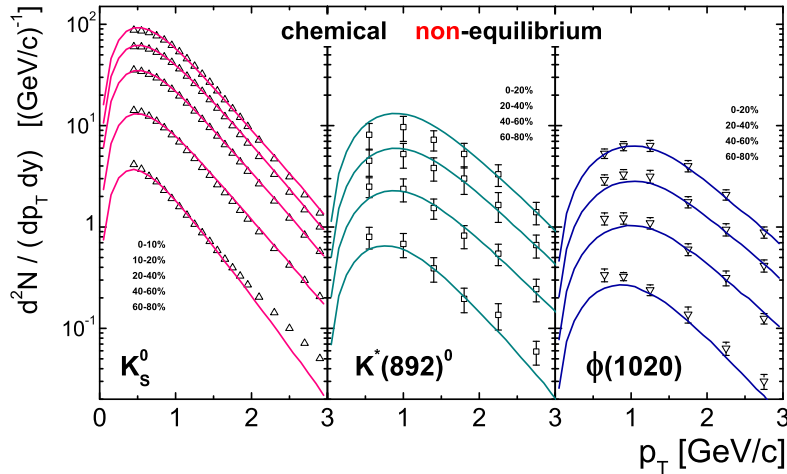


Figure 3. NEQ SHM predictions for K_S , $K^*(892)$, and ϕ , compared with the data from [16, 17].

the baryon and strangeness chemical potentials can be set equal to zero, $\mu_B \approx \mu_S \approx 0$. The parameters γ_q and γ_s are equivalent to the chemical potentials $\mu_q/T = \ln \gamma_q$ and $\mu_s/T = \ln \gamma_s$

$$\Upsilon_i \approx = \exp \left(\frac{\mu_q (N_q^i + N_{\bar{q}}^i) + \mu_s (N_s^i + N_{\bar{s}}^i)}{T} \right)$$

The new potentials are connected with the conservation of the sum of the number of quarks and antiquarks during the hadronization process, similarly as μ_B and μ_S are connected with the conservation of the difference of the quark and antiquark numbers. The introduction of such chemical potentials make sense if the hadronization process is fast and there is no significant volume expansion during this process [4, 5]. There exist also hints for a non-zero value of μ_q found in the scenario presented in Ref. [18].

3. Results

In Fig. 1 we show our results for the spectra of pions, kaons, and protons for central Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. In the upper panel we show the results for the chemical non-equilibrium model (NEQ SHM), whereas in the lower panel the spectra are shown for the chemical equilibrium scenario (EQ SHM). The thermodynamic parameters are taken from [5]: $T=138$ MeV, $\gamma_q=1.63$, $\gamma_s=2.05$. The fit of the spectra gives: $\tau_f=7.68$ fm and $r_{\max}=11.7$ fm. Correspondingly, for EQ SHM we use: $T=165.6$ MeV, $\tau_f=8.5$ fm and $r_{\max}=11$ fm. We observe that the chemical non-equilibrium model gives much better description of the ALICE data [9], especially for protons and in the low p_T region for pions. This is seen also more clearly in Fig. 2, where a linear scale is used.

Having fixed the model parameters with the spectra of pions, kaons and protons (for each accessible centrality bin), we can calculate the spectra of other hadrons. Fig. 3 shows the spectra of K_S , $K^*(892)$, and ϕ for various centrality selections. We find very good agreement between the model predictions and the data [16, 17]. This is quite interesting since $K^*(892)$ and ϕ have very different mean free paths in the medium. The fact that the spectra of these two particles are well reproduced by our framework supports the idea of a single freeze-out. Finally, in Fig. 4 we show the model spectra of hyperons and the data [16, 19]. The spectra of Λ are rather well reproduced for central collisions. We note that the model description can be further improved

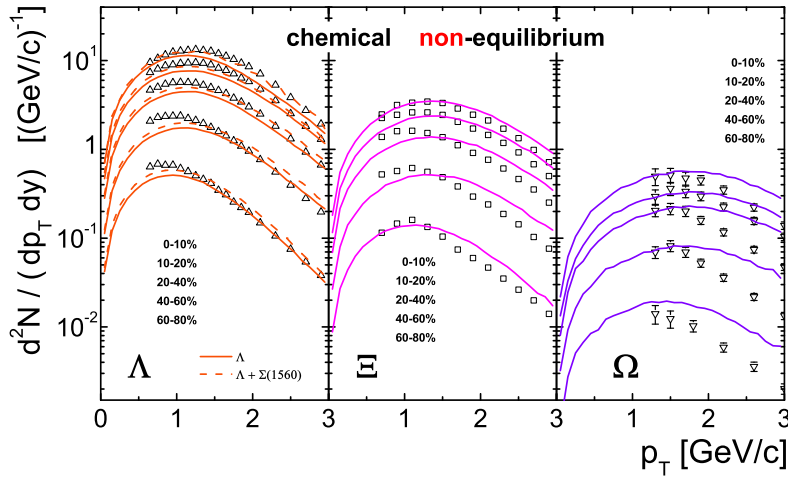


Figure 4. NEQ SHM model predictions for hyperons, compared with the data from [16, 19].

if the decay of $\Sigma(1560)$ is included. The spectra of Ξ and Ω are rather well described for the lowest measured values of p_T .

4. Conclusions

The non-equilibrium thermal model combined with the single-freeze-out scenario explains very well the spectra of pions, kaons, and protons. In particular, it explains the proton anomaly and the low- p_T enhancement of pions. With the parameters fixed by such fits, the NEQ SHM model gives also a rather good description of the strange hadron production (except for Ξ 's and Ω 's with large p_T). This work was supported by Polish National Science Center Grant DEC-2012/06/A/ST2/00390.

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