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HADRONISATION OF QUARK-GLUON PLASMA*

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Abstract

An analysis of particle production in heavy ion collisions within a thermal fireball model is performed. It is shown that presently available data on S-A collisions suggest two freeze-out stages with different thermal parameters for strange and non-strange particles. The assumption of non-complete strangeness saturation is also required in order to get an agreement of a thermal model with experimental data.

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Recent experiments with relativistic heavy ion collisions have shown a substantial enhancement in production of strange particles [1]. This result indicates that for a short time after heavy nuclei collisions one deals with very high density hadronic matter which can not be excluded to appear in deconfined, quark-gluon plasma phase. The initially produced matter will expand and break up into observable hadrons. Different evolution scenarios of hadronic system into finally measured particles can be studied. One possible scenario is an evolution in which the system after some short time thermalizes and remains in thermal equilibrium until the ultimately produced hadrons stop interacting [2]. In this case, no matter what the nature of the early stages of the produced matter was, the observed hadrons will reflect the properties of the last thermal state before freeze-out, the *equilibrium hadron gas*. However, it is not excluded that the system expands too rapidly to retain equilibrium during the entire history. Here, a particularly interesting alternative is the scenario of the sudden disintegration of a quark-gluon plasma into the final observed hadrons without ever going through equilibrium hadron gas phase. In this case it is in principle possible that hadrons will carry some relic information on quark-gluon plasma properties and parameters [2,3].

In the following we present the *thermal hadron gas* model interpretation of total particle multiplicity produced in S-A collisions at 200 A GeV energy [4]. As a basis we will use recent available data of WA-85 collaboration on strange baryon and anti-baryon production measured in S-W collisions [5].

Particle production rates in thermal model are given in terms of the three parameters necessary to specify the state of an equilibrium hadron gas, i.e., the temperature T , the baryon chemical potential μ_B , and the strangeness chemical potentials μ_S . The requirement of vanishing overall strangeness eliminates one of these parameters, e.g., μ_S and then the rates are fully determined by T and μ_B . The partition function, describing equation of state of hadronic matter can be also simplified. Close to freeze-out, particles are almost not interacting, thus the free-energy can be approximated by the sum of single-particle partition functions as follows [2]:

$$\ln Z(T, \mu_B, \mu_S) = \sum_{i=1}^N \left[W_i^m + \left(\lambda_B^{-B_i} \lambda_S^{S_i} + \lambda_B^{B_i} \lambda_S^{-S_i} \right) W_i \right]. \quad 1.1$$

Here the first term corresponds to non-strange mesons whereas the second term to strange meson and baryon contributions carrying baryon number B_i and strangeness S_i . The fugacity for the baryon number and for the strangeness is defined as $\lambda_B \equiv \exp(\mu_B/T)$ and $\lambda_S \equiv \exp(\mu_S/T)$ respectively. The phase space factors W_i for the various hadron species, have the form

$$W_i = \frac{d_i}{2\pi^2} \frac{V}{T} \frac{m_i^2}{K_2} \left(\frac{m_i}{T} \right), \quad 1.2$$

where d_i denotes the degeneracy of hadron state i , m_i its mass and V the volume of the system. In the sum in (1.1) we have included all particles and resonances listed in Particle Data Tables up to mass 2 GeV. The particle multiplicity N_i calculated from (1.1) is a sum of two contributions i.e., $N_i = W_i + \sum_j \Gamma_{ij} W_j$ where the first term corresponds to thermal and the second to resonance contributions with Γ_{ij} being the resonance decay branching ratio. The particle multiplicity ratio depends on T and μ_B .

These parameters can be fixed from two experimentally measured ratios. All the others are considered then as the predictions of the model.

The data [5] provide the ratios $\bar{\Lambda}/\Lambda = 0.2 \pm 0.01$ and $\bar{\Xi}/\Xi = 0.45 \pm 0.05$. Each of them leads to a band in the $T - \mu_B$ plane. The result is shown in fig.1, where we see that the two bands cross in the small region where $0.18 < T < 0.2$ and $0.2 < \mu_B < 0.28$. In fig.1 we also impose lines corresponding to the measured ratios $\bar{\Xi}/\bar{\Lambda} = 0.21 \pm 0.02$ and $\Xi/\Lambda = 0.095 \pm 0.0062$ [5].** As evidently seen in fig.1 these ratios can not be explained within the same set of parameters as required for $\bar{\Xi}/\bar{\Lambda}$ and $\bar{\Lambda}/\Lambda$. In the comparison of a thermal model with WA85 experiment we have assumed, however, a complete chemical equilibrium for strangeness production. As it was shown in [6] the time needed for saturation of the strange phase space in a hadron gas can be much longer than the typical lifetime of a thermal fireball. In order to account for the degree of chemical equilibrium in a hadron gas we include the additional strangeness saturation parameter γ_S in the model (1.1) by multiplying λ_S and λ_S^{-1} by constant factor γ_S [7]. The value of $\gamma_S < 1$ is to be expected in a hadron gas fireball [7]. In fig.2 the results on $\bar{\Xi}/\bar{\Lambda}$ and Ξ/Λ ratio are shown with $\gamma_S \sim 0.7$. Indeed, with this additional parameter the thermal model is consistent with all WA85 data. We should *note*, however, that this agreement is not sufficient to justify the validity of the model as we have reproduced *three* measured ratios by *three* parameters. As there is no more kinematically compatible data for particle production in S-W collisions we continue considering the results of NA35 [8] and EMU05 [3] collaborations on S-Ag and S-Pb collisions respectively. Although Ag is a significantly smaller target than W, nevertheless, we consider both of these experiments to belong to the same class.

The value of T and μ_B determined from WA85 experiment gives a good agreement with the result $K_S^0/\Lambda \simeq 1.22 \pm 0.5^*$ and $(K^+/\bar{K}^-)^{y \sim 2.3} \simeq 1.53 \pm 0.5$ in S-Ag collisions. In order to get an independent test on the value of the degree of strangeness saturation parameter γ_S we consider Λ/p ratio. The result $\Lambda/(p - \bar{p}) \simeq 0.57 \pm 0.18^*$ in S-Ag collisions is not compatible with the value $\gamma_S \simeq 0.7$. It would rather require strangeness phase space to be completely saturated, that is $\gamma_S \sim 1$. A further problem appears when one compares the entropy per baryon (S/B) ratio, measured in the final state particle multiplicity, with the result of the model. From EMU05, we have data on the ratio $D_Q \equiv (h^+ - h^-)/(h^+ + h^-) = 0.088 \pm 0.07$ from S-Pb interactions at rapidity interval $2.3 < y < 3.0$. The charge particle asymmetry parameter D_Q was shown [3] to be related with S/B as follows: $S/B \sim 4.5 D_Q^{-1}$. The S/B ratio in a hadron gas is shown in fig.3 for several different T . We note that in the range $0.2 < \mu_B < 0.28$ GeV and at $T = 0.18$ GeV, required to reproduce WA85 data, $S/B \sim 30$ which is lower than the measured result $S/B \sim 50$. This, would require temperature $0.11 < T < 0.14$ as seen in fig.3. We thus deduce that *different freeze-out temperatures* for strange and non-strange particles are required. The sequential freeze-out has immediate other observable consequences. It implies different freeze-out radii for kaons, R_K and pions R_π . Indeed, the interferometry experiment NA44 for S-Pb collisions measured $R_K < R_\pi$ [9]. From mean free path arguments [2], assuming the ratio of strange to non-strange particle cross-sections to be 0.5, one gets $R_K/R_\pi \sim 0.7$ which is in a good agreement with NA44 results [9]. For an isentropic expansion the freeze-out radius is inversely

**In figs.(1.2) the data for $\bar{\Xi}/\bar{\Lambda}$ and Ξ/Λ were corrected for p_t cut by the factor 0.86.

*The quoted value was obtained from dN_t/dy distributions [8] for $2.3 < y < 3.0$.

proportional to the freeze-out temperature. Thus, with $0.18 < T_K < 0.2$ from the fit to WA85 data, one gets $0.12 < T_\pi < 0.14$ GeV as the freeze-out temperature for non-strange particles. This is just the temperature range required to reproduce the final S/B measured value in EMU05 experiment. In fig.4 we show the band in $T - \mu_B$ plane calculated for $(p - \bar{p})/h^- \simeq 0.16 \pm 0.015^*$ and for D_Q as measured in S-Ag and S-Pb collisions respectively. As seen in fig.4 both of these experimental results are reproduced with almost the same set of thermal parameters. For T_π quoted above, one gets from fig.4, $0.2 < \mu_B < 0.27$ as the corresponding baryonic chemical potential at the non-strange particles freeze-out.

We compared hadron production rates in a thermal fireball model with some of presently available data on particle production in S-A collisions. We showed that the results on strange particle multiplicity ratios measured in WA85 for S-W and NA35 for S-Ag collisions require a freeze-out temperature $0.18 < T < 0.2$ and baryon chemical potential $0.2 < \mu_B < 0.28$. Strangeness is also found to be $\sim 30\%$ below a complete chemical equilibrium value. Pion, nucleon and non-strange meson production seem to require a considerable lower freeze-out temperature $0.12 < T < 0.14$ but almost the same baryon chemical potential $0.2 < \mu_B < 0.27$. In the hadron gas picture, it is in accord with the difference in mean free paths of the different hadrons in the medium: it suggests a sequential freeze-out, in which strange hadrons stop interacting earlier than non-strange particles [2].

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Fig. 1

Fig. 2

Fig. 3

Fig. 4