In-Medium Modifications of Hadron Masses and Chemical Freeze-Out in Ultra-Relativistic Heavy-Ion Collisions *

Wojciech Florkowski and Wojciech Broniowski

H. Niewodniczański Institute of Nuclear Physics, ul. Radzikowskiego 152, PL-31342 Kraków, Poland

Abstract

We confront the hypothesis of chemical freeze-out in ultra-relativistic heavy-ion collisions with the hypothesis of large modifications of hadron masses in nuclear medium. We find that the thermal-model predictions for the ratios of particle multiplicities are sensitive to the values of in-medium hadronic masses. In particular, the $\pi^+/p$ ratio decreases by 35% when the masses of all hadrons (except for pseudo-Goldstone bosons) are scaled down by 30%.

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Recent theoretical studies [1,2] indicate that hadron yields and ratios in ultra-relativistic heavy-ion collisions agree with predictions of a simple thermal model. According to this model all measured abundances of hadrons are consistent with the assumption of complete thermalization of hadronic matter at a temperature $T_{\text{chem}}$, baryon chemical potential $\mu^B_{\text{chem}}$, strangeness chemical potential $\mu^S_{\text{chem}}$, and isospin chemical potential $\mu^I_{\text{chem}}$. Thermodynamic parameters obtained from this type of analysis characterize the point in the evolution of the system when “primordial” hadron content is established. One refers to this point as to the chemical freeze-out. At this stage the system is a mixture of stable particles (pions, kaons, nucleons,...) and resonances ($\rho$, $\omega$, $\Delta$, ...). In the subsequent evolution the resonances decay, contributing to the final (observed) multiplicities of stable particles.

It has been shown that the chemical freeze-out parameters at CERN/SPS, BNL/AGS and GSI/SIS energies all correspond to a unique value of the energy per hadron [3]. Moreover, statistical models [4] are able to reproduce

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the particle yields in $e^+e^-$ collisions. A striking observation is that at very high energies the temperature $T_{\text{chem}} \sim 170\text{MeV}$ turns out to be the same for both elementary and nuclear collisions, although the final-state hadronic interactions are completely absent in the former case. This may indicate that chemical equilibrium is pre-established by the hadronization process [4–6].

In recent studies one distinguishes the chemical freeze-out from the thermal or kinetic freeze-out [5]. The latter is defined as the decoupling of strongly interacting matter produced in high-energy nuclear collisions into a system of essentially free-streaming particles. After the thermal freeze-out the hadrons practically stop to interact and travel freely to detectors. Chemical freeze-out is expected to occur at the same time or before the thermal freeze-out [5]. For Pb+Pb collisions at CERN/SPS energies one finds that the chemical freeze-out point occurs significantly earlier than the thermal point. This is indicated by the measurements of the hadron momentum spectra as well as two-particle momentum correlations [7], which show that the thermal freeze-out temperature $T_{\text{therm}} \sim 100\text{ MeV}$ is substantially lower than $T_{\text{chem}} \sim 170\text{ MeV}$. In addition, $T_{\text{chem}}$ is very close to the expected critical value for the deconfinement/hadronization phase transition, therefore the chemical composition of a hadronic system, according to the presented scenario, should be established shortly after hadronization.

Since the chemical freeze-out occurs at an early stage of the evolution of the system, where temperatures and densities are very high, we expect that hadronic properties, such as masses, widths, or coupling constants are influenced strongly by the medium. Such modifications are predicted in many theoretical calculations [8–11]. Moreover, they seem much desired [12,13] in view of the low-mass dilepton enhancement observed in the CERES [14] and HELIOS [15] experiments.

In order to study how the chemical freeze-out parameters are affected by the in-medium change of the hadron masses, we calculate the particle densities from the standard ideal-gas equilibrium expression

$$n_i = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i^* - \mu_{\text{chem}}^B B_i - \mu_{\text{chem}}^S S_i - \mu_{\text{chem}}^I I_i)/T_{\text{chem}}] \pm 1}, \quad (1)$$

where $g_i$ is the spin degeneracy factor of the $i$th hadron, $B_i, S_i, I_i$ are its baryon number, strangeness, and the third component of isospin, and $E_i^* = \sqrt{p^2 + (m_i^*)^2}$ is its energy. The latter explicitly depends on the in-medium hadron mass $m_i^*$.

In the thermal-model fits [1,2] one uses Eq. (1) with vacuum values of hadron masses $m_i^* = m_i$, and, in addition, applies finite–size and excluded–volume
corrections. They account for the finite size of the nuclear system and the finite volume occupied by the individual hadrons. The main effect of such corrections is a reduction of the absolute yields of particles with the particle ratios remaining close to predictions of the ideal-gas approach [2]. For Pb+Pb collisions at CERN/SPS energies the predictions of the thermal model are [2]:

\[ T_{chem} = 168 \text{ MeV}, \mu^B_{chem} = 266 \text{ MeV}, \]
\[ \mu^S_{chem} = 71 \text{ MeV}, \mu^I_{chem} = -5 \text{ MeV}. \] (2)

In our study we use these values in Eq. (1) and calculate the particle densities \( n_i \). We take into account all meson resonances with masses smaller than 1.28 GeV and baryon resonances with masses smaller than 1.45 GeV. Decays of resonances contribute to the final (measured) yields of stable hadrons. This is an important effect [1]. The needed branching ratios for the decays of resonances are taken from experiment [16]. In this paper, for clarity, we neglect the finite-size and the excluded-volume corrections. As mentioned above, they do not change significantly the ratios of particles. Indeed, within our simplified approach we reproduce the numbers of Ref. [2] at the level of 15%.

In principle, the in-medium masses of all hadrons may behave differently. For practical reasons we perform our calculation with the meson and baryon masses rescaled by the two universal parameters, \( x_M \) and \( x_B \), namely

\[ m^*_M = x_M m_M, \quad m^*_B = x_B m_B. \] (3)

In this way we change the masses of all hadrons except for pseudo-Goldstone bosons, i.e., pions, kaons and the eta, whose masses are kept fixed at vacuum values. In fact, results of many model calculations show stability of the pion mass against the change of temperature and density up to the point where the chiral phase transition occurs [17]. The branching ratios are kept at the vacuum values.

In Fig. 1 we show the \( \pi^+ / p \) ratio calculated for different values of the parameters \( x_M \) and \( x_B \). The solid line represents the case when the meson and baryon masses are rescaled the same way, \( x_M = x_B = x \) (BR-scaling [8]), the dashed line corresponds to the case when only the baryon masses are changed, \( x_M = 1 \) and \( x_B = x \), and the dotted line shows the case \( x_M = x \) and \( x_B = 1 \). In all three cases the values of \( x_M \) and \( x_B \) are restricted to the reasonable range of \( 0.6 < x < 1.1 \).

Our results presented in Fig. 1 show that large mass modifications lead to a substantial change of the \( \pi^+ / p \) ratio. The reduction of masses by 20% changes
Fig. 1. The $\pi^+/p$ ratio plotted as a function of the scaling parameter $x$. Solid line: all hadron masses (except for Goldstone bosons) are scaled with $x_M = x_B = x$. Dashed line: only baryon masses are scaled $x_M = 1$, $x_B = x$. Dotted line: only meson masses (except for Goldstone bosons) are scaled $x_M = x$, $x_B = 1$. The displayed behavior can be easily understood in qualitative terms. The strong increase of the dotted curve in Fig. 1, as the meson masses are decreased, is mostly caused by a larger population of the rho and omega mesons at the chemical freeze-out point. Subsequent decays of these mesons produce more pions, raising the $\pi^+/p$ ratio. We note that the rho and omega bring about half of the effect shown in Fig. 1. The other half comes from heavier resonances. Similarly, for the dashed curve, a lower mass of baryons results in the larger population of protons at the chemical freeze-out point, thus lowering the $\pi^+/p$ ratio. A universal scaling of the meson and baryon masses (solid line) partially cancels the above-described effects. Still, a significant effect remains. Other particle ratios are less sensitive to the mass modifications.

To conclude, we note that the thermal fit analysis leaves little room for modifications of hadron masses larger than, say, 10-20%. The quite impressive agreement with data reached in [2] would be deteriorated with significant mass modifications. However, it seems premature to jump to a general conclusion that masses of hadrons cannot significantly change in hot and dense
medium. One should bare in mind that at present we do not understand in sufficient detail the mechanisms of hadron production and evolution of the system created in heavy-ion collisions, and the appealing simplicity and numerical success of the thermal model may be misleading. One cannot exclude the possibility that a more elaborate or altogether different treatment will leave room for a substantial modification of hadron masses. In order to shed more light on this issue it would be useful to incorporate scaling of hadron masses, as well as other hadronic parameters, in various existing approaches to heavy-ion collisions.

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