The ratio of the particles multiplicities in the coalescent model of correlated quarks

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Abstract. The particles multiplicity ratio produced in hadron-hadron, hadron-nucleus and nucleus-nucleus collisions at high energies are calculated in the coalescence model of correlated quarks (CMCQ). Phenomenological parameters are given.

1. Introduction

The multiplicity and the ratios of particles multiplicity in hadron-hadron, hadron-nucleus and nucleus-nucleus collisions at high energies are one of the main characteristics for studying the properties of nuclear matter, which is formed in such a collision. Multiplicity is the number of particles that were born in a collision. The multiplicities ratio of different types of particles makes it possible to understand better the hadronization mechanism, the formation of QGP, baryon asymmetry, and so on.

The multiplicity of charged particles per interaction is found by direct measurement of the particles number in each interaction, and the average multiplicity of charged particles by integration of single-particle spectra in inclusive reactions (in such reactions the characteristics of some part of the secondary particles are studied).

The fact that as a result of multiple births a large number of particles arise, suggests the establishment of a statistical equilibrium in the interaction process. The original version of the statistical model for describing multiple processes was proposed by E. Fermi in 1959 [1]. In his work, the ideal gas model was used.

According to the Fermi hypothesis, the cross-section of the multiple production processes must be proportional to the phase volume. A model in which the entire phase volume is uniformly filled with states of the system is called statistical. The process of multiple creations, in this case, consists of the following: the colliding hadrons form a common system in which all of their energy is determined that determines the temperature of the system. Inside the volume of the system, a strong interaction of the nuclear field quanta occurs, as a result of which an equilibrium state is established in the volume that can be considered statistically.

Fermi’s point of view was criticized by L.D. Landau [2]. Indeed, at the first moment of the interaction, when a common system was formed and there is a strong interaction between the particles of the system, one can not generally speak of the number of particles, since as a result of a strong interaction they are continuously born and disappear. Such a process will occur as long as the particles interact with each other. The number of particles will be determined only in the second stage of the interaction, at the time of expansion, when the particles will disperse so much that they stop interacting. This will happen when the energy of the system falls to a value determined by the mass of the lightest hadron, the $\pi$ meson

$$E \sim kT \sim m_\pi c^2$$

(1)

When $E$ is energy in laboratory system, $k$ is Boltzmann constant, $T$ is temperature, $m_\pi$ is mass of $\pi$ meson, $c$ is speed of light. Look more into detail here [1].

During the expansion of the system, individual particles experience acceleration due to the mutual pressure effect: the state of the system is similar to liquid pressure, so Landau applied the hydrodynamics laws to a system of particles moving with relativistic velocities. The Landau theory is called hydrodynamic.
The multiplicity of the secondary particles $n$ of the Fermi and Landau theory is described in the same way:

$$n \sim E^{1/4}$$

(2)

Both of the above-mentioned models predict a power-law dependence of the number of secondary particles on energy. However, the experimental data with LHC are uniquely approximated by the logarithmic dependence [3]. Hence the need for a comprehensive experimental and theoretical study of the features of particle production at ultrarelativistic energies.

In recent years, new experimental data have appeared on the measurement of particle yields, for example, [4]. In [5, 6], within the framework of the CMCQ, the ratios of the particle yields in the experiments available at the time were calculated.

2. Coalescence model with correlated quarks and anti–quarks

To determine the multiplicities of the production of hadrons generated from thermalized QGP in ultrarelativistic heavy-ion collisions, we will use the coalescence model of correlated quarks (CMCQ) proposed in this paper. The main difference between the CMCQ and the simple coalescent quark model known in the literature, [5] consists in accounting for quark correlations and a significantly smaller number of free parameters. It is in the CMCQ that there is only one free parameter out of 5 after fixing all the others, while in the simple coalescent quark model there are five parameters left from the 12 ones included at the beginning.

A detailed scheme for calculating the hadron multiplicities is described in [6]. Therefore, in this article, we will not describe it. We only note how the phenomenological parameters of the model were determined and the contribution of gluons was calculated.

2.1 Determination of phenomenological parameters of the model

In the CMCQ the multiplicities of hadron production depend on 6 phenomenological parameters: $T$ – temperature, $\mu(T)$ is the chemical potential of light quarks, $F_S^c$ is the constant describing the contribution of the $s\bar{s}$ component to the structure of pseudoscalar and vector mesons, and the three constants – $C_M$, $C_B$ and $C_{\bar{B}}$, related to the spatial volumes of meson, baryon, and antibaryon production.

The chemical potential $\mu(T)$, as a function of the temperature $T$, was fixed independently from the experimental data on ultrarelativistic heavy ion collisions.

Comparing the theoretical multiplicities of hadron production with the experimental data, a temperature $T = 175$ MeV was recorded.

The parameter $F_S^c$, equal to $F_S = 3.5F_\pi = 458.5$ MeV, was recorded from the experimental data on the ratio of the production multiplicities $\eta(550)$ and $\pi^0(135)$ of mesons. The obtained numerical value $F_S = 3.5F_\pi = 458.5$ MeV gives good agreement with the experimental data on the ratio of the multiplicities $R_{\phi\pi}(q,T)$, $R_{\phi(\rho+\omega)}(q,T)$ and $R_{\phi K^0}(q,T)$.

From the experimental data on the ratios of the production of anti-omega-hyperons to omega hyperons $R_{\Omega\Omega}(q,T) = 0.46 \pm 0.15$ and lambda-hyperons to $K^0$-mesons, $R_{\Lambda K}(q,T) = 0.65 \pm 0.11$, the ratios of the constants were fixed:

$$\frac{C_B}{C_\bar{B}} = 0.46 \pm 0.15$$

(3)

and

$$\frac{C_M}{C_B} = 0.23 \pm 0.04$$

(4)

Thus, after fitting the experimental data on the production of hadrons in ultrarelativistic heavy-ion collisions, only one indeterminate parameter remains in the model—the constant $C_B$. The presence of one free parameter in the model is not a big problem for the CMCQ. Nevertheless, the absolute value of the constant $C_B$ can be fixed, in principle, from the analysis of cosmological applications of the model.

In order to fix the absolute value of the constant $C_B$, we consider the evolution of the number of antibaryons and baryons in the universe, suggesting that after the Big Bang the Universe passed the phase of the QGP at a temperature of $T = 175$ MeV.

Using the multiplicities of the baryons and antibaryons production of obtained in [5], it is possible to calculate the ratio of total antibaryons number $N_{\bar{B}}$ to total number of baryons $N_B$. 


In equation (5) we used the estimate (3) obtained from the experimental data on ultrarelativistic heavy ion collisions. The numerical value in the equation (5) can be checked under the assumption of baryon and antibaryon gases equilibrium. For equilibrium baryon and antibaryon gases, the distribution functions are equal, respectively:

\[
N_B(q, T) = \frac{2V}{(2\pi)^3} \exp \left( -\sqrt{\frac{p^2 + M_B^2}{T} + \frac{\mu_B(T)}{T}} \right) 
\]

\[
N_{\bar{B}}(q, T) = \frac{2V}{(2\pi)^3} \exp \left( -\sqrt{\frac{p^2 + M_{\bar{B}}^2}{T} - \frac{\mu_B(T)}{T}} \right) 
\]

where \( V \) is the volume of the universe. The ratio of the distribution functions is determined only by the chemical potential \( \mu_B(T) \).

\[
\frac{N_{\bar{B}}}{N_B} = \exp \left( -2\frac{\mu_B(T)}{T} \right) = \exp \left( -6\frac{\mu(T)}{T} \right) = 0.17 
\]

where we took into account the fact that \( \mu_B(T) = 3\mu(T) \) is well known in the approach of a thermalized QGP. The numerical value \( N_{\bar{B}}/N_B = 0.17 \) was obtained at \( T = 175 \text{ MeV} \) and the chemical potential defined by equation (1.4) from [5]. The estimate (8) agrees well with the result in equation (5).

Thus, we predict within the CMCQ that at the early stage of the development of the universe the number of antibaryons was almost an order of magnitude less than the number of baryons \( N_{\bar{B}} \sim 0.2N_B \). According to G. Börner [7], this is more than enough for the prerequisites for the appearance of life in the universe. We recall that within the framework of the standard approach described in the book of G. Börner [7], for every \( 10^9 \) antibaryons there were \( 10^9 + 1 \) baryons. In accordance with the standard approach, it is to this excess baryon that we owe our existence to the universe.

For the subsequent estimation of the value of the parameter \( C_B \), we use the fact that at the early stage of the development of the universe the total number of baryons and antibaryons \( (N_{\bar{B}} + N_B) \) was approximately equal to the total number of photons \( N_{\text{ph}} \) [7]:

\[
\frac{N_{\bar{B}} + N_B}{N_{\text{ph}}} \approx 1 
\]

Since the number density of photons is equal to:

\[
\frac{V}{N_{\text{ph}}} = \frac{2.404}{\pi} \times \gamma^3 
\]

where \( V \) is the volume of the universe, and the density of the number of baryons and antibaryons \( (N_{\bar{B}} + N_B)/V \), calculated at a temperature \( T = 175 \text{ MeV} \) is equal to:

\[
\frac{N_{\bar{B}} + N_B}{V} = C_B \times 0.442 \times \gamma^3 
\]

then, using equation (9), we can obtain an estimate of the value of the constant \( C_B \):

\[
C_B = 0.55 \pm 0.08 
\]

We get equation:

\[
C_B = 0.25 \pm 0.08 
\]

\[
C_M = 0.13 \pm 0.03 
\]

Thus, all phenomenological parameters are fixed in our model.

2.2 Contribution of gluons
According to the model [5, 6], the contribution of the gluon degrees of freedom should be the same for all hadron. This contribution can be written as:

\[ N_h(\bar{q}, T) = N_{h}^{\text{gq}}(\bar{q}, T) + C_g T^3 \exp \left( \frac{q}{T} \right) \]  

(15)

where \( N_{h}^{\text{gq}}(\bar{q}, T) \) is the multiplicity of the production of the \( h \)-hadron with momentum \( \bar{q} \) at temperature \( T \), described without the contribution of the gluon degrees of freedom. The last term on the right-hand side of the equation refers to the contribution of the gluon degrees of freedom. The constant \( C_g \) must be the same for all hadrons.

Using the experimental value of the ratio \( \bar{p}/p = 0.64 \pm 0.01 \pm 0.07 \) [8], the theoretical multiplicity value for antiprotons and protons, as calculated in [5], and taking into account the possible production of protons and antiprotons due to the strong decay \( \Delta(1232) \) and \( \Delta(1232) \) resonances, we make an estimate of the constant \( C_g \). It turns out to be equal to:

\[ C_g = (3.31 \pm 0.15) \times 10^{-10} \text{ MeV}^{-3} \]  

(16)

3. PYTHIA 8.230

Multiple particle productions in proton-proton collisions are due to many mechanisms. Multiple parton interactions are, in this context, the driving mechanism and are closely related to the spatial structure of the proton. At the parton level, each inelastic collision of protons can be represented as a set of hard and soft parton scattering, as well as practically non-interacting proton remnants. Hard parton interactions appear in the final state as hadronic jets, while soft partons lead to poorly collimated beams of hadrons, which often can not be distinguished as a jet. The latter basically constitute a background event. The ratio of soft and hard parton scattering depends on the energy and impact parameter of the proton-proton collision.

At the moment, when considering collisions at high energies (\( \sqrt{s} \sim 100 \text{ GeV} \)), the collision result is described as a set of parton sub collisions (described by perturbative QCD). More [9-11] is exactly what is implemented in PYTHIA 8.230.

4. Comparison CMCQ predictions with experimental data and modeling in PYTHIA 8.230

| Ratio of the multiplicities of particles | Model | Collaboration |
|-----------------------------------------|-------|---------------|
|                                         | The coalescent model of correlated quarks (the contribution of gluons) | PYTHIA 8.230 pp collision 200 GeV | STAR [4] pp collision 200 GeV |
| \( K^-/K^+ \)                           | 0.809 ± 0.018 | 0.888 ± 0.010 | 0.967 ± 0.040 |
| \( \pi^-/\pi^+ \)                       | 1.000 ± 0.001 | 0.930 ± 0.003 | 0.988 ± 0.043 |
| \( p/\pi^+ \)                           | 0.134 ± 0.016 | 0.233 ± 0.005 | 0.096 ± 0.008 |
| \( \bar{p}/\pi^- \)                     | 0.120 ± 0.017 | 0.060 ± 0.009 | 0.080 ± 0.006 |
| \( K^+/\pi^+ \)                         | 0.242 ± 0.014 | 0.100 ± 0.007 | 0.104 ± 0.008 |
| \( K^-/\pi^- \)                         | 0.175 ± 0.016 | 0.095 ± 0.020 | 0.102 ± 0.008 |

5. Conclusions

In this paper, several ratios of particle multiplicities were obtained, which were not considered earlier in the papers devoted to the coalescence model of correlated quarks. Also the latest results of the ratios of particle multiplicities are refined due to the gluon contribution. In addition, a simulation using a Monte Carlo PYTHIA
8.230 generator was performed. Theoretical data that were obtained with the help of the model of correlated quarks, as well as simulation data using the Monte Carlo PYTHIA 8.230 generator, were compared with the currently available experimental data on the STAR multiplicity ratio.

One can notice discrepancy between the results of the CMCQ calculation, the Monte Carlo simulation and experimental data when considering a ratio of the "baryon/meson" and $K$-mesons to $\pi$-mesons. These results show that the CMCQ needs improvement.

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