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AN ANALYSIS OF THE FEATURES OF CHARGED HADRON PRODUCTION IN COLLISIONS OF BISMUTH NUCLEI AT AN ENERGY OF 9.2 GEV USING THE BLAST-WAVE MODEL

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Abstract. The paper presents charged hadron invariant spectra obtained in Bi+Bi collisions at an energy of 9.2 GeV on the basis of simulation performed using the UrQMD hybrid generator and the MPDroot package. The spectra were analyzed in the framework of statistical and Blast-Wave models, resulting in the values of temperatures and baryonic chemical potentials corresponding to the stages of kinetic and chemical freeze-out in Bi+Bi collisions. The results were discussed in the context of the phase diagram of nuclear matter.

Keywords: quark-gluon plasma, charged hadrons, MPD, NICA, phase diagram, nuclear matter

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АНАЛИЗ ОСОБЕННОСТЕЙ РОЖДЕНИЯ ЗАРЯЖЕННЫХ АДРОНОВ В СТОЛКНОВЕНИЯХ ЯДЕР ВИСМУТА ПРИ ЭНЕРГИИ 9,2 ГЭВ С ПОМОЩЬЮ МОДЕЛИ BLAST-WAVE

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Аннотация. В работе представлены инвариантные спектры по поперечной массе для заряженных адронов в столкновениях ядер висмута (Bi + Bi) при энергии 9,2 ГэВ, полученные путем моделирования с использованием гибридного генератора UrQMD и пакета MPDroot. Проведен анализ спектров в рамках статистической и Blast-Wave моделей, в результате которого получены значения температуры и барионных химических потенциалов, соответствующих стадиям кинетического и химического вымораживания в столкновениях Bi + Bi. Полученные результаты рассмотрены в контексте фазовой диаграммы ядерной материи.

Ключевые слова: кварк-глюонная плазма, заряженные адроны, MPD, NICA, фазовая диаграмма; ядерная материя

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Introduction

The Multi-Purpose Detector (MPD) [1] is one of the two experimental facilities at the NICA (Nuclotron-based Ion Collider fAcility) [2], the flagship project of the Joint Institute for Nuclear Research (Dubna, Moscow Region, Russia).

The main objectives of the MPD experiment are to study the boundary of the phase transition and to find a critical point in the phase diagram of nuclear matter by analyzing particle production in heavy ion collisions in the energy range $\sqrt{S_{NN}}$ = 4–11 GeV [3].

The phase boundary of nuclear matter determines the transition of hadron matter to quark-gluon plasma (QGP) [4, 5] with an increase in temperature T and/or the baryonic chemical potential μ_B. The formation of the QGP and the corresponding phase transition in nucleus-nucleus collisions were experimentally confirmed at energies exceeding 100 GeV [4–6], which corresponds to temperatures of about 200 MeV and $\mu_B \approx 10$ MeV achieved in the collision. Nevertheless, study of the rest of the phase diagram and the search for QGP signatures in nuclear collisions at lower energies (below or around 100 GeV) remain major challenges.

To identify the potential signatures of a phase transition in nucleus-nucleus collisions at NICA energies, it is necessary to determine the available range of temperature T and baryonic chemical potential μ_B. The values of T and μ_B can be estimated by analyzing the characteristics of charged hadron production using the statistical model and the Blast-Wave model [7, 8] based on the approach of relativistic hydrodynamics.

This paper presents the invariant spectra for transverse mass m_T measured for charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$) in collisions of bismuth nuclei (Bi+Bi) at $\sqrt{S_{NN}}$ = 9.2 GeV; these results were obtained based on simulation data using the UrQMD hybrid generator [9] and the MPDroot package [1] reproducing the operation of the detector system at the MPD experiment.

Analysis of the obtained spectra is carried out within the framework of the statistical model and the Blast-Wave model. The results are considered in the context of the phase diagram of nuclear matter.

Evolution of nucleus-nucleus collisions

The process of evolution of relativistic collisions can be divided into four main stages:

initial stage,

thermalization and collective flow,

chemical freeze-out,

kinetic freeze-out [10].

Initial stage corresponds to primary interaction of colliding nuclei, accompanied by the exchange of gluons and quarks. This process leads to rapid heating of the system and potential production of QGP (if the values of T_{QGP} and μ_B necessary for the phase transition are reached).

Second stage. As a result of subsequent interactions between the particles, the system is thermalized, after which collective flow begins.

Third stage. Chemical freeze-out occurs when the particle system expands to a state where inelastic reactions altering its composition cease and the final particle ratios are established.

According to the statistical model, after the onset of chemical freeze-out, the antiproton to proton yield ratio is determined by the value of the baryonic chemical potential μ_B [11]:

$$\frac{\bar{p}}{p} = \exp\left(-\frac{2\mu}{T}\right) \Leftrightarrow \mu = T \cdot \frac{\ln\left(\bar{p}/p\right)}{2} \Leftrightarrow T = -\frac{2\mu}{\ln\left(\bar{p}/p\right)}. \quad (1)$$

Fourth stage. After chemical freeze-out starts, the particle system continues to expand and cool. When the mean free path of the particles becomes larger than the size of the system, elastic collisions stop, fixing the momentum distribution of the particles, which corresponds to the onset of kinetic freeze-out.

Phenomenological models such as Blast-Wave are used to study the characteristics of kinetic freeze-out [7, 8]. This model is based on the relativistic hydrodynamic approach and describes the collective motion of particles in an expanding system.

Blast-Wave model. The basis of the model is that heated matter has a high temperature, distributed nonuniformly: the temperature in the center of the particle system is higher than at its periphery, which creates a pressure gradient. According to the equations of hydrodynamics, matter flows outward from the center, forming a blast wave.

According to the Blast-Wave model, all hadrons are produced from quarks and gluons simultaneously, so consequently they acquire the same average velocity of radial flow. In this case, the expansion of the hadron system is described in terms of relativistic hydrodynamics.

The invariant spectra for the transverse mass $m_T = \sqrt{p_T^2 + m_0^2}$ can be described by the following formula within the Blast-Wave model:

$$\frac{dN}{m_T dm_T} = C\int^{R} r dr m_T I_0\left(\frac{p_T \sinh\rho}{T_0}\right) K_1\left(\frac{p_T \cosh\rho}{T_0}\right), \quad (2)$$

where C is the normalization constant; β_T is the average velocity of radial flow; T_0 is the kinetic freeze-out temperature; R is the maximum radius of the expanding system during the freeze-out stage; I_0, K_1 are the modified Bessel functions; $\rho(r)$ is the transverse acceleration depending on the particle coordinate,

$$\rho(r) = \tanh^{-1}(\beta_T)\cdot r/R.$$

C, β_T, T_0 are the free parameters of the model.

Measurement procedure

We used simulation data from 15,000,000 Bi+Bi collisions at $\sqrt{S_{NN}}$ = 9.2 GeV; the data were obtained using the MPDroot package [1]. The latter uses the hybrid UrQMD event generator [9] including a hydrodynamic approach; in addition, MPDroot allows reproducing the response of the detector subsystems of the MPD experiment via the Geant4 package [12, 13].

Detection of charged hadrons in MPD is carried out by analyzing, firstly, the energy losses of particles measured in the TPC (Time Projection Chamber), and secondly, the time of flight of the particles measured by the ToF (Time-of-Flight) detector. The details of the simulation and the particle detection procedure can be found in [3, 14].

Analysis of characteristics of charged hadron production

Determination of kinetic freeze-out parameters. Fig. 1 shows the invariant m_T spectra measured for charged hadrons at different centrality bins in Bi+Bi collisions at $\sqrt{S_{NN}}$ = 9.2 GeV. The lines show the fit of the obtained spectra by the corresponding function of the Blast-Wave model (see Eq. (2)).

Fitting of the invariant m_T spectra of different particles with the Blast-Wave function was carried out in the following ranges.

Charged hadron type	Approximation range, GeV
π^+, π^-	0.50–1.00
K^+, $\bar{p}$	0.12–1.00
K^-	0.40–1.00
p	0.20–1.00

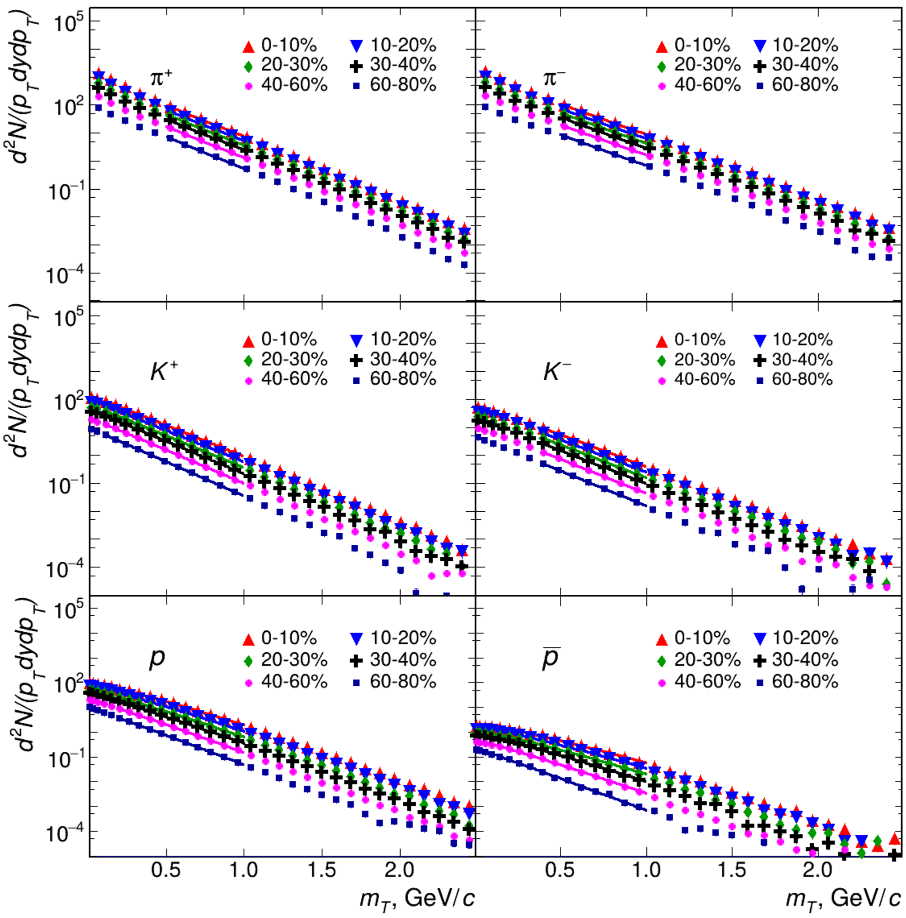

Fig. 1. Invariant transverse mass spectra measured for $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ particles at different centrality bins in Bi+Bi collisions at energy $\sqrt{S_{NN}}$ = 9.2 GeV. Fits to the spectra with the corresponding function of the Blast-Wave model (see Eq. (2)) are shown by straight lines

The fitting ranges were chosen so as to achieve the best agreement with the simulation data. It was found that the difference between the simulation data and the Blast-Wave function did not exceed 1%.

Since the Blast-Wave function is integral, the free fitting parameters (C, T_0, β_T) are sensitive to variation in the fitting range, the choice of initial parameter values and the constraints imposed on the parameter values. The impact of these factors was taken into account by estimating the systematic uncertainties.

For this purpose, the fitting parameters (given below) were varied by ±10%. These were the following conditions:

range bounds;

initial parameter values;

constraints on parameter values.

The final values of systematic uncertainties were determined by the quadrature sum of the percentage differences between the final values of the parameters and those obtained under different fitting conditions.

Fig. 2 shows the final values of the parameters T_0 and β_T obtained by fitting of invariant m_T with the Blast-Wave function for different types of charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$) depending on centrality of Bi+Bi collisions. Systematic uncertainties are represented by boxes.

We found that the kinetic freeze-out temperature T_0 shows no significant dependence on either the collision centrality or the type of charged hadrons. The average value of the kinetic freeze-out temperature T_0 = 109 MeV (red dashed line in Fig. 2,*a*).

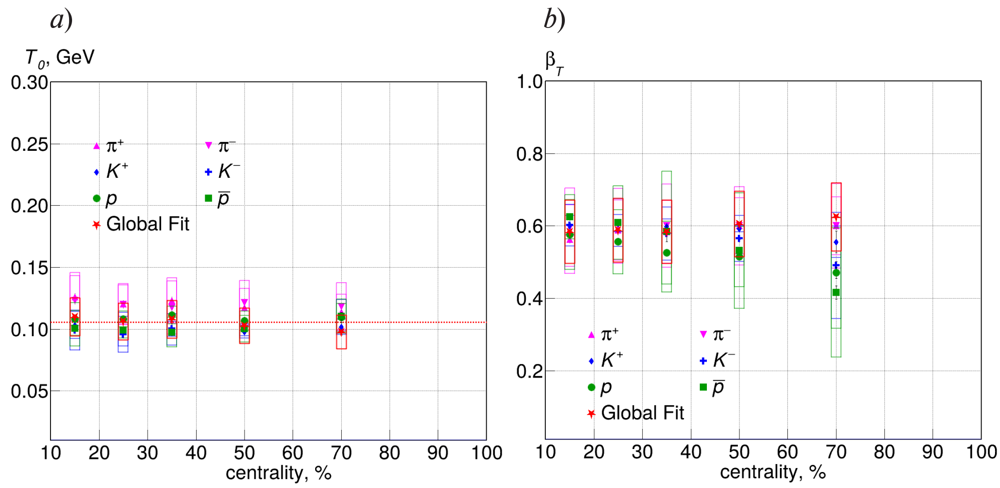

Fig. 2. Kinetic freeze-out temperature T_0 (*a*) and average velocity β_T of radial flow of particle system (*b*) depending on centrality of Bi+Bi collisions. The bars correspond to systematic uncertainty in determining the values of T_0 and β_T

The average value of T_0 = 109 MeV (red horizontal dashed line)

The average velocities β_T of radial particle flow show a decreasing trend with a decrease in the overlap of colliding nuclei (this corresponds to an increase in centrality as a percentage). Nevertheless, the decrease in β_T values in peripheral collisions, compared with the central ones, is insignificant taking into account systematic uncertainty.

Determination of phase transition parameters. The values of the baryonic chemical potential and temperature corresponding to the phase transition are estimated by calculating the antiproton to proton yield ratios ($\bar{p}/p$).

The values of ($\bar{p}/p$) measured in different centrality bins of Bi+Bi collisions are shown in Fig. 3,*a*. Evidently, they do not show a significant dependence on the collision centrality and the transverse momentum p_T. The average value of the ratio ($\bar{p}/p$) = 0.025 (shown by a red horizontal red dashed line) was used for further calculations.

According to calculations within the framework of quantum chromodynamics, the phase transition boundary can be expressed by the following formula [15]:

$$T_{QGP} = \frac{\sqrt{3/34}}{\pi}\sqrt{\sqrt{340\pi^2(220)^4 + 55\mu^4} - 15\mu^2}. \quad (3)$$

The baryonic chemical potential μ can be expressed in terms of temperature and the $\bar{p}/p$ ratio by Eq. (1). Thus, the temperature and the baryonic chemical potential corresponding to the phase transition can be found as the intersection point of the curve expressed by Eq. (3) and the straight line given by Eq. (1).

The following values of T_{QGP} and μ_B were obtained, corresponding to the phase transition in Bi+Bi collisions at NICA energies:

$$T_{\text{QGP}} = 131 \text{ MeV}, \ \mu_B = 247 \text{ MeV}.$$

Visualization of the obtained results on the phase diagram. Fig. 3,*b* shows the phase diagram of nuclear matter. The red line indicates the phase boundary calculated by Eq. (3). The lines correspond to the temperatures in terms of the baryonic chemical potential and the value found for $\bar{p}/p$ = 0.025 (see Eq. (2). The purple line in Fig. 3,b expresses the dependence $T(\mu_B, \bar{p}/p)$, obtained using the value $\bar{p}/p$ = 0.025 corresponding to Bi+Bi collisions at $\sqrt{S_{NN}}$ = 9.2 GeV.

Using Eq. (2), we additionally calculated the value of the baryonic chemical potential μ_B corresponding to the kinetic freeze-out temperature in Bi+Bi collisions at $\sqrt{S_{NN}}$ = 9.2 GeV (the temperature was determined earlier using the Blast-Wave model). The found value of μ_B = 205 MeV.

The kinetic freeze-out and phase transition temperatures corresponding to the energy of the PHENIX experiment ($\sqrt{S_{NN}}$ = 200 GeV) are given for comparison. The dependence $T(\mu_B, \bar{p}/p)$ as

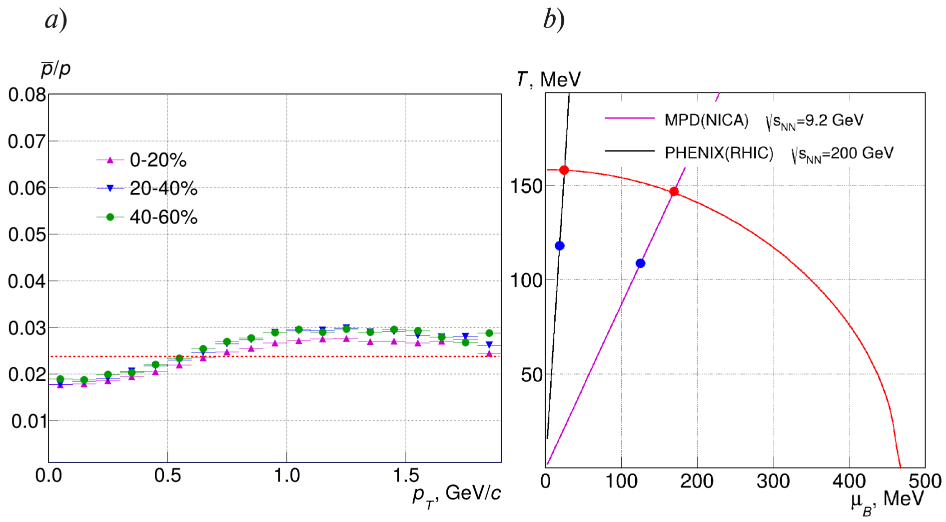

Fig. 3. Antiproton to proton yield ratios $\bar{p}/p$ as functions of transverse momentum, measured in different centrality bins (%) of Bi+Bi collisions at $\sqrt{S_{NN}}$ = 9.2 GeV (*a*) and corresponding phase diagram of nuclear matter (dependence of temperature on baryonic chemical potential) (*b*)

a straight line (shown in Fig. 3,*b* in black) is obtained taking into account the value of $\bar{p}/p$ = 0.79 measured in the PHENIX experiment at $\sqrt{S_{NN}}$ = 200 GeV.

The blue dots in Fig. 3,*b* mark the values of the temperature and the baryonic chemical potential of the particle system during a collision at the kinetic freeze-out stage, and the red ones mark these values at the phase transition stage.

Conclusion

We report on the transverse mass spectra of charged hadrons $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ obtained in simulations of Bi+Bi collisions at $\sqrt{S_{NN}}$ = 9.2 GeV using the hybrid UrQMD generator and the MPDroot package.

Analyzing the obtained spectra of charged hadrons within the Blast-Wave model, we found the values of the kinetic freeze-out temperature T_0 and the average velocity β_T of the particle system's radial flow depending on collision centrality.

Calculating the antiproton to proton yield ratios allowed to determine the temperatures T_0 and T_{QGP}, as well as the baryonic chemical potential μ_B corresponding to the kinetic freeze-out and phase transition. The following parameter values were obtained:

$$T_0 \approx 109 \text{ MeV}, \ \mu_B \approx 205 \text{ MeV for kinetic freeze-out;}$$

$$T_{QGP} \approx 131 \text{ MeV}, \ \mu_B \approx 247 \text{ MeV for phase transition.}$$

The presented results make it possible to estimate the accessible range of values for the temperature T and the baryonic chemical potential μ_B, which is important for potential signatures of the phase transition in nucleon-nucleon collisions at NICA energies.

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