Charged pion, kaon, proton and antiproton production in large collision systems

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Abstract. The main goal of PHENIX expirement, located at Relativistic Heavy-ion collider, is the investigation of quark-gluon plasma (QGP). One of the aspects of the QGP study is describing the process of its hadronization. Very important contribution to understanding of hadronization process was given by discovering of anomaly large ratio of protons production to pions production \( \frac{p}{\pi} \) in \( \text{Au+Au} \) collisions in comparison to the same ratio in proton-proton collisions. This effect was called baryon puzzle and was explained in a frame of recombination model of hadronization.

Although charged hadrons production has been previously studied in elementary proton-proton (\( p+p \)) collisions and symmetric \( \text{Au+Au} \) collisions, it has never been investigated before in the large asymmetric collisions systems (such as \( \text{Cu+Au} \)) or the collisions of large deformed nuclei (\( \text{U+U} \)). The study of such large collisions systems allows to study features of baryon and meson production versus collision geometry and system size.

1. Introduction

The main goal of PHENIX expierment, located at Relativistic Heavy-ion collider, is the investigation of quark-gluon plasma (QGP) - a state of matter, which is thought to consist of asymptotically free strong-interacting quarks and gluons, which are ordinarily confined inside atomic nuclei or hadrons. One of the common methods to study QGP properties is to measure hadron production in heavy-ion collisions.

Charged pion (\( \pi \)-meson), kaon (\( K \)-meson), proton and antiproton production has been previously studied [1] in elementary proton-proton (\( p+p \)) collisions at the energies of Relativistic Heavy-Ion Collider [2]. In such collisions, protons are produced approximately three times less than \( \pi \)-mesons at the intermediate transverse momentum \( (p_T) \) range due to a larger mass and a requirement of non-zero baryon number for the formation of a proton. However, in a large collision system such as \( \text{Au+Au} \) at \( \sqrt{s_{NN}}=200 \text{ GeV} \) the value of proton to \( \pi \)-meson ratio \( \frac{p}{\pi} \) obtained by PHENIX experiment [3] reaches the value of 0.8 [4]. Moreover, the value of \( p/\pi \) ratio in \( \text{Au+Au} \) collisions increases with the size of the nuclear overlap region, which is usually characterized by the number of nucleons, participating in the interaction (\( N_{\text{part}} \)). The larger \( N_{\text{part}} \), the more central becomes the interaction of two nuclei. At the same time kaon to pion ratio \( \frac{K}{\pi} \) does not show any dependence on \( N_{\text{part}} \). One of the ways to describe such behavior is to use recombination models [5].
According to recombination model hadrons are formed from quarks in QGP, which are close to each other in a phase-space, i.e have close values of momentum and coordinate. The main parameters of recombination models are the temperature of QGP, quark chemical potential and parameters, responsible for the condition of “closeness” of quarks in phase-space [6].

At present time all theoretical calculations and determination of listed parameters are based on experimental results, obtained only in symmetric Au+Au collision system. Measurements of charged hadrons production in asymmetric Cu+Au collision system and collision system of highly deformed uranium nucleus U+U can provide experimental support to recombination model calculations and to study features of baryon and meson production versus collision geometry and system size.

### 2. Analysis Method

In the PHENIX experiment measurements of charged hadrons are provided by the time of flight detector (TOF). TOF detector has a 80-100 ps timing resolution and covers $\pi/4$ in azimuth and $|y|<0.35$ in pseudo-rapidity. Thereby the $\pi/K$ and $K/p$ separation can be achieved up to 2 and 3 GeV/c in transverse momentum ($p_T$), respectively [3].

The most basic method of describing particle production is the calculation of invariant $p_T$ spectra. Invariant $p_T$ spectra characterize the number of hadrons $N_h$, in a given $p_T$ interval ($\Delta p_T$), and rapidity interval ($\Delta y$) and can be calculated according to the formula [4]:

$$\frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy} = \frac{N_h}{2\pi p_T N_{coll} \varepsilon_{rec} \Delta p_T \Delta y}$$

Where $\varepsilon_{rec}$ - is the efficiency of hadrons registration, obtained with the help of Glauber Monte-Carlo simulation.

Differences in baryon and meson production in a given collision system can be quantified with a ratio of baryon invariant spectra to meson invariant spectra. Differences in hadron production in proton-proton (p+p) and in collisions of heavy ions A+B are commonly described with nuclear modification factors ($R_{AB}$) [4]. $R_{AB}$ is a ratio of hadron invariant $p_T$ spectra in A+B collisions ($d^2N_{A+B}/dp_T dy$) to hadron invariant $p_T$ spectra in p+p collisions ($d^2N_{p+p}/dp_T dy$), normalized by number of binary nucleon-nucleon collisions ($N_{coll}$). That normalization allows to study collective effects, that occurs due to the influence of nucleons to each other. The $N_{coll}$ values, as well as $N_{part}$ values, have been calculated with the help of Glauber model. Nuclear modification factors ($R_{AB}$) can be calculated according to the formula:

$$R_{AB} = \frac{1}{N_{coll}} \frac{d^2N_{A+B}}{d^2N_{p+p}/dp_T dy}$$

In order to investigate properties of charged hadron production, $R_{AB}$ of $\pi^\pm$, $K^\pm$ and $(p+\bar{p})/2$ have been calculated in U+U and Cu+Au collisions and compared to neutral meson $R_{AB}$. Also $p/\pi$ and $K/\pi$ ratios have been obtained in U+U collisions in different centrality bins. Charged hadron $R_{AB}$, integrated over $p_T$ in the range $2 < p_T < 3$ GeV/c, have been compared to previous Au+Au results.

### 3. Results and discussion

Nuclear modification factors have been measured for $\pi^\pm$, $K^\pm$, $(p+\bar{p})/2$ in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. Comparison of measured charged hadron $R_{AB}$ with previously measured neutral meson ($\pi^0, \varphi, \omega, \eta, K_s$ and $K^{*0}$) $R_{AB}$ in the most central and the most peripheral collisions is presented on Fig. 1. In the most central collisions (0-20%) in the intermediate $p_T$ range 2 < $p_T$ < 3 GeV/c (anti)proton $R_{AB}$ values are larger.
Figure 1. The comparison of $\pi^\pm$, $K^\pm$, $(p+\bar{p})/2$ with $\pi^0$, $\varphi$, $\omega$, $\eta$, $K_s$ and $K^{*0}$ $R_{AB}$ versus $p_T$ in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV than $R_{AB}$ values of mesons. Moreover, difference in proton and meson production in this $p_T$ range is more significant in U+U collision system, which is larger, than Cu+Au collision system. Difference in proton and meson production decreases with increasing centrality (decreasing $N_{\text{part}}$ values), so in peripheral collisions $R_{AB}$ values of all presented hadrons are consistent within uncertainties.

In order to investigate dependence of light hadron production on $N_{\text{part}}$ in U+U collisions, $R_{AB}$ were integrated over $p_T$ ($\langle R_{AB} \rangle$) in the range $2.2 < p_T < 3$ GeV/c (Fig. 2). The ordering of integrated $\langle R_{AB} \rangle$ values can be seen: proton $\langle R_{AB} \rangle$ values are larger than meson $\langle R_{AB} \rangle$ values and $\langle R_{AB} \rangle$ values of mesons, containing strange quark ($K^{*0}$, $\varphi$) are larger than $\eta$ and $\pi^0$ meson $\langle R_{AB} \rangle$, which do not contain strange quark. Such enhancement of mesons containing (anti)strange quark over mesons, which do not contain (anti)strange quark is known as strangeness enhancement and is considered as a sign of QGP formation [7].

Although proton $\langle R_{AB} \rangle$ shows dependence on $N_{\text{part}}$ values it does not depend on the collision geometry. Fig. 3 shows comparison of proton $\langle R_{AB} \rangle$ in Cu+Au, Au+Au and U+U collision systems. Results in all systems are in agreement within uncertainties.
Figure 2. Light hadron $\langle R_{AB} \rangle$ versus $p_T$ in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV/c

Figure 3. Proton $\langle R_{AB} \rangle$ versus $p_T$ in Cu+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV/c and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV/c

Figure 4. The $p/\pi^+$ ratio versus $p_T$ in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV/c

Figure 5. The $K^+/\pi^+$ ratio versus $p_T$ in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV/c

With the aim to obtain quantitative difference of baryon and meson production ratio of $p/\pi^+$ have been calculated (Fig. 4). In the region $p_T > 1.5$ GeV/c the $p/\pi^+$ exhibits centrality dependence. At the same time ratio of kaon, which contains strange quark, to pion ($K/\pi$) does not show significant dependence on centrality (Fig. 5). Observation of this effect is consistent with previous results, obtained in Au+Au collisions, which were explained in the frame of recombintaion model [4].

4. Conclusion
This paper provides measurements of $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$ nuclear modification factors and particle ratios in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. The main obtained result is that proton production depends on $N_{part}$ and does not depend on the geometry of collision system. Moreover, proton $R_{AB}$ values are larger than meson $R_{AB}$ values at the central Cu+Au and U+U collisions at $2 < p_T < 3$ GeV/c. At the same $p_T$ region of central collisions possible sign of strangeness enhancement - important signature of QGP - was observed. Another important result is the observation of centrality dependence of $p/\pi$ ratio, which was
previously observed in Au+Au collisions and explained in the frame of recombination model. All obtained results provide experimental support for development of recombination model and clarification of its parameters.

References
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