The ϕ meson production in small collision systems observed by PHENIX

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Abstract. The measurements of light hadron production in small collision systems (such as p+Al, p+Au, d+Au, ^{3}He+Au) may allow to explore the quark-gluon plasma formation and to determine the main hadronization mechanism in the considered collisions. Such research has become particularly crucial with the observation of the light hadrons collective behavior in $p/d/^3$He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in p+Al collisions at the same energy at forward and backward rapidities. Among the large variety of light hadrons, ϕ meson is of particular interest since its production is sensitive to the presence of the quark-gluon plasma. The paper presents the comparison of the obtained experimental results on ϕ meson production to different light hadron production in p+Al and ^{3}He+Au at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity. The comparisons of ϕ meson production in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity to theoretical models predictions (PYTHIA model and default and string melting versions of the AMPT model) are also provided. The results suggest that the QGP can be formed in $p/d/^3$He+Au collisions, but the volume and lifetime of the produced medium might be insufficient for observation of strangeness enhancement effect. Conceivably, the main hadronization mechanism of ϕ meson production in p+Al collisions is fragmentation, while in $p/d/^3$He+Au collisions this process occurs via coalescence.

1 Introduction

The quantum chromodynamics (QCD) predicts [1] that at a sufficiently high temperature and / or density a state of deconfined quarks and gluons, so-called quark-gluon plasma (QGP), is formed. According to calculations based on the lattice QCD [2], the phase transition from hadron matter to the QGP occurs at the temperature of 150-200 MeV, which corresponds to the energy density of $\sim$ 1 GeV/fm^3. The experimental study of the phase transition and the QGP properties will help to understand the processes of the Universe evolution, the structure of neutron stars, and to clarify the features of the fundamental theory of strong interactions.

Collider experiments provided the evidence of a strongly interacting QGP formation in the laboratory conditions in relativistic heavy ion collisions (Au+Au, Cu+Cu, etc.) at the energy $\sqrt{s_{NN}}$ = 200 GeV [1, 3]. Recently, the signatures of the QGP existence were also observed in small collision systems such as p+Au, d+Au, and ^{3}He+Au [4]. Nonetheless, the evidences of the QGP in p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV were obtained only in

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forward and backward rapidities [5]. The comprehensive study of particle production in small collision systems at midrapidity ($|\eta| < 0.35$) can reveal the main light hadron production mechanism in these systems and the sufficient conditions for the QGP formation.

The study of ϕ meson production has been proven to be a convenient tool for the investigation of the QGP effects [6, 7]. The ϕ meson contains strange quarks ($s\bar{s}$) [8], and whereby its production in relativistic ion collisions is considered as a good probe for the study of strangeness enhancement effect [9] . Additionally, the ϕ meson has a mass comparable to the mass of the proton, and may provide additional study of the baryon enhancement effect [10].

However, not only QGP effects may influence the peculiarities of the ϕ meson production in relativistic ion collisions. Various cold nuclear matter (CNM) effects that reflect the initial state of the collision can also modify the ϕ meson production [11, 12]. Among CNM effects are multiple parton scattering, the initial state energy loss and the modification of the initial parton distribution functions in nuclei and others.

To interpret experimental results on ϕ production in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at midrapidity, reveal the possible QGP effects and distinguish them from CNM ones the comparisons with all available experimental data and different theoretical models are provided.

As a non-QGP baselines PYTHIA [13, 14] and default version of AMPT model [15] are used. To describe the QGP effects the experimental data were compared to the predictions of the string melting version of AMPT [16].

2 Data analysis and theoretical models

Data sets used in the current study were collected by the PHENIX experiment at RHIC [17] in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at midrapidity ($|\eta| < 0.35$). The ϕ meson production was studied via kaon decay channel.

According to Glauber model [18] in absence of the collective effects, relativistic ion collision can be presented as a superposition of elementary nucleon-nucleon collisions. However, various hot and cold nuclear effects may affect the evolution of colliding system. To study the effects affecting the particle production in ultrarelativistic collisions, nuclear modification factors R_{AB} are used [19] and are calcucated as

$$R_{AB} = \frac{d^2N_{AB}/dydp_T}{N_{coll} \cdot d^2N_{pp}/dydp_T}$$

where $d^2N_{AB}/dydp_T$ ($d^2N_{pp}/dydp_T$) is the per-event yield of particle production in $A + B$ ($p + p$) collisions and N_{coll} is a number of binary nucleon-nucleon collisions. $\langle N_{\mathrm{coll}} \rangle$ values were estimated with Glauber model using Monte-Carlo simulation.

To reveal the possible QGP effects the ϕ meson R_{AB} measured in the current analysis were compared to previous results on π^0, $\pi^{\pm}$, $K^{\pm}$, K^* and $p(\bar{p})$ production in central p+Al and ^{3}He+Au collisions at midrapidity. The parameters of analysed particles are shown in the Table 1 [8].

To theoretically interpret the obtained experimental results, PYTHIA and AMPT model calculations were used.

The PYTHIA model was developed for the generation of events in high-energy collisions considering that QGP phase is not beeing formed. Any modifications in particle production are scrutinized as a result of various CNM effects.

The flow of PYTHIA program can be roughly divided in three main stages. In the first stage the nature of the event and the physics process are determined. Then all subsequent

Table 1: Particle masses, decay channels, mean lifetimes and branching ratios

Decay	Mass, MeV/c^2	Mean lifetime, fm/c	Br, %
$\pi^0 \to \gamma\gamma$	134.9770 ± 0.0005	(2.54 ± 0.54)·10^7	98.823± 0.034
$K^* \to \pi^\pm K^\mp$	891.66 ± 0.26	4.16 ± 0.05	66.6 ± 0.1
$\phi \to K^+K^-$	1019.455 ± 0.020	46.3 ± 0.4	48.9 ± 0.5
Charged hadrons ($h^\pm$)			
$\pi^\pm$	139.57018 ±0.00035	(7.7763± 0.0001)·10^{15}	-
$K^\pm$	493.677 ± 0.016	(3.6980 ± 0.0006)·10^{15}	-
$p(\bar{p})$	938.2720813± 0.0000058	stable	-

activities on the partonic level are generated, involving initial- and final-state radiation, multiple parton–parton interactions and the structure of beam remnants. As a result of this stage a realistic partonic structure is obtained. Finally, Lund string fragmentation model [20] is used for the hadronization of obtained parton configuration.

For generation of the events in relativistic p+A and A+B collisions a new model PYTHIA/Angatyr was developed [14]. Within the framework of this model, the A + B collision is described as a superposition of elementary nucleon-nucleon collisions of different types (elastic, diffractive, absorbing).

In the current study ϕ meson R_{AB} obtained via PYTHIA model were calculated as a ratio of ϕ meson invariant spectra in A+B collision calculated with PYTHIA/Angatyr to the ϕ meson invariant spectra in p+p collision calculated with PYTHIA 8, normalized to the experimental $\langle N_{\rm coll}\rangle$ values.

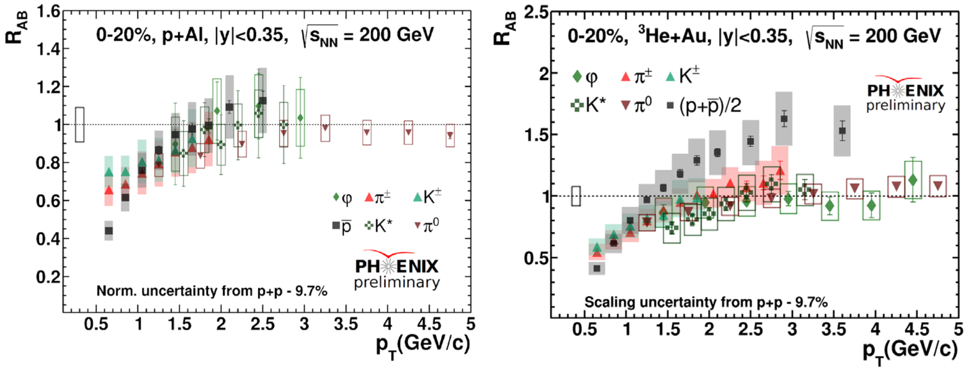
The AMPT model comprises of two different configurations - default and string melting versions - and thereby provides a comprehensive study of relativistic ion collision evolution. In AMPT model particle production from initial colliding system is considered to be from either hard or soft process. In the default version of AMPT model only partons from hard processes are involved into the Zhang's Parton Cascade (ZPC) [21], and than Lund string fragmentation model [20] is implied for hadronization. In the final stage the hadron cascade based on A Relativistic Transport model for hadrons (ART) [22] is implemented.

The string melting version of AMPT model differs from the default version in the partons cascade and the hadronization mechanism. In this case, exicited strings from soft processes are melted to the partons and are involved in the ZPC along with partons from hard processes. Therefore, QGP phase is formed. Additionaly, the coalescense from the QGP [23] is used for hadronization.

The ϕ meson R_{AB} based on AMPT model were calculated as a ratio of ϕ meson invariant p_T spectra in A+B collision to the experimental p+p baseline [24] and normalized to the experimental $\langle N_{\rm coll}\rangle$ values.

3 Results

The comparison of the ϕ meson R_{AB} to π^0, $\pi^\pm$, $K^\pm$, K^* and $p(\bar{p})$ R_{AB} is shown in the Fig. 1 for the most central (0-20% centrality class [25]) p+Al and ^{3}He+Au collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV. In p + Al collisions all light hadron production show conformity at midrapidity. Nevertheless, in central ^{3}He+Au collisions protons yields are enhanced relatively to the binary scaled yields in p+p collisions, i.e. baryon enhancement might be observed. At the same time all mesons R_{AB} independently of quark content lie on the same curve, and are equal to unity within uncertainties at high-p_T. These results might draw an assumption that



(a) (b)

Figure 1: The comparison of ϕ meson to π^0, $\pi^{\pm}$, $K^{\pm}$, K^* and $p(\bar{p})$ nuclear modification factors in (a) p+Al and (b) ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity ($|\eta|$ < 0.35). The normalization uncertainty from $p+p$ ($\sim$ 9.7%) is not shown. Here and below vertical bars correspond to statistical errors and rectangles – to systematic ones. The box near unity corresponds to the normalization uncertainty.

strangeness enhancement effect does not reveal itself in p+Al and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity.

Figure 2 shows the comparison of experimental R_{AB} results on ϕ meson production in p+Al, p+Au, d+Au [7], and ^{3}He+Au at $\sqrt{s_{NN}}$ = 200 GeV to the PYTHIA model predictions. From the figure one can seen that PYTHIA model calculations are in agreement with p+Al experimental data within uncertainties. However PYTHIA calculations fail to predict the $p/d/^3$He+Au data, having smaller ϕ meson R_{AB} values.

Figure 3 shows the comparison of experimental ϕ meson R_{AB} in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV to the AMPT model predictions. The ϕ meson R_{AB} in p+Al collisions are overpredicted by the string melting version of the AMPT model calculations, whereas the default version calculations demonstrate more conformity. The ϕ meson R_{AB} in $p/d/^3$He+Au collisions are in agreement with string melting version of the AMPT model calculations within uncertainties and are underestimated by default version of AMPT.

4 Summary

PHENIX has measured ϕ meson production in small collision systems (p+Al, p+Au, d+Au, and ^{3}He+Au) at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity (η < 0.35). The results are compared to different light hadron production in considered collisions. The comparisons of ϕ meson R_{AB} to theoretical models predictions (PYTHIA model, default and string melting versions of the AMPT model) are also provided.

The comparison of ϕ meson R_{AB} to π^0, $\pi^{\pm}$, $K^{\pm}$, K^* and $p(\bar{p})$ R_{AB} suggests that baryon enhancement might be observed in ^{3}He+Au collisions and it seems to be absent in p+Al collisions, while strangeness enhancement effect does not reveal itself in both collision systems within uncertainties. The obtained results may indicate that particle production mechanism is different in p+Al and ^{3}He+Au collisions. Moreover it evidences in favour that QGP can

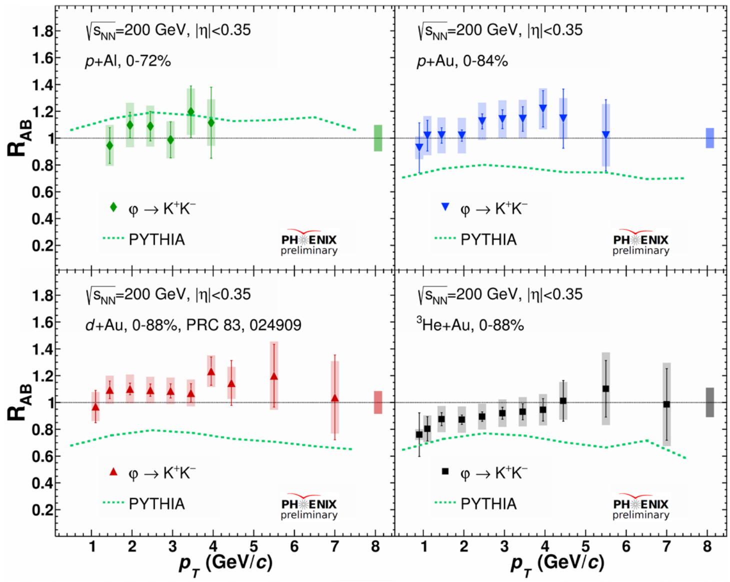


Figure 2: The comparison of ϕ meson R_{AB} in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity ($|\eta|$ < 0.35) obtained in the experiment to PYTHIA model predictions.

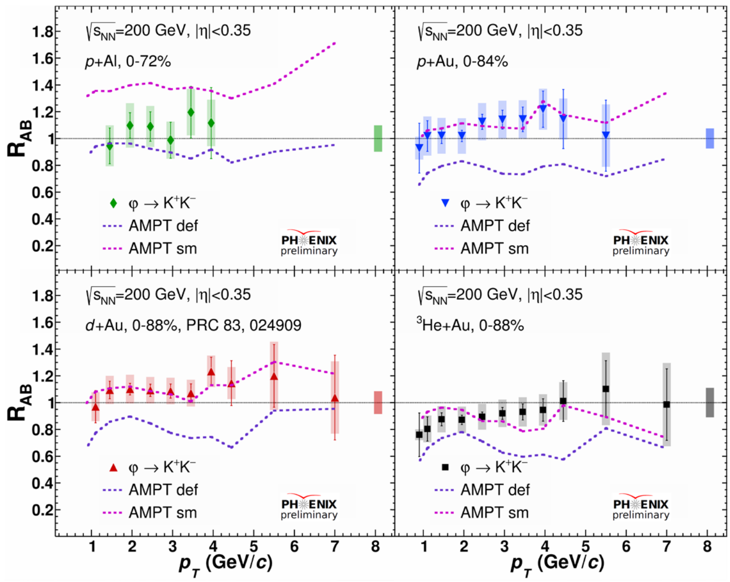


Figure 3: The comparison of ϕ meson R_{AB} in p+Al, p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity ($|\eta|$ < 0.35) obtained in the experiment to default (def) and string melting (sm) versions of the AMPT model predictions.

be formed in ^{3}He+Au collisions, but the volume and lifetime of the produced medium might be insufficient for strangeness enhancement effect observation.

The ϕ meson R_{AB} in p+Al collisions at midrapidity are well described with PYTHIA model and default version of AMPT model predictions. This may indicate that the main ϕ meson hadronzation mechanism is fragmentation, while the influence of coalescence mechanism is insignificant.

The ϕ meson R_{AB} in $p/d/^3$He+Au collisions at midrapidity are in agreement with predictions of the string melting version of AMPT model within uncertainties, whereas PYTHIA model and default version of AMPT model predictions underestimates the experimental data. This result evidences in favour that QGP is beeing formed in $p/d/^3$He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and main ϕ meson production mechanism in this case might be coalescence.

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