

Model calculations of φ -meson production in small collision systems

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Abstract. Ultrarelativistic ion collisions provide the unique possibility to study the quark-gluon plasma, a state of matter formed in the universe at the very first moments after the Big Bang. The minimal temperature and baryon density for the quark-gluon plasma formation requires scrutiny, since the signatures of the quark-gluon plasma formation are observed in large systems (such as Au+Au) at $\sqrt{s_{NN}} = 200$ GeV, whereas collective effects in $p+p$ collisions are not revealed. The φ -meson production measurements are considered to be a convenient tool to investigate the collision dynamics, as it is sensitive to the quark-gluon plasma effects. To interpret the nuclear modification effects and to study the process of the possible QGP formation the comparison with different theoretical models predictions is needed. This paper presents the comparison of the obtained experimental results on φ -meson production in small collision systems ($p+Al$, $p+Au$) at $\sqrt{s_{NN}} = 200$ GeV to default and string melting versions of the AMPT model and PYTHIA model predictions. The results indicate that the minimal conditions (temperature and baryon density) for a QGP formation may lie in between in $p+Al$ and $p+Au$ collisions.

1. Introduction

It is generally accepted that in the first moments after the Big Bang, a first order/cross-over phase transition from nuclear matter consisting of hadrons to an unbound state of quarks and gluons, also known as Quark Gluon Plasma (QGP) [1], occurred in the universe.

The detailed study of heavy-ion collisions at RHIC and LHC suggested, that the colliding system evolution is the same as the one of the early Universe [2]. Therefore, investigation of medium with partonic degrees of freedom (i.e. QGP) is one of the most significant directions of research in relativistic ion collision physics.

It was established that QGP is formed in large collision systems such as Au+Au[3], Cu + Au at $\sqrt{s_{NN}} = 200$ GeV and U+U at $\sqrt{s_{NN}} = 192$ GeV [4] whereas $p+p$ collisions dynamics is well described with pQCD calculations [5]. The recent observation of the collective behavior in small collision systems such as $p+Au$, $d+Au$, ^3He+Au provides the possibility to assume that QGP could be formed in these collisions [6]. To reveal the minimal conditions for the QGP formation in small collision systems further study is required.

One of the ways to study QGP widely used in relativistic ion collisions is measurements of light hadron production [3]. The study of nuclear modification in the collision allows observation of various hot (suggesting that QGP is formed) [7, 8] and cold (reflecting the initial state of the collision) [9, 10] nuclear matter effects. To distinguish the effects owing to QGP formation from



other effects the theoretical understanding of the processes is extremely important. It can be provided by the comparison with different model calculations.

Among the large variety of light hadrons, φ -meson is of particular interest since it contains strange quarks ($s\bar{s}$), has relatively small hadronic interaction cross-section, and longer than QGP lifetime (42 fm/c vs. 5 fm/c [2]) [11].

This paper presents the experimental results on φ -meson production in small collision systems (p +Al, p +Au) at $\sqrt{s_{NN}} = 200$ GeV and its comparison to default and string melting versions of the AMPT model [12] and PYTHIA model [13, 14] predictions.

2. Data analysis

Experimental data sets used in the analysis were collected by PHENIX experiment at RHIC [15] at the energy of $\sqrt{s_{NN}} = 200$ GeV for p +Al and p +Au collisions at midrapidity ($\eta < 0.35$).

Table 1. The φ -meson mass, decay channel, mean lifetime and branching ratio

Decay	Mass, MeV/c ²	Mean lifetime, fm/c	Br, %
$\varphi \rightarrow K^+ K^-$	1019.455 ± 0.020	46.3 ± 0.4	48.9 ± 0.5

The φ -meson production was measured using the kaon decay channel. The values of the φ -meson mass, mean lifetime and probability of decay via the kaon channel (Br) are presented in Table 1 [11].

Nuclear modification factors R_{AB} [16] of nuclei collisions are used to study collective effects, affecting the spectra and are calculated as

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

where $d^2 N_{AB}/dydp_T$ is the φ -meson invariant yield for a certain centrality bin of $A+B$ collision, $d^2 N_{pp}/dydp_T$ - is the corresponding φ -meson invariant yield for $p+p$ collisions, $\langle N_{coll} \rangle$ - the number of nucleon-nucleon collisions in the $A+B$ system for selected centrality intervals, estimated with the Glauber Monte-Carlo simulation, and f_{bias} - Bias factor [17]. The $p+p$ reference data used in the analysis is taken from [18]. In case $R_{AB} = 1$, it is likely that there are no nuclear matter effects in the nucleus collision, and the interaction can be represented as a superposition of the elementary nucleon-nucleon collisions. Otherwise, if $R_{AB} > 1 (< 1)$, then the particle yields are enhanced (suppressed), which might indicate the presence of various hot and cold nuclear matter effects in the $A+B$ collision.

Experimental values of φ -meson nuclear modification factors in p +Al and p +Au collisions at $\sqrt{s_{NN}} = 200$ GeV are compared with theoretical predictions obtained using the PYTHIA and AMPT software packages.

The Lund string fragmentation model is widely used to describe $p+p$ collisions and for QCD calculations [19]. It implies that the strong interaction, that is the gluon exchange between quarks, is represented in the form of a string, endings with quarks.

In 1997, on its basis, the PYTHIA software package was created, which aims to simulate the hadronization process, soft and hard QCD processes. The modern implemented version of the model is PYTHIA 8.303 [13], that was used in the current study for calculation of φ -meson invariant spectra in $p+p$ collisions.

To generate the collisions with heavy ions (heavier than p), a new PYTHIA/Angantyr hybrid model [14] was developed. In this model the $A+B$ collision is described as combination of the binary nucleon-nucleon collisions, considering a distinction between its different types. The φ -meson R_{AB} were estimated following the procedure used for experimental data as a ratio of the

φ -meson production spectrum in p +Al, p +Au, d +Au or ^3He +Au collision to the same hadron production spectrum in p + p collision at the same energy $\sqrt{s_{NN}} = 200$ GeV, normalized by the same as in experiment N_{coll} values. Thereby the inaccuracy of the φ -meson spectra description in p + p collisions cancels.

Another theoretical model widely used for describing the relativistic ions collision evolution is AMPT model [12], which provides a possibility to study the process of the possible QGP formation. The AMPT default model consists of the following components: the initial conditions; partonic cascade, considering confined state of quarks and gluons; the conversion from the partonic to the hadronic matter based on Lund string fragmentation model; and hadronic interactions. In the extended string melting version of the AMPT model, the strings melt into partonic degrees of freedom (QGP phase is being formed) and a quark coalescence model [20] is used to combine partons into hadrons. The baseline for the AMPT calculations of R_{AB} is φ -meson invariant p_T spectra from experimental p + p collisions [18].

3. Results

Figure 1 shows the comparison of experimental R_{AB} results on φ -meson production in p +Al and p +Au at $\sqrt{s_{NN}} = 200$ GeV to the PYTHIA/Angantyr model predictions. The results suggest that PYTHIA calculations have a discrepancy with experimental p +Au data at $\sqrt{s_{NN}} = 200$ GeV, whereas φ -meson R_{AB} in p +Al collisions are in agreement with PYTHIA result within uncertainties.

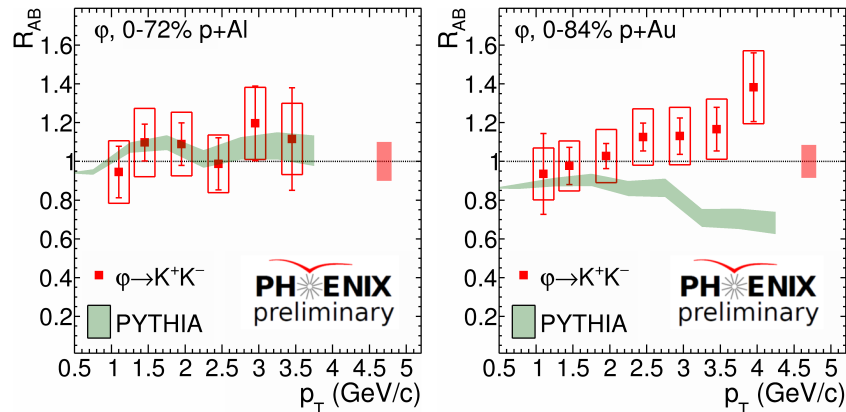


Figure 1. The comparison of the experimental R_{AB} results on φ -meson production in p +Al and p +Au collisions at $\sqrt{s_{NN}} = 200$ GeV at midrapidity ($|\eta| < 0.35$) to PYTHIA model predictions.

Figure 2 shows the comparison of experimental R_{AB} results on φ -meson production in p +Al and p +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 default string melting version of the AMPT model calculations, whereas the default version calculations demonstrate more conformity. The φ -meson R_{AB} in p +Au collisions are described in opposite way. The experimental data is in agreement with string melting version of the AMPT model calculations and underestimated by default version.

4. Conclusions

The nuclear modification factors for φ -mesons were measured in p +Al and p +Au collisions at $\sqrt{s_{NN}} = 200$ GeV at midrapidity ($|\eta| < 0.35$) and compared to default and string melting versions of the AMPT model and PYTHIA model predictions.

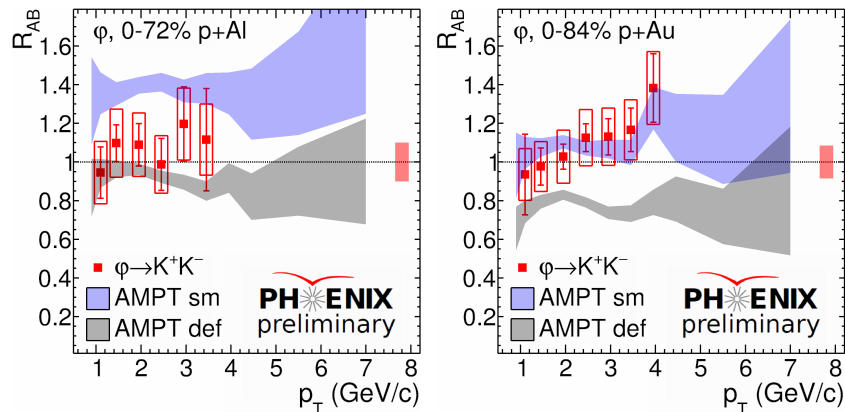


Figure 2. The comparison of the experimental R_{AB} results on φ -meson production in $p+Al$ and $p+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV at midrapidity ($|\eta| < 0.35$) to default (def) and string melting (sm) versions of the AMPT model predictions.

The φ -meson R_{AB} in $p+Al$ collisions are well described with PYTHIA model and default version of AMPT model predictions, which might indicate the absence of collective effects in the interaction.

Contrary to this, φ -meson R_{AB} in $p+Au$ collisions are in agreement with string melting version of AMPT model predictions within uncertainties, whereas PYTHIA model and default version of AMPT model predictions underestimates the experimental data. This might indicate that QGP is being formed in $p+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

In conclusion, the minimal conditions (temperature and baryon density) for a QGP formation may lie in between the conditions of $p+Al$ and $p+Au$ collisions.

The further study of QGP effects in small system collisions, such as ^3He+Au , and comparison of all available experimental results to theoretical predictions considering hot and cold nuclear matter effects is necessary to reveal possible QGP formation.

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