Phi meson measurements in Cu+Au collisions at 200 GeV and in U+U collisions at 192 GeV

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Abstract. A major objective in the field of high-energy nuclear physics is to quantify and characterize the quark-gluon plasma (QGP) formed in relativistic heavy-ion collisions, representing an ideal liquid with parton degrees of freedom [1-4]. Due to the very short lifetime the ϕ-meson can decay in QGP, thereby providing a key information on the hot and dense medium properties created in the relativistic heavy ion collisions. In central Cu+Au collision, the smaller nucleus is fully enveloped in the larger one thus reducing the contribution of nucleon-nucleon collisions in the low-density nuclear corona region. The U+U collision system provides the largest energy density available at RHIC. Also, the uranium nucleus is highly asymmetric, which leads to different parametrizations of the U+U collision geometry. In this report we will present latest results on the ϕ-meson production in Cu+Au at √s_{NN} = 200 GeV and U+U collisions at √s_{NN} = 192 GeV using the PHENIX detector at the RHIC [5]. This report presents invariant transverse momentum spectra and nuclear modification factors of ϕ-meson.

1. Introduction

A series of important discoveries in 2005 allowed all the collaborations at the Relativistic Heavy Ion Collider (RHIC) to make a statement about the detection of quark-gluon plasma (QGP), representing an ideal liquid with partonic degrees of freedom [1-4]. One of the most important discoveries was the effect of jet quenching, which consists in suppressing the yields of particles with large transverse momentum in A+A interactions [6]. This effect is explained on the assumption that the hard scattered partons, before being fragmented into hadrons, lose some of their energy in a dense nuclear matter formed in the final state. The ϕ-meson has several features that make it a valuable probe of the medium created in high energy heavy-ion collisions. As ϕ-meson is composed solely of s and anti-s quarks, its production is sensitive to the abundance of strange quarks in the system. Enhanced production of the ϕ-meson in heavy-ion collisions was proposed as a signature of QGP formation [7]. The ϕ-meson peak in the mass spectrum is well separated from the other resonances and has a narrow decay width as well, thus providing an experimentally clean signal.

The study of QGP properties and characteristics usually includes a comparison of the various observed quantities in nucleon-nucleon collisions (A+B) and in proton-proton collisions (p+p) at the same center-of-mass energy. The formation of hot nuclear matter (HNM) – QGP is one way of explaining the modifications in A+B collisions with respect to p+p. There are also alternative ways of explaining nuclear modifications, which are usually associated with the formation of cold nuclear matter (CNM). CNM is usually referred to as such effects as multiple scattering of an incident proton in a target.
nucleus (Cronin effect) [8, 9], initial-state energy loss [10], modifications of the parton distribution function [11].

One way to study HNM and CNM is the rapidity dependence of particle production in asymmetric collisions with a light scattering particle and a heavy target. Jet quenching, which is the QGP effect, was experimentally observed in central collisions of symmetric systems (Cu+Cu, Au+Au at RHIC; Pb+Pb at the LHC). Also, the PHENIX collaboration has investigated CNM effects using J/ψ meson data in Cu+Au collisions at forward and backward rapidities [12] and φ-meson data in d+Au collisions at forward, mid- and backward rapidities [13]. Comparison of production of φ-mesons in Cu+Au and d+Au systems and to J/ψ production in Cu+Au collisions may help to study the CNM and HNM effects in the φ-meson production.

In this report we will present latest results on the φ-meson production in Cu+Au at √sNN = 200 GeV and U+U collisions at √sNN = 192 GeV at forward and backward rapidities using the PHENIX detector at the RHIC. This report presents invariant transverse momentum spectra and nuclear modification factors of φ-meson.

2. Data Analysis

This report presents the data obtained by the PHENIX detector in the RHIC Cu+Au dataset from 2012. The φ-mesons are reconstructed via two muon decay channel with a branching ratio \( BR(\phi \to \mu^+\mu^-) = (2.89 \pm 0.19) \times 10^{-4} \) [14]. In this analysis, the Minimum Bias (MB) trigger is used. 4.73 billion MB events within ±10 cm z-vertex and 0%-93% centrality has passed that trigger.

The φ-meson raw yields are determined from \( \mu^+\mu^- \) candidate pair invariant mass distributions accumulated in the selected φ-meson transverse momentum and event centrality ranges. These distributions are fitted to Gaussian and polynomial (third order in data and first order in simulation), which describe the signal and the background, respectively. The φ-meson raw yields are obtained as the difference between the sum of the distribution bin content in a 2 sigma region under the peak and the polynomial fit integral in the same region. The expected width of Breit–Wigner (BW) distribution is estimated from the fit to the simulation with a natural width of φ-meson. In the fits to the data we limit the width of BW to the value extracted from simulation within ±10% window. The φ-meson yield is calculated as the sum of the bins in the histogram inside the invariant mass window [1.010, 1.028] GeV/c² less the integrated polynomial background over the same mass window.

For this analysis we used the results of GEANT3 [15] Monte-Carlo simulation of the 2012 PHENIX detector setup. Dependence of detector mass resolution on φ-meson transverse momentum is estimated from zero width simulation. Pythia 6.42 [16] obtained the reconstruction efficiency of dimuon decays of φ-mesons. Reconstruction efficiencies \( \varepsilon_{\text{re}} \) were then evaluated as a ratio of reconstructed to generated φ-mesons for appropriate kinematic bin. Obtained φ-meson yields are corrected for the limited acceptance and detector effects with the reconstruction efficiency. The detector construction causes larger acceptance in the south arm (Au-going direction) than in the north arm (Cu-going direction). Also, the \( \varepsilon_{\text{re}} \) has a centrality and \( p_T \) dependence. The high multiplicity effects influence is accounted by embedding simulated φ-meson into real Cu+Au collision events and then analysed in the same way as in real data.

The φ-meson invariant \( p_T \)-spectra are calculated as:

\[
\frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy} = \frac{1}{2\pi p_T N_{\text{events}} Br \varepsilon_{\text{eff}}(p_T) \Delta p_T \Delta y} \frac{N(\Delta p_T)}{N(\Delta p_T)}
\]

where \( p_T \) is the transverse momentum of φ-meson; \( \Delta p_T \) is the bin width in transverse momentum; \( y \) – bin width in rapidity; \( N(\Delta p_T) \) is the number of observed mesons (meson yield); \( N_{\text{events}} \cdot \text{number of sampled MB events within the relevant centrality selection} \); \( \varepsilon_{\text{eff}} \) is the reconstruction efficiency of φ-meson; \( Br \) is the branching ratio to dimuons. To study the collective effects that affect the inclusive φ-meson production spectra, nuclear modification factors of φ-meson in Cu+Au collisions are calculated according to the relation...
\[ R_{\text{CuAu}} = \frac{1}{N_{\text{coll}}} \frac{dN_{\text{CuAu}}}{d\sigma_{pp}} \]  

Where \( dN_{\text{CuAu}} = \frac{1}{2\pi p_T} \frac{d^2 N_{\text{CuAu}}}{dp_T dy} \) is the inclusive \( \phi \)-meson production spectrum in Cu+Au collisions, \( d\sigma_{pp} = \frac{1}{2\pi p_T} \frac{d^2 \sigma_{pp}}{dp_T dy} \) is the inclusive differential cross section for the \( \phi \)-meson production in p+p collisions at the same center-of-mass energy [17], \( N_{\text{coll}} \) is the number of nucleon nucleon collisions in the Cu+Au system for selected centrality intervals estimated with the Glauber-model Monte-Carlo simulation.

3. Results

Figure 1 shows the resulting invariant \( p_T \) spectra measured for \( \phi \)-meson in Run12 Cu+Au in 0% – 93% centrality, different \( y \) intervals as described in equation 1. In the Cu-going direction (1.2 < \( y \) < 2.2), fewer \( \phi \)-mesons are produced than in the Au-going direction (−2.2 < \( y \) < −1.2). This can be associated with the larger multiplicity in the Au-going direction coupled with both HNM and CNM effects.

![Figure 1](image-url)  

**Figure 1.** Invariant yield as a function of transverse momentum for 1.2 < \( |y| \) < 2.2 and 0%–93% centrality. The Cu-going direction corresponds to the forward rapidity, 1.2 < \( y \) < 2.2, while the Au-going direction corresponds to the backward rapidity, −2.2 < \( y \) < −1.2.

The nuclear modification factor \( R_{\text{CuAu}} \) as a function of transverse momentum is shown in Figure 2. Central collisions provide a dominant contribution to the nuclear modification factors. The figure 2 shows an enhancement in the Au-going direction at low \( p_T \), that is similar in scale to that observed in the Au-going direction in d+Au collisions. \( R_{\text{CuAu}} \) is consistent with unity in the Cu-going direction. That indicate similar nuclear modification between the two collision systems.

The nuclear modification factor \( R_{\text{CuAu}} \) as a function of \( y \) for two rapidity intervals, 1.2 < \( |y| \) < 1.8 and 1.8 < \( |y| \) < 2.2 are plotted at figure 3. The rapidity dependences of the nuclear modification factors of the \( \phi \)-meson in the Cu+Au and d+Au are similar. Particularly, \( \phi \)-meson production is enhanced in the Au-going direction. In Cu+Au collisions, the \( J/\psi \) meson yield is strongly suppressed in the Au-going direction compared to the \( \phi \)-meson yield at the same
Figure 2. The nuclear modification factor $R_{\text{CuAu}}$ as a function of transverse momentum for $1.2 < |y| < 2.2$ and 0%–93% centrality. The $p_T$ bins are $1 < p_T < 2.5$ and $2.5 < p_T < 5$ GeV/c, and the data points are placed at the mean $p_T$ of the bin. The Cu-going direction corresponds to the forward rapidity, $1.2 < y < 2.2$, while the Au-going direction corresponds to the backward rapidity, $-2.2 < y < -1.2$.

The $J/\psi$ meson yield is strongly suppressed in Cu+Au collisions in the Au-going direction compared to the $\phi$-meson yield in the same rapidity range. This is similar to the differences observed between $\phi$-meson and $J/\psi$ nuclear modification in d+Au collisions [12, 13]. These differences could be attributed to changes between soft and hard production mechanisms between these mesons.

Figure 3. The nuclear modification factor $R_{\text{CuAu}}$ as a function of rapidity for $1 < p_T < 5$ GeV/c and 0%–93% centrality. The rapidity bins are $1.2 < |y| < 1.8$ and $1.8 < |y| < 2.2$ and the data points are placed at the mean $y$ of the bin. Also included are previous PHENIX results for $\phi$-mesons in d+Au collisions [13] represented by open circles and $J/\psi$ mesons in Cu+Au collisions [12] represented by open triangles. Positive rapidity, $1.2 < y < 2.2$, corresponds to the Cu-going and dgoing directions, while negative rapidity, $-2.2 < y < -1.2$, is the Au-going direction.
4. Summary
In summary, invariant yields and nuclear modification factors for $\phi$-meson have been measured in Cu+Au collisions at $\sqrt{S_{NN}} = 200$ GeV for $1.2 < |y| < 2.2$ and $1.0 < p_T < 5.0$ GeV/c via the dimuon decay channel as a function of $p_T$ and rapidity. The $\phi$-meson yields in Cu+Au collisions are found to be larger in the Au-going direction than in the Cu-going direction. The same behavior, characteristic of CNM, was observed previously at PHENIX in d+Au at the same rapidity and energy [13]. In addition, at previous measurements at midrapidity for Cu+Cu and Au+Au collisions the $\phi$-meson production for these kinematics is expected to have substantial contributions from HNM. A competition between CNM and HNM production mechanisms appears relevant for $\phi$-meson production at forward rapidity for heavy-ion collisions and a comprehensive description is needed from soft and hard physics models. For a more detailed study, $\phi$-meson production in Cu+Au and U+U collisions at midrapidity will be considered.

Acknowledgments
We acknowledge support from Russian Ministry of Science, state assignment 3.1498.2017/4.6.

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