Comparative analysis of strange meson production in heavy ion collisions

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Abstract. The study of deconfinement state of nuclear matter called quark-gluon plasma (QGP) and phase transition of QGP to hadronic gas is the main goal of high energy physics. Some of the important signatures of QGP formation in heavy-ion collisions include strangeness enhancement at intermediate values of the transverse momentum ($p_T$) and a jet quenching effect at high $p_T$ values. Nuclear modification factors ($R_{AB}$) for light hadrons are used to quantify these effects. The $K^*$ and $\varphi$ mesons can serve as a good probes to investigate QGP properties, because these mesons contain (anti)strange quark and its yields can be measured in a wide $p_T$ range. Comparison of experimental data with theoretical model calculations is important for understanding the evolution of heavy-ion collision. One of the most commonly used event generators to describe experimental results of collider experiments is Pythia8. This paper shows, that Pythia8 predicts $R_{AB}$ values of $K^*$ and $\varphi$ less than $R_{AB}$ values in experimental data. Consequently, additional (hidden)strange particle production mechanisms are involved.

1. Introduction
Investigation of proton-proton and nucleus-nucleus collisions at the RHIC and LHC experiments are extremely important for the development of high-energy physics [1]. Heavy ion collisions provide opportunity to study deconfined nuclear matter called quark-gluon plasma (QGP) [2] and phase transition of QGP to hadronic gas. The base line of the relativistic heavy-ion physics is the study of p+p interactions. The dynamics of p+p collisions is well described by next-to-leading order perturbative quantum chromodynamics (NLO pQCD) [3]. Despite this success of pQCD, physics of heavy-ion collisions are still poorly understood. One of the main promising ways to study heavy ion collisions is the comparison of experimental data with theoretical predictions laid down in Monte Carlo generators of heavy ion collisions.

The most common generator for investigation of proton-proton collisions is Pythia8 [4]. Over the last three decades this event generator has succeeded in simulating the dynamics of strong and electroweak processes with very high momentum transfer scales where perturbation theory is applicable. For description of nucleus-nucleus collisions, Angantyr model has been added to Pythia8. That model includes cold nuclear matter (CNM) effects [5, 6] such as multiparton interaction, high string density. Thereby, comparison of Pythia8 predictions with experimental data allows to distinguish cold and hot nuclear matter effects occurred in heavy ion collisions.

One of the main signatures of the QGP formation is strangeness enhancement in the intermediate values of the transverse momentum ($p_T$), which manifests in increase of the yield of
hadrons containing (anti)strange quarks relative to yields of hadrons consisting of non-strange quarks [7]. Chiral symmetry restoration in the QGP is the reason that production of $s\bar{s}$ pair is more efficient than the production of $u\bar{u}$ and $d\bar{d}$ pairs [8]. Due to the content of (anti)strange quarks, $K^{*0}$ ($d\bar{s}$) and $\varphi$ ($s\bar{s}$) mesons are a suitable tool for studying of the QGP properties. The formation of these particles in heavy-ion collisions can be investigated with the help of Pythia8 Angantyr model.

Nuclear modification factor of particles are used to study collective effects in collisions of heavy nuclei. It can be calculated according to the formula:

$$R_{AB} = \frac{\sigma_{AB}^{inel}}{\sigma_{pp}^{inel}} \cdot \frac{d^2\sigma_{AB}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

where $d^2\sigma_{AB}/dydp_T$ is the particle yield in heavy ion collisions for selected centrality bin, $d^2\sigma_{pp}/dydp_T$ is the cross-section in p+p collisions, $N_{coll}$ is the average number of binary collisions per event in heavy ion collisions and $\sigma_{pp}^{inel}$ is the total inelastic cross-section, which is 42.2±3.0 mb.

This paper presents nuclear modification factors of the $K^{*0}$ meson measured in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. Comparisons of $K^{*0}$, $\varphi$, and $\pi^0$-mesons $R_{AB}$ values with Pythia8 theoretical predictions in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have been carried out.

2. Data Analysis

Experimental data used in the current analysis was obtained by the PHENIX detector at RHIC in Cu+Au and U+U collisions. The $K^{*0}$ meson are reconstructed via $K^{*0} \rightarrow K^+\pi^-$ ($K^{*0} \rightarrow K^-\pi^+$) decay channel with a branching ratio (probability of the decay via considered channel) $Br = 0.67$.

The $K^{*0}$-meson yields were extracted via invariant mass distribution of $K^\pm$ and $\pi^\pm$ mesons. Oppositely charged particles that are registered in a single collision are combined into pairs. This distribution contains both the signal or foreground, combinatorial background and noncombinatorial backgrounds. Combinatorial background arises due to random combination of $K\pi$ pair and can be taken into account by comparing the invariant mass distribution with the artificial mass distribution, obtained by combining tracks from one event with tracks from another event of the same centrality and vertex class. This procedure is called mixed-event technique [9]. The residual background, which mostly comes from other meson decays, is a smooth function of mass, so the $K^{*0}$-meson signal can be well distinguished.

The invariant mass distribution of pairs $K^\pm\pi^\mp$ was fitted with relativistic Breit–Wigner function and the second order polynomial, which describe the signal and the noncombinatorial background, respectively. The analysis method is described in the details in [10].

Invariant $p_T$-spectra of $K^{*0}$-mesons have been calculated as:

$$\frac{1}{2\pi p_T} \cdot \frac{d^2N}{dp_Tdy} = \frac{1}{2\pi p_T} \cdot \frac{1}{2} \cdot \frac{1}{N_{ext} \cdot Br \cdot \epsilon_{eff} \cdot N(\Delta p_T)} \cdot \frac{N(\Delta p_T)}{\Delta p_T \Delta dy}$$

where $p_T$ is the transverse momentum of $K^{*0}$-meson; $\Delta p_T$ is the bin width in transverse momentum; $\Delta y$ - bin width in rapidity; $N(\Delta p_T)$ is the number of observed mesons (meson yield); $N_{ext}$ - the number of sampled events within the relevant centrality selection; $\epsilon_{eff}$ is the reconstruction efficiency of $K^{*0}$-meson; $\frac{1}{2}$ points to the average of $K^{*0}$ and $\bar{K}^{*0}$.

3. Results

The nuclear modification factors $R_{AB}$ of $K^{*0}$, $\varphi$ [11, 12, 13], and $\pi^0$ [14, 15] as a function of transverse momentum $p_T$ in Cu+Au and U+U collisions are shown in Figure 1 and Figure 2,
respectively. Yields of $K^{*0}$ and $\varphi$ mesons are less suppressed in the most central collisions (Figure 1a, 2a) in the intermediate $p_T$-range than yields of $\pi^0$ mesons [16, 17]. This can be explained by strangeness enhancement effect [18]. The difference between the nuclear modification factors decreases as the centrality tends to peripheral collisions. The nuclear modification factors in the most peripheral collisions (Figure 1b, 2b) have the same values within the systematic uncertainties for all considered mesons.

**Figure 1.** Nuclear modification factors of $K^{*0}$, $\varphi$, and $\pi^0$ mesons measured as a function of $p_T$ in the most central 0-20% (a) and the most peripheral 60-80% (b) Cu+Au collisions at the energy of $\sqrt{s_{NN}} = 200$ GeV. Error bars and open boxes around points show statistical and $p_T$-dependent systematic uncertainties. Boxes at the unity shows $p_T$-independent systematic uncertainties.

**Figure 2.** Nuclear modification factors of $K^{*0}$, $\varphi$, and $\pi^0$ mesons measured as a function of $p_T$ in the most central 0-20% (a) and the most peripheral 40-80% (b) U+U collisions at the energy of $\sqrt{s_{NN}} = 193$ GeV. Error bars and open boxes around points show statistical and $p_T$-dependent systematic uncertainties. Boxes at the unity shows $p_T$-independent systematic uncertainties.
The comparison of \( K^*0, \varphi, \) and \( \pi^0 \) \( R_{AB} \) values obtained in experiment with \( R_{AB} \) values of \( K^*0, \varphi, \) and \( \pi^0 \) calculated in Pythia8 is presented on Figure 3. In central Cu+Au collisions in whole \( p_T \) range (1.5 GeV/c < \( p_T \) < 8.0 GeV/c) \( R_{AB} \) values of \( \pi^0 \) meson in experimental data and Pythia8 are in agreement within uncertainties. In the intermediate \( p_T \) range (2.0 GeV/c < \( p_T \) < 5.0 GeV/c) \( R_{AB} \) values of \( K^*0 \) and \( \varphi \) calculated in Pythia8 underpredict \( R_{AB} \) values of \( K^*0 \) and \( \varphi \) in the experimental data. This might indicate the formation of a medium (QGP) in which the production of (anti)strange quarks prevails over non-strange ones.

**Figure 3.** Nuclear modification factors of \( K^*0, \varphi, \) and \( \pi^0 \) mesons measured as a function of \( p_T \) in the central (a) and peripheral (b) Cu+Au collisions at the energy of \( \sqrt{s_{NN}} = 200 \) GeV. Error bars and open boxes around points show statistical and \( p_T \)-dependent systematic uncertainties.

### 4. Summary

This paper presents the measurements of the nuclear modification factors of \( K^*0 \) mesons in Cu+Au collisions at the energy of \( \sqrt{s_{NN}} = 200 \) GeV and U+U collisions at the energy of \( \sqrt{s_{NN}} = 193 \) GeV in the pseudorapidity region \( |\eta| < 0.35 \), in the range of the transverse momentum 1.55 < \( p_T \) < 5.75 GeV/c and for four centrality of events.

In central Cu+Au and U+U collisions in the intermediate transverse momentum range, \( \varphi \) and \( K^*0 \) meson yields are less suppressed than the yields of non-strange \( \pi^0 \)-mesons. This might indicate that additional particle production mechanisms are involved in the \( K^*0 \) and \( \varphi \)-mesons production. Pythia8 model predictions have a discrepancy with the experimental results.

It is necessary to compare the production of strange particles to other (e.g. AMPT [19], iEBE-Vishnu [20]) model predictions (especially those which include quark-gluon phase) in order to better describe the hot and cold nuclear matter effects.

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