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Production of $K(892)^{*0}$ Mesons in Small Collision Systems in the PHENIX Experiment

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Abstract—Investigation of nuclear matter effects in relativistic ion collisions, especially quark–gluon plasma (QGP) effects, is one of the main goals of the PHENIX experiment. Hadron production measurement is considered to be a useful tool for studying nuclear interactions at high energies. The $K(892)^{*0}$ meson with its constituent strange quark allows investigating such QGP effects as strangeness enhancement and flavor dependence of partonic energy loss. Measurement of K^{*0} meson production in small collision systems makes it possible to investigate dependence of QGP formation conditions on the collision system size. Invariant transverse momentum (p_T) spectra and nuclear modification factors (R_{AB}) of the K^{*0} meson as a function of p_T measured in p + Al, p + Au, and ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are presented.

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INTRODUCTION

To study nuclear matter properties under extreme conditions ($\varepsilon \geq 1$ GeV/fm^3) is an important objective in high-energy physics. The deconfinement state called quark–gluon plasma (QGP) is achieved under those conditions. In the laboratory, the QGP properties can be investigated using collisions of ultrarelativistic nuclei [1].

An indication of QGP formation is the jet quenching effect that manifests itself in suppression of particle emission at high transverse momentum p_T in central collisions of heavy ions. This phenomenon is caused by quark and gluon energy loss in the QGP. Another important indication of QGP formation is excessive emission of strange particles with intermediate transverse momenta. This effect may manifest itself in enhanced emission of hadrons consisting of (anti)strange quarks as compared to emission of hadrons consisting of the first-generation quarks (u and d) [2]. This phenomenon is a result of the restoration of chiral symmetry in the QGP that leads to a decrease in the strange quark mass and consequently to a lower threshold of strangeness production in ultrarelativistic collisions [3].

Apart from being influenced by the hot nuclear matter effects related to QGP formation, particle emission in heavy-ion collisions may also suffer influence of the cold nuclear matter effects [4], such as the Cronin effect [5], multiple parton rescattering [6], modification of initial parton distribution functions in a nucleus [7], etc. These processes may affect the change in the cross section of hard parton processes in nucleus–nucleus collisions relative to proton–proton collisions [8]. Measurement of light hadrons (including K^{*0} mesons) in collisions of small systems (such as p + Au, d + Au, and ^{3}He + Au) is a way to study the influence of cold nuclear matter on collective effects [9, 10].

In this work, possible formation of the QGP in light collision systems at the energy $\sqrt{s_{NN}}$ = 200 GeV was studied by measuring K^{*0} meson production. The short lifetime and the quark content ($\bar{d}s$) of the K^{*0} meson make it sensitive to properties of hot dense matter and production of strange hadrons from the early parton phase (i.e., QGP) [11].

MEASUREMENT TECHNIQUE

The decay channel $K^{*0} \to K^+ + \pi^-$ ($\overline{K^{*0}} \to K^- + \pi^+$) was used to detect K^{*0} mesons. The invariant mass ($m_{K\pi}$) and the transverse momentum ($p_{TK\pi}$) of a pair of the K and π mesons were calculated on the basis of the two-particle decay kinematics

$$m_{K\pi}^2 = (E_K + E_\pi)^2 - (\vec{p}_K + \vec{p}_\pi)^2, \quad (1)$$

$$p_{TK\pi}^2 = (p_{xK} + p_{x\pi})^2 + (p_{yK} + p_{y\pi})^2, \quad (2)$$

where $E_K = \sqrt{\vec{p}_K^2 + m_K^2}$ and m_K = 0.436 GeV; $E_\pi = \sqrt{\vec{p}_\pi^2 + m_\pi^2}$, and m_π = 0.139 GeV.

The invariant mass distribution of the pair of the K and π mesons with different signs involves both the K^{*0} meson signal useful for analysis and the combinatorial background that arises from a random combination of a pair of the K and π mesons that are not K^{*0} meson decay products. The combinatorial background is estimated using the event mixing technique [12]. The goal of the physical analysis is to extract K^{*0} meson yields from the invariant mass distribution of pairs of K and π mesons. Yields of K^{*0} mesons were obtained by integrating the invariant mass distribution in the interval of ± 100 MeV/c^2 near the K^{*0}-meson mass (0.895 GeV/c^2) after subtraction of the combinatorial background.

Two-dimensional invariant mass and transverse momentum distributions are divided into $p_{\rm T}$ intervals and approximated by the Breit–Wigner function in the relativistic representation convolved with the Gaussian function (RBW) for describing the K^{*0} meson signal. The residual background is approximated by the second-degree polynomial

$$\mathrm{RBW} = \frac{1}{2\pi}\frac{MM_0\Gamma}{\left(M^2 - M_0^2\right)^2 + M_0^2\Gamma^2}, \quad (3)$$

where M_0 is the Particle Data Group (PDG) mass [13] of the K^{*0} meson, Γ is the PDG decay width of the K^{*0} meson, and M is the experimental particle mass.

The invariant K^{*0} meson production spectrum in each transverse momentum interval is calculated as

$$\frac{1}{2\pi p_{\rm T}}\frac{d^2N}{dp_{\rm T}dy} = \frac{1}{2\pi p_{\rm T}}\frac{1}{N_{\rm events}Br}\frac{c_{\rm bias}}{\varepsilon_{\rm eff}\left(p_{\rm T}\right)}\frac{N\left(\Delta p_{\rm T}\right)}{\Delta p_{\rm T}\Delta y}, \quad (4)$$

where $p_{\rm T}$ is the transverse momentum of the meson; $\Delta p_{\rm T}$ is the transverse momentum interval; y is the rapidity; $N(\Delta p_T)$ is the number of mesons detected by the experimental setup (meson yields); $N_{\rm events}$ is the total number of analyzed events in the chosen centrality range; $\varepsilon_{\rm eff}(p_{\rm T})$ is the efficiency of K^{*0} meson reconstruction in the PHENIX setup by the Monte Carlo method; $Br = 0.667$ is the meson decay probability in the investigated channel; and $c_{\rm bias}$ is the Bayes factor.

Nuclear modification factors of particles in collisions of heavy nuclei are used to study collective effects influencing invariant transverse momentum spectra of particle production and are calculated according to the formula

$$R_{\rm AB} = \frac{d^2N_{\rm AB}\left(p_{\rm T}\right)/dydp_{\rm T}}{N_{\rm coll}/\sigma_{pp}^{\rm inel}\, d^2\sigma_{pp}/dydp_{\rm T}}, \quad (5)$$

where $d^2N_{\rm AB}/dydp_{\rm T}$ is the invariant spectrum of particle production in collisions of light and heavy nuclei, $d^2\sigma_{pp}/dydp_{\rm T}$ is the invariant differential cross section for hadron production in $p + p$ collisions at the same center-of-mass energy, $N_{\rm coll}$ is the average number of binary nucleon–nucleon collisions per event in p + Al, p + Au, and ^{3}He + Au interactions, and $\sigma_{pp}^{\rm inel}$ is the inelastic cross section for proton–proton scattering, here $\sigma_{pp}^{\rm inel} = 42.2$ mb [14].

RESULTS AND DISCUSSION

Figure 1 shows invariant K^{*0} meson spectra measured in p + Al and p + Au collisions in four centrality bins, and in ^{3}He + Au collisions in five centrality bins at the energy $\sqrt{s_{NN}} = 200$ GeV. Calculations were performed by formula (4).

Figure 2 shows results of measuring nuclear modification factors of K^{*0} mesons in central and peripheral p + Al, p + Au, and ^{3}He + Au interactions at $\sqrt{s_{NN}} = 200$ GeV. Calculations were conducted using formula (5).

In central p + Au collisions, nuclear modification factors $R_{p\rm Au}$ for K^{*0} mesons in the range of intermediate transverse momenta ($2 < p_{\rm T}$ (GeV/c) < 5) take on the values from 1.0 to 1.4. They are larger than $R_{\rm HeAu}$ in this $p_{\rm T}$ range. The nuclear modification factors $R_{p\rm Al}$ and $R_{\rm HeAu}$ for K^{*0} mesons in the above transverse momentum range are close to unity. In peripheral p + Al, p + Au, and He + Au collisions, $R_{\rm AB}$ are close to unity in the entire $p_{\rm T}$ range.

Figure 3 presents a comparison of the nuclear modification factors of K^{*0}, ϕ, π^0, $\pi^\pm$, and $K^\pm$ mesons and protons (antiprotons) in central and peripheral p + Al and ^{3}He + Au interactions at $\sqrt{s_{NN}} = 200$ GeV.

In central ^{3}He + Au collisions [15], $R_{\rm AB}$ of protons is larger than $R_{\rm AB}$ of mesons, while $R_{\rm AB}$ of mesons equals within the statistical and systematic errors irrespective of their quark content. In central p + Al collisions, no difference is observed for $R_{\rm AB}$ of all light hadrons. The result qualitatively agrees with the recombination model [16].

CONCLUSIONS

Invariant spectra and nuclear modification spectra of K^{*0} mesons are measured in p + Al, p + Au, and ^{3}He + Au collisions at the energy $\sqrt{s_{NN}} = 200$ GeV in the pseudorapidity region $|\eta| < 0.35$, in the transverse momentum interval $1.55 < p_{\rm T} < 5.75$ GeV/c.

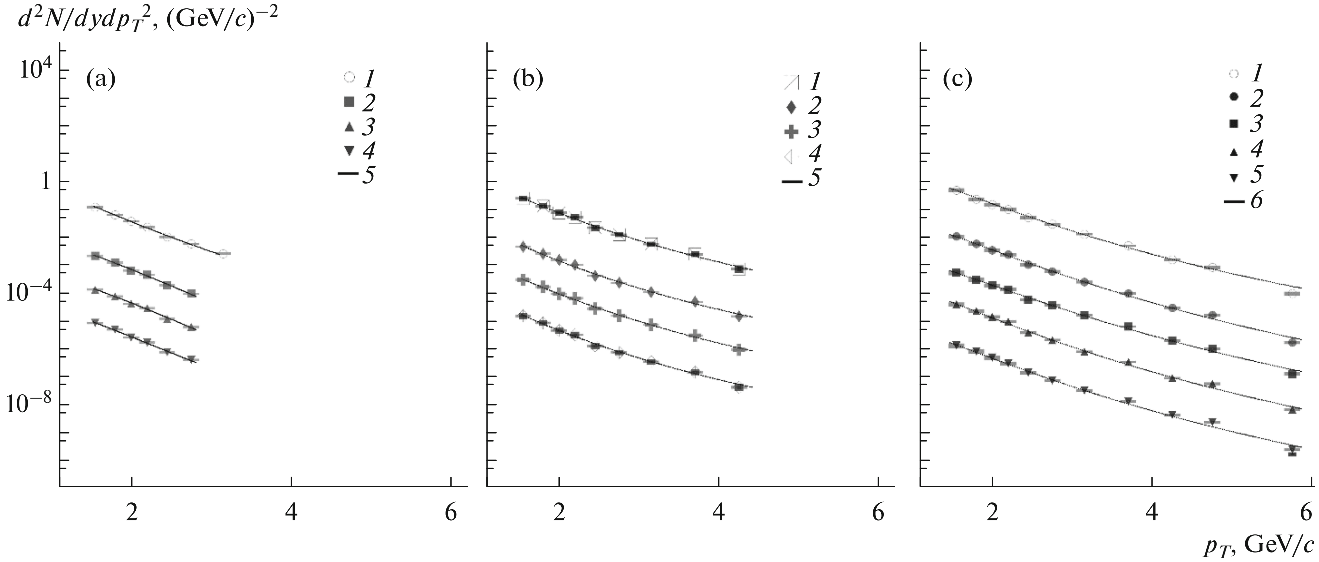

Fig. 1. Invariant spectra of K^{*0} mesons in p + Al, p + Au, and ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. (a) p + Al collisions at $\sqrt{s_{NN}}$ = 200 GeV, (*1*) 0–72%, (*2*) 0–20%, (*3*) 20–40%, (*4*) 40–72%, (*5*) approximation by the Levi function [14]; (b) p + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, (*1*) 0–84%, (*2*) 0–20%, (*3*) 20–40%, (*4*) 40–84%, (*5*) approximation by the Levi function; (c) ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, (*1*) 0–88%, (*2*) 0–20%, (*3*) 20–40%, (*4*) 40–60%, (*5*) 60–88%, (*6*) approximation by the Levi function. Error bars and rectangles correspond to statistical and systematic measurement errors.

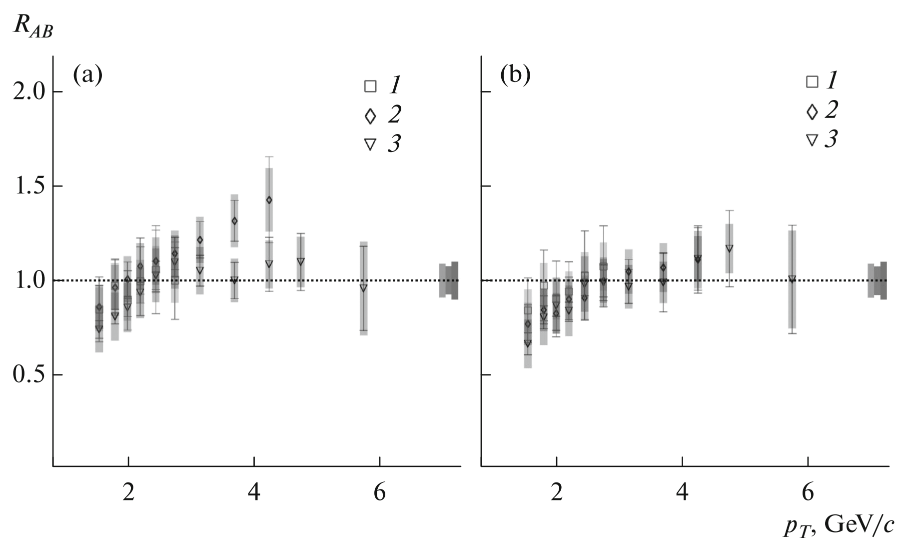

Fig. 2. Nuclear modification factors for K^{*0} mesons in p + Al, p + Au, and ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. (1) R_{AB} for K^{*0} mesons in p + Al collisions at $\sqrt{s_{NN}}$ = 200 GeV, (2) R_{AB} for K^{*0} mesons in p + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, (3) R_{AB} for K^{*0} mesons in ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Centrality: (a) 0–20%; (b) 0–72% (*1*), 0–84% (*2*), 0–88% (*3*). Error bars and rectangles correspond to statistical and systematic measurement errors.

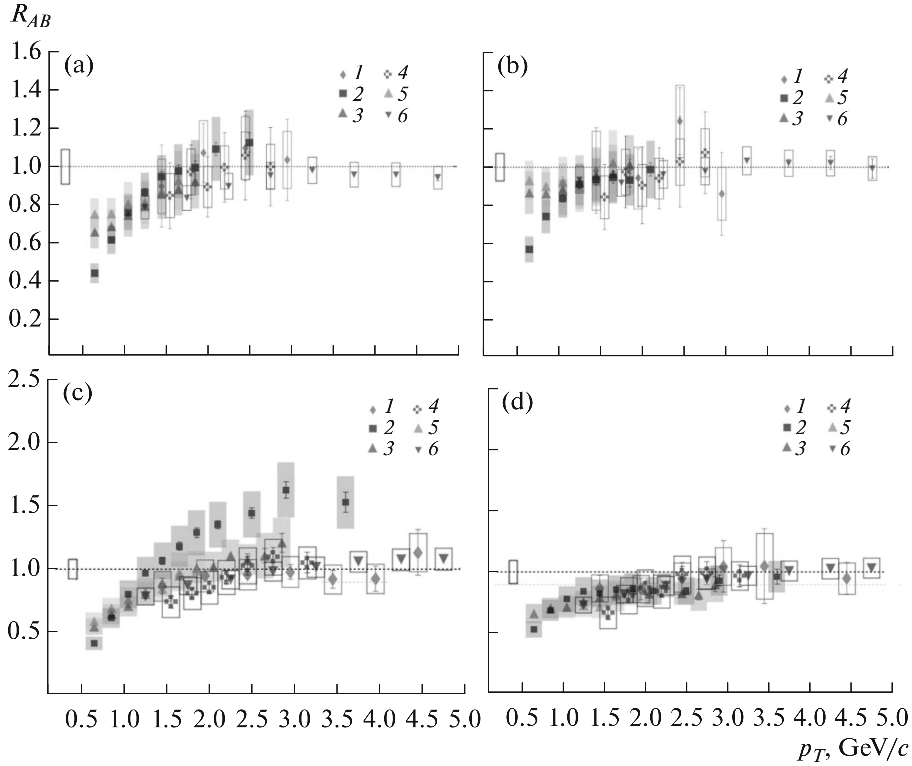

Fig. 3. Comparison of nuclear modification factors for light mesons in (a) central and (b) peripheral p + Al collisions at $\sqrt{s_{NN}}$ = 200 GeV and (c) central and (d) peripheral ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. (*1*) $\phi \to K^-K^+$; (*2*) $p(\bar{p})$; (3)$\pi^\pm$; (*4*) $K^{*0} \to K\pi$; (*5*) $K^\pm$; (*6*) $\pi^0 \to \gamma\gamma$. Error bars and rectangles correspond to statistical and systematic measurement errors.

Values of R_{AB} for the K^{*0} meson in various light collision systems (p + Al, p + Au, and ^{3}He + Au) at $\sqrt{s_{NN}} = 200$ GeV and for K^{*0}, ϕ, π^0, $\pi^\pm$, $K^\pm$, and $p(\bar{p})$ in central and peripheral p + Al and ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV were compared. Values of nuclear modification factors for the K^{*0} meson in central p + Au collisions in the intermediate transverse momentum range are larger within systematic errors than in central ^{3}He + Au collisions in the same transverse momentum range.

The values of $R_{p\mathrm{Al}}$ and R_{HeAu} for K^{*0}, ϕ, π^0, $\pi^\pm$, and $K^\pm$ mesons are unity within systematic measurement errors in all centrality intervals and in the entire p_{T} range. The results indicate that cold nuclear matter effects do not influence the difference in suppression levels of K^{*0}, ϕ [17], and π^0 observed in collisions of heavy ions [18–20].

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