Strangeness production in PHENIX experiment

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Abstract. The PHENIX experiment at RHIC has measured production of $K^\pm$, $K_s$, $K^*$ and $\phi$-mesons in $p+p$, $d+Au$, $Cu+Cu$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. While $p+p$ collisions provide a baseline and are used for precision tests of pQCD calculations, for heavier colliding systems such as $d+Au$, $Cu+Cu$ and $Au+Au$ nuclear modification factors are studied at different centralities. These systematic studies enrich current understanding of the strange meson production and its difference from light quark hadrons. The role of radial flow and coalescence in particle production is discussed.

1. Introduction
A strongly coupled quark gluon plasma (QGP) was discovered in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) [1]. Unlike up and down quarks, strange quarks are not present in colliding nuclei and are formed in collisions between constituents of the QGP. Therefore, the measurement of particles, which contain strange quarks, is an effective way to compare with hadrons that contain only light quarks and investigate the properties of the hot and dense matter formed in heavy ion collisions. Particles with strangeness content cover a wide range of masses and include mesons and baryons, which makes them a perfect tool to study features of hadron production such as radial flow and recombination at intermediate $p_T$ and energy loss flavor dependence at high $p_T$.

RHIC [2] at Brookhaven National Lab is one of the biggest operating particle accelerators designed to study heavy ion collisions at high energies. Two big experimental setups operate at RHIC nowadays: STAR [3] and PHENIX [4]. RHIC is a flexible and reliable accelerator complex with an extensive experimental program. A lot of operational time is devoted to beam energy scanning and switching between colliding nuclei. Up to now RHIC has provided 9 combinations of nuclei and 11 energies, while beam luminosity has been permanently increased from to run to run.

The PHENIX experimental setup consists of central and forward arms. Rapidity and azimuthal coverage are $|\eta| < 0.35$ and 90 degrees for each central arm (east and west), respectively. For forward arms, rapidity coverage expands from $1.2 < |\eta| < 2.2$ and azimuthal coverage is 360 degrees for each forward arm (north and south).

Charged particle track reconstruction in the PHENIX central arms is performed with drift and pad chambers [5], which have high momentum and spatial resolution. The main purpose of the electromagnetic calorimeter [6] is to measure the energy and coordinates of photons and electrons originating from the interaction region. Two time-of-flight systems [7, 8] in the east and west central arms of the PHENIX spectrometer are used for particle identification in low and intermediate transverse...
momentum regions. PHENIX also provides excellent capabilities for muon measurements at forward rapidity. The main detectors responsible for muon registration are Muon Trackers and MuID [9].

PHENIX central tracking starts to work from an approximately two meter radius outside of the central magnetic field. In order to measure the momenta of charged particles, the assumption that all of the charged particles originate from primary vertex of the collision is made. Therefore, momenta values of all particles originating from the decay of long lived hadrons, like \( \Lambda \), \( K_s \) etc, are not measured accurately, and production measurements of such particles become problematic. The PHENIX experiment is mostly focused on short lived particle production measurements. Due to small central arms acceptance, it is also difficult to measure multi-particle decays in low \( p_T \) region. This paper is devoted to measurements of short lived hadron production in intermediate and high \( p_T \) region except for \( K^\pm \) and \( \phi \)-mesons in \( e^+e^- \) decay mode also measured at low \( p_T \).

**Figure 1.** Invariant transverse momentum spectrum of \( K_s \)-mesons in p+p collisions at \( \sqrt{s_{NN}} = 200 \) GeV compared to predictions of different Pythia tunes and Phojet.

**Figure 2.** Invariant transverse momentum spectrum of \( K^* \)-meson in p+p collisions at \( \sqrt{s_{NN}} = 200 \) GeV compared to predictions of different Pythia tunes and Phojet.

2. Measurements in p+p collisions

The invariant transverse momentum spectra for \( K_s \) and \( K^* \)-mesons measured by the PHENIX experiment in p+p collisions at 200 GeV in central arms are shown in figure 1 and figure 2 respectively. Results for \( K^* \) and \( \phi \)-mesons were obtained as well and are shown in [10]. These spectra are used as a baseline to compare with more complex and heavy colliding systems, such as \( p+A \) and \( A+A \) interactions. Moreover, these spectra are needed for event generator tuning, pQCD checks and available parameterizations of fragmentation functions. As seen from the figures available, the tunes of Pythia and Phojet cannot describe the measured spectra; some of the tunes manage to partially describe spectra, while others fail.

The PHENIX experiment has also measured \( \phi \)-meson production in p+p collisions at \( \sqrt{s_{NN}} = 200 \) GeV at forward rapidity in \( \mu^+\mu^- \) decay channel. The invariant transverse momentum spectrum of \( \phi \)-meson obtained in p+p collisions at \( \sqrt{s_{NN}} = 200 \) GeV at forward rapidity is presented in figure 3. Rapidity dependence of \( \phi \)-meson production is presented in figure 4. These dependencies are used for pQCD checks, event generator tuning and to study rapidity dependence of nuclear modification factors of \( \phi \)-meson. As seen from the figures different tunes of Pythia and Phojet are not able to fully describe presented results.

The Pythia ATLAS-CSC and default tunes describe forward rapidity data except for the \( \phi \)-rapidity distribution. For the midrapidity \( K_s \) and \( K^* \)-mesons data the PYTHIA ATLAS-CSC tune and Phojet seem to work reasonably well in \( p_T \) region above 2 GeV/c.
3. \( R_{AB} \) measurements in \( d+Au, Cu+Cu \) and \( Au+Au \) collisions

In the high \( p_T \) region particle production is governed by fragmentation of hard-scattered partons. Hard processes are characterized by small cross section and large value of transferred momentum. This fact allows to describe hard processes in heavy ion collisions as superposition of nucleon nucleon interactions. Such processes can be compared with \( p+p \) collisions when scaled by the number of binary collisions \(- N_{coll}\).

The difference between heavy ion collisions and simple superposition of nucleon nucleon interactions lies in the presence of collective effects. These effects are often being studied with nuclear modification factor \( R_{AB} \), which is calculated as the ratio of particle yield in heavy ion collision to yield of same particles in proton-proton collisions scaled by number of binary collisions \(- N_{coll}\).

![Figure 3. Invariant transverse momentum spectrum of \( \phi \)-mesons in \( p+p \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV compared to predictions of different Pythia tunes and Phojet.](image1)

![Figure 4. Rapidity dependence of \( \phi \)-mesons production in \( p+p \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV compared to predictions of different Pythia tunes and Phojet.](image2)

3.1. \( R_{dA} \) measurements

Since the number of nucleons participating in \( d+Au \) interaction is rather small, such collisions are used as a control experiment where QGP is not formed. Figure 5 shows nuclear modification factors obtained in \( d+Au \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV in PHENIX central arms for most central (a) and peripheral (b) collisions.

Nuclear modification factors in peripheral collisions are equal to unity, which means that peripheral \( d+Au \) collisions can be described as a sequence of non-correlated binary collisions. In central \( d+Au \) collisions, cold nuclear matter effects can be seen: non-zero enhancement in particle production at intermediate \( p_T \) region, which is significantly different between baryons and mesons and a hint of hadron suppression in high \( p_T \) region. It is important to note that the behavior of mesons with strange quarks is similar to other mesons even though particle masses and quark contents are different.

Particle enhancement at intermediate \( p_T \) is a characteristic of Cronin effect which is often explained by multiple parton scatterings in the initial state; although this explanation cannot describe baryon/meson differences seen in the central \( d+Au \) collisions.

Figure 6 presents nuclear modification factors of \( \phi \)-mesons obtained in \( d+Au \) collisions at 200 GeV at forward and backward rapidities from most central to peripheral collisions. In the Au-going direction, clear enhancement can be seen, which is a characteristic of Cronin effect, while in \( d \)-going direction \( \phi \)-meson yields are suppressed, which may suggest influence of shadowing. This effect was previously seen by PHOBOS in charged hadron density [11]. The enhancement and suppression gradually decrease from central to peripheral collisions.
At the present moment, there is no numerical description of rapidity dependence observed for nuclear modification factors of $\phi$-mesons in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Therefore, the explanation of the Cronin effect as soft multiple parton scatterings in the initial state may not be fully justified.

Figure 5. Nuclear modification factors obtained for $\pi^0$, $K^*$, $K_s$, $\phi$-mesons and protons in PHENIX central arms in most central (a) and peripheral (b) $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Lines and boxes represent statistic and systematic uncertainties respectively.

Figure 6. Nuclear modification factors obtained for $\phi$-mesons in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV in forward and backward rapidities from most central to peripheral collisions. Lines and boxes represent statistic and systematic uncertainties respectively.

3.2. $R_{AA}$ measurements

Figure 7 shows the comparison of nuclear modification factors obtained in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for $K_s$, $K^*$, $\phi$ and $\pi^*$-mesons at different centralities. In peripheral collisions, $R_{CuCu}$ factors are equal to unity, which suggests sequential non-correlated nucleon-nucleon interactions. In central collisions, all particle yields are equally suppressed at high $p_T$ by a factor of 2. In the intermediate $p_T$
region, the suppression of particles containing strange quarks is smaller than that of pions. Despite the mass difference, all particles with strange quarks have the same suppression pattern.

Figure 8 presents $R_{AA}$ comparison between Cu+Cu and Au+Au results at $\sqrt{s_{NN}} = 200$ GeV for the similar number of nucleons participating in the interaction $- N_{\text{part}}$. In peripheral collisions, nuclear modification factors are equal to unity except for protons, which show non-zero enhancement. In central collisions, a clear suppression hierarchy can be seen: the pion’s yield is suppressed, the proton’s yield is enhanced, while particles containing strange quarks lie in between.

Intermediate $p_T$ results obtained in Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV can be qualitatively described with recombination models [12]. After comparison with data, these models indicate that for $\phi$-mesons recombination of thermal partons dominates over hard processes in a wider $p_T$ range than for pions, which can qualitatively explain the difference in $R_{AA}$ values between particles with strange quarks and pions. The difference between baryons and mesons originates from baryons obtaining larger kick in momentum than mesons, because of the presence of 3 quarks instead of 2.

Recombination models assume that there should be a source of thermal partons, which can be associated with quark gluon plasma. It is important to note that for RHIC recombination models do not give numerical predictions of particle production spectra, which can be compared with data.

**Figure 7.** Comparison of nuclear modification factors obtained in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for $K$, $K^*, \phi$ and $\pi^0$-mesons at different centralities. Lines and boxes represent statistic and systematic uncertainties respectively.

**Figure 8.** $R_{AA}$ comparison between Cu+Cu and Au+Au results at $\sqrt{s_{NN}} = 200$ GeV for the similar number of nucleons participating in the interaction. Lines and boxes represent statistic and systematic uncertainties respectively.
Another approach to describe intermediate $p_T$ difference in $R_{AA}$ is radial flow. High multiplicity of particles produced in heavy ion collisions leads to intense interaction between hadrons. The evolution of heavy ion collisions suggests that a phase of a quickly expanding strongly interacting system exists. Each hadron gets increases in velocity equal to velocity of the wave front. The heavier the particle the more momentum it gets with the same velocity increase. This approach can qualitatively describe the difference in $R_{AA}$ between mesons containing light quarks and baryons.

Figures 9 and 10 show particle yield ratios: baryons to mesons with strange quarks. Particles for these ratios were chosen to have similar masses but different quark content. Both ratios (protons to $K^*$-mesons in $p+p$ (Cu+Cu) collisions at $\sqrt{s_{NN}} = 200$ GeV and protons to $\phi$-mesons in $p+p$ (Au+Au) collisions at $\sqrt{s_{NN}} = 200$ GeV) show a hint of flattening in a $p_T$ region up to 2.5 GeV/$c$, which may suggest that spectra shapes are determined by the mass of the particle in this $p_T$ region. This fact may be the evidence of radial flow development.

PHENIX has also measured the production of particles with strange quarks in $\sqrt{s_{NN}} = 62.4$ GeV collisions. High $p_T$ particle suppression is explained by parton energy loss in a hot and dense matter formed in central heavy ion collisions. The change in collision energy changes parton energy loss and system size, and therefore allows for the study of particle production in different conditions.

Figure 11 shows the comparison of nuclear modification factors obtained for $\phi$-mesons, pions and protons in central Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Hadron yields are less suppressed; although the suppression pattern is similar to the one observed in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV. Pion yields are suppressed, and proton yields are enhanced while $\phi$-mesons, particles with strange quarks, lie in between. This fact may suggest that recombination works here as well and the source of thermal partons can be associated with quark gluon plasma.

4. Conclusions

Particles with strangeness content are a perfect tool to study hadron production mechanisms and properties of hot and dense matter formed in heavy ion collisions. Peripheral $d+Au$ and heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV follow binary scaling. Central $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV show
non-zero Cronin enhancement at intermediate $p_T$ and a hint of suppression at high $p_T$. Rapidity dependence of nuclear modification factors for $\phi$-mesons has been observed in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

![Graph](image)

**Figure 11.** Nuclear modification factors for $\phi$, $\pi^0$-mesons and protons in central Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Lines and boxes represent statistic and systematic uncertainties respectively.

In central heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV at high $p_T$ all hadrons are equally suppressed while at intermediate $p_T$ suppression of strange mesons lie between pions and protons. A similar suppression pattern is observed in heavy ion collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Recombination and radial flow are two alternative explanations of experimental results.

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