Modification of hadron production in small and large systems observed by PHENIX

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Abstract. Hadron production in \( p + p \), \( p + A \), \( A + A \) collisions gives possibility to look inside Quark Gluon Plasma, allowing to study its properties and characteristics. It is one of the main objectives for the high-energy nuclear physics. PHENIX has performed measurements of \( \pi^0 \), \( \eta \), \( K_S \), \( K^* \), \( \varphi \) and \( \omega \) meson production in \( p + p \), \( p + Al \), \( p(d,3\text{He})+Au \), \( Cu+Cu \), \( Cu+Au \), \( Au+Au \) and \( U+U \) collisions at top RHIC energies. This rich collection of data give opportunity for detailed studies of the cold and hot nuclear matter effects from small to large systems. The paper presents obtained spectra and nuclear modification factors and theoretical model predictions where available.

1. Introduction

The ultra-relativistic heavy-ion collisions provide a capability to investigate the properties of quark-gluon plasma (QGP) - state of matter at very high temperature and/or density where quarks and gluons are in the deconfined state [1]. The QGP study is one of the main goals of PHENIX experiment [2].

One of the ways to investigate QGP properties in experiments is to measure the yields of final state particles. Parton energy loss in QGP, called jet quenching [3], manifests itself as a suppression of hadron production at high transverse momentum \( p_T \) range in heavy-ion (A+B) collisions as compared to the expectations from elementary proton-proton collisions. Another signature of the QGP formation is the strangeness enhancement in A+B collisions that is an abundant production of strange flavored hadrons [4]. Particles, containing strange quarks, are considered to be a convenient tool to investigate QGP.

The light hadron production was well studied in symmetric Au+Au and Cu+Cu collisions at \( \sqrt{s_{NN}} = 200 \) GeV at RHIC [5, 6]. The paper reports new results in asymmetric Cu+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. Systematical study of light hadron production is continued in collisions of deformed uranium nuclei at \( \sqrt{s_{NN}} = 192 \) GeV, which can provide more information about jet quenching and therefore the characteristics of the QGP.

In small collision systems, the identification of collective behavior with the hydrodynamic expansion of any potential QGP requires further scrutiny [7]. The study of light hadron production with different masses, quark content, life-times and flavor in small collision systems like \( p+Al \), \( p+Au \), \( d+Au \) and \( 3\text{He}+Au \) can help to explore possible onset of collectivity in such collisions as well as cold nuclear matter effects, which are important for interpreting of heavy-ion results.
2. Large systems
The \((p + \bar{p})/2, \pi^0, \eta, K_S, K^*, \varphi, \text{and } \omega\)-meson nuclear modification factors in Cu+Au collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\) as a function of transverse momentum are shown in Fig. 1. In all figures vertical bars correspond to statistical uncertainties and rectangles – to systematic ones.

The current data suggest an ordering of nuclear modification factors at \(p_T < 5 \text{ GeV/c}\):

\[ \frac{(p + \bar{p})}{2} R_{AB} > \varphi & K^* \ R_{AB} > \pi^0 & \eta \ R_{AB} \]

The difference between \(\varphi\) and \(K^*\)-meson containing strange quarks \(R_{AB}\) and \(R_{AB}\) of \(\pi^0\)-meson and \(\eta\)-mesons can be explained in terms of strangeness enhancement. The enhancement of baryons to mesons observed in Cu+Au central collisions is qualitatively consistent with the recombination model [8]. At high \(p_T > 5 \text{ GeV/c}\) all light hadrons \(R_{AB}\) exhibit similar shape, therefore this suppression at high-\(p_T\) can be related to energy loss. In peripheral Cu+Au collisions all considered hadrons \(R_{AB}\) exhibit similar shape within systematic uncertainties.

Integrated light hadron nuclear modification factors were calculated in large systems for more detailed study. There is no difference in the integrated \(\langle R_{AB} \rangle\) of \(\varphi\)-meson between Au+Au, Cu+Cu, Cu+Au and U+U collisions and \(\langle R_{AB} \rangle\) of \(\pi^0, \eta, K_S\)-mesons between U+U, Au+Au and Cu+Cu collisions. This might indicate that the suppression level scales with the average size of the nuclear overlap region.

![Figure 1](image1.png)

**Figure 1.** Nuclear modification factors \(R_{AB}\) as a function of \(p_T\) measured for \(\varphi, \pi^0, \eta, \omega, K_S, K^*, K^\pm\), and \((p + \bar{p})/2\) in Cu+Au collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\)

![Figure 2](image2.png)

**Figure 2.** \(\langle R_{AB} \rangle\) for \(\varphi\)-mesons integrated at \(p_T > 2.0\text{GeV/c}\) in Au+Au, Cu+Cu, Cu+Au, and U+U collisions as a function of \(N_{\text{part}}\) (a). \(\langle R_{AB} \rangle\) for \(\pi^0, \eta, K_S, \omega, \) and \(\varphi\)-mesons integrated at \(p_T > 5\text{GeV/c}\) in Cu+Au, Au+Au and Cu+Cu collisions as a function of \(N_{\text{part}}\) (b).
3. Small systems

ϕ, π^0, π^±-meson and $\bar{p}$ nuclear modification factors in $p+Au$ collisions are shown in Fig. 3. The current data suggest an enhancement of $p R_{AB}$ in the central collisions whereas $ϕ$, $π^0$, $π^±$-mesons are consistent with each other. This enhancement disappears in the peripheral collisions. The same baryon vs. meson differences were observed in $d+Au$ collisions and were reproduced by recombination model [5].

![Figure 3](image1)

**Figure 3.** Nuclear modification factors of $ϕ$, $π^0$, $π^±$-meson and antiproton $\bar{p}$ in $\sqrt{s_{NN}} = 200$ GeV $p+Au$ as a function of transverse momentum plotted for the most central and most peripheral collisions.

The PHENIX collaboration measured invariant yields of $π^0$-mesons and $ϕ$-mesons in $p+Al$, $p+Au$ and $^3He+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Figure 4 shows obtained nuclear modification factors $R_{AB}$ for $ϕ$ and $π^0$-mesons in various small systems at moderate $p_T$. The nuclear modifications are different from the ones seen in heavy ion collisions. The $π^0$ modification (Figure 4 (a)) at high $p_T$ in all systems are the same for the same centrality class, with a suppression in central and an enhancement in peripheral collisions. At low $p_T$ the Cronin-like enhancement in central collisions shows a clear ordering with projectile size, and is largest for $p+Au$. In contrast no nuclear modification is observed in peripheral collisions. Nuclear modification factors of $ϕ$-mesons (Figure 4 (b)) show only a hint of ordering within uncertainties in intermediate $p_T$ range. In peripheral collisions no modification of $ϕ$ is observed.

![Figure 4](image2)

**Figure 4.** Nuclear modification factors of $π^0$ (a) and $ϕ$ (b) mesons in small systems at $\sqrt{s_{NN}} = 200$ GeV

For a more detailed study, integrated nuclear modification factors of $π^0$-mesons at the different $p_T$ range were calculated in small systems. Figure 5 (a) shows integrated $π^0 \langle R_{AB} \rangle$ at

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*Note: Images and captions have been removed for brevity.*
intermediate $p_T$ range from 4 to 6 GeV/c as function of $N_{\text{coll}}$ in $p+$Al, $p+$Au, $d+$Au, and $^3\text{He}+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The enhancement at intermediate $p_T$ range apparently scale with number of collisions. Figure 5 (b) shows the same plot for $\pi^0$, but at high $p_T > 8$ GeV/c and as a function of the number of collisions per one projectile participant $N_{\text{coll}}/N_{\text{proj}}$. In this plot the different nuclear modification factors behavior for Al and Au target systems is observed. The $\langle R_{AB} \rangle$ of $\pi^0$ seems to scale with $N_{\text{coll}}/N_{\text{proj}}$ for small systems with the same target at high-$p_T$. However, the suppression level of modification is independent of the projectile and not driven by the target thickness, therefore it seems that this suppression is not related to energy loss.

Figure 5. $\pi^0$-meson integrated nuclear modification factors in $\sqrt{s_{NN}} = 200$ GeV various collision systems at (a): transverse momentum range 4 < $p_T$ < 6 GeV/c as a function of $N_{\text{coll}}$ (b): transverse momentum range $p_T$ > 8 GeV/c as a function of $N_{\text{coll}}/N_{\text{proj}}$.

$R_{pA}$ of $h^\pm$ in 200 GeV $p+$Al/Au at forward rapidity is plotted as a function of $p_T$ in the left panels of Fig. 6. The suppression of forward hadrons is consistent with an $R_{pA}$ calculated using EPPS16+PYTHIA and nCTEQ15+PYTHIA [9, 10]. Nuclear modification factors of $h^\pm$ in $p+$Au and $p+$Al collisions at backward rapidity as a function of the number of participants ($N_{\text{part}} \approx N_{\text{coll}} + 1$ for $p + A$ systems) is shown in the right panel of Fig. 6. The results at backward rapidity are scaling with number of collisions and number of participants and are well predicted by pQCD multiscattering calculations [11].

Figure 6. $\varphi$-meson and charge hadron integrated nuclear modification factors as a function of $p_T$ in $p+$Al and $p+$Au minimum bias collisions at $\sqrt{s_{NN}} = 200$ GeV (a). $h^\pm$ integrated $R_{AB}$ as a function of $\langle N_{\text{coll}} \rangle$ in $p+$Al and $p+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV (b).
4. Conclusion
PHENIX experiment has measured invariant yields and $R_{AB}$ of $(p + \bar{p})/2$, $\pi^0$, $\eta$, $K_S$, $\varphi$, $K^*$ and $\omega$ mesons in $p(d,^3\text{He})+\text{Au}$, $\text{Cu}+\text{Cu}$, $\text{Cu}+\text{Au}$, $\text{Au}+\text{Au}$, $\text{U}+\text{U}$ collisions at top RHIC energies.

The $(p + \bar{p})/2$, $K^*$, $\varphi$, $\pi^0$, $\eta$, $K_S$, and $\omega$ exhibit three different suppression patterns in large systems collisions: $(p + \bar{p})/2$ $R_{AB} > \varphi \& K^*$ $R_{AB} > \pi^0 \& \eta$ $R_{AB}$. These results provide a contribution to the understanding of the strangeness enhancement competing with energy loss as well as additional examination of fragmentation and recombination models. There is no difference in the various light meson integrated $\langle R_{AB} \rangle$ between heavy-ion collisions systems. This might indicate that the suppression level scales with the average size of the nuclear overlap region.

In contrast to large systems in $p+$Au collisions only $(p + \bar{p})/2$ show different suppression pattern compared to $\varphi$, $\pi^0$, and $\pi^\pm$-mesons while in peripheral collisions all light hadron $R_{AB}$ consistent with each other. A hint of ordering with projectile size in central $p+$Au, $d+$Au and $^3\text{He}+$Au collisions is observed ($R_{^3\text{He}+\text{Au}} < R_{d+\text{Au}} < R_{p+\text{Au}}$ for $\varphi$ and $\pi^0$-mesons). The enhancement at intermediate $p_T$ range apparently scales with number of collisions. The suppression level of modification is independent of the projectile and not driven by the target thickness, therefore it seems that this suppression is not related to energy loss. The results at backward rapidity are scaling with number of collisions and number of participants and are well predicted by pQCD multiscattering calculations.

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