\( \Delta, K^* \) and \( \rho \) Resonance Production And Their Probing of Freeze-out Dynamics at RHIC

Haibin Zhang
for the STAR Collaboration
Brookhaven National Laboratory and Yale University
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We report the measurements of the transverse momentum spectra and invariant mass distributions of \( \Delta(1232) \rightarrow \pi p \), \( K^*(892)^{0,\pm} \rightarrow \pi K \) and \( \rho(770)^0 \rightarrow \pi^+\pi^- \) in \( \text{Au+Au} \) and \( p+p \) collisions at \( \sqrt{s_{NN}}=200 \text{ GeV} \) using the STAR TPC at RHIC. These resonances provide sensitive probes to examine the evolution dynamics in the hadronic medium through their decay and regeneration processes. The particle ratios of \( K^*/K, \rho/\pi \), \( \Delta/p \) and \( \rho/\pi \), the \( K^*, \rho \) and \( \Delta \) apparent masses and the dependence of these quantities on centrality provide evidence of dynamical interaction and re-scattering between hadrons close to freeze-out. The dependence of resonance yields on the strength of their hadronic cross sections and the lifetime between the freeze-outs will also be discussed. In the intermediate \( p_T \) region \( (2 < p_T < 4 \text{ GeV}/c) \), the nuclear modification factors \( (R_{CP} \text{ and } R_{AA}) \) of \( K^* \) are similar to those of \( K_S \) and smaller than those of baryons \( (\Lambda) \). In the intermediate \( p_T \) region, no strong dependence on the particle masses is seen in the data.

I. PHYSICS

Resonances are strongly decaying particles which have lifetimes of about a few fm/c. Compared to other stable particles (such as \( \Lambda, D^0 \), etc.), resonances have unique characteristics to probe various properties of the hot dense matter produced in relativistic heavy ion collisions. First, in a hot dense matter, resonances are in close encounter with other strongly interacting hadrons. These resonances in-medium effects related to the high density and/or high temperature of the medium can modify various resonance properties, such as masses, widths and even the mass line shapes [1]. Resonances extremely short lifetimes will enable us to directly measure these in-medium effects. Second, resonances can decay between the chemical and kinetic freeze-outs of the fire ball and their decayed daughters can undergo a period of interaction with the hadrons in the medium. This resonance decayed daughters re-scattering effect can destroy part of the primordial resonance yields [2]. Hadrons in the medium can interact with each other to re-generate resonance signals [2]. Thus measuring resonance yields and their ratios to corresponding stable particles in relativistic heavy ion collisions compared to elementary \( p+p \) collisions will enable us to probe the dynamics between the chemical and kinetic freeze-outs. Third, some resonances, such as \( K^*, \phi \), etc., are heavy mesons with their masses close to baryons. Thus we can study various physics topics through these heavy meson resonances, such as to identify whether the nuclear modification factor in the intermediate \( p_T \) region depends on mass or particle species (i.e. meson/baryon).

II. MEASUREMENTS

During the second RHIC run (2001-2002), RHIC (the Relativistic Heavy Ion Collider) performed \( \text{Au+Au} \) and \( p+p \) collisions at \( \sqrt{s_{NN}}=200 \text{ GeV} \). In the STAR (the Solenoidal Tracker at RHIC) detector, the \( \text{Au+Au} \) collision minimum bias trigger was defined by requiring coincidences between two ZDCs (Zero Degree Calorimeter) which measured the spectator neutrons. The \( \text{Au+Au} \) collision central trigger was defined using the scintillator CTB (Central Trigger Barrel) and both the ZDCs. The \( p+p \) collision minimum bias trigger was defined using coincidences between two BBCs (Beam-Beam Counter) that measured the charged particles multiplicity near beam rapidity. In this analysis, about 2M \( \text{Au+Au} \) minimum bias triggered, 2M \( \text{Au+Au} \) central triggered and 6M \( p+p \) minimum bias triggered collisions events are used, which were taken mainly using the TPC (Time Projection Chamber) in the STAR detector.

Through the ionization energy loss \( (dE/dx) \) in the TPC, charged pions and kaons are identified with momentum up to about 0.75 GeV/c, protons and anti-protons are identified with momentum up to about 1.1 GeV/c. The \( K^0(770) \) resonance invariant mass spectra are reconstructed using the like-sign technique [3] via the decay channel \( K^0 \rightarrow \pi^+\pi^- \). The \( K^*(892) \) and \( \Delta^{++}(1232) \) resonances invariant mass spectra are reconstructed using the event-mixing technique [3] via the decay channels \( K^{*0} \rightarrow K^+\pi^- \), \( K^{*\pm} \rightarrow K_S^0\pi^\pm \) and \( \Delta^{++} \rightarrow p\pi^+ \), respectively. The \( K_S^0 \) signals used in the \( K^{*\pm} \) reconstruction are measured from a decay topology method via \( K_S^0 \rightarrow \pi^+\pi^- \).
III. RESULTS

From the reconstructed $\rho^0(770)$, $K^*(892)$ and $\Delta^{++}(1232)$ resonances invariant mass spectra, a relativistic Breit-Wigner function multiplied by a phase space factor is used to fit with the resonance signals and the resonance masses are extracted from the fit. Figure 1 shows the measured $\rho^0$ and $K^{*0}$ masses in p+p and Au+Au collisions as a function of $p_T$ and the $\Delta^{++}$ mass as a function of charged hadron multiplicity in p+p and Au+Au collisions. From this figure, we can see that a significant downward $\rho^0$ (compared to the average $\rho^0$ mass measured in $e^+e^-$ and p+p collisions) and $K^{*0}$ (compared to Monte Carlo studies which have the 896.1 MeV/c$^2$ $K^{*0}$ mass input and consider the same kinematic cuts and acceptance in real data analysis) mass shift at low $p_T$ region has been observed and this downward mass shift is $p_T$ dependent. These $\rho^0$ and $K^{*0}$ mass shifts at low $p_T$ region indicate that the resonances in-medium effect may have already modified the resonances properties and low $p_T$ resonances have less chances to escape the medium compared to higher $p_T$ resonances so that low $p_T$ resonances properties can be more likely to be affected by the in-medium effects. A significant $\Delta^{++}$ (compared to the $\Delta^{++}$ mass in Au+Au) mass shift toward low masses has also been observed in p+p and Au+Au collisions and this mass shift becomes smaller as the multiplicity increases while the $\rho^0$ mass shift becomes larger as the multiplicity increases. The $\Delta^{++}$ and $\rho^0$ mass shift multiplicity dependence can be possibly explained by the resonances $t$-channel interaction in the medium which might be able to push the $\rho^0$ mass down and push the $\Delta^{++}$ mass up based on their observed masses in p+p collisions. Various theoretical calculations concerning the resonances high temperature and/or high density related in-medium effects also indicate similar resonances mass shifts.

![FIG. 1: Left: the $\rho^0$ mass as a function of $p_T$ in minimum bias p+p, high multiplicity p+p and peripheral Au+Au collisions. The brackets stand for systematic uncertainties. The dashed lines represent the average of the $\rho^0$ mass measured in e$^+e^-$ and p+p. The shaded areas indicate the $\rho^0$ mass measured in p+p. Middle: the $K^{*0}$ mass as a function of $p_T$ in minimum bias p+p and central Au+Au collisions. Shadows represent systematic uncertainties in p+p. The red line stands for the $K^{*0}$ mass 896.1 MeV/c$^2$ from p+p collisions and Au+Au collisions with different centralities (right four symbols). The black line stand for the $\Delta^{++}$ mass 1232 MeV/c$^2$ from p+p collisions.](image)

From the fit to the resonance invariant mass spectra at mid-rapidity $|y| < 0.5$ for each $p_T$ bin, the $\rho^0$, $K^*$ and $\Delta^{++}$ resonances raw yields can be extracted in p+p and various centralities in Au+Au collisions. After efficiency and acceptance correction, the above resonances invariant yield $((2\pi)^{-1}d^2N/p_Tdp_Tdy)$ or $(2\pi)^{-1}d^2N/m_Tdm_Tdy)$ spectra as a function of $m_T$ (in Au+Au collisions) or $p_T$ (in p+p collisions) can be achieved. The $m_T$ spectra in Au+Au collisions are then fit with an exponential function $(2\pi)^{-1}d^2N/m_Tdm_Tdy = dN/dy \times (2\pi T(m_0 + T))^{-1}\exp(-(m_T - m_0)/T)$ to extract the resonances mid-rapidity yields $dN/dy$ and the inverse slope parameters $T$. The resonances $p_T$ spectra in p+p collisions can be well fit with a power law function $(2\pi)^{-1}d^2N/p_Tdp_Tdy = A \times (1 + p_T/(|p_T|(n - 3)/2))^{-n}$ indicating the hard processes at larger $p_T$ region ($p_T > 2$ GeV/c) in p+p collisions.

The stable charged hadrons ($\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$) mid-rapidity yields $dN/dy$ have also been measured in the STAR experiment in Au+Au and p+p collisions at $\sqrt{s_{NN}}=200$ GeV. Thus the resonances to their corresponding stable hadrons ratios can be calculated. Figure 2 shows the $K^{*0}/K$, $\rho^0/\pi$, $\Delta^{++}/p$ and $\phi/K$ ratios as a function of number of charged hadrons in p+p and various centralities in Au+Au collisions. From this figure, we can see that the $K^{*0}/K$ ratios in Au+Au collisions are significantly smaller than in p+p collisions. This $K^{*0}/K$ ratio suppression in Au+Au collisions may indicate that between the chemical freeze-out and kinetic freeze-out, more $K^*$ resonance signals are destroyed by the daughter particles’ re-scattering effect than the signals produced by the re-generation effect, since the $\pi - \pi$ total interaction cross section, which mainly determines how strong the
The $K^*/K$, $p^0/\pi$, $\Delta^{++}/p$ and $\phi/K$ ratios as a function of number of charged hadrons in $p+p$ (open symbols) and various centralities in $Au+Au$ (solid symbols) collisions.

The re-scattering effect is significantly larger than the $K-\pi$ total interaction cross section \cite{13}, which decides the re-generation effect. In the case of the $\rho$ resonance, both the re-scattering and re-generation effects are determined by the $\pi-\pi$ total interaction cross section. Thus the $\rho^0/\pi$ ratios in both $p+p$ and peripheral $Au+Au$ collisions are comparable. In the case of the $\Delta$ resonance, the $p-\pi$ total interaction cross section is about 1.2 times of the $\pi-\pi$ total interaction cross \cite{13} so that the observed $\Delta^{++}/p$ ratios are increasing from $p+p$ collisions to peripheral $Au+Au$ and to central $Au+Au$ collisions. In the case of the $\phi$ resonance, its lifetime is relatively larger ($\sim 40$ fm/c) compared to the $\rho$, $K^*$ and $\Delta$ resonances so that a smaller portion of the $\phi$ signals may decay before the kinetic freeze-out. On the other hand, the $K-K$ total interaction cross section to produce a $\phi$ meson is small \cite{13}. Strong re-scattering and re-generation effects are not expected in the case of $\phi$ meson between the chemical and kinetic freeze-outs. Thus the $\phi/K$ ratios in $p+p$ and $Au+Au$ collisions are comparable to each other.

In the STAR experiment, the $\Lambda$ and $K^0_S$ nuclear modification factor $R_{CP} (= [d^2N/dp_T/\eta/N_{coll}]_{central}$)
\[ \frac{d^2N}{dpt/d\eta/N_{coll}} \text{ have been measured} \] . In the intermediate \( pt \) region (1.6 < \( pt < 4 \text{ GeV/c} \)), the \( \Lambda \) and \( K^0_s \) \( R_{CP} \) are significantly smaller than unity indicating the high \( pt \) jets lose energy through gluon radiation while traversing through a dense matter. It has also been observed that the nuclear modification factors are significantly different for \( \Lambda \) and \( K^0_s \) with \( pt > 1.6 \text{ GeV/c} \). It’s important to identify whether this \( R_{CP} \) difference is due to a mass effect or a particle species effect since \( \Lambda \) is a baryon and \( K^0_s \) is a meson. The \( K^* \) resonance is a meson but with its mass close to the \( \Lambda \) baryon. The left panel of Figure 3 shows the \( K^* \) nuclear modification factor \( R_{CP} \) and \( R_{AA} \) (= \( d^2N^{AA}/dp^2/\eta/d\eta \)) as a function of \( pt \) and compared to the \( \Lambda \) and \( K^0_s \) \( R_{CP} \). From this figure, we can see that both the \( K^* \) \( R_{CP} \) and \( R_{AA} \) at \( pt < 1.6 \text{ GeV/c} \) are smaller than the \( \Lambda \) and \( K^0_s \) \( R_{CP} \) indicating the \( K^* \) daughter particles’ re-scattering effect destroys low \( pt \) signals. At \( pt > 1.6 \text{ GeV/c} \), the \( K^* \) daughter particles’ re-scattering effect is weak since high \( pt \) \( K^* \) resonances have more chances to escape the fire ball and avoid the re-scattering effect. In Figure 3, we can see that both the \( K^* \) \( R_{CP} \) and \( R_{AA} \) are closer to the \( K^0_s \) \( R_{CP} \) and different from the \( \Lambda \) \( R_{CP} \) at \( pt > 1.6 \text{ GeV/c} \). Thus a strong mass dependence of the nuclear modification factor has not been observed in this analysis.

Identified hadron elliptic flow \( v_2 \) measurements have shown that in the intermediate \( pt \) region (2 < \( pt < 4 \text{ GeV/c} \)), \( v_2 \) obeys the simple scaling law \( v_2(pt) = n v_2^0(pt/n) \), where \( n \) is the number of valence quarks of the hadron \( [14] \). In the case of the \( K^* \) resonance, if the \( K^* \) is produced from a hadronizing quark gluon plasma via quark recombinations, the \( K^* \) \( v_2 \) obeys the scaling law with \( n = 2 \); if the \( K^* \) is produced in the hadronic final state via \( K - \pi \) scattering, the \( K^* \) \( v_2 \) obeys the scaling law with \( n = 4 \) \( [15] \). The final observed \( K^* \) \( v_2 \) at the intermediate \( pt \) region should be a combination of the above two extreme cases with certain fractions. It is important to measure the \( K^* \) \( v_2 \) and the combination fractions to probe the resonance production mechanism in relativistic heavy ion collisions. The right panel of Figure 3 shows the \( K^0_s \) \( v_2 \) as a function of \( pt \) measured in minimum bias triggered \( \text{Au+Au} \) collisions compared to the \( K^0_s \) (with \( n = 2 \) in the scale law) and \( \Lambda \) (with \( n = 3 \) in the scale law) \( v_2 \). Due the large errors of the the measured \( K^0_s \) \( v_2 \), no significant difference has been seen between the \( K^0_s \) \( v_2 \) and the \( v_2 \) of \( K^0_s \) and \( \Lambda \). More statistics is needed in the coming \( \text{Au+Au} \) run in 2004 at RHIC to precisely measure the \( K^* \) \( v_2 \).

**IV. CONCLUSIONS**

During the second RHIC run, the \( \rho^0(770) \), \( K^*(892) \) and \( \Delta^{++}(1232) \) resonances have been measured using the TPC of the STAR detector in \( p+p \) and \( \text{Au+Au} \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). A downward mass shift has been observed for the \( \rho^0 \) and \( K^{*0} \) resonances as a function of \( pt \) and for the \( \Delta^{++} \) resonance as a function of charged hadron multiplicity in both \( p+p \) and \( \text{Au+Au} \) collisions indicating the resonances in-medium effects might have already modified the resonances properties in the medium. The \( K^{*0}/K \), \( \rho^0/\pi \) and \( \Delta^{++}/p \) ratios in \( p+p \) and \( \text{Au+Au} \) collisions have been calculated and various dynamics in the hadron medium between chemical and kinetic freeze-outs in relativistic \( \text{Au+Au} \) collisions have been discussed. The \( K^* \) nuclear modification factor \( R_{CP} \) and \( R_{AA} \) have been measured as a function of \( pt \) and in the intermediate \( pt \) region (\( pt > 1.6 \text{ GeV/c} \)). There is no significant mass dependence has been observed for the nuclear modification factor by comparing the \( K^* \) \( R_{CP} \) and \( R_{AA} \) to the \( \Lambda \) and \( K^0_s \) \( R_{CP} \).

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