Resonances at RHIC

Zhangbu Xu†§
† Physics Department, Brookhaven National Laboratory, Upton, NY 11973

Abstract. In this report, we discuss the measurement of the hadronic decay modes of resonances in relativistic heavy-ion collisions, emphasizing on RHIC results. The study of resonances can provide: (1) the yield and spectra of more particles with different properties to study whether the system is in thermal equilibrium; (2) an independent probe of the time evolution of the source from chemical to kinetic freeze-out and detailed information on hadronic interaction at later stage; (3) the study of medium effects at a late stage of the collisions; (4) a measurement of flavor and baryon/meson dependence of particle production at intermediate $p_T (> 2 \text{ GeV/c})$.

0.1. Hadron Production in Heavy-Ion Collisions
Historically, the discovery of several important resonances ($\Sigma(1385)$, $K^*(892)$, $\rho^0(770)$, $\eta$, etc.) helped confirm the quark model (the Eightfold way) in the early 60’s [1]. Among more than four thousand particles discovered, most of them are resonances [2]. In a simple system such as $e^+e^-$ collisions at $\sqrt{s} = 91$ GeV, the production characteristics of 46 different particles have been measured [3]. With same way of counting, only 13 particles ($\pi^\pm$, $\pi^0$, $K^\pm$, $K^0$, $\rho^0$, $\eta$, $\phi$, $K^{*0}$, $J/\Psi$, $p$, $\Lambda$, $\Xi$, $\Omega$) have been measured in ultrarelativistic heavy-ion collisions up to date.

The soft processes of QCD hadronization and interaction are not calculable with a perturbative approach and instead rely on phenomenological models to describe the particle production. In a simple system, such as $e^+e^-$ collisions, the string and cluster fragmentation can be used in Monte Carlo Models or in an empirical model to describe the data [4]. In heavy-ion collisions, sufficient interactions among particles after their creation may lead to thermalization and therefore a thermal model could be used to describe the data. In fact, thermal models have been able to successfully fit the data and extract thermal parameters such as temperature and chemical potential at AGS, SPS and RHIC energies [5]. In these models, a large fraction of the measured yields of stable particles comes from the feeddown of resonance decays. In some cases, it is the dominant contribution to the measured value. For example, in JETSET and

§ mailto: xzb@bnl.gov
thermal models, less than 20% of measured pions (30% kaons) do not originate from resonances \[4, 5\], while the resonance production in elementary collisions is dominated by primary production. It is therefore important to measure resonances to constrain the feed-down and to continue testing the validity of thermal models. The same argument is applicable to transport models (such as UrQMD \[6\], AMPT \[7\]) and hydrodynamic models.

The first $K^*$ measurement by STAR on $K^*(892)/h^-$ \[8\] at $\sqrt{s}_{NN} = 130$ GeV/c is consistent with thermal fit \[5\] with the combined statistical error and systematic error of the order of 30%. The ratio $K^{*0}/K$ is less model dependent than $K^{*0}/h^-$ since both particles have similar quark content and differ only in their spin and mass. The right panel in Fig. 1 shows that this ratio is independent of beam energy in $pp$, $\bar{p}p$ and $e^+e^-$. Thermal model predicts this ratio to be 0.32 at chemical freeze-out at RHIC \[5\]. The STAR results on $K^*(892)/K = 0.26 \pm 0.03 \pm 0.07$ \[9\] in central Au+Au collisions at $\sqrt{s}_{NN} = 130$ GeV/c and $K^*(892)/K = 0.20 \pm 0.01 \pm 0.03$ \[9\] in central Au+Au collisions at $\sqrt{s}_{NN} = 200$ GeV/c with improved statistical and systematic uncertainty \[8\] show that this ratio does have a centrality dependence and is significantly lower than thermal model prediction or results from $pp$ collisions measured by the same experiment. Significant decrease of $\Lambda(1520)$ in Au+Au collisions with respect to $pp$ and thermal calculation are also observed \[10\].

\[8\]

**Figure 1.** Left panel: $K^{*0}/K$ ratio and $\phi/K^*$ ratio as function of charged hadron multiplicity in Au+Au collisions at $\sqrt{s}_{NN} = 200$ GeV. The filled symbols are results from $pp$ collisions. The line is a prediction from thermal model \[5\]. Right panel: $K^{*0}/K$ ratio and $\phi/K^*$ ratio as function of beam energy in $e^+e^−$, $pp$, $\bar{p}p$ and Au+Au collisions. Filled symbols are for Au+Au collisions and the open symbols are for elementary collisions.

Whether the remarkable success of the statistical model may simply mean phase-space dominance and the “temperature” and “chemical” potentials are nothing but Lagrange multiplier characterizing the phase-space integral \[11\] is still unclear. The existence of flow is considered a strong evidence that certain amount of rescattering
takes place among the particles in the bulk matter formed in heavy-ion collisions. However, as stated in Ref. [11], “to which extent they are sufficient to form matter in the Boltzmann sense is, however, not clear”. The strong rescattering and regeneration of resonances after chemical freeze-out as discussed are direct evidence of rescattering of particles in the bulk matter formed in heavy-ion collisions. It is difficult to imagine that such interaction will not be stronger at even earlier stage.

0.2. Time Evolution of the System

Resonances which decay into strongly interacting hadrons inside the dense matter are less likely to be reconstructed due to the rescattering of the daughter particles. On the other hand, resonances with higher \( p_T \) have a larger probability of decaying outside the system and, therefore, are more likely to be reconstructed. Examples of how these measurements can be used as a signature of freeze-out dynamics are shown in Refs. [8, 12, 13].

Recent transport model (UrQMD) calculation shows significant modification of resonance population and \( p_T \) spectrum at mid-rapidity due to rescatterings [6]. In addition, the resonance yield could be increased during the rescattering phase between chemical freeze-out (vanishing inelastic collisions for both stable particles and resonances) and kinetic freeze-out (vanishing elastic collisions) via, for example, the elastic process \( \pi K \rightarrow K^{*0} \rightarrow \pi K \). This regeneration mechanism partially compensates for resonance decays during a possible long expansion of the system and increases the observable ratio \( K^{*0}/K \). The \( \pi \pi \) scattering is the dominant process in destroying the reconstruction of \( K^* \) at later stage while the \( K\pi \) reaction is the dominant channel of \( K^* \) regeneration. The \( \pi \pi \) cross section is larger than the \( K\pi \) cross section by a factor of \( \sim 5 \) [14] around the resonances. This means that at sufficiently late stage, the rescattering of the daughters via the scattering of decay pions will be much larger than the regeneration process via the \( K\pi \) reaction. Therefore, significant effect from these rescattering should be detectable experimentally.

It has been shown in this conference that there is a significant decrease of \( K^*/K \) [9] and \( \Lambda^*/\Lambda \) [10] ratios while \( \phi/K \) ratio is independent of beam specie and centrality [10, 11]. This indicates that the yields are related to the cross section of the interactions between their decay daughters and the surrounding hadrons. It can also be seen from the \( p_T \) spectra of \( K^* \) and \( \phi \) as shown in right panel of Fig. 3 that the low \( p_T \) part of \( K^* \) is suppressed relative to \( \phi \) and other particles. Resonances being discussed are \( \phi(1020) \), \( K^{*\pm}(892) \), \( \Lambda(1520) \), \( \Sigma(1385) \), \( \Delta^{++}(1232) \), \( \rho^0(770) \) and \( f_0(980) \). The ordering of the lifetime is \( \phi(1020) > \Lambda(1520) > \Sigma(1385) > K^*(892) > f_0(980) > \Delta^{++}(1232) > \rho^0(770) \). The ordering of their regeneration cross section is \( \Delta^{++}(1232) \geq \rho^0(770) > f_0(980) > K^*(892) > \Sigma(1385) > \Lambda(1520) > \phi(1020) \). Meanwhile, the rescattering of daughters in all cases is dominated by either \( \pi\pi \) or \( p\pi \).
The ordering of their mass difference to ground state is $\Sigma(1385)/\Lambda < \Delta^{++}(1232)/p < K^*(892)/K < \Lambda(1520)/\Lambda < \rho^0/\pi < f_0/\pi$. If the rescattering is the dominant process, the resonance yields and $p_T$ spectra will be related to the lifetime and cross sections. On the other hand, if the dominant processes are both the regeneration and rescattering with a long time expansion which tend to equilibrate the yields at kinetic freeze-out, the resonance yields and $p_T$ spectra will be related to the Boltzmann factor. By systematically comparing the yields and $p_T$ distributions of resonances with other particles it may be possible to distinguish different freeze-out conditions; e.g. sudden freeze-out \cite{12,13} or a slow hadronic expansion \cite{17}. From the preliminary results of $K^*/K^-, \Lambda(1520)/\Lambda, \rho^0/\pi^-, f_0/\pi^-$ and $\phi/K^-$ \cite{18,9,10,16} measured by STAR and the comparison with thermal model predictions at chemical freeze-out \cite{5}, it seems that the ratios follow the regeneration cross section. This implies that large rescattering of daughters happens after chemical freeze-out. However, the regeneration is not enough to compensate the loss to equilibrate the yield due to fast freeze-out and/or decreasing temperature.

It has been noted that \cite{8,19,20} due to the overpopulation of $\pi$'s at kinetic freeze-out, the resonances having a $\pi$ daughter will have higher yield due to additional pion chemical potential. This will change the ordering of the particle ratios mentioned above. With these precise measurements, it is now clear that the yield of resonances are not consistent with thermal predictions \cite{5,13} at chemical freeze-out. The interpretations of these results are being actively pursued as seen in these proceedings and recent publications. The results from the combination of a thermal model as the initial condition together with the UrQMD transport model compared to the measured yields and spectra of resonances and other particles will constrain both the thermal model and evolution of the system \cite{6,21}. Additional results from $\Delta^{++}$ and $\Sigma(1385)$ are coming soon from STAR as well \cite{22}. STAR is also carrying out the studies of resonance elliptic flow ($v_2$) and decay angular distribution ($\cos \theta^*$) which are sensitive to the geometry of the system and the rescattering \cite{18,9}. These studies, however, require much more statistics and better systematical error than the yields and $p_T$ spectra.

0.3. Medium Effect in Hot and Dense Matter

Among the proposed signals of phase transitions in hot, dense nuclear matter produced via relativistic heavy-ion collisions are modifications of the meson resonance production rates and their in-medium properties \cite{19}. When the resonance lifetime is comparable to the evolution time scales of the phase transition, the measured properties associated with the resonance (such as mass, width, branching ratio, yield and transverse momentum ($p_T$) spectra) will depend upon collision dynamics and chiral properties of the medium at the high temperature and high energy density.
The famous result is the enhancement of dileptons in the medium mass range around 500 MeV by CERES/SPS [23]. Models with in-medium mass modification of \( \rho^0 \) were proposed to explain the large enhancement. The resonances measured in the hadronic decay channel probe only the late stages of the collision. It has been argued that significant effect on the reconstructed resonance mass can exist in such late stage due to phase space [20, 24], interference [25], rescattering [6] and dynamical effects [20, 19]. As shown in [18, 9] and here in Fig. 2, STAR has observed significant mass shifts in both \( \rho^0 \rightarrow \pi^+\pi^- \) and \( K^* \rightarrow \pi K \) decays [9, 18]. The mass positions are consistently lower than the PDG (Particle Data Group [3]) values and \( p_T \) dependent with a large discrepancy at lower \( p_T \) and with the measured values approaching the PDG values at higher \( p_T \). It was found that the \( \rho^0 \) mass at low \( p_T \) was about -30 MeV/\( c^2 \) and -70 MeV/\( c^2 \) below the PDG values in \( pp \) and peripheral Au+Au collisions while the \( K^{*0} \) value is about -15 MeV/\( c^2 \) below the PDG values. The statistical error of \( K^{*0} \) in Au+Au collisions is too large to be conclusive. The mass and width of other resonances (\( \phi, \Sigma^* \) and \( \Lambda^* \)) and strange particles (\( K^0_S, \Lambda \)) are consistent with the PDG values within the STAR experimental resolution [16, 10, 26].

![Figure 2.](image)

**Figure 2.** Left panel: \( \rho^0 \) mass as function of \( p_T \) in Au+Au collisions with centrality of 40-80%. The filled circles are results from the fit to a Breit-Wigner function modified by a phase-space factor. Right panel: \( K^{*0} \) mass vs \( p_T \) in \( pp \) and Au+Au collisions.

The first question one should ask is whether the mass shift of these particles (especially the copiously produced \( \rho^0 \) vector meson) has been observed anywhere. In fact, previous measurements of the \( \rho^0 \) meson in hadronic \( Z^0 \) decays by the OPAL, DELPHI and ALEPH collaborations indicate that the \( \rho^0 \) line shape is considerably distorted from a relativistic p-wave Breit-Wigner shape, especially at relatively low momentum in multipion systems [27, 28, 29, 32]. A mass shift that may be -30 MeV/\( c^2 \) or larger was observed [27, 29]. The OPAL experiment at LEP has reported \( \rho^\pm \) mass shifts of -10 to -30 MeV/\( c^2 \) in the position of the maximum of the resonance consistent with the observed \( \rho^0 \) mass shift [27]. In the paper by the DELPHI collaboration, the
low momentum region, below 2.3 GeV/c was excluded and a Breit-Wigner shape was used to fit the \( \rho^0 \) \cite{28,32}. Although the fitted mass was some five standard deviations below the PDG value, rates for the \( \rho^0 \) were nonetheless extracted using a conventional Breit-Wigner shape \cite{28,32}. The DELPHI collaboration reported the \( \rho^0 \) mass as 757\( \pm \)2 MeV/c\(^2\) \cite{28}, which should be compared to the PDG average value of 775.9\( \pm \)0.5 MeV/c\(^2\) from \( \tau \) decays and \( e^+e^- \) interactions. The ALEPH collaboration also reported that the \( \rho^0 \) resonance in the data seemed to be shifted towards lower masses \cite{29}.

In pp collisions, the \( \rho^0 \) meson has been measured at \( \sqrt{s} = 27.5 \) GeV \cite{30}. This is the only pp measurement used in the hadroproduced \( \rho^0 \) mass average reported in the PDG. In this measurement, a \( \rho^0 \) mass of 0.7626\( \pm \)0.0026 GeV/c\(^2\) was obtained from a fit by a relativistic p-wave Breit-Wigner function times the phase space \cite{30}. However, if the \( \rho^0 \) is fit only to a relativistic p-wave Breit-Wigner function, a mass shift of -30 MeV/c\(^2\) is observed.

In what follows, I would like to discuss some of the predicted effects on the mass and width of the \( \rho^0 \) in the medium.

0.3.1. Phase Space and Rescattering

If the resonance observed is generated from scattering (e.g. \( \pi^+\pi^- \rightarrow \rho, K\pi \rightarrow K^* \)), then the mass distribution will have contribution from the phase space population of the parents (which are also daughters). This distribution is characterized by the Boltzmann distribution in a thermal system that tends to populate the low invariant mass of the resonances and therefore effectively shifts the resonance peak to lower values. Since in the invariant mass distribution (without contamination from particle misidentification often present in the experiments) the parents (daughters) distribution represents the phase space and the experimental acceptance and efficiency, the \( \rho^0 \) mass is often obtained by fitting the same event distribution of \( \pi^+\pi^- \) to

\[
BG + PS \times BW = BG + BG \times BW = BG(1 + BW),
\]

where BG corresponds to the background, PS is the phase space factor and BW is the relativistic p-wave Breit-Wigner (e.g. Ref. \cite{27,28,30} which was referred to in PDG). However, this has a strong assumption that all resonances are created by final state rescattering. In elementary collisions (\( e^+e^- \), \( pp \) and \( \bar{p}p \)), some of the resonances are directly from string fragmentation which should not be modified by the phase space population of other particles. In heavy-ion collisions, such a fit is better justified since the system is much larger and lives longer. This thermal factor has been discussed in several papers \cite{20,24}. Usually, this contribution to the total mass shift is quite small (<20 MeV) and scales roughly with \( \Gamma^2 \).

A more detailed study can be done using transport models, such as UrQMD \cite{6}. The left panel in Fig. 4 shows the \( \rho^0 \) mass for different centrality from UrQMD in
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Au+Au collisions. The mass shift is about -30 MeV/c^2 for central Au+Au collisions and vanishes for peripheral collisions.

0.3.2. Interference and Bose-Einstein Effect

There are several sources of \( \pi^+\pi^- \) correlations around the \( \rho^0 \) mass:

- Direct \( \rho^0 \) production and its decay via \( \rho^0 \to \pi^+\pi^- \);
- \( \pi\pi \) scattering via \( \rho^0 \) resonant state; \( \pi^+\pi^- \to \rho \to \pi^+\pi^- \);
- Direct \( \pi\pi \) scattering via \( \pi^+\pi^- \to \pi^+\pi^- \);
- Interference between previous two scatterings;
- Other \( \pi\pi \) waves (S-, P-, D-waves).

The interference has been studied in great detail in the coherent \( \rho^0 \) photoproduction. The STAR Collaboration used the same detectors and the same beam to trigger on the \( \rho^0 \) photoproduced in ultraperipheral Au+Au collisions. The mass and width are consistent with the PDG values and the interference strength is consistent with other experiments \[31\]. It has been argued that a similar interference may happen in \( \rho^0 \) production in \( \pi^+\pi^- \) scattering \[25\]. This, however, may not be compatible with vector meson dominance (VMD) \[34\]. The \( \rho^0 \) line shape in multihadronic \( Z^0 \) decay is addressed in details in Ref. \[32\]. The final state Bose-Einstein effect was introduced to explain the \( \rho^0 \) line shape measured at LEP \[27, 28, 29, 32, 19\].

0.3.3. \( \rho^0 \) Mass In-Medium Modification

Although the effects mentioned above are interesting effects on their own, in heavy-ion collisions the most interesting effect is to identify the modification of particle (vector meson) properties in the medium. The modification of the hadron spectral distribution even at dilute systems are of particular interest since it will be a precursor toward the chiral phase transition \[19\]. A couple of calculations using Brown-Rho scaling or dynamic width broadening can qualitatively explain the mass shift \[19, 20\]. The preliminary results from STAR clearly should be compared with theoretical calculations more quantitatively in order to understand to what extent the measurements reflect a true in-medium modification \[19\]. The hadronic channel measured by STAR coupled with future measurements of the dilepton channel of vector mesons will provide an unique tool to study the in-medium effects as well as the properties of the hot and dense matter.

0.4. Mass or Baryon/Meson Dependence at Intermediate \( p_T \)

A very prominent effect seen at RHIC is that the \( p_T \) spectra of different particles are very different from that of pp collisions at intermediate \( p_T \) \[33\]. The effect has been attributed to either a baryon-meson effect or a mass dependence from radial flow. Unfortunately, the baryons are often heavier than mesons (protons are heavier
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than pions and Λ’s are heavier than kaons). The meson resonances such as φ and $K^*$ are as heavy as protons, but have the properties of mesons (two valence quarks). Therefore, it is important to study the $p_T$ spectra of these particles to distinguish baryon-meson or mass effect. The left panel in Fig. 3 depicts the particle spectra of $\pi, K, p, \Lambda, K^{*0}, \phi$ and $\Xi$ measured by all four RHIC experiments $[35, 38, 9, 10, 36, 26]$. The right panel in Fig. 3 shows the $p_T$ spectra of particles with similar mass in central Au+Au collisions measured by STAR. The $\bar{p}$ spectrum includes the hyperon decay feed-down. The spectra of $\bar{p}, \phi$ and $\Xi$ are scaled by a factor of 0.5, 2.5 and 5 respectively. It is surprising to see that these spectra are very close to each other in the intermediate $p_T$ range between 1 GeV/$c$ and 4 GeV/$c$. Although the rescattering at late stages suppresses the $K^*$ yield, the intermediate $p_T$ region ($p_T<1.5$ GeV/$c$) has a smaller effect $[6]$. For $p_T<1.0$ GeV/$c$, we can see that particles with different properties deviate from each other. For example, $\phi$ has a smaller hadron cross section and therefore has steeper slope at low $p_T$, while the $K^{*0}$ daughters rescatter in the hadronic matter and the low $p_T$ $K^{*0}$’s are suppressed. A study of the $\phi/K^*$ ratio at intermediate $p_T$ will reveal the production mechanism, e.g. fragmentation and recombination at partonic level $[37]$. From Fig. 3 we see that the $\phi/K^{*0}$ is about 0.4. This is similar to the value in $pp$ collisions, as shown in Fig. 4. This indicates that the changes from $pp$ to central Au+Au collisions are similar for the $\phi$ and $K^{*0}$. Further comparison between experimental data and theoretical predictions on these spectra are needed.

Figure 3. $\pi, K, p, \Lambda, K^{*0}, \phi$ and $\Xi$ $p_T$ spectra in central Au+Au collisions measured at RHIC. See text for details.

Since there are more quark than antiquark jets and final hadrons from gluon jets should have equal number of particles and antiparticles, one should find more $p, \Lambda, K$ and $K^*$ than $\bar{p}, \bar{\Lambda}, \bar{K}$ and $\bar{K}^*$ at mid-rapidity in heavy-ion collisions. It was found that the flavor dependence and suppression factor would be a good probe of
the energy loss and other novel effects [38, 33]. Fig. 4 shows the HIJING simulation of antiparticle to particle ratio as function of $p_T$ at midrapidity ($|y|<0.5$) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. It can be seen that the ratios of $\bar{K}/K$ and $\bar{K}^*/K^*$ have the same sensitivity to the flavor dependence of particle production as $\bar{p}/p$ and $\bar{\Lambda}/\Lambda$. In addition, the $K^{*+}$ measurement will allow the measurement of the isospin effect by using $K^{*+}/K^* \simeq 1.0$ and comparing to the flavor dependence of $\bar{K}^*/K^*$. Experimentally, the momentum resolution of lower $p_T$ particles is better than higher $p_T$ due to the rigidity (curvature) in the magnetic field (e.g. STAR). The reconstruction of two or three lower momentum daughters to form a high $p_T$ particle is less sensitive to the distortion when we want to study the flavor and isospin effect. Experiments [39] have shown that the ratios of $K^+/K^-$ and $\bar{\Lambda}/\Lambda$ at low $p_T$ do not depend on $p_T$. It is important to find the onset (on $p_T$) of the strong flavor dependence as predicted.

![Figure 4](image.png)

Figure 4. Left: $\rho^0$ mass integrated over all $p_T$ from UrQMD vs centrality in Au+Au collisions. Right: Effect of valence quark in particle ratio. HIJING simulation of antiparticle to particle ratio as function of $p_T$. In case of $K^*$, we have $\bar{K}^*/K^*$ (flavor) and $K^{*+}/K^{*0}$ (isospin).

In summary, studies of strongly interacting resonant states open new approaches to the study of relativistic heavy-ion collisions. We found that the yields of resonances deviate from thermal fits at chemical freeze-out. This is likely related to the evolution of the system and continuous interactions after chemical freeze-out. The observation of $\rho^0$ and $K^{*0}$ mass shifts in both $pp$ and Au+Au collisions are actively investigated theoretically and experimentally. These results show clear dynamic effects at the freeze-out. The transverse momentum spectra of resonances at intermediate and high $p_T$ can help disentangle different effects.

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