Resonance production in heavy ion collisions

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Abstract. Recent results of resonance production from RHIC at $\sqrt{s_{NN}} = 200$ GeV and SPS at $\sqrt{s_{NN}} = 17$ GeV are presented and discussed in terms of the evolution and freeze-out conditions of a hot and dense fireball medium. Yields and spectra are compared with thermal model predictions at chemical freeze-out. Deviations in the low transverse momentum region of the resonance spectrum of the hadronic decay channel, suggest a strongly interaction hadronic phase between chemical and kinetic freeze-out. Microscopic models including resonance rescattering and regeneration are able to describe the trend of the data. The magnitude of the regeneration cross sections for different inverse decay channels are discussed. Model calculations which include elastic hadronic interactions between chemical freeze-out and thermal freeze-out based on the $K(892)/K$ and $\Lambda(1520)/\Lambda$ ratios suggest a time between two freeze-outs surfaces of $\Delta \tau > 4$ fm/c. The difference in momentum distributions and yields for the $\phi(1020)$ resonance reconstructed from the leptonic and hadronic decay channels at SPS energy are discussed taking into account the impact of a hadronic phase and possible medium modifications.

1. Introduction

In heavy ion collisions an extended hot and dense fireball medium is created. The properties (mass, width, momentum distribution, yield) of the produced resonances depend on the fireball conditions of temperature and pressure. During the fireball expansion the short lived resonances and their hadronic decay daughters may interact with the medium. Two freeze-out surfaces can be defined, chemical and thermal, representing the conditions when inelastic and elastic interactions cease respectively. In a dynamical evolving system produced resonances decay and may get regenerated. Hadronic decay daughters of resonances which decay inside the medium may also scatter with other particles from the medium. For SPS and RHIC energies these are mostly pions. This results in a signal loss, because the reconstructed invariant mass of the decay daughters no longer matches that of the parent. Leptonic decay daughters on the other hand are unaffected by the nuclear medium due to their small interaction cross section. The rescattering and regeneration (pseudo-elastic) processes for resonances and their decay particles depend on the individual cross sections and are dominant after chemical but before the kinetic freeze-out. These interactions can result in changes of the reconstructed resonance yields, momentum spectra, widths and mass positions.
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Rescattering will decrease the measured resonance yields while regeneration will increase them.

Microscopic model calculations attempt to include every step in a heavy ion interaction in terms of elastic and inelastic interactions of hadrons and strings. They are therefore better able to describe the rescattering and regeneration of the resonances from fireball interactions. The prediction of a specific model (UrQMD) is a signal loss for some of the resonances due to more rescattering than regeneration in the low momentum region $p_{T} < 1$ GeV for the hadronic decay channels $^{1,2}$ Comparisons between the yield and momentum spectra of the hadronic and leptonic decay channels can indicate the magnitude of the rescattering and regeneration contribution between chemical and thermal freeze-out. In order to try to understand the medium effect during the evolution and expansion of the hot and dense fireball, we compare resonance yields and spectra (width and mass) from elementary p+p and heavy ion collisions and the results from the leptonic and hadronic decay channels. An observed difference may give an indication of in-medium modification of resonance properties.

2. Resonance Reconstruction

The signal loss due to rescattering is caused by the method of measurement, the invariant mass is not properly reconstructed if one of the decay daughters rescatters with another particle of the surrounding medium. All the resonances are reconstructed by the invariant mass of the decay daughters. The decay candidates are identified by different techniques, their energy loss (dE/dx), energy or displaced vertex (V0-reconstruction). The resonance signal is obtained by the invariant mass reconstruction of each daughter combination and subtraction of the combinatorial background calculated by mixed event or like-signed techniques. The resonance ratios, spectra and yields are measured at mid-rapidity for RHIC at $\sqrt{s_{NN}} = 200$ GeV and over 4$\pi$ for SPS at $\sqrt{s_{NN}} = 17$ GeV. The central trigger selection for Au+Au collisions at RHIC takes the 5% or 10% and for Pb+Pb collisions at SPS the 5% of the most central inelastic interactions. The setup for the p+p interaction is a minimum bias trigger.

3. Resonance Yields

The resonance multiplicities at mid-rapidity for p+p and peripheral to central Au+Au collisions at RHIC energies are obtained for $\phi(1020)$ $^{3}$, $\Delta(1232)^{++}$ $^{4}$, K(892) $^{5}$, $\Lambda(1520)$ $^{6,7}$ and $\Sigma(1385)$ $^{8}$. In order to compare different collision systems we normalize the yield to the yield of the corresponding measured ground state particle. Under the assumption that the Au+Au collision system is only a superposition of p+p collisions we would expect the same resonance/non-resonance ratio. Fig11 shows the resonance/non-resonance ratios normalized to the K(892)/K measurement in p+p. The $\Lambda(1520)/\Lambda$ and the K(892)/K ratio decreases from p+p to peripheral and central Au+Au collisions.
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Figure 1. Resonance/non-resonance ratios of $\phi/K^-$ [8], $\Delta^+/p$ [4], $\rho/\pi$ [9], $K^{0}/K^-$ and $\Lambda(1520)/\Lambda$ [6, 7] for p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity. The ratios are normalized to the $K(892)/K^-$ ratio measurement in p+p. Statistical and systematic errors are included.

The observed ratios cannot be described by thermal model predictions [10], most likely because rescattering of the decay daughters in the medium and regeneration are contributing to the yield. If only rescattering occurs then the shorter lifetime of the $K(892)$ (4 fm/c) compared to the $\Lambda(1520)$ (13 fm/c) would result in a larger suppression for $K(892)/K$ than for the $\Lambda(1520)/\Lambda$ ratio. This implies that the regeneration cross section is larger for the $K^+\pi$ channel than for the $K+p$ channel. The $\phi(1020)/K$ ratio is constant in all collision systems within errors and can be described with the thermal model, which is expected because only a small fraction of the $\phi(1020)$ are decaying inside the fireball due to the long lifetime of the $\phi(1020)$ (46 fm/c). The expected contribution of rescattering for the short lived $\Delta(1232)$ (1.7 fm/c) is larger than that for the $K(892)$ and the $\Lambda(1520)$. However the $\Delta(1232)/p$ ratio does not decrease from p+p to Au+Au collisions and is on the order of 41% ± 22% higher than the thermal model prediction. This indicates a large cross section for the regeneration of $\Delta(1232)$ resonance in the p+π channel. The $\Delta(1232)$ can be re-created until $T = 80-90$ MeV close to the kinetic freeze-out [11]. The $\Sigma(1385)/\Lambda$ ratio appears to follow the same trend as the $\Delta(1232)/p$ [8]. This implies that the $\Lambda+\pi$ regeneration cross section is nearly as high as the $p+\pi$ regeneration cross section. From this observation we can conclude that
there is a ranking order of the cross section for the different regeneration processes:
\( \sigma_{p+\pi} \geq \sigma_{\Lambda+\pi} > \sigma_{K+\pi} > \sigma_{K+p} \). The microscopic model calculations (UrQMD) are able to reproduce the resonance/non-resonance ratios in Au+Au collisions for most resonances \[1, 2\]. However the UrQMD prediction for the \( \Sigma(1385)/\Lambda \) ratio is in the order of 40\% \(\pm\) 20\% too high. In this calculation the assumption was made that the \( \Lambda+\pi \) regeneration cross section is the same than for \( p+\pi \). The trend of data would suggest that the \( \Lambda+\pi \) regeneration cross section is smaller than the \( p+\pi \) cross section.

4. Momentum Distribution

Fig. 2 shows the momentum distribution of \( \Delta^{\prime+} \), \( \rho \), \( K(892) \) and \( \phi(1020) \) from central (\( \rho \) peripheral) Au+Au collisions from the STAR experiment at RHIC compared to thermal model predictions \[12\].
Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV confirm this trend. A strong increase $\langle p_T \rangle$ for resonances is observed from p+p to the most peripheral Au+Au measurement. The same trend is not present for the ground state particles (see Fig 3) [3, 4, 5].

![Graph showing $\langle p_T \rangle$ for resonances and ground state particles in p+p and Au+Au collisions versus number of charged particles](STAR_preliminary)

**Figure 3.** The $\langle p_T \rangle$ for resonances and ground state particles in p+p and Au+Au collisions versus number of charged particles [3, 4, 5, 8].

5. Time Scale

Depending on the length of the time interval between chemical and kinetic freeze-out, $\Delta \tau$, the magnitude of the suppression factor of the measured resonance will change due to contributions from rescattering and regeneration. A model using thermally produced particle yields at chemical freeze-out and an additional rescattering phase, including the lifetime of the resonances and decay product interactions within the expanding fireball, can yield an estimated $\Delta \tau$ [13, 14, 15]. This model does not include regeneration and therefore predicts a lower limit of the lifetime between the two freeze-out surfaces. The two ratios K(892)/K and Λ(1520)/Λ are expected to have a larger rescattering contribution. A $\Delta \tau > 4$ fm/c results if chemical freeze-out occurs at 160 MeV.

6. Leptonic and Hadronic Decay Channels

In heavy ion collisions direct comparisons of the spectra and yields obtained from leptonic and hadronic decay channels of a single resonance may show the influence of the hadronic interaction phase after chemical freeze-out. The $\phi(1020)$ is one of the
resonances where we have measurements of the leptonic and hadronic decay channel. At SPS energies the reconstruction of the \( \phi(1020) \) in the different decay channels seemingly leads to differing \( \phi(1020) \) kinematics and yields (\( \phi \) puzzle).

Fig. 4 shows the transverse momentum distribution from the hadronic decay \( \phi \rightarrow K^+ + K^- \) (NA49) and the leptonic decay \( \phi \rightarrow \mu^+ + \mu^- \) (NA50) \([16,17]\). The inverse slope parameter from fits to the momentum spectra, indicated as lines, are \( T = 305 \pm 15 \) MeV for hadronic decay and \( T = 218 \pm 10 \) MeV for leptonic decay. The extracted yield from the extrapolation of the momentum spectrum of the leptonic decay is a factor of \( 4 \pm 2 \) higher than the one for the hadronic decay. Measurements of the \( \phi(1020) \) reconstructed via the hadronic and leptonic decay from CERES presented by A. Marin \([21]\) at this conference confirm the NA49 results (\( \phi \rightarrow K^+ + K^- \)) in terms yield and momentum distribution and the NA50 yield for the \( \phi \rightarrow e^+ + e^- \) decay. First results from NA60 experiment show an improved invariant mass signal (significance > 20) for the \( \phi \rightarrow \mu^+ + \mu^- \) channel \([22]\), which should result in a conclusive contribution to the \( \phi \) puzzle at SPS.

Microscopic calculations (UrQMD) estimate a suppression of 20-30\% of the \( \phi(1020) \) yield in the hadronic decay channel due to rescattering of the kaon decay daughters in the low momentum region \( p_T < 1 \) GeV \([1,2]\). The rescattering is negligible for the leptonic decay due to the very low cross section of interaction with the hadronic phase. Therefore the lower signal in the low momentum region of the hadronic decay (NA49)
compared to the leptonic decay (NA50) is in agreement with the model. However the signal loss of 20-30% from the model calculation is not sufficient to explain the factor of 4 ± 2 in the measured yield of the data.

This allows for possible medium effects on the resonance production which are likely to occur at an earlier stage, before chemical freeze-out. Alternative calculations to describe in medium modification of the \( \phi(1020) \) resonance were published recently by K. Haglin and E. Kolomeitsev [18, 19, 20]. Here the lifetime of the \( \phi(1020) \) resonance is modified towards smaller lifetimes due to modification of the spectral functions in the hot and dense fireball and therefore more of the \( \phi(1020) \) resonances decay inside the medium. This will introduce a larger signal loss due to rescattering of the hadronic decay daughters.

7. Feeddown from Resonances

Finally I would like to conclude with a small remark. If we interpret particle spectra of ground state particles we have to take into account that a large fraction of the particles are coming from resonance feeddown, as already pointed out by E. Schnedermann et al. [23]. For the proton we have 42% from \( \Lambda \)'s, 21% from \( \Delta \)'s, and 11% from \( \Sigma^0 \)'s (statistical model [24]). Therefore only 26% of the protons are primary produced protons. 35% of the \( \Lambda \)'s are from \( \Sigma(1385) \) and 20% from \( \Sigma^0 \)'s (statistical model) decays. If we take the contribution of multiple rescattering and regeneration processes during the expansion of the fireball source into account, the number of primary particles will be further reduced, because the regeneration does not necessarily involve the actual resonance decay particles. Since the lifetimes of the \( \rho \) and \( \Delta(1232) \) are very short compared to the lifetime of the fireball, we would expect a larger number of \( \pi \)'s and protons coming from a \( \Delta(1232) \) decay than from higher mass baryons. Therefore many \( \pi \)'s and protons are coming from a later stage of the evolution of the fireball source and their momentum distribution might be different from the primary produced particles. Conclusions based on the momentum distributions of particle spectra in terms of flow and freeze-out temperatures have to take the contribution from resonance decays into account.

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