Resonance Absorption and Regeneration in Relativistic Heavy Ion Collisions

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The regeneration of hadronic resonances is discussed for heavy ion collisions at SPS and SIS-300 energies. The time evolutions of Δ, ρ and ϕ resonances are investigated. Special emphasize is put on resonance regeneration after chemical freeze-out. The emission time spectra of experimentally detectable resonances are explored.

The study of strongly decaying resonances is one of major topics that came up in recent years [1]. Recently, detailed experimental studies of hadron resonances became available. Up to now $\rho, \Lambda^*, \Sigma^*\Delta, K^{0*}$ and Φ resonances have been reconstructed from hadron correlations in heavy ion reactions at the full SPS and highest RHIC energy [2–9].
This exciting new data poses serious constraints on our understanding and modeling of hadronic interactions in the late expansion stage of massive nuclear collisions. Especially the apparent suppression of K^{0*} and Λ^* resonances (together with Δ enhancement in central reactions compared to the thermal model estimates [10] questions the notion of an instantaneous chemical freeze-out as assumed in thermal models. In fact, it demonstrates that the ideas of a directly observable Quark-Gluon-Plasma (QGP) fireball without a longliving hadronic stage in scenarios with strong supercooling [11] seems not in line with the experimental data. Whether hadronic statistical models can be used to understand the resonance data is still not clear, see e.g. [12,13]
First ideas how to understand a modification of the resonance yields had been brought forward by [8] where a modification the inverse slope of the Φ meson was discussed. Later this idea was picked up by [14] in terms of a thermal models plus absorption afterburner. However, this thermal absorption model fell short of the data, because it neglected the regeneration of hadron resonances in the expansion stage.
Comprehensive studies of $\rho, K^{0*}, \Sigma, \Lambda$ and Λ^* hadron resonance yields and spectra within a transport approach were presented in [15–17] for SPS and RHIC energies. For Pb+Pb collisions at 158 AGeV it was shown that within the transport simulation a chemical freeze-out (where most of the inelastic interactions cease and elastic and pseudo-elastic interaction take over) around 6 fm/c is present. However, it was also shown that elastic and pseudo-elastic reactions might still alter the reconstructable resonance yields and distributions due to absorption of daughter particles and regeneration (refeeding).

As shown in Fig. 1, recent data by the STAR Collaboration [2] indicates interesting resonance to ground-state ratios as a function of centrality. E.g., the K^{0*}/K and the $\Lambda^*/(\Lambda+\Sigma^0)$ ratios decrease, while the Φ/K and Δ^{++}_{1232}/p ratios stay constant or might even show a slight increase with centrality.

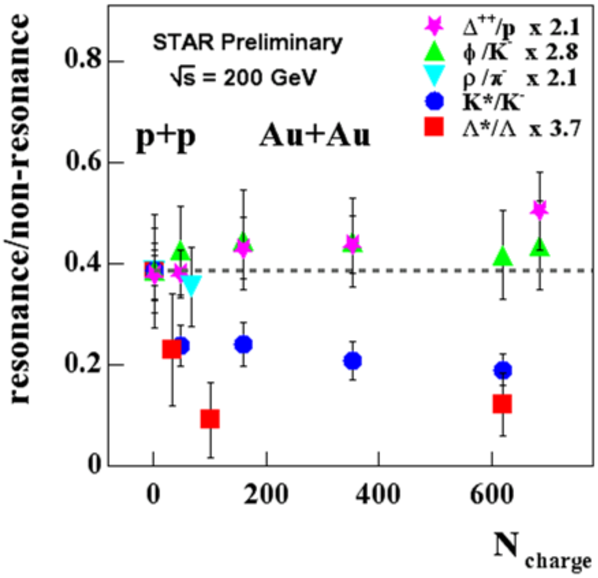

FIG. 1. Compilation of measured particle ratios in pp and Au+Au collisions at $\sqrt{s}$ = 200 AGeV as a function of centrality. Figure is taken from [2]

Let us now investigate possible mechanisms that produce at the same time a slight increase of the Δ^{++}/p ratio and a suppression of K^*/K ratio. As a tool we employ the UrQMD model [18,19] which is based on the covariant propagation of hadrons, resonances and strings.

In the present calculations, modifications due to rescattering and regeneration are present in nearly all spectra and yields of short lived resonances. Especially for the Δ_{1232} and the ρ^0_{770}, which both have lifetimes of approximately 1-1.5 fm/c this effect alters the spectra drastically. As will be shown next the calculation predicts a difference between reconstructable resonances and all decayed resonances. Fig. 2 shows the rapidity distributions of the Δ^0_{1232} and the ρ^0_{770} for central Pb+Pb collision at the SPS energy of 158 AGeV. Full symbols depict the resonances which decayed during the collision and, in case of the ρ are reconstructable in the dileptonic decay channel. Open symbols show those resonances where the hadronic decay products did not rescatter after their creation. In

Fig. 2 one observes a suppression by a factor of 6 for the ρ meson and a suppression by a factor of 3 for the Δ. In Fig 3 one observes a suppression by a factor of 7 for the ρ and a suppression by a factor of 6 for the Δ. This can be understood because of the different meson/baryon ratio at the different energies, i.e. a higher baryon density at 30 AGeV compared to 158 AGeV.

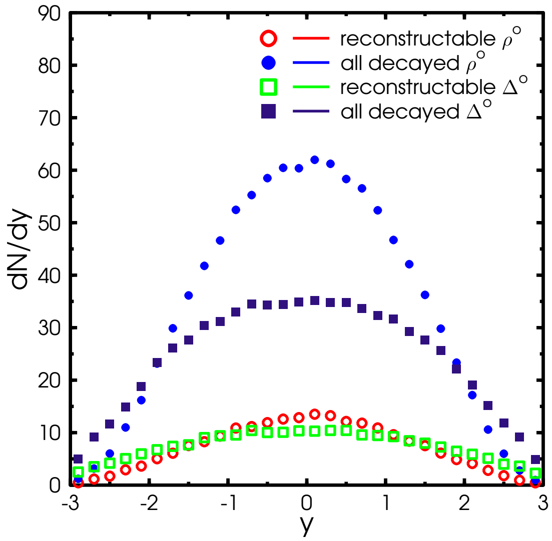

FIG. 2. Rapidity distributions of Δ^0_{1232} and ρ^0_{770} for central Pb+Pb collisions at 158 AGeV. A strong suppression of in hadron correlations reconstructable resonances compared to those reconstructable via leptons (indicated as 'all decayed') is visible.

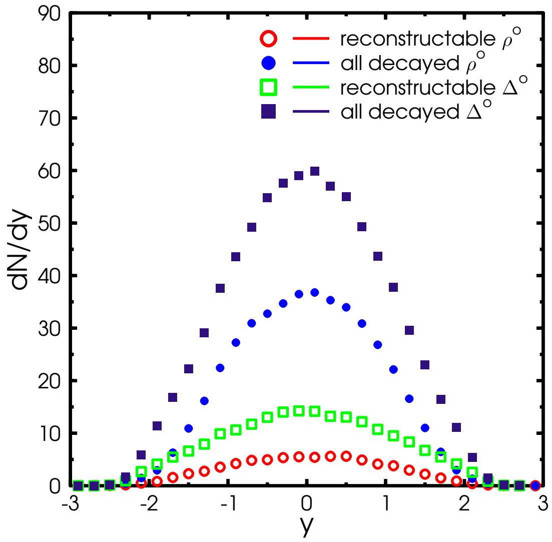

FIG. 3. Rapidity distribution of Δ^0_{1232} and ρ^0_{770} for central Pb+Pb collisions at 30 AGeV. A strong suppression of in hadron correlations reconstructable resonances compared to those reconstructable via leptons (indicated as 'all decayed') is visible.

Fig. 4 shows the decay time distribution of reconstructable resonances in Pb+Pb at 158 AGeV. Most reconstructable Δ^0_{1232}'s and ρ^0_{770}'s stem from the late stage of the collision ($t_{\text{decay}} \geq 10$ fm/c). The Φ_{1020} shows a different behaviour, since it has a very small hadronic cross section and a lifetime of 44 fm/c, which leads to a decay of a large part of the Φ mesons outside the fireball.

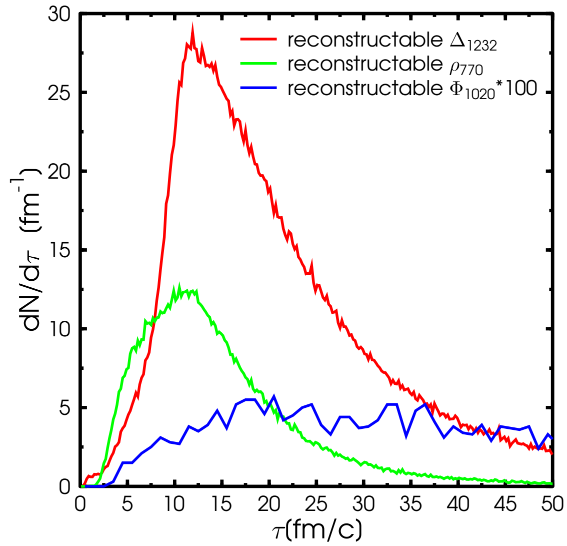

FIG. 4. Decay time distribution of reconstructable resonances for Pb+Pb collisions at 158 AGeV. Detectable Δ_{1232} and ρ_{770} resonances stem from late stages of the collision. The Φ mesons decays mostly outside of the collision zone (Note that the Φ distribution is multiplied by 100).

In order to investigate the refeeding aspects two scenarios are studied. The first scenario allows for a qualitative understanding of the refeeding process: Here, the calculation is stopped roughly at the chemical freeze-out at 6 fm/c [15]. At this point all resonances are forced to decay. Then the calculation is continued. The full line in Fig. 5 shows the time evolution of all Δ_{1232} resonances since the beginning. The dotted line shows the time evolution of the Δ_{1232} resonances which regenerate after the complete decay at 6 fm/c. On clearly observes that the regeneration of the Δ resonances is strong and allows the delta yield to regain its full strength after additional 6 fm/c propagation.

Let us now turn to the ρ resonance as shown in Figure 6. The ρ_{770} does not reach its initial value as the Δ_{1232} does. This is because of the smaller and strongly energy dependent cross sections for the reaction $\pi\pi \rightarrow \rho_{770}$ compared to the reaction $p\pi \rightarrow \Delta_{1232}$. While for a break-up time of 6 fm/c regeneration of the rho is still possible, absorption effects take over when the system is more cooled down because most of the $\pi\pi$ interactions will be at $\sqrt{s}_{\pi\pi} \ll m_\rho$.

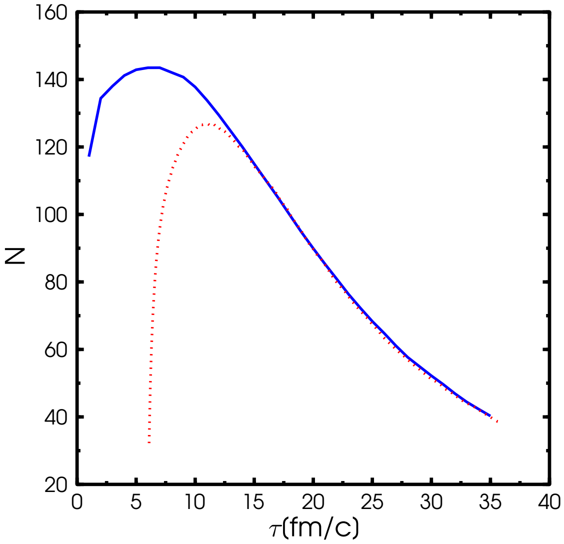

FIG. 5. Time evolution of the Δ yield for Pb+Pb collision at 158 AGeV. The full line is the evolution in the standard calculation. The dashed line depicts the evolution of the Δ_{1232} when all resonances were forced to decay at 6 fm/c.

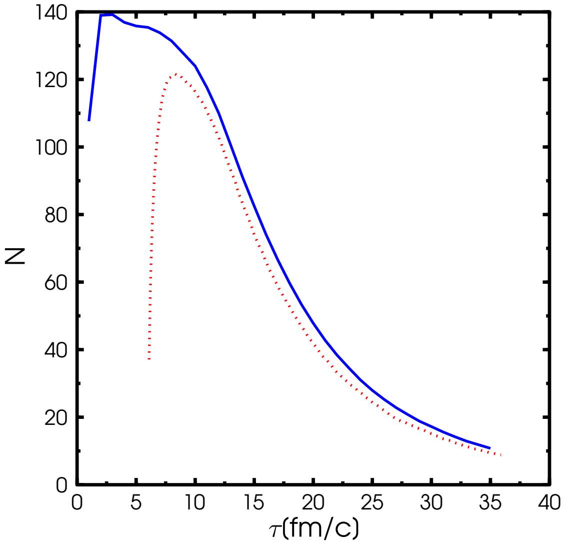

FIG. 6. Time evolution of the ρ yield for Pb+Pb collision at 158 AGeV. The full line is the evolution in the standard calculation. The dashed line depicts the evolution of the ρ when all resonances were forced to decay at 6 fm/c.

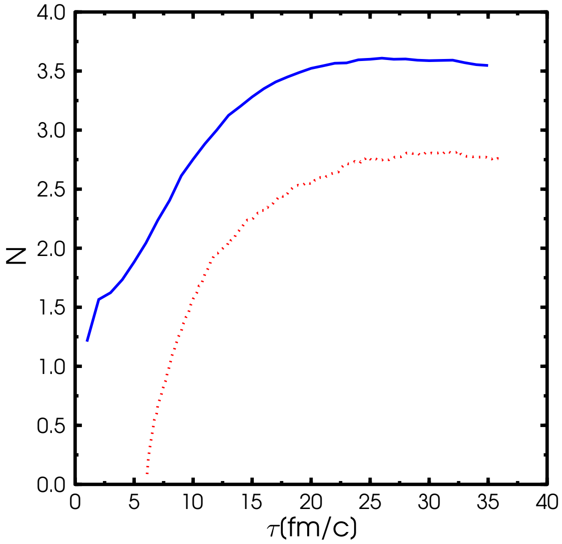

FIG. 7. Time evolution of the Φ yield for Pb+Pb collision at 158 AGeV. The full line is the evolution in the standard calculation. The dashed line depicts the evolution of the Φ when all resonances were forced to decay at 6 fm/c.

Let us now probe this assumption with a particle with more exotic decay branchings. Figure 7 depicts the number of Φ resonances as a function of time - again for the full calculation (full line) and the modified calculation (dashed line). The multiplicity of the Φ meson resonance does not reach the value from the full calculation, but falls short by 40% even after additional 30 fm/c. In contrast to the ρ and Δ regeneration is difficult in the Φ channel, because the probability for $K\overline{K} \rightarrow \Phi$ is suppressed due to the low Kaon densities and the small width of the Φ.

Let us now turn to a quantitative analysis of the regeneration processes as shown in Fig. 8. Here, we track all decay products of a resonance. When a daughter particle from a resonance decay directly reforms a resonance of the same type in the next interaction it is marked as 'regenerated'. Note that only ρ^0_{770} into ρ^0_{770} or Δ^{++}_{1232} into Δ^{++}_{1232} are counted as directly 'regenerated'. This explains the low percentage of regenerated resonances in the early stage of the collision, where resonances are directly produced, e.g. from $pp \rightarrow \Delta + X$.

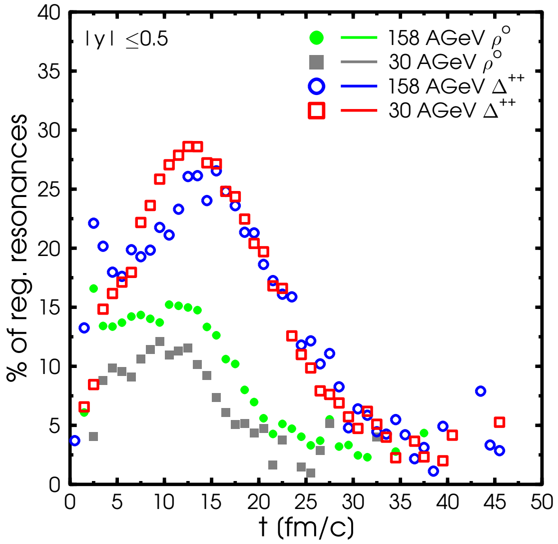

FIG. 8. Ratio of regenerated/all decayed resonances as a function of time for Pb+Pb collisions at 30 AGeV and 158 AGeV. Open symbols indicate the Δ resonance, while full symbols show the ρ resonance.

The Delta (open symbols) regeneration peaks around 10-12 fm/c with a direct regeneration probability between 25% (158 AGeV) and 30% (30 AGeV) and stays strong throughout the final expansion stage of the reaction. In contrast, the direct rho (full symbols) regeneration is weak (only 10-15% at both energies) and becomes negligible after 12 fm/c.

To summarize, the importance of the regeneration of resonances in heavy ion collisions was studied. It was shown that a full regeneration of the Δ_{1232} abundancies on time scales of 6 fm/c is possible within the present model. In contrast to the rho, a large regeneration probability of Deltas was found which might explain the slight enhancement of the Δ^{++}/p ratio with centrality. Further investigation of the regeneration and absorption dynamics are currently under way.

ACKNOWLEDGEMENTS

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[1] P. Braun-Munzinger, Summary talk at the Quark Matter 2004 Conference in Oakland, CA, USA.
[2] C. Markert [STAR Collaboration], J. Phys. G **30** (2004) S1313 [arXiv:nucl-ex/0404003].
[3] C. Markert [STAR Collaboration], arXiv:nucl-ex/0308029.
[4] C. Markert [STAR Collaboration], J. Phys. G **28** (2002) 1753 [arXiv:nucl-ex/0308028].
[5] P. Fachini [STAR Collaboration], J. Phys. G **30** (2004) S565 [arXiv:nucl-ex/0305034].
[6] P. Fachini, Acta Phys. Polon. B **35** (2004) 183 [arXiv:nucl-ex/0311023].
[7] P. Fachini, J. Phys. G **30** (2004) S735 [arXiv:nucl-ex/0403026].
[8] S. C. Johnson, B. V. Jacak and A. Drees, Eur. Phys. J. C **18** (2001) 645 [arXiv:nucl-th/9909075].
[9] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **71** (2005) 034908 [Erratum-ibid. C **71** (2005) 049901] [arXiv:nucl-ex/0409015].
[10] P. Braun-Munzinger, D. Magestro, K. Redlich and J. Stachel, Phys. Lett. B **518** (2001) 41 [arXiv:hep-ph/0105229].
[11] E. E. Zabrodin, L. V. Bravina, L. P. Csernai, H. Stöcker and W. Greiner, Phys. Lett. B **423**, 373 (1998) [arXiv:hep-ph/9806207].
[12] W. Broniowski, W. Florkowski and B. Hiller, Phys. Rev. C **68** (2003) 034911 [arXiv:nucl-th/0306034].
[13] G. Torrieri, J. Letessier, J. Rafelski and S. Steinke, Acta Phys. Polon. B **35** (2004) 2911 [arXiv:nucl-th/0411007].
[14] G. Torrieri and J. Rafelski, Phys. Lett. B **509** (2001) 239 [arXiv:hep-ph/0103149].
[15] M. Bleicher and J. Aichelin, Phys. Lett. B **530** (2002) 81 [arXiv:hep-ph/0201123].
[16] M. Bleicher, Nucl. Phys. A **715** (2003) 85 [arXiv:hep-ph/0212378].
[17] M. Bleicher and H. Stöcker, J. Phys. G **30** (2004) S111 [arXiv:hep-ph/0312278].
[18] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41** (1998) 225 [arXiv:nucl-th/9803035].
[19] M. Bleicher *et al.*, J. Phys. G **25** (1999) 1859 [arXiv:hep-ph/9909407].