EPJ Web of Conferences **259**, 10008 (2022)
SQM 2021

https://doi.org/10.1051/epjconf/202225910008

Resonance production in Pb+Pb collisions at 5.02 TeV

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Abstract. The yields, mean transverse momenta, and flow of K^{*0}, ρ^0, $\Lambda(1520)$ resonances provide an evidence of a late stage hadronic rescattering in ultra-relativistic central heavy ion collisions [1]. Using hydrodynamic + hadronic afterburner simulations of Pb+Pb collisions at 5.02 TeV we achieve a reasonable description of resonance yields and spectra as a function of collision centrality. We demonstrate that the measurements of $\Lambda(1520)$'s mean transverse momentum allow to constrain the unknown branching ratios of $\Sigma^* \to \Lambda(1520)\pi$ decays. Hadronic dynamics leads to an enhanced $\Delta(1232)$ production in central collisions.

Ultra-relativistic collisions of Pb nuclei at the energy $\sqrt{s_{\rm NN}} = 5.02$ TeV per nucleon pair are conducted at the Large Hadron Collider. During a time of order 10 fm/c (= 10^{-22} s), these collisions create a highly compressed and heated quark-gluon plasma, which undergoes an explosive expansion, cools down, and turns into hadrons. The dynamics is simulated as an expansion of a fluid droplet using relativistic hydrodynamics. The later dilute-stage phase is modeled by a hadronic afterburner, in which hadrons undergo a chain of elastic and inelastic collisions and resonance formations and decays. If a resonance R is produced at the quark-gluon plasma hadronization, it does not necessarily survive through the hadronic rescattering. It can collide with other hadrons, forming a higher mass resonance, which may later decay into other products than original resonance (schematically $R + X \to R' \to A + B$). It may as well decay, and after one of the decay products scatters, the resonance R cannot be recovered experimentally. On the other hand, a new resonance of the same type can be formed in a hadronic scattering. Therefore, the measured yields and spectra of resonances can be sensitive to the hadronization and the subsequent various hadronic reactions. The sensitivity of resonance production to the hadronic rescattering stage has indeed been observed in multiple simulations within different approaches: RQMD [2], UrQMD [3–7], PHSD [8–10], and hybrid EPOS + UrQMD [11–13]. Overall, the results on resonance production from these simulations agree with experimental measurements by STAR Collaboration in pp and AuAu collisions at 200 GeV [14, 15] and ALICE Collaboration in pp, pPb, and PbPb at 2.76 and 5.02 TeV [16–19]. In this work, we attempt to gain a qualitative understanding of how the large network of reactions in the hadronic afterburner describes the experiments.

We employ an open-source 3-dimensional relativistic viscous fluid dynamic code `MUSIC v3.0` [20–22] to simulate the hydrodynamic expansion of the collision fireball. The detailed model setup for the hydrodynamic stage was discussed in Ref. [1]. Thermal hadrons are generated on a constant energy density hypersurface $\epsilon_p = 0.2\,\mathrm{GeV/fm^3}$ (corresponding in our

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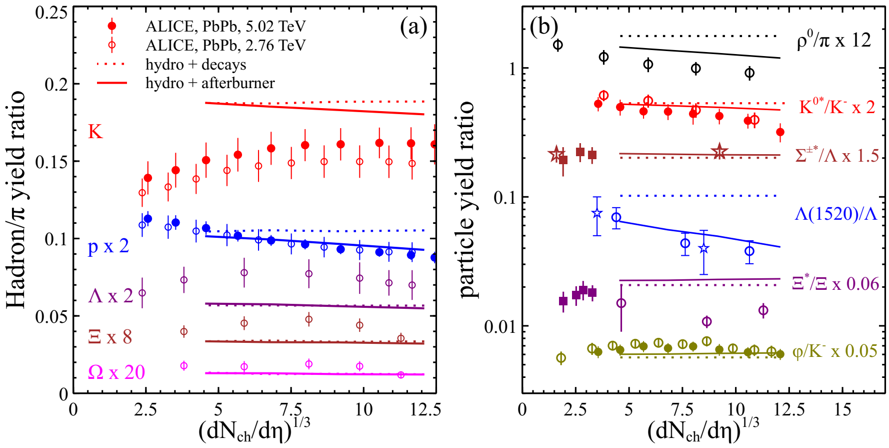

Figure 1. Midrapidity yield ratios of stable hadrons (a) and selected resonances (b) in pPb, PbPb, and AuAu collision. Ratios are shown as a function of a charged particle multiplicity per unit of pseudorapidity, $dN_{ch}/d\eta$, at $\eta = 0$. Dotted lines correspond to hydrodynamics simulation and resonance decays, full lines stand for the simulation with account of hadronic rescattering after hydrodynamical stage. The results of simulations are compared to experimental data from PbPb collisions at 5.02 TeV (full circles) [24, 25], PbPb collisions at 2.76 TeV (open circles) [16–18, 26–29], pPb collisions at 5.02 TeV (squares) [19], and AuAu collisions at 200 GeV (stars) [15].

case to temperature $T \approx 145$ MeV) and inserted into the `SMASH` hadronic hadronic transport simulations [23]. Switching on and off $2 \to 2$ inelastic reactions, such as $NN \to N\Delta$, $NN \to NN^*$, $NN \to N\Delta^*$ (N^* and Δ^* denote all nucleon- and delta-resonances) and strangeness exchange reactions, we found that the resonance yields are almost unchanged. Therefore, one can think of a hadronic afterburner in terms of multiple resonance excitations and decays, with at most a 10% correction for yields of baryon resonances from annihilation reactions. In SMASH, all the resonance formations and decays respect the detailed balance principle: matrix elements of forward and reverse reactions are identical. In SMASH multi-particle decays are artificially substituted by a chain of reversible $2 \to 1$ decays, for example $\omega \leftrightarrow \rho\pi$, $\rho \leftrightarrow \pi\pi$. Our simulation [1] provides a reasonable description of pion, kaon, proton, and resonance yields as a function of centrality, and a somewhat worse description of strange baryons, see Fig. 1.

Some resonances, such as ϕ, Σ(1385), Ξ(1530), are almost unaffected by the hadronic stage. For example, the $\phi(1020)$ has a long vacuum lifetime $c\tau = 46.4 \pm 0.14$ fm/c, and at temperatures below 150 MeV its mean free path in hadronic matter exceeds $\hbar c/\Gamma_{col} = 10$ fm [30]. In transport simulations, the mean free path is substantially larger because most of the reactions in [30] are usually not implemented. The regeneration rate $K^+K^- \to \phi(1020)$ is small because, by detailed balance principle, it is proportional to the width of ϕ. In summary, even in central Pb+Pb collisions, the fireball is transparent to ϕ, and the regeneration is negligible. This is also the case for Ξ(1530), which has a large mean free path in the hadronic medium and low regeneration cross-section. Indeed, one can see in Fig. 1 (b) that the flat trend of Ξ^*/Ξ could describe data, while the model overshoots the value of Ξ^*/Ξ by almost a factor of 2. This is also the case for EPOS + UrQMD model [12]. Based on this overestimation, we conjecture that Ξ(1530) interacts with pions and forms higher mass Ξ^* states, which are reactions not included in UrQMD or SMASH. Such reactions could decrease the yield of Ξ(1530). Unlike for $\phi(1020)$ and Ξ(1530) the fireball is not completely transparent

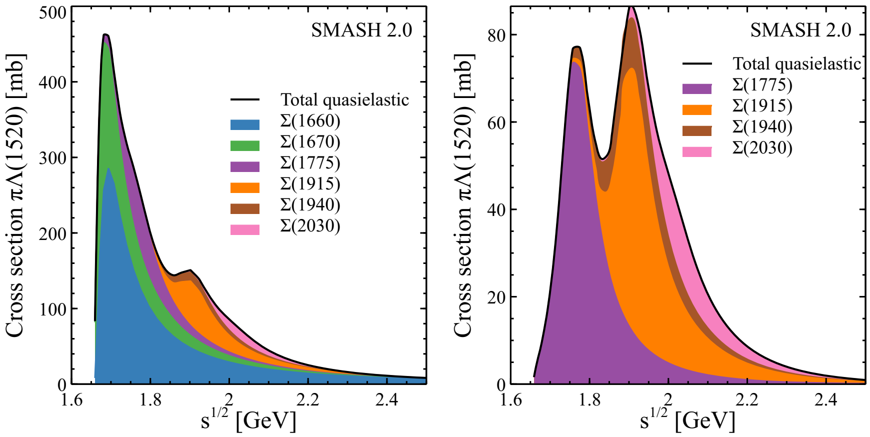

Figure 2. Cross sections of $\Lambda(1520)\pi \rightarrow \Sigma^*$ in `SMASH 2.0`. Left panel: Σ(1660) and Σ(1670) included; right panel: Σ(1660) and Σ(1670) not included.

for Σ(1385). However, the rescattering and regeneration processes are balanced, and overall the afterburner does not affect Σ(1385) yield.

For the resonances ρ^0, K^{*0}, and Λ(1520) the mean free paths at $T = 145$ MeV are below 3 fm. The fireball is opaque for them, which justifies the application of a partial chemical equilibrium thermodynamic (PCE) model [31], which explains the ρ^0, K^{*0}, and Λ(1520) yields rather well by assuming an isentropic expansion, where the yields of stable hadrons including decay contributions from resonances are fixed. However, we observe that the PCE model cannot explain the results of our simulations when a broader set of resonances is compared [1]. To better understand the microscopic origin of resonance suppression, we look in more detail at Λ(1520), for which the suppression is the largest. We find that in SMASH Λ(1520) has a very large interaction cross-section with pions, forming Σ^* resonances, $\Lambda(1520)\pi \rightarrow \Sigma^*$. The total $\Lambda(1520)\pi \rightarrow \Sigma^*$ cross-section is shown in Fig. 2, in SMASH it reaches a tremendous value of 460 mb. The partial cross-sections such as $\Lambda(1520)\pi \rightarrow \Sigma(1660)$ or $\Lambda(1520)\pi \rightarrow \Sigma(1775)$ are proportional to the branching ratio of the corresponding Σ^* state into $\Lambda(1520)\pi$ [23]. Many of these branching ratios are not known experimentally, in particular $\Lambda(1520)\pi \rightarrow \Sigma(1660)$ and $\Lambda(1520)\pi \rightarrow \Sigma(1670)$. After setting the latter to zero we obtain a much smaller cross-section of around 80 mb, see Fig. 2. We find that the mean transverse momentum $\langle p_T \rangle$ of Λ(1520) is rather sensitive to this cross-section, therefore by measuring the $\langle p_T \rangle$ one can constrain the branching ratios of $\Sigma^* \rightarrow \Lambda(1520)\pi$.

Our final observation in this study is that some resonances are not suppressed in central collisions but rather enhanced. In particular, the Δ(1232) is enhanced by at least 15%. The branching ratios of Δ^* resonances into Δ are well-constrained experimentally, which reduces the possible uncertainty of this observation. We also checked that switching on and off $2 \rightarrow 2$ reactions, many of which involve Δ(1232), does not change our result – the Δ is still significantly enhanced. It would be interesting to verify the Δ(1232) enhancement experimentally in $\Delta^{++} \rightarrow p\pi^+$ or in $\Delta^+ \rightarrow pe^+e^-$ decay channels, which may however turn to be challenging.

D.O. was supported the U.S. Department of Energy (DoE) under Grant No. DE-FG02-00ER4113. C.S. was supported in part by the National Science Foundation (NSF) under grant number PHY-2012922 and by the U.S. DoE under contract number DE-SC0021969, DE-SC001346, and within the framework of the Beam Energy Scan Theory (BEST) Topical Collaboration.

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