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Exploring the hadronic phase of relativistic heavy-ion collisions with resonances in ALICE

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Abstract.
Hadronic resonances, having short lifetimes, are useful for studying the hadron-gas phase that characterizes the late-stage evolution of high-energy nuclear collisions. Indeed, regeneration and rescattering processes occurring in the hadron gas modify the measured yields of hadronic resonances and can be studied by measuring resonance yields as a function of system size and comparing them to model predictions with and without hadronic interactions. Measurements of the differential yields of resonances with different lifetime, mass, quark content, and quantum numbers help in understanding particle production mechanisms, the lifetime of the hadronic phase, strangeness production, parton energy loss, rapidity yield asymmetry, and collective effects. With its excellent tracking and particle identification capabilities, the ALICE experiment measured a comprehensive set of mesonic and baryonic resonances. We present recent results on resonance production in pp, p–Pb, Xe–Xe and Pb–Pb collisions at various center-of-mass energies, highlighting new results of $K^{*\pm}$, $\Lambda(1520)$, and $\Sigma^{*\pm}(1385)$. The results are also compared to lower energy measurements and model calculations.

1 Introduction

High-energy heavy-ion (AA) collisions allow studying the deconfined quark-gluon plasma (QGP) and its properties created in such collisions. The hot and dense medium created in heavy-ion collisions evolves with time and cools down, it reaches a temperature or time such that the deconfined quarks and gluons combine to form hadrons, after that hadron resonance gas is formed. The hadronic resonance production serves as a unique tool to understand the properties of the hadronic phase, i.e, the phase between chemical freeze-out (when inelastic collisions among the constituents cease) and kinetic freeze-out (when elastic collision ceases) created in heavy-ion collisions. Due to their short lifetimes ($\sim$ fm/c), resonance yields and particle ratios are expected to be modified due to the interaction of their decay products within the hadronic medium via regeneration and rescattering processes. Recent measurements of the particle ratios of resonance to stable hadron, such as K^{*0}/K show a decreasing trend with charged particle multiplicity in heavy-ion collisions. The K^{*0}/K yield ratio at most central collisions is suppressed in comparison to peripheral heavy-ion collisions. It is understood

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that K^{*0} has a short lifetime ($\sim$ 4 fm/c), so rescattering processes mainly modify the yield of K^{*0} [1]. Recently, a theoretical study suggests the lifetime of resonance is not the only key indicator to understanding the suppression of hadronic resonances; the final yield of resonances depends on other factors such as mean free path, cross section of decay products, and chemical freeze-out temprature [2]. The systematic comparison of measurements related to various resonances with different lifetimes, quark content, and varying mass may enable us to investigate the dynamics of the hadronic phase and study the lifetime of the hadronic phase.

2 Analysis details

Due to their short lifetime, resonances cannot be detected directly. They are reconstructed from their hadronic decay products using the invariant mass method. A detailed description of the ALICE detector setup and its performance is available at [3]. The sub-detectors relevant for these studies are the Time Projection Chamber (TPC), the Time-of-Flight detector (TOF), the Inner Tracking System (ITS), covering pseudorapidity window of $|\eta| < 0.9$, and the V0A ($2.8 < \eta < 5.1$) and V0C ($3.7 < \eta < 1.7$) detectors [4]. The ITS and TPC are used for charged-particle tracking and primary vertex reconstruction. Particle identification is done by measuring specific energy loss in the TPC gas and the time-of-flight information using TOF. The V0 detectors are used for triggering and centrality measurement. The measurements of hadronic resonance production are carried out at midrapidity ($|y| < 0.5$) for heavy-ion collisions. Depending on the analysis, the combinatorial backgrounds have been estimated using event mixing or like-sign method. For strange and multi-strange hadrons, a set of topological selections are applied. The raw yields are extracted from the signal distribution after subtracting the combinatorial background. After the combinatorial background subtraction, the distribution is fitted with a fit function (Breit-Wigner or Voitgian) for the signal and polynomial function of different order for the residual background distribution. Further, the raw p_T spectrum is corrected for the detector acceptance × efficiency and branching ratio.

3 Results and discussion

Figure 1 (left) shows the transverse momentum (p_T) spectra of K^{*0} and ϕ compared with blast wave model predictions (upper) and the ratio of data to model predictions (below) for most central (0-10%) in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The Blast Wave model predictions are obtained using parameters from fits to pion, kaon, and (anti)proton p_T distributions [5]. It is observed that at low p_T (< 3 GeV/c), the data to model predictions ratio for K^{*0} is suppressed, whereas ϕ, the blast wave prediction describes the p_T spectrum well in the measured p_T range. It is expected that the ϕ yield is not significantly affected modified as its larger lifetime ($\sim$ 42.6 fm/c) and is consistent with the Blast Wave model because it does not have a rescattering effect. Figure 1 (right) shows the ratio of resonance yields to those of long-lived particles as a function of the cubic root of the average charged-particle multiplicity ($\langle dN_{ch}/d\eta \rangle^{1/3}$ is proportional to the radius of the particle-emitting source) for various resonances in different collision systems and energies measured by the ALICE [1] and STAR [6] Collaborations. A decreasing trend with multiplicity in the ratios ρ/π, $K^{0,*\pm}/K$, and $\Lambda(1520)/\Lambda$ is observed when going from peripheral to central collisions, whereas the $\Sigma^{*\pm}/\Lambda$, Ξ^{*0}/Ξ, and ϕ/K ratios are nearly constant across all systems and centrality classes. The new measurement of $K^{*\pm}$ is consistent with previous results of K^{*0} in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. These results suggest the dominance of rescattering effects over regeneration in the hadronic phase. However, the new measurements of $\Lambda(1520)$ is carried out

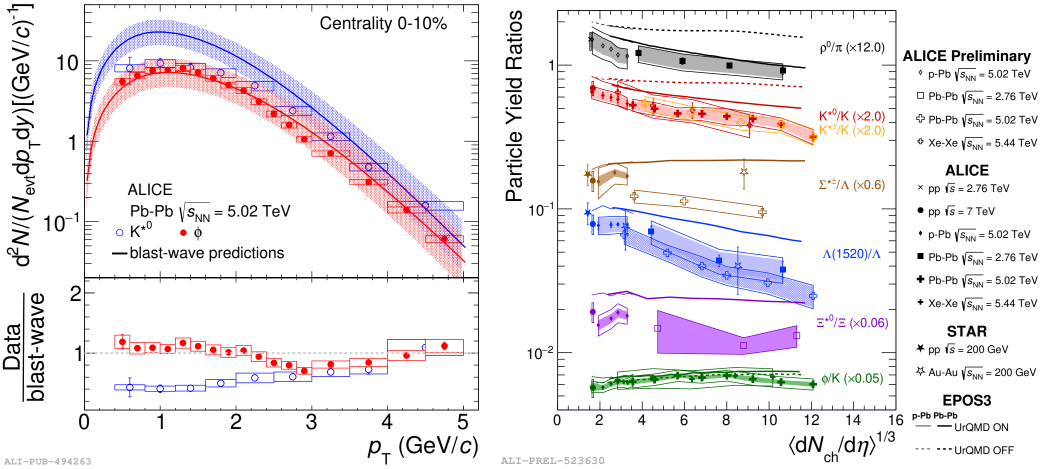

Figure 1. Left: transverse momentum distributions of K^{*0} (blue) and ϕ (red) resonances in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV along with blast wave predictions. The shaded bands indicate the uncertainties in the fit parameters of the model distributions. The lower panels show the ratios of the measured distribution to the values from the model. Right: summary of p_T-integrated yield ratios of different resonances to their ground state particles (ρ/π, $K^{0,*\pm}/K$, $\Sigma^{*\pm}/\Lambda$, $\Lambda(1520)/\Lambda$, Ξ^{*0}/Ξ and ϕ/K) as a function of $\langle dN_{ch}/d\eta\rangle^{1/3}$ in pp, p–Pb, Xe–Xe and Pb–Pb collisions along with model predictions from EPOS3 (with and without URQMD) and STAR data.

in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with high statistics, it is found that $\Lambda(1520)/\Lambda$ is more suppressed than $K^{0,*\pm}/K$ as a function of $\langle dN_{ch}/d\eta\rangle^{1/3}$ even though its lifetime is about 3 times longer than $K^{0,*\pm}$. The ratios are compared to the EPOS3 with UrQMD [7], which qualitatively describes the measurements.

The measured suppression in particle ratios (resonance to stable hadron yield), is most probably considered one of the causes due to the rescattering of decay products in the hadronic phase. The timespan between chemical and kinetic freeze-out ($\tau_{\rm kin} - \tau_{\rm chem}$) is estimated using the exponential decay law as $r_{\rm kin} = r_{\rm chem} \times e^{(\tau_{\rm kin}-\tau_{\rm chem})/\tau_{\rm res}}$ under assumption of i) negligible regeneration effects and ii) simultaneous freeze-out occur for all particle species from particle ratios [1]. In this calculation, the measured yield ratio in pp collisions is used as a proxy for $r_{\rm chem}$ at chemical freeze-out, $r_{\rm kin}$ is the measured yield ratio in Pb-Pb collisions, and $\tau_{\rm res}$ is the proper lifetime of resonance [1].

Results for the estimated duration of hadronic phase as a function of $\langle dN_{ch}/d\eta\rangle^{1/3}$ is shown in Fig. 2 for various resonances particles in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV. It increases with increasing system size for all particles, which is the mirror image of decreasing trend of particle ratios as a function of system size. The time duration obtained from ρ/π, $K^{0,*\pm}/K$ ratios are lower than the time calculation obtained from Λ^*/Λ. It may be due to the simplest assumption of the exponential decay model, neglecting regeneration effects and sudden freeze-out for all particles.

4 Conclusions

ALICE has measured several resonances with varying lifetimes (from 1–50 fm/c), quark content, and mass in different colliding systems and energies. A suppression in p_T-differentail

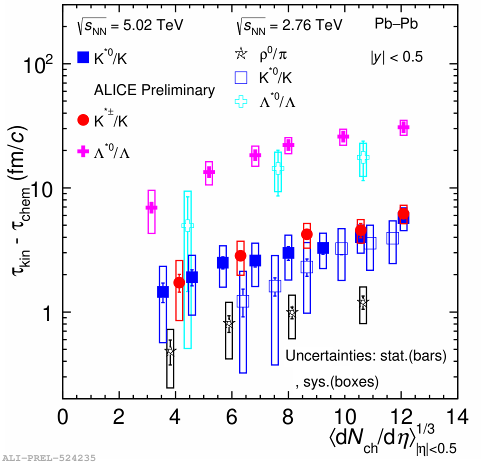

Figure 2. Lower limit on the hadronic phase lifetime between chemical and kinetic freeze-out as a function of $\langle {\rm d}N_{\rm ch}/{\rm d}\eta\rangle^{1/3}$ for different resonances in Pb-Pb collisions at LHC energies. The statistical and systematic errors are represented by vertical bars and boxes around the data points.

yield of K^{*0} in compared to blast wave predictions at low $p_{\rm T}$ in most central heavy-ion collisions suggests that rescattering effects play a dominant role at low $p_{\rm T}$. The suppression in $p_{\rm T}$-integrated yield ratios of ρ/π, $K^{0,*\pm}$ /K is observed in central heavy-ion collisions, suggesting that rescattering is the dominant process over regeneration in the hadronic phase. However, yield ratios of long-lived resonances (ϕ/K) remain flat with multiplicity, not significantly affected by rescattering and regeneration processes. Recently, the new measurement of $\Lambda(1520)/\Lambda$ ratio shows stronger suppression than $K^{0,*\pm}$/K. The simplest exponential decay model without considering the regeneration effects is used to estimate the lower limit of the hadronic phase lifetime for ρ, $K^{0,*\pm}$, Λ^{*0} in Pb–Pb collisions $\sqrt{s_{\rm NN}}$ = 5.02 TeV. The estimated lifetime of the hadronic phase increases with system size, and values of Λ^* is higher than ρ, and $K^{0,*\pm}$. It suggests that the final yield of resonances depends not only on the resonance lifetime but also on factors such as the mean free path of resonances, cross section of decay products, and chemical freeze-out temperature.

In the future, precise and new measurements in Run 3, along with more realistic parameterization for the modification of resonance yield, will help us further understand the hadronic phase and its lifetime in heavy-ion collisions at LHC energies.

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