A kinetic model for resonances within a hydrodynamic description of hadronic phase produced in relativistic nuclear collisions

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Introduction

Relativistic heavy ion collisions provide the necessary conditions for forming a hot and dense thermalized partonic medium called Quark Gluon Plasma (QGP). This short-lived phase rapidly cools down hydrodynamically and, as a result of confinement, hadronizes near the critical temperature ($T_c \simeq 156$ MeV) to form a medium with hadronic degrees of freedom. The hydrodynamic evolution for QGP is predicted to stop at the chemical freeze-out boundary ($\sim T_c$), and the hadronic phase follows cascade evolution with momentum transfer through elastic collisions. Recent advancements have shown the hadronic medium to have transport properties that are comparable to that of a low viscous fluid. Further, introducing a thermodynamic equation of state is possible even if a system is away from equilibrium, indicating the applicability of far-from-equilibrium hydrodynamic evolution. In this study, we explore the applicability of hydrodynamics to the hadronic medium and also try to explain the hadronic phase lifetime and certain resonance particle yields at kinetic freeze-out.

Methodology

In an earlier study, we had explored the applicability of hydrodynamics by studying the Knudsen number (Kn) and Reynolds number (Re) in the hadronic phase using a hadron resonance gas (HRG) formalism [1]. In this work, we follow up our results by deriving the second-order viscous Müller-Israel-Stewart (MIS) hydrodynamic equations for massive particles considering the 1+1D hydrodynamics with transverse expansion [2]. We approximated the medium to constitute pions that are in equilibrium, and the initial conditions are obtained from the excluded volume HRG at T_c. An estimate of the hadronic phase lifetime is obtained by using the limiting condition $Kn < 1$ for the applicability of hydrodynamics. On obtaining the hadronic phase lifetime, we explore the resonance particle yields as functions of system size (denoted as $\langle dN_{ch}/d\eta \rangle$) and transverse momentum (p_T). We have chosen $\rho(770)^0$, $K^*(892)^0$ and $\phi(1020)$ resonances with mean lifetimes of 1.3 fm/c, 4.16 fm/c and 46.3 fm/c respectively for our calculations. A kinetic model approach is followed, which gives the final state yield of resonance particles ($A \rightleftharpoons BC$) as [2].

$$
\begin{aligned}
N_f^A(\tau_f, p_T) &= \epsilon(\tau_f, p_T)\lambda_D(\tau_f, p_T) \\
&\times \big[N_i^A(\tau_c, p_T) + N^B(p_T)N^C(p_T) \\
\times \int_{\tau_c}^{\tau_f} &\Gamma_F(p_T)[V(\tau)\epsilon(\tau, p_T)\lambda_D(\tau, p_T)]^{-1} d\tau\big]
\end{aligned}
$$

where $\lambda_D(\tau, p_T)$ and $\epsilon(\tau, p_T)$ give the contribution of natural decay ("ND") and comoving hadron induced decay ("CMD"), respectively, to re-scattering ($A \to BC$) at time τ. $\Gamma_F(p_T)$ gives the corresponding regeneration effect ($BC \to A$) ("R").

Results and Discussion

In Fig.1, the yield ratios of resonance to stable particles ($K^*(892)^0/K$ (left), $\phi(1020)/K$ (middle), and $\rho(775)^0/\pi$ (right)) produced at kinetic freeze-out in heavy ion collisions is estimated within our model and compared with the experimentally obtained values [2]. The $K^*(892)^0/K$ and $\phi(1020)/K$ estimates show a considerable agreement with experimental values while the $\rho(775)^0/\pi$ values are under-

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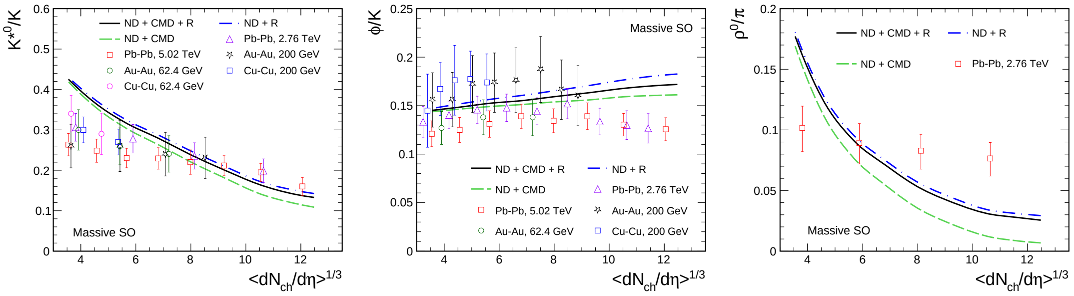

FIG. 1: The $K^*(892)^0/K$ (left), $\phi(1020)/K$ (center) and $\rho(775)^0/\pi$ (right) ratios obtained using our model in comparison with the results from ALICE and RHIC [2].

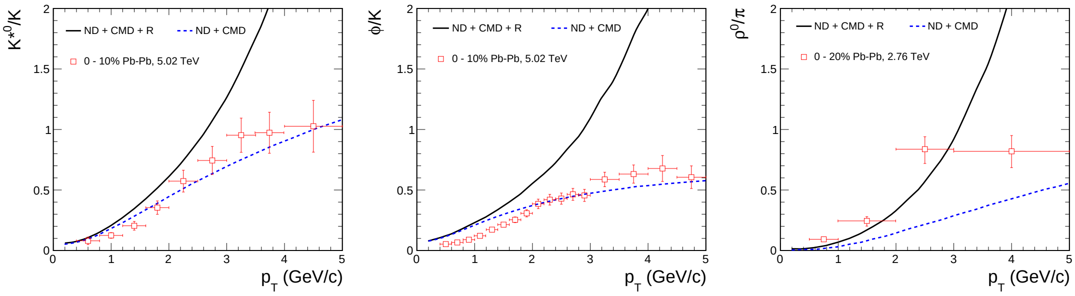

FIG. 2: Transverse momentum (p_T) dependent $K^*(892)^0/K$ (left), $\phi(1020)/K$ (center) and $\rho(775)^0/\pi$ (right) ratio compared with results from the ALICE collaboration [2].

estimated by our model at high multiplicities. The "ND" component drives the trend obtained for $K^*(892)^0/K$ and $\rho(775)^0/\pi$ estimates as their natural decay lifetimes are sufficiently small. For $\phi(1020)/K$, the lifetime is considerably larger than the hadronic phase lifetime, and thus, there is very little change in particle yield due to natural decay. The effect of co-moving hadrons-induced decay and regeneration is seen to play important roles at higher multiplicities, while at low multiplicities, their impact is marginal.

We have also studied these particle ratios as a function of p_T and the results are shown in Fig.2 [2]. A qualitative agreement between the experimental and model estimates is obtained for all three particle ratios for $p_T < 3$ GeV. At high p_T, due to limitations of the hydrodynamic framework and increased resonance production beyond the initial statistical yields at high p_T, the "ND+CMD+R" case overestimates the particle ratios. For "ND+CMD" case, which ignores regeneration effects, these ratios tend to be much lower towards higher p_T. The model can be further improved by including all hadrons in the fluid dynamical phase and by introducing a more complete description of decay and regeneration to account for the variations compared to experimental data.

References

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[2] R. Scaria, C. R. Singh and R. Sahoo, arXiv:2208.14792 [hep-ph] (2022).