In the pursuit of kinetic freeze-out boundary in ultrarelativistic p+p, p+Pb and Pb+Pb collisions

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Introduction

Relativistic heavy-ion collisions allow us to study primordial matter produced a few microseconds after the Big Bang. Multiple theories are available to explain the evolution of the matter produced in such collisions. It is considered that two freeze-out boundaries govern the dynamics after the collisions. The first involves a chemical freeze-out where inelastic collisions stop, and the second is the kinetic freeze-out where elastic collisions cease. The time elapsed between these two freeze-out boundaries is known as the hadronic phase lifetime. However, finding the chemical freeze-out boundary is somewhat easier than locating the kinetic freeze-out boundary due to the presence of a well marked temperature. Hadronic resonances, which have a wide range of lifetimes, provide an excellent probe and an opportunity to estimate the kinetic freeze-out boundary based on their yields at the final state [1]. In this article, we explore an alternative method based on the 1+1D hydrodynamics to obtain kinetic freeze-out boundary and thus estimate the hadronic phase lifetime. We also try to explain the final state yield of the $K^*(892)^0$ resonance particle based on our current approach [2].

Formalism

The hydrodynamical evolution of the hadronic medium is approximated to follow 1+1D second-order viscous hydrodynamics, given as [3];

$$\frac{dT}{d\tau} = -\frac{T}{3\tau} + \frac{\phi}{12aT^3\tau} \tag{1}$$

$$\frac{d\phi}{d\tau} = -\sigma bT^3\phi - \frac{1}{2}\Big(\frac{1}{\tau} - 5\frac{1}{T}\frac{dT}{d\tau}\Big) + \frac{8aT^4}{9\tau} \tag{2}$$

where the constants are given by $a = \pi^2/30$ and $b = 3\zeta(3)/\pi^2$. $\sigma = 4\pi r_h^2$ where $r_h = 0.25$ fm is the hadron hard-core radius based on the range of interaction. ϕ gives the effect of dissipative terms on the temperature evolution given by Eq.1. The volume evolution of the system is assumed to be isentropic [2]. The validity of hydrodynamics is governed by the Knudsen number (Kn) such that hydrodynamics ends when $Kn > 1$. Knudsen number is defined as; $Kn = \lambda/D$. where λ and $D = 2R$ are mean free path and characteristic system size, respectively, as explained in Ref.[2].

The initial state yields of all particles including $K^*(892)^0$ resonances are obtained from the Excluded Volume Hadron Resonance Gas (EVHRG) model considering the chemical freeze-out temperature to be equal to the critical temperature obtained in LQCD calculations [2]. Further, rescattering and regeneration effects are taken into account as mentioned below;

$$N_f(\tau_f) = \epsilon(\tau_f)\lambda_D(\tau_f)\big[N_i(\tau_c) + N_\pi N_K \times \int_{\tau_c}^{\tau_f} \Gamma_F[V(\tau)\epsilon(\tau)\lambda_D(\tau)]^{-1}d\tau\big] \tag{3}$$

where λ_D gives the effect due to natural decay, ϵ gives the effect of decay due to co-moving hadrons, and Γ_F gives the effect of regeneration. N_i, N_π and N_K are the initial yields of $K^*(892)^0$, $\pi^{\pm}$ and $K^{\pm}$ particles, respectively.

Results and Discussion

All particles and resonances with mass up to 2.25 GeV have been considered in this analysis. A small value for Kn denotes the applicability of hydrodynamics, and this parameter

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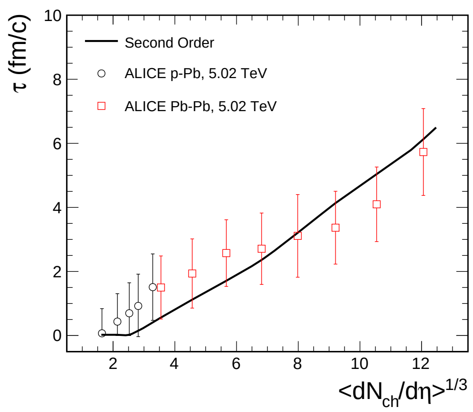

FIG. 1: Hadronic phase lifetime obtained in our calculations is compared with the results from the ALICE experiment for 5.02 TeV *p*-Pb and Pb-Pb collisions at the LHC.

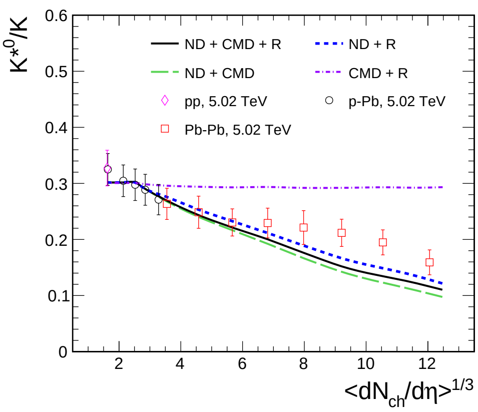

FIG. 2: The obtained $K^*(892)^0/K$ ratio is compared with the results from ALICE over different species at 5.02 TeV collisions.

has been used to obtain the end point of hydrodynamic evolution (τ_f). Knowing the initial time (τ_c), at which temperature $T = T_c$, obtained by employing a transverse expansion scenario, the hadronic phase lifetime can be easily found. In Fig.1, we show the estimated hadronic phase lifetime observed in our calculations and we compare our results with those obtained in the ALICE experiment at LHC [1]. We see an excellent agreement in the results obtained in our calculations with the estimate from the ALICE experiment by using a simple natural decay formalism.

Resonances provide an essential tool for studying the hadronic phase as their lifetimes vary widely. Thus they can undergo rescattering and regeneration within the medium; subsequently, their yields are affected based on the system lifetime. The $K^*(892)^0$ meson is an excellent example with a lifetime of 4.16 fm, which is of the order of hadronic phase lifetime and is thus used to probe the hadronic phase. In Fig.2, we have tried to explain the $K^*(892)^0/K$ final state ratio obtained in experiments based on the hadronic phase lifetime obtained in our calculations. The labels "ND", "CMD", and "R" used in the figure denote effects due to natural decay, co-moving hadrons induced decay and regeneration, respectively. It is observed that the final state yield of $K^*(892)^0$ mesons is affected mainly by their natural decay within the hadronic medium. The effect of co-mover induced decay and regeneration become more prominent only in the higher multiplicity classes, which have higher lifetimes, as seen in Fig.1. The absence of natural decay is similar to having a large lifetime, and it is seen that the yield remains constant over the entire multiplicity range considered. This observation is similar to the case of $\phi(1020)$ mesons seen at LHC [1], which have a long lifetime of 46.3 fm.

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