Hadronic Phase Lifetime and QCD Phase boundary in Ultra-relativistic Collisions at the RHIC and LHC: Collision System and Event Multiplicity Dependence

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1. Introduction

Understanding the time evolution of ultra-relativistic collisions and the underlying physics, has been one of the major interests of contemporary high energy nuclear physics. When two Lorentz contracted nuclei collide at ultra-relativistic energies, a possible state of Quark-Gluon Plasma (QGP) is expected to be formed. QGP is a new state of matter having partonic degrees of freedom which exists at very high temperature and/or energy density, consisting of asymptotically free quarks and gluons. The created fireball then expands because of very high energy deposition in a small volume with ultra-high temperature. Then it cools down till the particles reach a kinetic freeze-out and finally are detected by the detectors. The hadrons start forming right after the collision according to their masses. After a certain temperature known as the chemical freeze-out temperature ($T_{\rm ch}$), the hadron formation ceases and the stable particle numbers become fixed, marking the beginning of hadronic phase. After some time, the momentum transfer between the particles ceases at a temperature called as the kinetic freeze-out temperature ($T_{\rm th}$), marking the end of the hadronic phase. Hadronic resonances, whose lifetimes are very short, like K^{*0} can be used as probes to estimate the lower limit of hadronic phase lifetime in ultra-relativistic proton-proton, p–Pb and heavy-ion collisions. K^{*0} decay within this hadronic phase and their daughter particles undergo multiple scatterings. Due to this, the ratio of K^{*0}/K decreases. The regenerations of K^{*0} are not so dominant because of the lower K-K and K-π scattering cross-sections. We have estimated the hadronic phase lifetime of K^{*0} in different collision systems by using the relation,

$$[K^{*0}/K]_{\rm kinetic} = [K^{*0}/K]_{\rm chemical} \times e^{-\Delta t/\tau}, \quad (1)$$

where τ is the lifetime of K^{*0} and Δt is the hadronic phase lifetime multiplied by the Lorentz factor.

On the other hand, relatively long-lived resonances like ϕ mesons can act as useful probes to locate the QCD phase boundary. This is obtained from the effective temperature of ϕ meson by fitting Boltzmann-Gibbs Blast-Wave function to its p_T spectra. Finally we observe the dependence of hadronic phase lifetime and QGP phase boundary on the final state charged-particle multiplicity. We fit the Boltzmann-Gibbs Blast-Wave (BGBW) function to the $p_{\rm T}$ spectra of ϕ meson up to $p_{\rm T} \sim$ 3 GeV/c to get the $T_{\rm th}$, the true freeze-out temperature and $\langle\beta\rangle$, the average velocity of medium, which can then be used to find out the effective temperature, $T_{\rm eff}$ using the following relation.

$$T_{\rm eff} = T_{\rm th} + \frac{1}{2}m\langle\beta\rangle^2 \quad (2)$$

2. Results and Discussion

The hadronic phase lifetime show linear increase as a function of charged particle multiplicity, as shown in Fig. 1. This suggests that for a given charged-particle multiplicity the hadronic phase lifetime is similar irrespective of the collision energy and collision systems for

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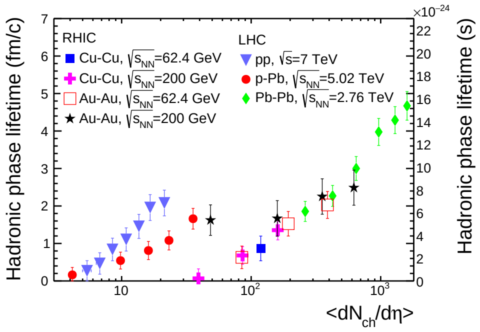

FIG. 1: (Color Online) Hadronic phase lifetime as a function of charged-particle multiplicity for different collision systems at RHIC and LHC energies.

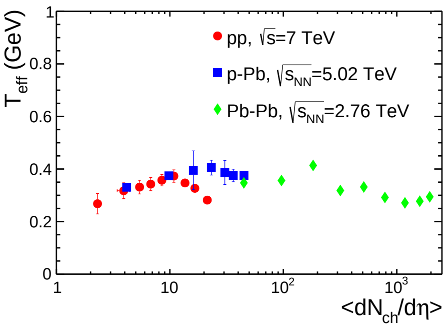

FIG. 2: (Color Online) Effective temperature for ϕ meson as a function charged-particle multiplicity for different collision systems.

heavy-ion collisions. However, the small collision systems like pp and p-Pb collisions at the LHC show different evolution trends compared to heavy-ion collisions.

From the Blast-Wave fits, we find the values of $\langle\beta\rangle$ and $T_{\rm th}$ for all collision systems in different centralities. We observe that for low charged-particle multiplicity, the system freezes out early, means it freezes out at high $T_{\rm th}$. As the charged-particle multiplicity becomes more, the system is possibly going through QGP phase, which results in the system taking a longer time to attain the kinetic freeze-out. As a result, the kinetic freeze-out temperature drops abruptly in all the collision systems. We also observe that $\langle\beta\rangle$ increases smoothly in all the collision systems upto a certain extent. However, for pp collisions at a certain charged-particle multiplicity ($\simeq 10-20$), $\langle\beta\rangle$ shows a sudden increase. We know that $\langle\beta\rangle$ is larger for a system that goes through QGP phase. This suggests a higher probability of QGP formation after this particular charged-particle multiplicity which may have been the reason for the sudden increase in $\langle\beta\rangle$. Fig. 2 shows the effective temperature of ϕ meson as a function of charged-particle multiplicity. The ϕ meson keeps the information of QGP phase boundary intact, as it hardly suffers from any rescattering. This suggests that the location of QCD phase boundary is weakly dependent on the final state charged-particle multiplicity.

3. Summary

1. Irrespective of the collision energy and collision systems for heavy-ion collisions, the hadronic phase lifetime is similar for a given charged-particle multiplicity. However, the small collision systems like pp and p–Pb collisions at the LHC show different evolution trends compared to heavy-ion collisions.

2. We observe that the hadronic phase lifetime strongly depends on final state charged-particle multiplicity, whereas the QGP phase shows very weak dependence. This concludes that the hadronization from a QGP state starts at a similar temperature irrespective of collision energy and collision systems, while the hadronic phase lifetime is strongly dependent on final charged particle multiplicity. The details of the work can be found in Ref. [1] .

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References

[1] D. Sahu, S. Tripathy, G. S. Pradhan and R. Sahoo, arXiv:1909.05788 [hep-ph] and its references.