QGP Phase Boundary and Plasma Lifetime From Thermal Properties of ϕ Mesons

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Heavy ion collisions at ultra-relativistic energies could produce a state of matter which is governed by partonic degrees of freedom, called Quark-Gluon Plasma (QGP). The nature of the deconfinement transition is of great importance. In this article, we have used ϕ meson as a probe to study the QCD phase boundary and to estimate the QGP lifetime.

The transverse momentum ($p_{\rm T}$) spectra of ϕ-mesons measured for AGS, SPS and RHIC energies have been analyzed in order to obtain the inverse slope parameter, $T_{\rm eff}$. This effective temperature has contributions from both the (random) thermal and the collective motions in the transverse direction. $T_{\rm eff}$ of a hadron of mass $'m'$ can be related to the 'true' freeze-out temperature ($T_{\rm th}$) and average radial flow velocity ($\langle v_{\rm r}\rangle$) at the decoupling surface as: $T_{\rm eff} = T_{\rm th} + \frac{1}{2}m\,\langle v_{\rm r}\rangle^2$. The ϕ meson is expected to obtain most of its collective flow from the partonic phase, as it suffers from less hadronic rescattering. The $\langle v_{\rm r}\rangle$ values for central heavy ion collisions are obtained from the best fit of the blastwave formula to the $p_{\rm T}$ spectra. The large values of $\langle v_{\rm r}\rangle$ at RHIC energies indicate that QGP has undergone substantial radial flow. The similarity of the extracted $T_{\rm th}$ to the critical temperature $T_{\rm c}$ predicted by lattice calculations imply that the ϕ meson freezes out near the phase boundary and could be used to extract the properties of QCD matter near the transition point.

A compilation of measured data for central heavy ion collisions for $T_{\rm eff}$, for low $p_{\rm T}$ range ($0 < p_{\rm T} \leq 3.0$ GeV/c) and at mid-rapidity has been made. The results are depicted in Fig. 1 as a function of collision energy $\sqrt{s_{\rm NN}}$. $T^{\phi}_{\rm eff}$ shows an increase with $\sqrt{s_{\rm NN}}$ (also with $\epsilon_{\rm Bj}$, the Bjorken energy density) up to lower SPS energy. A further increase in collision energy leads to an increase of early temperature and pressure of the system. As a consequence, the $p_{\rm T}$ of the produced hadrons and hence the $T_{\rm eff}$ increase with collision energy. This is followed by the region of constant temperature which corresponds to higher SPS energies, where it is expected that the system undergoes a deconfinement transition with the creation of a co-existing phase of partons and hadrons, which is signaled by a plateau-like structure in the above spectrum. The resulting modification of Equation of State (EoS) suppresses the transverse expansion. This observation of a plateau-like structure is equivalent to a liquid-gas phase transition with the involvement of latent heat of the system, leading to a first order phase transition. Thus the experimental data indicate a first order phase transition, with a mixed phase stretching energy density between ~ 1 and 3.2 GeV/fm^3 (figure to be shown), corresponding to higher SPS energy regime. At higher energies (corresponding to RHIC energies), $T^{\phi}_{\rm eff}$ further increases with collision energy. The EoS at the early stage becomes stiff, again leading to increase in early pressure and temperature. The thermal component, $T^{\phi}_{\rm th}$, also shows a similar behavior with an increase in going toward the RHIC energies. This could be related to the onset of deconfinement corresponding to SPS energy regime.

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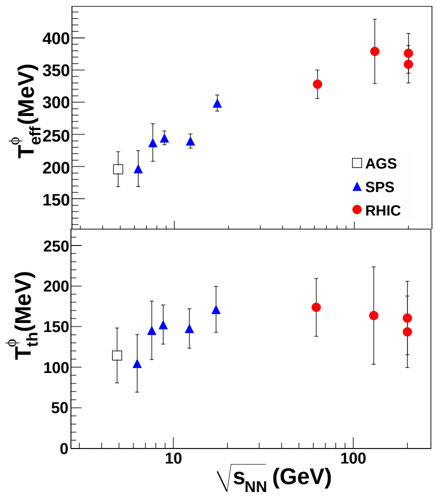

FIG. 1: Top panel: $T^{\phi}_{\rm eff}$ and the bottom panel: $T^{\phi}_{\rm th}$ as a function of $\sqrt{s_{\rm NN}}$.

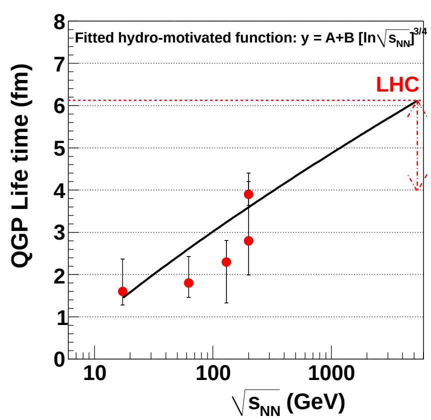

FIG. 2: QGP lifetime as a function of center-of-mass energy.

One of the important observables to look at a possible deconfinement phase transition is the effective thermodynamic degrees of freedom of the system, g which is given by: $\frac{\epsilon}{\rm T^4} = \frac{\pi^2}{30} g(\rm T)$, where ϵ is the energy density of the system. This value of g changes by a large factor while going from hadronic to a deconfined state of matter. For an ideal gas of massless, non-interacting constituents, g counts the number of bosonic degrees of freedom and fermionic degrees of freedom weighted by 7/8. Thus for the deconfined QGP state with three flavors, it yields, g = 47.5 and so $\epsilon/{\rm T}^4 \sim 16$. lQCD calculations for $\epsilon/{\rm T}^4$ as a function of T show that energy density rises rapidly in a narrow temperature interval around $T = 170$ MeV. If the transition occurs at $T_c \sim 170$ MeV as expected, the temperature of ϕ at the 'true' freeze out should saturate close to T_c which is observed in the present work.

To estimate the quantity, ϵ/T^4 at the phase boundary we need to know both the energy density and the temperature at the transition point. The value of $T_{\rm th}$ is determined from the $p_{\rm T}$ spectra of the ϕ. For ϵ we replace the formation time in the formula for $\epsilon_{\rm Bj}$ by some proper time τ_c when the transition is over. Our aim is to estimate τ_c which may be treated as the time that marks the end of the partonic phase. We compare the values of ϵ/T^4 obtained from the analysis of the data with the value obtained from lattice QCD calculations. The quantity $\epsilon_{\rm Bj}/T^4_{\rm th}$ for RHIC is compared with the highest value of ϵ/T^4 obtained in lQCD calculations corresponding to value of $g \sim 47.5$ for 3-flavor partonic phase and estimate the value of τ_c. Similar procedure is followed for other colliding energies. The variation of τ_c, the life time of plasma, with $\sqrt{s_{\rm NN}}$ is depicted in Fig. 2. We note that the τ_c increases logarithmically with $\sqrt{s_{\rm NN}}$. A value of $\tau_c \sim 4-6\ fm/c$ is predicted at $\sqrt{s_{NN}} = 5.5\ TeV$ for LHC [1]. The form of the fitted function is motivated by the fact that energy density scales logarithmically with collision energy and the time $\sim \epsilon^{\frac{3}{4}}$: a solution expected for asymptotically large ϵ from the Bjorken scaling solution.

References

[1] R. Sahoo *et al.*, *Phys. Rev.* **C** (Under Review), arXiv: 1007.4335 [nucl-ex] and references therein.