Proc Indian Natn Sci Acad **81** No. 1 February 2015 Special Issue, pp. 152-157

DOI: 10.16943/ptinsa/2015/v81i1/48062

Study of D-Measure from Polyakov-Nambu-Jona-Lasinio Model

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(Received on 30 April 2014; Accepted on 11 August 2014)

We present the first case study of the net charge fluctuations in terms of $D - measure$ within the framework of an effective model viz. Polyakov Nambu-Jona-Lasinio model. The net charge fluctuation is obtained from the charge susceptibility computed in this model. A parameterization of the freeze-out curve in heavy-ion experiments has been used to obtain D as a function of the collision energy.

Key Words : Fluctuation; Heavy-Ion Collision; PNJL Model; D-Measure

Introduction

Strongly interacting matter at very high temperatures and densities is expected to undergo a transition from the color confined hadronic phase with broken chiral symmetry to the partonic phase with restored chiral symmetry and/or deconfined quarks and gluons (Meyer-Ortmanns H, 1996). A good understanding of this transition is relevant for studies in the fundamental interactions in particle physics, as well as for the physics of early universe and neutron stars. Thus it has become an issue of great interest in recent years, both theoretically and experimentally. To this end, it is essential to identify unambiguous signals which would establish the formation of the quark-gluon plasma (QGP). One such viable signal is the fluctuations of net electric charge Q. It has been argued that since the unit of Q in the hadronic phase is 1, and that in the QGP phase is 1/3, the net charge fluctuation in the two phases would have very distinct values, even if the net charge remains unaffected (Jeon *et al.*, 1999, 2000).

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Measuring Charge Fluctuations

To reduce systematic uncertainties in measurements in heavy-ion experiments, it is useful to consider suitable ratios of quantities that are expected to have similar behavior. One such suitable observable could be the ratio of net charge Q to total charge N_{ch} given as, $F = \frac{Q}{N_{ch}}$ (Jeon *et al*., 2000). Using ratio R of total positive charge N_+ to total negative charge N_-, one may now define a quantity D (Bhattacharyya *et al*., 2012b) as,

$$D = \langle N_{ch}\rangle \left\langle \delta R^2 \right\rangle = 4\frac{\left\langle \delta Q^2 \right\rangle}{\langle N_{ch}\rangle} = 4\frac{\chi_Q}{n_{ch}/T^3}. \tag{1}$$

Here $n_{ch} = \langle N_{ch}\rangle /V$ is the total charge density which may be obtained by adding the contributions from particle and anti-particle distributions. χ_Q is the dimensionless charge susceptibility which may be obtained from the pressure P of the system as,

$$\chi_Q \left(T, \frac{\mu_Q}{T}\right) = \frac{\partial^2}{\partial(\frac{\mu_Q}{T})^2} \left(\frac{P\left(T, \frac{\mu_Q}{T}\right)}{T^4}\right), \tag{2}$$

where μ_Q is the electric charge chemical potential.

In Ref. (Jeon *et al*., 2000), a simple estimate of D was made considering the hadronic phase to be a gas of pions and the partonic phase as described by Lattice Gauge Theory. This gave the value of D to be ~ 4 for the hadronic phase and ~ 1 for QGP phase. For experimental comparison one can refer to (Adams *et al*., 2003; Abelev *et al*., 2012).

Results in PNJL Model

Here we use the Polyakov loop enhanced Nambu$-$Jona-Lasinio (PNJL) model (Meisinger *et al*., 1996b; Fukushima, 2004; Megias *et al*., 2006c) considering 2 flavor (Ratti *et al*., Ghosh *et al*., 2008) as well as 2+1 flavor (Ciminale *et al*., 2008; Bhattacharyya *et al*., 2010a). Detailed studies of fluctuations and correlations of various conserved charges were performed with the PNJL model both for 2 flavor (Ghosh *et al*., 2006; Mukherjee *et al*., 2007) and for 2+1 flavor (Bhattacharyya *et al*., 2010b, 2011, 2012a) systems.

The behavior of χ_Q and n_{ch}/T^3 with T/T_c is shown in Fig. 1 for various values of the baryon chemical potential μ_B considering the cases of 2 and 2+1 flavor systems. Here T_c is the critical temperature at the corresponding values of μ_B. As T increases they all tend towards the limit of free gas at $\mu_B = 0$.

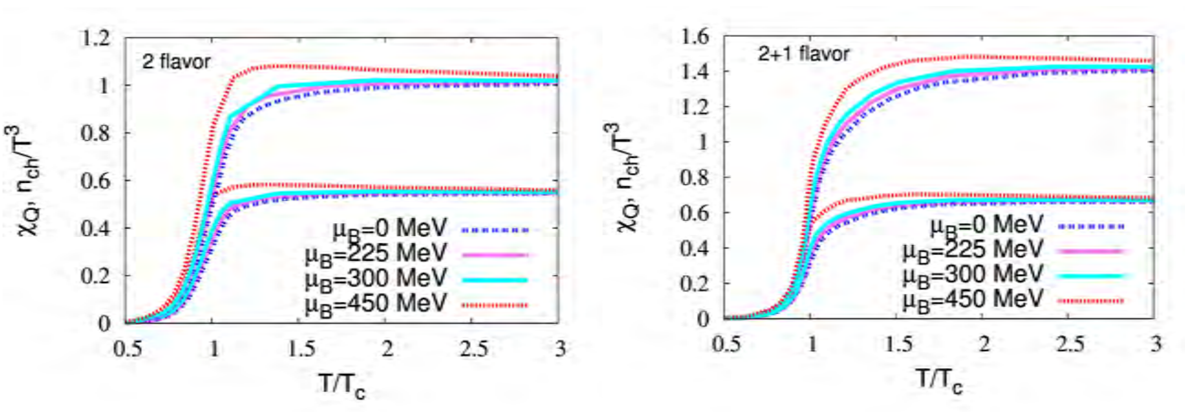

Fig. 1: Variation of χ_Q and n_{ch}/T^3 (lower and upper set of curves) with T/T_c for different values of μ_B for 2 flavor and 2+1 flavor

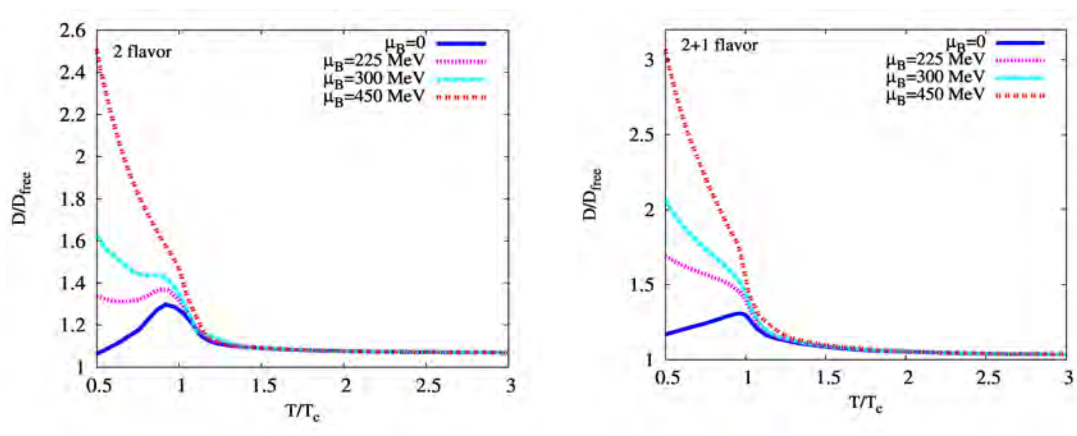

Fig. 2: Variation of D with T/T_c for different values of μ_B around $\mu_Q = 0$

We now consider in Fig. 2 the quantity D/D_{free} and study its temperature and density variations. Here $D_{free}(T, \mu_B)$ is the temperature and chemical potential dependent limit of $D(T, \mu_B)$ for a free massless gas of quarks. We have chosen four representative values of μ_B. As observed in Fig. 2, $D > D_{free}$ implies that n_{ch} is much more suppressed than χ_Q in the confined phase. This effect seems to be much more prominent as μ_B is increased. The variation of D/D_{free} with μ_B at different temperatures is shown in Fig. 3. Again we find D to remain above its free field limit for all T and μ_B. For a lower temperature ~ 100 MeV, there is an initial rise and a subsequent fall with increasing μ_B, while for larger T there is a just a monotonous fall.

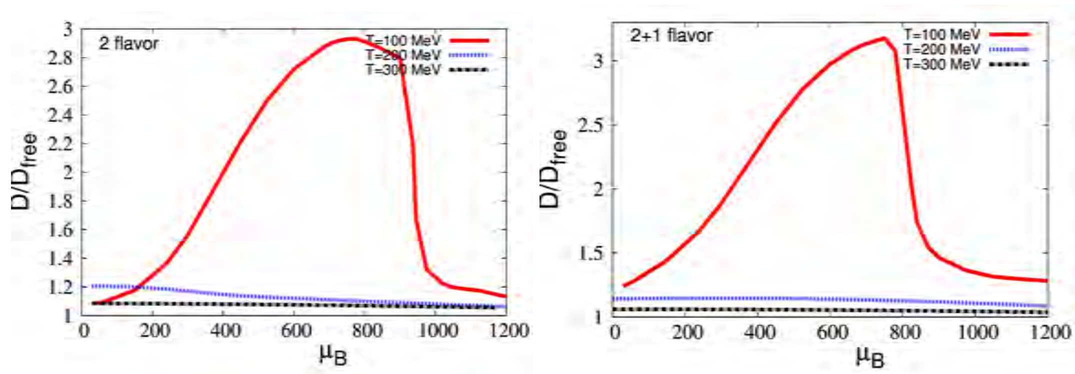

Fig. 3: Variation of D/D_{free} with μ_B for three values of T around $\mu_Q = 0$

Connection with heavy-ion collision experiments: With an input of temperature and chemical potential from freeze-out parametrization (see e.g. (Karsch *et al.*, 2011)) one may study the expected nature of D for different experimental conditions.

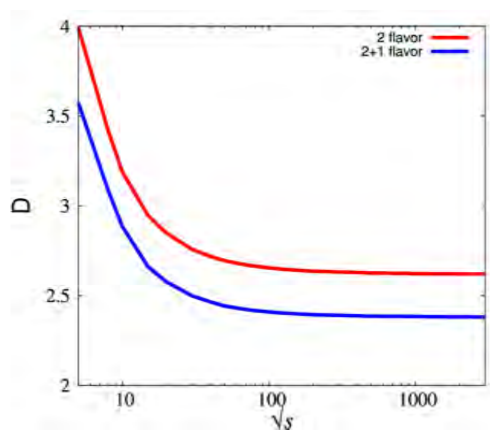

Fig. 4: D as a function of $\sqrt{s}$ computed along the freeze-out curve

Results are shown in Fig. 4. We have varied $\sqrt{s}$ from 5 GeV to 3 TeV (Bhattacharyya *et al.*, 2012b). D picking up an initial high value drops down and saturates gradually for increasing $\sqrt{s}$. It is highly exciting to find that the general features of D vs $\sqrt{s}$ curve obtained using the PNJL model are similar to those obtained directly in heavy-ion collision experiments as shown in Fig. 4 of Ref.(Abelev *et al.*, 2012). Furthermore the numerical range of D itself is exceptionally consistent.

It should however be remembered that D as given in Fig. 4 is the value obtained when the system is in complete thermal equilibrium. Since here we are on the freeze-out curve, we are always inside the hadronic phase. Thus if our results become completely consistent with experimental results the outcome will be that there is no signature of partonic phase in D, even if the phase existed transiently inside the fireball.

Acknowledgement

This work is funded by CSIR, UGC (DRS & UPE) and DST. We thank Tapan Nayak, Anirban Lahiri and Sarbani Majumder for useful discussions.

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