Strongly Interacting Matter in the Medium

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1. Abstract

Novel phases of strongly interacting matter are expected to occur at high temperatures and densities. At low temperatures and densities the dominant degrees of freedom in our nature are color-singlet bound states of hadrons. However, at high temperatures and densities these hadrons break up to liberate quarks and gluons and form the quark-gluon plasma (QGP). Furthermore, the broken chiral symmetry is also restored under such extreme conditions. The experimental exploration of the *putative* phase transitions from the confined hadronic phase to the deconfined QGP phase is being pursued actively in the RHIC and LHC and also in the future experiment at FAIR. It is well known that QCD is *the* theory of strong interaction. However, the phase transition region is quite far from the assymptotic regime of QCD and is described by the non-perturbative physics. So the study of these hot and dense matter becomes quite non-trivial. There are two ways to study the properties of strong interaction physics, one is the Lattice gauge theory and other is by using effective models of QCD. The basic motivation of using an effective model is to capture the symmetries of QCD. These models are much easier to handle and provide information in the domain where lattice gauge theory (LGT) fails.

One of these models is the Nambu-Jona-Lasinio (NJL) model which incorporates the global symmetries of QCD quite nicely. A four quark interaction term in the NJL Lagrangian is able to generate the physics of spontaneous breaking of chiral symmetry - a property of QCD which is manifested as the nondegenerate chiral partners of the low-mass hadrons. But the gluon fields are integrated out in the NJL model. So the major drawback of the NJL model is a reasonable description of the physics of color confinement. In this respect, the Polyakov loop extended NJL (PNJL) model tries to incorporate both the chiral symmetry and the confinement properties by introducing a background temporal gluon field which is coupled to the quark by the covariant derivative. The Polyakov loop is defined as the trace of the Wilson line. We have studied 2+1 flavour PNJL model with three-momentum cutoff regulator. In 2+1 flavour PNJL model, there are four-quark and six-quark interactions. Six-quark interaction mimics the QCD anomaly as it preserves $SU(3)_L \otimes SU(3)_R$ symmetry but breakes the $U(1)_A$ symmetry. But the six-quark interaction term introduces serious problem of instability of the vacuum. In order to resolve the problem we have added higher order eight-quark interaction term. The eight-quark interaction again make the potential bound from below.

The central theme of our work is to look at the thermodynamic properties of strongly interacting matter. The order parameter corresponding to the chiral phase transition is defined by the chiral condensate $\bar{q}q$ and for the deconfinement transition is defined by the Polyakov Loop Φ. At zero and small finite densities the variation of order parameters with temperature show a continuous crossover transition. However at high density the order parameters show a gap in the temperature variation signalling a first order phase transition. This indicates that there must be a critical end point (CEP) in the phase diagram of QCD. We observed that the eight-quark interaction drives the CEP to a low chemical

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potential and a high temperature value which is closer to the lattice data. Furthermore, our study concludes that the inclusion of eight-quark interaction is essential to limit μ_C/T_C below 2.5 as suggested by Lattice calculations.

We have also studied the thermodynamic quantities with the PNJL model. The pressure jumps along the phase boundary and then almost saturates for all the cases. We have also studied $(\epsilon - 3P)/T^4$ with temperature in PNJL model where ϵ is the energy density and P is the pressure. This quantity is a measure of the conformal anomaly. It shows a peak at the transition temperature, which indicates the maximum deviation from the conformal limit, $\epsilon = 3P$. We have investigated the quark number density with the NJL and PNJL model. In NJL model the peak of the number density near the transition region is much higher than the PNJL model. This indicates that the coupling of quarks with the Polyakov loop reduces the weight of the number density as thermodynamically active degrees of freedom. We observe that due to the eight-quark interaction quark number density increases above the transition temperature. For hydrodynamical investigations of relativistic heavy-ion collisions the speed of sound and specific heat are important quantities. In PNJL model specific heat shows a sharp peak at the transition temperature and its value converges well with the conformal gas at high temperature. The speed of sound shows a minimum at the transition temperature and its value is slightly below the ideal gas value at temperature $2.5T_C$. The softest point of the equation of state is found to be $(P/\epsilon)_{min} \sim 0.07$ for PNJL model with six-quark and $(P/\epsilon)_{min} \sim 0.06$ for PNJL model with eight-quark interaction.

In the experimental search for the phase transition, fluctuations are key quantities. Fluctuations are suitable measures for the chiral crossover. We have studied susceptibilities in the PNJL model supporting the idea of locating the critical end point using fluctuations. We have obtained the diagonal susceptibilities and the higher order derivatives by the Taylor expansion of pressure for two kinds of PNJL model near $\mu_X = 0$, where μ is the chemical potential and $X = B$, Q and S. Here B is the baryon number, Q is the charge quantum number and S is the strangeness quantum number. In all cases the second derivative of pressure c_2^X show a steep rise near the transition region, which indicates near the transition region the fluctuation increases. However at higher temperature c_2^X almost saturates and almost converges to the ideal gas value. This result is quite consistent with the lattice data. The higher order fluctuation c_4^X shows a peak near T_C for both models and the result matches with the lattice data. The finite height of the peak confirms the crossover nature of transition at $\mu = 0$. Both c_6^X and c_8^X show rapid variation around T_C for all cases.

In order to understand the thermal properties of the medium beyond the bulk thermodynamic properties, we need to study the spectral functions of different mesonic channels. In the pion and sigma channels, reasonably sharp structure was found still at 1.1 T_C; also the two states are not degenerate at these temperatures. Suppressing the anomaly term above T_C leads to much broader and degenerate structures in these two channels. Since the structure of the π resonance above T_C is of importance for RHIC phenomenology, this sensitivity implores one to look for the restoration or otherwise of the $U(1)_A$ anomaly at T_C by looking at suitable observables. It will be interesting to explore the phenomenological implications of these behaviors.