Properties and Signals of QCD Phase Transition, Critical Point and Quark Gluon Plasma

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Introduction

A good enough progress has been made to understand the QCD phase transition but most of the things are still very much unclear. Even the phase boundary between the two phases ie., HG and QGP remains in the literature as a conjectured one. Also the existence and location of proposed critical end point (CEP) on the QCD phase diagram is still unknown. Critical End Point is terminal point of the first order phase transition line between HG and QGP phases. Lattice QCD calculations which are the first principle method to evaluate the EOS and to study the nature of QCD phase transition, have done enough progress at zero bayon chemical potential (μ_B). These numerical calculations first revealed that the transition between HG and QGP phase at $\mu_B = 0$ and large T is a smooth crossover. However, these calculations are still not reliable at finite μ_B and thus not very useful to determine the existence and exact location of CEP which, if exists, lies at finite μ_B. Heavy ion collision experiments e.g, Relativistic heavy ion collider (RHIC) etc. have made tremendous effort to find out QGP as well as CEP. However, due to lack of proper theoretical guidance, it still seems quite difficult task. Thus at this point it is of utmost importance to phenomenologically find out a proper and realistic EOS for QCD matter which works well at zero as well as at finite μ_B and thus provides a way to study the properties of the QCD phase transition. It is also important to propose unambigious signals to detect QGP as well as to search the location of CEP using heavy ion collision experiments.

The plan of the thesis is outlined as follows : **Chapter 1** starts with a brief introduction about the conjectured QCD phase diagram. The nature and properties of QCD CEP is also presented briefly. Further, a brief review of various theoretical efforts e.g., lattice QCD calculations, effective models and phenomenological models (e.g bag model) is presented. The low temperature phase of QCD is HG and, therefore, it is important to know the behaviour of HG at different thermodynamical situations. A brief review of different statistical models (e.g, ideal HG model, excluded volume HG models etc.) used as the HG EOS in context to their success and shortcomings is provided. It also depicts different experimental signals proposed to detect the QCD CEP and the other details of various phases of strongly interacting matter.
Chapter 2 starts with a brief description of EOS of QGP using bag model after the perturbative corrections of the order of $\alpha_s^{3/2}$ in strong interaction coupling constant α_s using finite temperature field theory. The advantage of the bag model clearly lies in determining the thermodynamic parameters in the region of nonzero as well as large baryon chemical potential, which is still not properly accessible in the lattice calculations. It is followed by a brief introduction of a new thermodynamical consistent exclude volume model to obtain the EOS of HG. Further, we construct a first order deconfining phase boundary between HG and QGP phase employing Gibbs' criteria of thermodynamic equilibrium using our HG EOS and bag model for QGP EOS. The precise location of end point of this first order deconfining phase boundary is also obtained as CEP on the phase diagram [1].

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In **Chapter 3**, construction of a hybrid model to provide a unified description to HG as well as QGP phases is presented. Hybrid model suitably combines HG EOS obtained from our excluded volume model and QGP EOS from quasiparticle models (QPM). QPM provides more realistic description of QGP in comparison to crude bag model. In the quasiparticle model the system of interacting massless quarks and gluons can be effectively described as an ideal gas of massive quasiparticles. We demonstrate the construction of a first order deconfining phase boundary between HG and QGP phase using our hybrid model after implying Gibbs' criteria. Again an end point of this first order deconfining phase boundary is obtained. It lends support to the finding that the location of an end point or CEP being independent of model used in the construction [2].

In **Chapter 4**, we extend the hybrid model proposed in chapter 3 to calculate the transport properties alongwith thermodynamical properties of strongly interacting matter. We show the variations of these quantities with temperature and compare our curves with the lattice data for the entire QCD matter. We also extend our studies of the above quantities for finite μ_B so that our results can be put to test whenever the lattice calculations in future become feasible. This chapter also provides a possible way to get smooth crossover between HG and QGP phases at $\mu_B = 0$ as observed in lattice calculations. It also provides enough reasons to prove that the end point of first order deconfinement phase boundary obtained using our hybrid model is a QCD CEP where the phase transition is of second order [3]. A location in terms of collision energies is proposed to detect this CEP in heavy ion collision experiments [4].

Charmonium (J/ψ) is a bound state of charm (c) and anti-charm ($\bar{c}$) quark. Its suppression due to the Debye screening of colour charge in QGP medium was proposed as a signal to confirm the possible existence of QGP in heavy ion collision experiments. **Chapter 5** presents a model to calculate J/ψ suppression arising from the QGP medium alone. It starts with the derivation of cooling law for viscous QGP produced in the collision at mid-rapidity region by using Bjorken hydrodynamical expansion. To obtain the pressure and energy density of the QGP at initial time, QPM is again employed here. This highlights a major difference between our present approach and most of the earlier models which used crude bag model description for QGP to obtain J/ψ suppression. The present model which studies the charmonium suppression arising due to colour screening by QGP suitably describes the experimental data at various collision energies (i.e., at super proton syncrotron (SPS), relativistic heavy ion collider (RHIC) and large hadron collider (LHC)), simultaneously [5]. Similarly, suppression pattern of upsilon Υ (9.4 GeV/c^2), a bound state of bottom (b) and anti-bottom ($\bar{b}$) quark, is also presented and compared with the available experimental data [6].

In **Chapter 6**, we present a summary and conclusion drawn from this work and provide some insights in this area for future research work.

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References

[1] C. P. Singh, P. K. Srivastava, S. K. Tiwari, Phys. Rev. D80, 114508 (2009); Erratum-ibid: Phys. Rev. D83, 039904 (2011).
[2] P. K. Srivastava, S. K. Tiwari, C. P. Singh, Phys. Rev. D82, 014023 (2010).
[3] P. K. Srivastava, C. P. Singh, Phys. Rev. D85, 114016 (2012).
[4] P. K. Srivastava, C. P. Singh, Int. J. Mod. Phys. A28, 1350051 (2013).
[5] P. K. Srivastava, M. Mishra, C. P. Singh, Phys. Rev. C87, 034903 (2013).
[6] P. K. Srivastava, S. K. Tiwari, C. P. Singh, Phys. Rev. C88, 044902 (2013).