QCD phase transition at high temperature and density

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The strong interaction, as described by Quantum Chromodynamics (QCD), shows a rich phase structure at finite temperature and density. At low temperatures and densities, the dominant degrees of freedom are color-singlet bound states of hadrons. However, due to the asymptotic freedom of QCD, it is expected that at very high temperatures and densities these hadrons break up to liberate quarks and gluons and form the quark-gluon plasma (QGP). The experimental exploration of such a phase transition from the confined hadronic phase to the deconfined QGP phase is being pursued actively in the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) and more data are expected from the future experiment at FAIR.

Confinement and chiral symmetry breaking are the most fundamental properties of strong interaction physics at low temperature and density, where the physics is mainly governed by the non-perturbative QCD. In principle, the deconfinement phase transition and chiral phase transition are defined in two extreme limits of current quark mass. Deconfinement phase transition and its order parameter is well defined for infinite current quark mass and chiral phase transition is exact for zero quark mass. But in real world with a finite value of quark masses, the nature of these two phase transitions is an open question. Another important feature of the QCD phase diagram is the existence of the critical end point (CEP), where first order phase transition, from hadronic phase to quark-gluon-plasma (QGP) phase, ends. However, the exact location of CEP is still unknown. Investigation of these properties of strongly interacting matter are necessary to understand the various astrophysical and cosmological scenario.

The thermodynamic aspect of the phase transition from hadronic phase to QGP phase can be understood properly if we study the thermodynamic variables like quark number susceptibility (QNS), isospin number susceptibility (INS), energy density (ϵ), pressure (p), specific heat (C_V) and speed of sound (v_s) etc. Susceptibilities are related to fluctuations via the fluctuation-dissipation theorem. A measure of the intrinsic statistical fluctuations in a system close to thermal equilibrium is provided by the corresponding susceptibilities. At zero chemical potential, charge fluctuations are sensitive indicators of the transition from hadronic matter to QGP. Also the existence of the CEP can be signalled by the divergent fluctuations. For the small net baryon number, which can be met at different experiments, the transition from hadronic to QGP phase is continuous and the fluctuations are not expected to lead any singular behavior.

Such a deconfined phase of strongly interacting matter can be produced in the laboratory by ultra-relativistic collisions of heavy ions. Significant parts of different experimental heavy-ion programs are dedicated to studying quarkonium yields. Such studies are motivated by the suggestion of Matsui and Satz that quarkonium suppression could be a signature of deconfinement. In fact, the observation of anomalous suppression of J/ψ at SPS energies was considered to be a key signature of deconfinement. The $\Upsilon^{'}$s having three states with different binding energies are far richer probes of the QCD dynamics in p+p and Pb+Pb collisions than the charmonia states. It is therefore important to achieve a good understanding of their production mechanism in the vacuum as well as of how the nuclear ef-

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fects in proton-nucleus collisions affect them. At Large Hadron Collider (LHC) energy, the cross section of bottomonia production is large and also the detector technologies enabled the study of various bottomonia states separately both in p+p and heavy-ion collisions. As proposed by different theories, bottomonium is an important and clean probe of hadronic collisions for at least two reasons. First, the effective field theory approach, which provides a link to first principles QCD, is more suitable for bottomonium due to better separation of scales and higher binding energies. Second, the statistical recombination effects are less important due to the higher mass of bottom quarks. Experimentally, the bottomonia are detected via their decay in the dimuon channel. Bottomonia can be reconstructed with better mass resolution and smaller combinatorial background due to higher mass as compared to other resonances. All these properties make bottomonium a good probe of QGP formation in heavy-ion collisions.

I plan to address these issues in the lecture.