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Models for Strong Interaction Physics

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Abstract

We review the developments in various models describing strong interaction physics. The models provide an intuitive way of understanding the complex phenomenon associated with strong interactions. Models also help us to delve into regions of couplings and other thermodynamic conditions of interest that are still out of reach of the first principle method - quantum chromodynamics. At the same to ascertain the merits of the models they should be contrasted to the results obtained from quantum chromodynamics at least in its region of validity, and to the available experimental data. Here we shall discuss about our progress in that direction.

Keywords: Strong interaction, heavy-ion collision, phase diagram, fluctuations.

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1. Introduction

Understanding the bulk thermodynamic properties of strongly interacting matter has become a core issue in ultra-high energy heavy-ion collision experiments for the last few decades. The phase diagram of strong interaction physics is the holy grail that needs to be uncovered in the experimental and theoretical endeavors today. A wealth of knowledge exists on the relevant thermodynamic properties. Still it is far from being conclusive. The theory of strong interactions - Quantum Chromodynamics (QCD), predicts an extremely large coupling strength in the region of intermidiate temperatures and densities of the matter created by the current set of experiments. Thus usual perturbative formulation (pQCD) is supposed to be inadequate. Most often pQCD is useful in the initial state of the heavy-ion interactions and for the physics of hard particles produced in the interactions [1, 2]. For the matter at very high temperatures also pQCD may be a good first principle method [3], though a more satisfactory description is obtained with the matter divided in hard and soft modes with an augmented approach - the Hard Thermal Loop (HTL) resummation schemes [4] and the HTL perturbation theory [5].

To study the bulk thermodynamic properties of strongly interacting matter at intermidiate temperatures attained at the present heavy-ion accelarators, the only first principle framework seems to be the non-perturbative formulation of QCD with lattice regularization (LQCD) [6]. In this formulation the analytic calculation of the free energy of strong interactions is still a million dollar problem. One has to take resort to numerical computation, and that too with the best super computers put together. This is because, the free energy and all other thermodynamic observables are to be obtained by a direct implementation of the path integral method. With an enormous number of integration variables a huge computation cost has to be bourne. The continuum limit of LQCD, when obtained unambiguously, would finally lay down the answer to the physics of strong interactions. Present day LQCD computations have crossed a number of milestones in that direction, but yet to have reached the final goal.

Though the achievements of LQCD is commendable at zero densities, the path to finite densities is yet more troublesome. This is because of the inherent Monte Carlo integration scheme, where the statistical weight factor

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becomes complex. Given that no better alternative integration technique exits for such a huge multidimensional integration, one has to live with this problem and find regions in phase space where this problem is minimal. One such possibility is to use a significant overlap of configurations close to the transition region which will enable one to map out a phase boundary in the QCD phase diagram via multiparameter reweighting [7]. Another approach may be to expand the free energy as a Taylor series in the chemical potential with the coefficients evaluated at zero chemical potential [8]. Among other possibilities are the extraction of free energy for an imaginary chemical potential for which the Monte carlo weight factors are always real, and then analytically continuing the result to real chemical potentials [9]. This approach works in the region where chemical potential is less than the corresponding temperature in the phase diagram due to periodicity in the imaginary chemical potential direction [10]. Among other approches are the canonical ensemble method where the quark number is held fixed rather than the chemical potential for the commonly used grand canonical ensemble [11], and the density of states method [12] where the difficulty of complex weight factor is replaced by the difficulty in precisely determining the density of states. Note that all the above approaches are mainly concerned on how to lower or transfer the problem of complex weight factor in the Monte Carlo integration. An alternative integration technique would be more desirable to avoid this problem altogether.

2. Models for strong interaction

2.1. Phenomenological models

Thus most of the interesting information at the intermidiate chemical potentials we have today come from various QCD inspired models. Models in the field of strong interaction has a long history. In fact the birth of strong interaction happened through the satisfactory explanation of the hadron spectrum through the *constituent quark model* [13], following the success of the periodic table of hadrons - the *Eight-fold way* [14]. The success of the quark model led to the question as to whether these were physical and whether they can be observed. The experiments from 1966 to 1978 at the Stanford Linear Accelarator proved beyond doubt that the quarks are physical constituents of hadrons. Finally a proper renormalizable theory - Quantum Chromodynamics - emerged to explain the physics of strong interactions [15]. The lack of observation of free quarks was understood as a physical confinement effect due to the sharp increase of running coupling of the interactions [16].

Working out any information in the strong coupling regime has however remained formidable even today. This gave rise to a number of interesting models for confinement physics. The most prominent are the *Bag model* and the *String model* [17]. In the Bag model the quarks are supposed to be free inside a confining boundary whereas in the String model the quarks are bound with a linear energy flux. Both these models gave a more or less satisfactory description of the hadron masses and spectrum. Even today the modern numerical event generators use the String fragmentation for hadronization of partons created in collider experiments [18]. Similarly, a modern avatar of the Bag model that has been very successful in describing data from LQCD is the quasi-particle model (QPM) [19]. Here the quarks as well as the transverse gluons form the soup of quasi-particles inside a bag, and lowest order pQCD effects are incorporated.

A parallel phenomenological approach to study multipartiparticle production was the statistical bootstrap model in which highly excited lumps of hadronic matter created were supposed to behave as particle resonances, leading to an exponential growth of the particle spectrum [20]. The particles and resonances may thermalize to form a *fireball*. With the spectrum growing exponentially the temperature of the fireball soon reaches a limiting value - the Hagedorn temperature. In the light of deconfinement physics this limiting temperature has today been seen to be close to the transition temperature of confined hadrons to deconfined quark gluon matter. The model is used nowadays to callibrate results in experimental and theoretical studies in strong interactions. [21]. Statistical models of strong interactions thus became fashionable. Studies of scaling of particle multiplicities became important. As the energies of collider experiments increased the scaling laws kept changing [22]. Later entropy scaling was proposed to give the ultimate scaling law for multiparticle production [23]. In terms of chaotic and coherent sources the final picture was obtained for center of mass energy ranging from 22 GeV to 900 GeV per incident particle [24]. With the current LHC data at center of mass energy 2.3 TeV per incident particle we find this scaling to still hold true [25]. Today the most popular statistical model is the thermal model in which all known particles and resonances are identified (directly or indirectly) in the experiments and are then put into corresponding Bose or Fermi statistics to get the best set of unique thermodynamic parameters. Surprisingly enough the model does indeed give a satisfactory description of particle production [26].