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Nuclear Physics A 931 (2014) 257–266

NUCLEAR PHYSICS A

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Baryonic matter and beyond

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Received 3 August 2014; received in revised form 1 October 2014; accepted 2 October 2014

Available online 7 October 2014

Abstract

We summarize recent developments in identifying the ground state of dense baryonic matter and beyond. The topics include deconfinement from baryonic matter to quark matter, a diquark mixture, topological effect coupled with chirality and density, and inhomogeneous chiral condensates.

Keywords: High baryon density; Nuclear matter; Quark matter; Topological effects

1. Onset of deconfinement at high temperature

Color *confinement* in QCD is still a big mystery and some may want to think that color *deconfinement* would be more understandable; otherwise, we have no idea what we are talking about when it comes to the so-called quark–gluon plasma (QGP). It is our belief that the QGP has been created in the laboratory by means of nucleus–nucleus collision at high enough energy at RHIC in Brookhaven and LHC in CERN. It is not our present aim to challenge this widely accepted interpretation. The goal of this contribution should be to encourage for physics opportunities of the lower-energy nucleus–nucleus collision mainly in the context of the QCD phase diagram research. Since our theoretical understanding in finite-density QCD is so poor, what we can do the best is to make a guess from what we have known. In other words, we must carry extrapolation out from known physical states, or preferably interpolation between known states if possible.

In this section we discuss the extrapolation from high temperature and zero density along the phase transition. Nowadays it is said that the lattice QCD simulation has unveiled all features of QCD thermodynamics as long as the baryon chemical potential is much smaller than the temperature T. Indeed, the lattice QCD simulation is so powerful that precise data of the pressure, the

http://dx.doi.org/10.1016/j.nuclphysa.2014.10.011

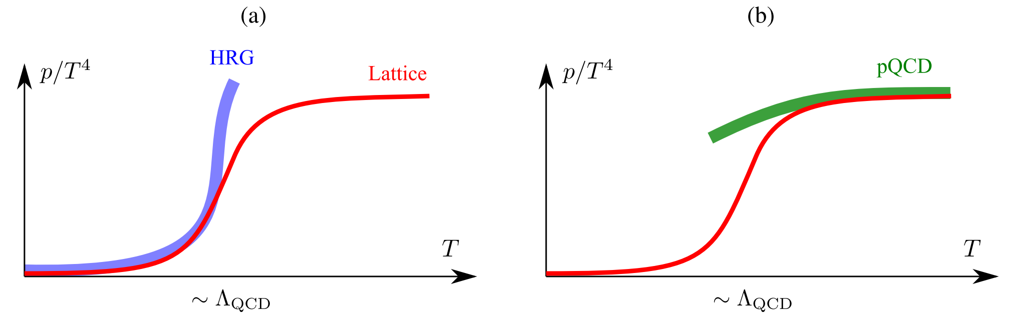

Fig. 1. Schematic figures of the normalized pressure as a function of T.

internal energy, the entropy density, etc., are available as functions of T. Historically speaking, because the QCD transition temperature turned out to be $T_c \sim \Lambda_{QCD}$ in early lattice QCD studies, the dream for the QGP factory came to reality [1,2]. Fig. 1 is a schematic of the dimensionless pressure p/T^4 that effectively measures the physical degrees of freedom in the thermal system. It is quite conceivable to interpret the rapid rise in p/T^4 as the liberation of colored particles; N_c quarks and $(N_c^2 - 1)$ gluons.

Thus, answering the following question seems easy: where do you find color deconfinement? Your answer would be that it takes place at $T_c \sim \Lambda_{QCD}$ where p/T^4 starts growing up. This conservative answer is of course not wrong, but not completely satisfactory. For the increasing behavior of p/T^4 another interpretation is possible, as illustrated by the HRG line in Fig. 1(a) that schematically describes the thermodynamics predicted in the hadron resonance gas (HRG) model. The HRG assumes a gas of non-interacting hadrons in a thermal bath. Each hadron hardly contributes to the entire thermodynamics, but the whole sum from hundreds of hadrons amounts to a substantial portion of the total pressure. As a side remark I note that it is a bit subtle whether the hadron interaction is incorporated or not in the HRG model. Some claim that interaction is correctly taken into account via higher resonating states. Such a claim is true if all the S-matrix poles are picked up by existing bound states and/or resonances. There may be, however, missing contribution from branch cut associated with threshold behavior and from hidden states not listed on the particle database. The theoretical foundation for the validity of the HRG estimate should deserve future investigations.

In any case, the fact is that the coincidence between the lattice QCD and the HRG is becoming better and better up to T_c as the lattice QCD approaches the continuum limit and the physical quark mass. Above T_c, eventually, the HRG badly blows up, which is to be regarded as the breakdown of the HRG model. Here, I would point out two non-trivial problems in this HRG results, which will provide us with a useful insight when we address the dense matter.

The first problem is that we can no longer consider that the rapid rise in p/T^4 should be attributed to color deconfinement. It could be induced by hundreds of hadrons even without colored particles at all. This is why I wrote; it is not wrong but not completely satisfactory to say that deconfinement takes place when p/T^4 shows a quick increase. Then, you may wonder, as a radical extreme, if it makes logical sense that the system keeps hadrons as relevant degrees of freedom for any T including $T > T_c$. We already know that the standard HRG is not valid above T_c, but the question is what exactly breaks down there. Does the hadronic description lose its meaning at all or is it only a part of assumption made in the HRG that goes invalid?