MAGNETIC SHIFT OF THE CHEMICAL FREEZEOUT AND ELECTRIC CHARGE FLUCTUATIONS*

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The phenomenological implication of the inverse magnetic catalysis, *i.e.* a modification in the QCD phase transition temperature under a strong magnetic field, is discussed.

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1. Introduction

The magnetic field is a useful tool to probe microscopic properties of matter [1]. Quark matter under a strong magnetic field is an interesting research subject in the contexts of neutron star structures and relativistic heavy-ion collisions. It is well-known that the chiral condensate is enhanced by the magnetic field effect, which is commonly referred to as the magnetic catalysis. The QCD phase diagram is accordingly changed with increasing magnetic field. One natural anticipation is that the (pseudo-)critical temperature for chiral restoration should be pushed up by the magnetic field because the critical temperature is usually proportional to the condensate value at zero temperature in any BCS-type theories. In this way, the chiral sector of QCD would be significantly affected by the magnetic field, while there is no direct coupling between the gluons and the magnetic field, and so it is unlikely that the deconfinement is so much influenced by the magnetic field.

In many chiral models including the Polyakov loop coupling, such unlocking of chiral restoration and deconfinement had been speculated. Contrary to model predictions, however, the lattice-QCD simulations have revealed decreasing behavior of the critical temperature with increasing magnetic field (see Ref. [2] for an overview). Such a lattice-QCD observation is completely opposite to what was expected from the magnetic catalysis, and this

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is the reason why this decreasing behavior of the critical temperature is called the inverse magnetic catalysis. It should be noted that this name, the inverse magnetic catalysis, was originally proposed to indicate the finite-density property, which is understandable even in the mean-field approximation, but the new inverse magnetic catalysis at finite temperature needs something beyond the mean-field treatment.

Many scenarios have been proposed to account for the inverse magnetic catalysis; some of them just introduced magnetic changing model parameters. In principle, all model parameters may have non-trivial dependence on the magnetic field, and the main contributions could result from the strong coupling constant running with the magnetic field scale. In the approaches based on chiral models, however, there are still large uncertainties, and it is quite difficult to extract model-independent information. Here, we discuss an alternative non-chiral approach to the inverse magnetic catalysis.

2. Inverse magnetic catalysis in the hadron resonance gas model

The hadron resonance gas (HRG) model is the most successful phenomenological model to reproduce the lattice-QCD data as well as the experimentally observed abundances of various particles. The model has no free parameter and the thermodynamics quantities are estimated with all known hadrons listed in the table of Particle Data Group. One might think that only pions can make a sizable contribution to thermodynamics around the temperature up to Λ_{QCD} due to the Boltzmann factor. Indeed, the Boltzmann factor is much smaller for heavier hadrons, but there are more and more resonances at higher energies, and eventually, the degeneracy (or the entropy in thermodynamic term) can overcome the small Boltzmann factor at some temperature. At this temperature, which is to be identified as the so-called Hagedorn temperature, the pressure, the internal energy density, the entropy density, *etc.* blow up, which effectively signifies deconfinement phase transition, even though physical degrees of freedom are still hadrons only.

When the internal energy suddenly changes, the inter-particle distance also changes, and then the interaction is turned off. In this way, it is expected that the particle species are frozen immediately after the deconfinement phase transition. In analogy to chemical reactions, this idea of frozen hadronic species is called the chemical freezeout. Interestingly, in the HRG model, the chemical freezeout points determined by the thermal fit of the experimental data are distributed very nicely on the curve drawn by the condition, $E/N \simeq 1$ GeV, where E is the internal energy and N is the sum of particles and anti-particles. We note that N is not the net-particle number, and this quantity is defined only within the HRG model (so not really measurable in the lattice-QCD simulation).

If the inverse magnetic catalysis occurs under the strong magnetic field, the chemical freezeout points must be shifted. In other words, now we have a nice model that can reproduce the chemical freezeout points without free parameter. If we put this model into a magnetic environment, we should be able to see something consistent with the inverse magnetic catalysis. This is a simple idea, and the idea works quite good, as seen in Fig. 1. Without any parameter tuning, the condition, $E/N = 0.9 \sim 1$ GeV, in the HRG model leads to a shift of the chemical freezeout points to higher temperatures by the effect of the magnetic field, and this shift quantitatively agrees with what is observed in the lattice-QCD simulation. Therefore, the HRG model gives the most robust and unambiguous explanation for the understanding of the inverse magnetic catalysis. The reason why the chemical freezeout point is pushed up is that the masses of charged hadrons significantly drop down in the magnetic field. Then, E increases, and N increases. Nevertheless, it is not so trivial whether E/N increases or decreases. The fact is, the increase in E is greater, and E/N increases, so that a smaller temperature can achieve $E/N = 0.9 \sim 1$ GeV.

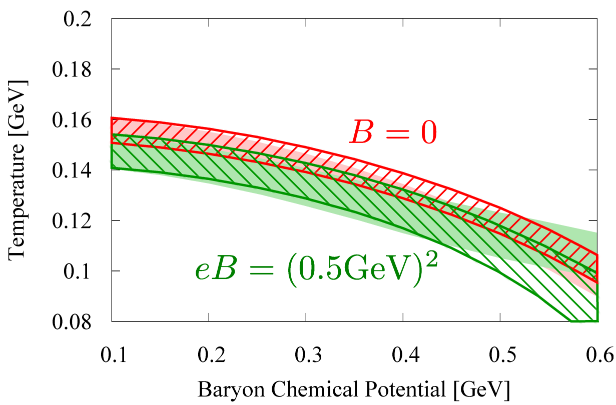

Fig. 1. Chemical freezeout shift by the magnetic field. The band corresponds to $E/N = 0.9 \sim 1$ GeV. Figure is from Ref. [3].

3. Electric charge fluctuations

The important question is how we can confirm such magnetic effects in the heavy-ion collision experiments. If we see the magnetic shift of the chemical freezeout, it would be a signal candidate, but the shift is about 10 MeV, and it is not easy to make a strong conclusion. A better signal we propose is the charge fluctuation measurement. Charged hadrons are easy to detect in the experiment, and needless to say, they are very sensitive to the magnetic field.

Figure 2 shows the calculated charge susceptibility in the HRG model with and without the magnetic field. The shaded bands represent results without the charge conservation, while the slant lines represent results with the charge conservation. In the heavy-ion collision system, it is indispensable to impose the conservation laws with respect to electric charge and strangeness. The strangeness conservation has a minor effect, but the electric charge conservation tends to kill the charge fluctuations. Still, as seen in Fig. 2, the charge susceptibility exhibits enhancement by the magnetic field. It is worth mentioning that the enhancement becomes larger at higher baryon density. This is given an immediate explanation; at higher baryon density, the system has more protons that would become lighter in the magnetic field.

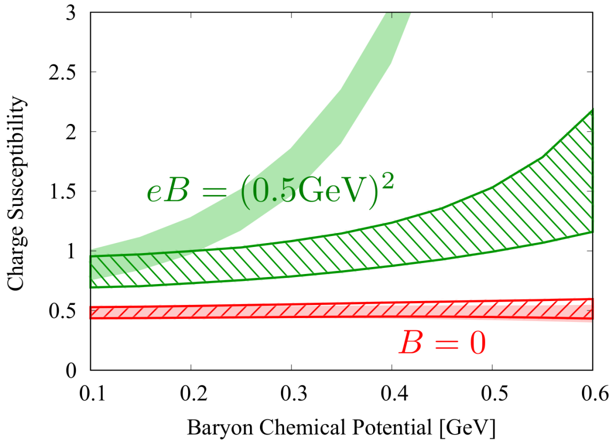

Fig. 2. Charge susceptibility calculated in the HRG model, with and without the magnetic field, and with and without the charge conservation. Figure is from Ref. [3].

From this point of view, the lower energy collision as performed in the beam energy scan program is quite promising to discover something attributed to the magnetic effect. Although the biggest magnitude of the magnetic field is smaller, the life time is longer, and protons in the high-density environment sensitively react to the magnetic field.

So far, we have discussed the results at a fixed magnetic field, $eB = (0.5\ \text{GeV})^2$, in Figs. 1 and 2. Now, we can take a different viewpoint to change the magnetic field at a fixed baryon chemical potential, and then the plot is presented in Fig. 3. The charge susceptibility shows a characteristic curve; it is rather insensitive to the magnetic field up to around 0.2 GeV^2, and then the charge susceptibility rapidly arises at $eB = 0.2 \sim 0.25\ \text{GeV}^2$. This result implies that there may be a sort of phase transition there and the state of matter beyond $eB \sim 0.2\ \mathrm{GeV}^2$ may acquire some exotic properties. One possibility is, in view of the fact that the electric charge fluctuations are so huge, the electric conductivity may become very large then. If this happens, the time-dependent magnetic field can be easily sustained by induction current, and the lifetime of the magnetic field is further elongated. This scenario is quite appealing, giving us a better prospect in the low-energy heavy-ion collision, and surely deserve more investigations in the future.

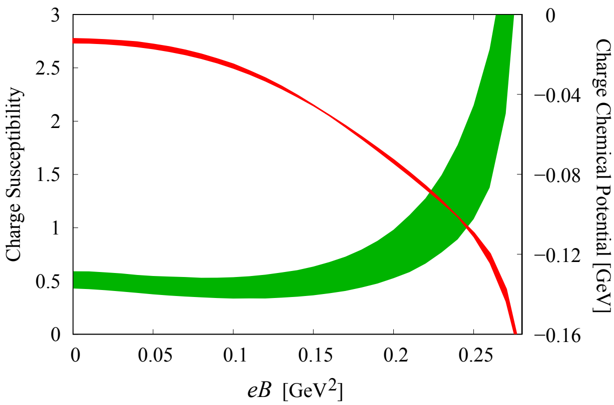

Fig. 3. Magnetic field dependence of the charge susceptibility and the charge chemical potential necessary to keep the electric neutrality of the system. The baryon chemical potential is fixed to be 0.6 GeV. Figure is from Ref. [3].

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