Thermodynamics of two-flavor lattice QCD with an improved Wilson quark action at non-zero temperature and density

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Abstract. We report the current status of our systematic studies of the QCD thermodynamics by lattice QCD simulations with two flavors of improved Wilson quarks. We evaluate the critical temperature of two flavor QCD in the chiral limit at zero chemical potential and show the preliminary result. Also we discuss fluctuations at none-zero temperature and density by calculating the quark number and isospin susceptibilities and their derivatives with respect to chemical potential.

1. Introduction

In order to extract unambiguous signals for the QCD phase transition from the heavy-ion collision experiments, quantitative calculations from first principle are indispensable. At present, the lattice QCD simulation is the only systematic method to do so and various interesting results have been already reported. So far, most lattice QCD studies at finite temperature (T) and chemical potential (µq) have been performed using staggered-type quark actions with the fourth-root trick of the quark determinant. Thus, the other actions such as the Wilson-type quark actions are necessary to control and estimate systematic errors due to lattice discretization.

Several years ago, the CP-PACS Collaboration has studied the QCD thermodynamics using the Iwasaki (RG) improved gauge action and the two-flavor clover improved Wilson quark action [1]. We revisit this action armed with recent techniques at finite chemical potential µq. In this report, we present on our preliminary results for the critical temperature at µq = 0 as well as the quark number and isospin susceptibilities at finite µq. The latter are related to the physics of the possible critical point in the (T, µq) plane.

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2. Critical temperature of two-flavor QCD

The critical temperature ($T_c$) is one of the most fundamental quantities in the QCD thermodynamics. We renew the analysis of $T_c$ done in [1] performing additional simulations at $\beta = 6/g^2 = 1.8$ for $N_t = 4$ and 1.95 for $N_t = 6$. We determine the pseudo-critical point $\beta_{pc}$ defined from the peak of Polyakov loop susceptibility on $N_s^3 \times N_t = 16^3 \times 4$ and $16^3 \times 6$ lattices, as a function of the hopping parameter $K$.

It is confirmed in Ref. [1] that a subtracted chiral condensate satisfies the scaling behavior with the critical exponents and scaling function of the three-dimensional O(4) spin model. The reduced temperature $t$ and external magnetic field $h$ are identified to $t \sim \beta - \beta_{ct}$ and $h \sim m_q$, respectively, where $\beta_{ct}$ is the critical transition point in the chiral limit. Assuming that the pseudo-critical temperature from the Polyakov loop susceptibility follows the same scaling law as the O(4) spin model, $t_{pc} \sim h^y$ with $y = 0.537(7)$, we fit the data of $\beta_{pc}$ by $\beta_{pc} = \beta_{ct} + Ah^{1/y}$ with two free parameters, $\beta_{ct}$ and $A$, in the range of $\beta = 1.8$–1.95 for $N_t = 4$ and $\beta = 1.95$–2.10 for $N_t = 6$. First, we adopt the definition $m_q a \sim 1/K - 1/K_c$ as the quark mass where $K_c$ is the chiral point where the pion mass vanishes at $T = 0$ for each $\beta$. See Fig. 1 (left). We calculate the critical temperature $T_c$ in the chiral limit using $T = 1/N_0 a$. The lattice spacing $a$ is estimated from the vector meson mass assuming $m_V(T = 0) = m_{\rho} = 770$ MeV at $\beta_{ct}$ on $K_c$. By this procedure, we obtain the preliminary results $T_c = 183(3)$ MeV for $N_t = 4$ and $174(5)$ MeV for $N_t = 6$. We also calculate $\beta_{ct}$ using the relation of $m_q^{AWI} \propto m_{PS}^2$, where $m_{PS}$ is the pseudo-scalar meson mass and $m_q^{AWI}$ is the quark mass obtained from the axial vector Ward-Takahashi identity. The results of $T_c$ are $173(3)$ MeV ($N_t = 4$), $167(3)$ MeV ($N_t = 6$) for $h = (m_{PS} u)^2$ and $166(3)$ MeV ($N_t = 4$) for $h = m_q^{AWI} u$. We note that these O(4) fits reproduce the data of $\beta_{pc}$ much better than a linear fit $\beta_{pc} = \beta_{ct} + Ah$. From these analyses, we tentatively conclude that the critical temperature in the chiral limit is in the range $170$–$186$ MeV for $N_t = 4$ and $164$–$179$ MeV for $N_t = 6$. There is still a large uncertainty from the choice of the fit ansatz. To remove this, we are performing further simulations at lighter quark masses.

Next, we compare our results with those of the staggered quark action. We plot the results of the pseudo-critical temperature ($T_{pc}$) in unit of Sommer scale ($r_0$) as a function of $m_{PS} r_0$ in Fig. 1 (right) together with those by the RBC-Bielefeld Collaboration using 2+1 flavor p4-improved staggered quark action [2]. As seen in this figure, results of $T_{pc}$ obtained by different quark actions seem to approach the same function of $m_{PS} r_0$ as $N_t$ increases.

A care is in order when we convert $T_c, r_0$ ($T_{pc}, r_0$) to $T_c (T_{pc})$ in MeV using a physical value of $r_0$. Because the phenomenological estimate of $r_0$ has large theoretical uncertainties, it looks convenient to adopt a lattice result. Unfortunately, lattice results for $r_0$ suffer from sizable ambiguities yet. The RBC-Bielefeld Collaboration adopted the value $r_0 = 0.469(7)$ fm, which was obtained by Gray et al. [3] from a bottomonium mass splitting using the AsqTad-improved staggered quark action. On the other hand, the CP-PACS+JLQCD Collaboration found $r_0 = 0.516(21)$ fm from a study of light hadron spectrum using the clover-improved Wilson quark action [4]. This leads to about 10 % difference in the value of $T_c$ and makes it difficult to naively compare results from different groups.
Calculations are reported in Ref. [5]. ∂ staggered fermions [6].

Basic features are quite similar to those found previously with the p4-improved Wilson quark action, the hadron resonance gas model, the continuum extrapolation. A large enhancement in the quark number fluctuations near the critical point in the (T, µq) plane and may be experimentally detected by an event-by-event analysis of heavy ion collisions. The fluctuations can also be studied by numerical simulations of lattice QCD calculating the quark number and isospin susceptibilities, which are singular at the critical point, whereas χI shows no singularity there.

Hadronic fluctuations at finite µq

Hadronic fluctuations at finite density are observables closely related to the critical point in the (T, µq) plane and may be experimentally detected by an event-by-event analysis of heavy ion collisions. The fluctuations can also be studied by numerical simulations of lattice QCD calculating the quark number and isospin susceptibilities, χq and χI. They correspond to the second derivatives of the pressure with respect to µq and µI, where µI is the isospin chemical potential. From a phenomenological argument in the sigma model, χq is singular at the critical point, whereas χI shows no singularity there.

We perform simulations at mPS/mV = 0.65 and 0.80 on a 16³ × 4 lattice. We calculate the χq and χI and their second derivatives with respect to µq and µI at µq = µI = 0. (Note that the odd derivatives are zero at µq = 0.) The details of the calculations are reported in Ref. [5].

The left panel of Fig. 2 shows χq/T² (circle) and χI/T² (square) at mPS/mV = 0.8 and µq = µI = 0 as functions of T/Tpc. We find that χq/T² and χI/T² increase sharply at Tpc, in accordance with the expectation that the fluctuations in the QGP phase are much larger than those in the hadron phase. Their second derivatives ∂²χq/∂(µq/T²) and ∂²χI/∂(µq/T²) are shown in Fig. 2 (right). We find that basic features are quite similar to those found previously with the p4-improved staggered fermions [6]. ∂²χI/∂(µq/T²) remains small around Tpc, suggesting that there are no singularities in χI at non-zero density. On the other hand, we expect a large enhancement in the quark number fluctuations near Tpc as approaching the critical point in the (T, µq) plane. The dashed line in Fig. 2 (right) is a prediction from the hadron resonance gas model, ∂²χq/∂µq² ≈ 9χq/T². Although current statistical errors in Fig. 2 (right) are still large, we find that ∂²χI/∂(µq/T²) near Tpc is much larger than that at high temperatures. At the right end of the figure, values of free quark-gluon gas (Stefan-Boltzmann gas) for Nf = 4 and for Nf = ∞ limit are shown. Since the lattice discretization error in the equation of state is known to be large at Nf = 4 with our quark action, we need to extend our study to larger Nf for the continuum extrapolation.

3. Hadronic fluctuations at finite µq

The left panel of Fig. 2 shows χq/T² (circle) and χI/T² (square) at mPS/mV = 0.8 and µq = µI = 0 as functions of T/Tpc. We find that χq/T² and χI/T² increase sharply at Tpc, in accordance with the expectation that the fluctuations in the QGP phase are much larger than those in the hadron phase. Their second derivatives ∂²χq/∂(µq/T²) and ∂²χI/∂(µq/T²) are shown in Fig. 2 (right). We find that basic features are quite similar to those found previously with the p4-improved staggered fermions [6]. ∂²χI/∂(µq/T²) remains small around Tpc, suggesting that there are no singularities in χI at non-zero density. On the other hand, we expect a large enhancement in the quark number fluctuations near Tpc as approaching the critical point in the (T, µq) plane. The dashed line in Fig. 2 (right) is a prediction from the hadron resonance gas model, ∂²χq/∂µq² ≈ 9χq/T². Although current statistical errors in Fig. 2 (right) are still large, we find that ∂²χI/∂(µq/T²) near Tpc is much larger than that at high temperatures. At the right end of the figure, values of free quark-gluon gas (Stefan-Boltzmann gas) for Nf = 4 and for Nf = ∞ limit are shown. Since the lattice discretization error in the equation of state is known to be large at Nf = 4 with our quark action, we need to extend our study to larger Nf for the continuum extrapolation.
4. Conclusion

We reported the current status of our study of QCD thermodynamics using the two-flavor improved Wilson quark action. The critical temperature is estimated from the Polyakov loop susceptibilities on $16^3 \times 4$ and $16^3 \times 6$ lattices. We discussed uncertainties from the chiral extrapolation and the scale parameter. Our preliminary result of $T_c$ in the chiral limit is in the range of $T_c = 170–186$ MeV for $N_t = 4$ and $T_c = 164–179$ MeV for $N_t = 6$.

The fluctuations of quark number and isospin densities were also discussed. Although the statistical errors are still large, we find that $\chi_q$ seems to increase rapidly near $T_{pc}$ as $\mu_q$ increases, whereas the increase of $\chi_I$ is not large near $T_{pc}$. These behaviors qualitatively agree with the previous results obtained with the p4-improved staggered fermions.

We also studied the static quark free energies, Debye screening masses and spatial string tension at finite temperature with the same action, which are reported in detail in Ref. [7].

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