LLNL-PROC-676443

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August 18, 2015

Origin of Mass and Strong Coupling Gauge Theories (SCGT15)
Nagoya, Japan
March 3, 2015 through March 6, 2015

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Thermodynamics in 8-Flavor QCD

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Motivated by the scenario of electroweak baryogenesis in the walking technicolor (WTC) model, we investigate thermodynamic properties of 8-flavor QCD by using Monte Carlo simulations in the lattice gauge theory. We adopt HISQ and tree-level Symanzik improved actions. We show that the chiral susceptibility has a peak structure, and the ratio of chiral and pion susceptibilities starts showing an inflection point with a decreasing fermion mass. These results suggest the existence of the chiral phase transition in 8-flavor QCD.

Keywords: Lattice Gauge Theory, Conformal/Walking Dynamics, Chiral and Electroweak Phase Transitions.

1. Introduction

The baryon number asymmetry in the Universe (BAU) indicates that baryogenesis took place in the early stage of the Universe. The baryogenesis requires processes satisfying Sakharov's three conditions, 1) baryon number violation, 2) C and CP violation, 3) out-of-equilibrium. In the standard model in particle physics, the only electroweak phase transition has a possibility to satisfy 1) and 2). However, lattice studies on the standard model at finite temperature (T)[1] has shown that a rapid crossover instead of the first-order phase transition, which is necessary for 3), occurs in the electroweak gauge-Higgs sector. Thus, the standard model fails to explain BAU. If a walking technicolor (WTC) model[2] replaces the Higgs sector of the standard model, the finite T chiral phase transition of that model is of

great interest for the electroweak baryogenesis. Recently, LatKMI Collaboration has shown that the 8-flavor ($N_f = 8$) QCD is a candidate of WTC[3]. That theory, which is of $N_f \geq 3$, is expected to have first-order phase transition, *a la* Pisarski and Wilczek[4].

The first-principle studies on the 8-flavor QCD thermodynamics with the lattice gauge theory is demanded and the subject in this proceedings. Since 8-flavor QCD seems to be in the boarder of the conformal and confined phases, it is challenging to extract signals of the chiral phase transition; The most important signal is the peak in the chiral susceptibility ($\chi_{\rm chiral}$), while it has not been shown yet in the previous works[5,6]. In this proceedings, we show that the $\chi_{\rm chiral}$ has a peak, which suggests the physical chiral transition in 8-flavor QCD at least for the adopted fermion mass range. Furthermore, we investigate the fermion mass dependence of the ratio of chiral and pion susceptibilities ($R_\pi = \chi_{\rm chiral}/\chi_\pi$), whose inflection point for varying T indicates the chiral phase transition. If the chiral dynamics exists, the inflection point should evolve with a decreasing fermion mass, while there is no reason to expect that in the conformal window. We will show that the former is the case in the 8-flavor QCD.

2. Lattice Setup

The Monte Carlo simulations are organized to keep a consistency to zero temperature simulations[3]: We have utilized the MILC-code[7] with some modifications, and adopted tree-level Symanzik gauge action and HISQ fermion action.

We used the lattice box size $(L_s, L_t) = (24, 12)$ and $(32, 16)$ with the fixed aspect ratio $L_s/L_t = 2$, and temperature $T = 1/(L_t a(\beta_{\rm L}))$ ($a(\beta_{\rm L})$ = lattice spacing at lattice coupling $\beta_{\rm L}$) is controlled by varying $\beta_{\rm L} \in [2.8, 4.0]$. We will find the critical coupling ${\beta_{\rm L}}^{\rm c}$ associated with a chiral phase transition temperature $T_c = 1/(L_t a({\beta_{\rm L}}^{\rm c}))$. In the strong coupling region $\beta_{\rm L} \lesssim 3.5$, the HISQ fermion cannot achieve a good acceptance ratio in Hybrid Monte Carlo (HMC) algorithm with Metropolis tests, and we alternatively used Hybrid Moleculer Dynamics (HMD). Systematic errors due to the lack of Metropolis tests have not been investigated yet in this proceedings.

The lattice fermion mass is set to be $m_f \times a(\beta_{\rm L}) = 0.02$ or 0.04. We shall consider the fermion mass normalized by temperature as follows: $\tilde{m}_f(\beta_{\rm L}) \equiv [m_f \cdot a(\beta_{\rm L})] \times L_t = m_f \times [a(\beta_{\rm L}) \cdot L_t] = m_f/T$. At the critical coupling, we have $\tilde{m}_f({\beta_{\rm L}}^{\rm c}) = m_f/T_c$ which measures the strength of fermion mass effects. In the present studies, we have three values on $\tilde{m}_f({\beta_{\rm L}}^{\rm c}) = \{0.02 \cdot 12,\ 0.02 \cdot 16,\ 0.04 \cdot 12\}$ at the transition. We have generated $\mathcal{O}(1000)$ gauge configurations with $\mathcal{O}(3000 - 10000)$ trajectories at each point of the parameter space explained above. Using those configurations, we have evaluated the chiral condensate, Polyakov loops, and their susceptibilities.

3. Results

We investigate the ratio of chiral and pion susceptibilities $R_\pi = \chi_{\rm chiral}/\chi_\pi$. In the chiral limit, the R_π gets vanishing (unity) in the chiral broken (restored) phase and thus very sensitive to the chiral phase transition[8]. Even for the case with a finite fermion mass $m_f > 0$, the R_π shows a rapid increase near the chiral transition/crossover[5]. Since the R_π is dimensionless, it is renormalization invariant under the $\beta_{\rm L}$ variation upto physical mass changes.

In the left panel of Fig. 1, we show R_π as a function of $\beta_{\rm L}$. A larger $\beta_{\rm L}$ corresponds to a higher temperature, $T = 1/(L_t a(\beta_{\rm L}))$. As the fermion mass $\tilde{m}_f(\beta)$ gets smaller, the R_π becomes a step-function-like. Resultantly, the inflection point appears for $\tilde{m}_f = 0.02 \cdot 12$ (blue circles/squares) as indicated by the peak of the R_π-increasing rate (middle panel), though the error-bars are largish. This suggests the growing signal of the chiral phase transition/crossover as a fermion mass becomes smaller. In the right panel of Fig. 1, we show the chiral susceptibility $\chi_{\rm chiral}$ as a function of $\beta_{\rm L}$ for $\tilde{m}_f = 0.02 \cdot 12$. The decreasing trend is due to the scale variation with $\beta_{\rm L}$. We find the peak at $\beta_{\rm L} = 3.08$, which suggests the chiral phase transition ${\beta_{\rm L}}^{\rm c} \simeq 3.08$.

These observations support that the 8-flavor QCD at zero temperature would be in the chiral broken phase rather than the conformal phase. We note that the real parts of Polyakov loops start significantly deviating from zero at $\beta_{\rm L} = 3.16$, which is slightly larger than ${\beta_{\rm L}}^{\rm c}$.

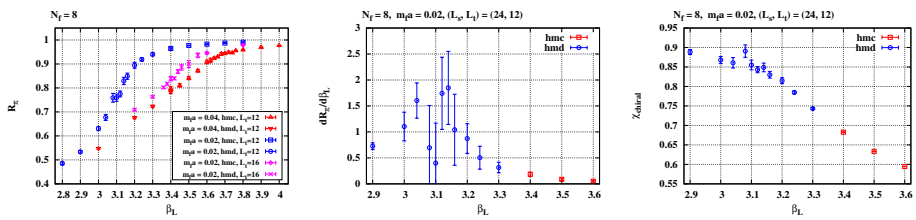

Fig. 1. The susceptibility ratio R_π (left), its increasing rate $dR_\pi/d\beta_{\rm L}$ (middle), and the chiral susceptibility $\chi_{\rm chiral}$ (right) as a function of lattice bare couplings $\beta_{\rm L}$ associated with a temperature via $T = 1/(L_t a(\beta_{\rm L}))$.

4. Summary and Outlook

Motivated by the electroweak baryogenesis in WTC scenario, we have investigated thermodynamic property of 8-flavor QCD by using Monte Carlo simulations in the lattice gauge theory. In contrast to the other group activities[5,6], we have shown a *Peak Structure in the Chiral Susceptibility*, which suggests the physical chiral transition in 8-flavor QCD. The susceptibility ratio $R_\pi = \chi_{\rm chiral}/\chi_\pi$ becomes more step-function-like with a decreasing fermion mass m_f, implying the growing signal

of the chiral phase transition/crossover as m_f becomes smaller.

We should note that the aforementioned results are still preliminary and the existence of the chiral phase transition in 8-flavor QCD would not be conclusive. It is mandatory to estimate the systematic errors coming from the use of HMD in the strong coupling region as a next step.

Besides, there are several subjects to be investigated in future. First, it is desirable to investigate a phase transition of 8-flavor QCD for sufficiently small fermion masses without a contamination of un-physical bulk transitions. This requires a much larger lattice volume with much smaller bare fermion masses. Second, it is interesting to study Dirac eigen values of 8-flavor QCD at finite T with a help of Wilson flow smearing technique as performed in[6]. Third, it is necessary to set a scale by using the Wilson flow. This requires the zero temperature simulations at ${\beta_{\rm L}}^{\rm c}$ which corresponds to the chiral phase transition/crossover temperature at finite temperature simulations.

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Prepared by LLNL under Contract DE-AC52-07NA27344.