Thermal effects on quark-gluon mixed condensate $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ from lattice QCD

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In this report, we present the first study of the thermal effects on the quark-gluon mixed condensate $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$. The importance of the mixed condensate can be understood because the chirality of the quark in the operator $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ flips as $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle = g\langle\bar{q}_R(\sigma_{\mu\nu}G_{\mu\nu})q_L\rangle + g\langle\bar{q}_L(\sigma_{\mu\nu}G_{\mu\nu})q_R\rangle$, and thus the mixed condensate plays the role of an alternative chiral order parameter. Therefore, in the study of the chiral restoration at finite temperature, which is essential to understand the spontaneous chiral symmetry breaking of QCD and on-going RHIC experiments, the thermal effects on the mixed condensate become suitable physical quantity to analyze. Here, we note that $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ characterizes different aspect of the QCD vacuum from the usual quark condensate $\langle\bar{q}q\rangle$. In particular, $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ reflects the color-octet components of quark-antiquark pairs in the QCD vacuum, while $\langle\bar{q}q\rangle$ reflects only the color-singlet q-$\bar{q}$ components. The mixed condensate $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ thus represents the direct correlation between color-octet q-$\bar{q}$ pairs and the gluon field strength $G^A_{\mu\nu}$. Furthermore, the mixed condensate affects the hadron phenomenology through the framework of the QCD sum rule. Actually, it is know that the mixed condensate plays an important role in the QCD sum rule for the baryonic properties, such as N-Δ splitting [1]. Recent study [2] also shows that the parameter $g\langle\bar{s}\sigma_{\mu\nu}G_{\mu\nu}s\rangle/\langle\bar{s}s\rangle$ is a key quantity for the prediction on the parity of the recently discovered penta-quark baryon, $\Theta^+(1540)$.

For the analysis of the thermal effects on the mixed condensate $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$, we use the $SU(3)_c$ lattice QCD with the Kogut-Susskind (KS) fermion at the quenched level. Note that the KS-fermion preserves the explicit chiral symmetry for the quark mass $m = 0$, which is a desirable feature to study the condensate of chiral order parameters. We use the following lattices, i) $\beta = 6.0$, $V = 16^3 \times N_t$ ($N_t = 16, 12, 10, 8, 6, 4$), ii) $\beta = 6.1$, $V = 20^3 \times N_t$ ($N_t = 20, 12, 10, 8, 6$), iii) $\beta = 6.2$, $V = 24^3 \times N_t$ ($N_t = 24, 16, 12, 10, 8$), which correspond to $0 \lesssim T \lesssim 500$MeV with the spatial volume of $L^3 \simeq (1.6 - 1.8\text{fm})^3$. We generate 100 gauge configurations for each lattice. Moreover, in the vicinity of the phase transition point, $20^3 \times 8$ at $\beta = 6.1$ and $24^3 \times 10$ at $\beta = 6.2$, where the fluctuations of the condensates get larger, we generate 1000 gauge configurations for the accurate estimate. In each configuration, we measure the condensate on 16 different space-time points at $\beta = 6.0$ and 2 points at $\beta = 6.1$ and 6.2. We calculate the condensate at the physical quark mass of $m \simeq 20, 35$ and 50MeV, and extrapolate the results to $m = 0$, to determine the condensate in the chiral limit. The detailed formulations are given in Refs. [3, 4, 5].

We estimate the thermal effects on $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ as well as $\langle\bar{q}q\rangle$, by taking the ratio between the values at finite and zero temperature. In figure 1, we plot the thermal effects on $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$. We find a drastic change of $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ around the critical temperature $T_c \simeq$ 280MeV. This is the first observation of chiral-symmetry restoration through $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$. We obtain $T_c/\sqrt{\sigma} = 0.64(4)$, which is consistent with the coincidence of chiral-symmetry phase restoration and the confinement/deconfinement phase transition. We also find that the thermal effects on $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ are remarkably weak below T_c, namely, $T \lesssim 0.9\,T_c$. We obtained the same features as $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ for the thermal effects on $\langle\bar{q}q\rangle$.

We then quantitatively compare the thermal effects of $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle$ and $\langle\bar{q}q\rangle$. For this

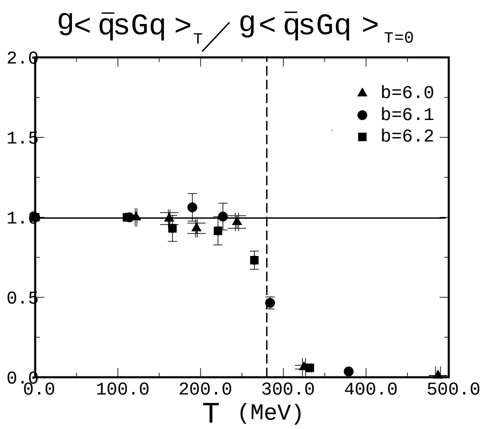

Figure 1: The quark-gluon mixed condensate $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle_T$ at finite temperature T normalized by $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle_{T=0}$. The vertical dashed line denotes the critical temperature $T_c \simeq 280$MeV in quenched QCD.

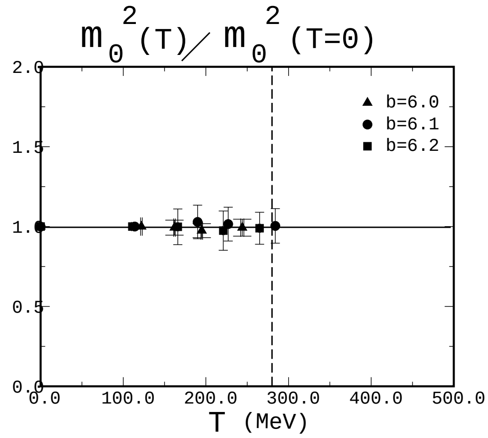

Figure 2: The ratio $m_0^2(T) \equiv g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle_T/\langle\bar{q}q\rangle_T$ normalized by $m_0^2(T=0)$ plotted against T. This result indicates the same chiral behavior between $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle_T$ and $\langle\bar{q}q\rangle_T$.

purpose, we plot the ratio $m_0^2(T) \equiv g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle_T/\langle\bar{q}q\rangle_T$ normalized by $m_0^2(T=0)$ for $T \lesssim T_c$ in figure 2. We observe that $m_0^2(T)$ is almost independent of the temperature, even in the very vicinity of T_c, which can be interpreted that $g\langle\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q\rangle_T$ and $\langle\bar{q}q\rangle_T$ obey the same thermal behavior. This result is rather nontrivial because, as was noted before, these two condensates characterize different aspects of the QCD vacuum. As an interesting possibility, this common thermal behavior may indicate a universal behavior of chiral order parameters near T_c, which provides new aspects on the chiral structure of the QCD phase transition.

For further studies, a full QCD lattice calculation is in progress in order to analyze the dynamical quark effects on the condensates, from which we expect to get deeper insight on the chiral structure of the QCD vacuum at finite temperature.

Acknowledgements

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References

[1] S. Narison, "QCD Spectral Sum Rules", (World Scientific, 1989) p.1 and references therein.
[2] J. Sugiyama, T. Doi and M. Oka, Phys. Lett. **B581** (2004) 167.
[3] T. Doi, N. Ishii, M. Oka and H. Suganuma, Phys. Rev. **D67** (2003) 054504.
[4] T. Doi, N. Ishii, M. Oka and H. Suganuma, Nucl. Phys. **A721** (2003) 934; Prog. Theor. Phys. Suppl. **151** (2003) 161; Nucl. Phys. **B129** (Proc. Suppl.) (2004) 566; Proc. of "Quark Confinement and the Hadron Spectrum V" (World Scientific, 2003) p.381, hep-lat/0212025; T. Doi, H. Suganuma, M. Oka and N. Ishii, Proc. of "Color Confinement and Hadrons in Quantum Chromodynamics (Confinement 2003)" (World Scientific, 2004) p.398, hep-lat/0311015.
[5] T. Doi, N. Ishii, M. Oka and H. Suganuma, hep-lat/0402005 (2004).