# Flux tube profiles in two-color QCD at low temperature and high density

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## PURPOSE

- Understanding the physics of QCD in extreme conditions at finite temperature and density.
- What we want to investigate
  - Phase diagram on T-μ plane
  - Thermodynamic quantities
  - Nonperturbative properties (color confinement, χSB, …)

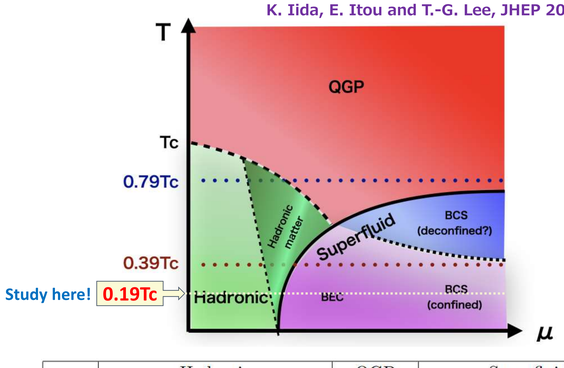
## TWO-COLOR QCD WITH Nf=2

- In this work, we examine the temperature and density dependence of the phase and color flux tube structure of dense two-color QCD with two-flavor Wilson fermions by using a lattice simulation to avoid the sign problem.
- 2-color QCD has the same properties as 3-color QCD, e.g. color confinement and spontaneous chiral symmetry breaking.
- It is expected to provide insights for 3-color QCD.
- Lattice setup — K. Iida, E. Itou and T.-G. Lee, PTEP 2021 (2021) 013B05; K. Iida, E. Itou and T.-G. Lee, JHEP 2001 (2020) 181
  - Gauge part : Iwasaki gauge action
  - Fermion part : Two-flavor Wilson fermion action including the quark number operator and the diquark source term
  - Lattice volume $32^4$ lattice
  - Parameters $\beta = 0.800,\ \kappa = 0.159,$ $T = 0.19 T_c$

| $(\mu, j)$ | phase |
|---|---|
| (0.00, 0.00) | Hadronic |
| (0.25, 0.00) | Hadronic |
| (0.35, 0.02) | BEC |
| (0.50, 0.02) | BCS |
| (0.70, 0.02) | BCS |

## SCHEMATIC PICTURE OF PHASE DIAGRAM

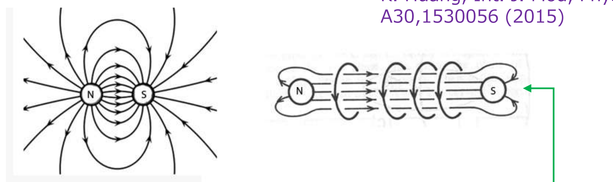
K. Iida, E. Itou and T.-G. Lee, PTEP 2021 (2021) 013B05
K. Iida, E. Itou and T.-G. Lee, JHEP 2001 (2020) 181




| | Hadronic | Hadronic matter | QGP | Superfluid | |
|---|---|---|---|---|---|
| | | | | BEC | BCS |
| $\langle \lvert L \rvert \rangle$ | zero | zero | non-zero | | |
| $\langle qq \rangle$ | zero | zero | zero | non-zero | $\propto \mu^2$ |
| $\langle n_q \rangle$ | $\langle n_q \rangle = 0$ | $\langle n_q \rangle > 0$ | $\langle n_q \rangle \geq 0$ | non-zero | $\langle n_q \rangle / n_q^{\mathrm{tree}} \approx 1$ |

## DUAL SUPERCONDUCTOR PICTURE

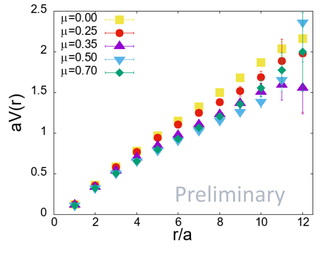
- In QCD vacuum, color magnetic monopoles condense instead of the formation of Cooper pairs in the BCS theory of normal superconductivity (dual superconductor), leading to color confinement via the dual Meissner effect. G. 'tHooft (1976), S.Mandelstam (1976)
- Many numerical evidence for the dual superconductor picture of the QCD vacuum. Shiba-Suzuki (1994), Y.Matsubara et al.(1994), Cea-Cosmai(1995), G.S.Bali et al.(1998), A.Di Giacomo et al.(1999), ...
- Color electric field between quark and antiquark is squeezed into tube-like structure. The formation of color flux provides a linear potential between quark and antiquark.
- Flux tubes
  - Magnetic field of a magnetic dipole — K. Huang, Int. J. Mod, Phys. A30,1530056 (2015)

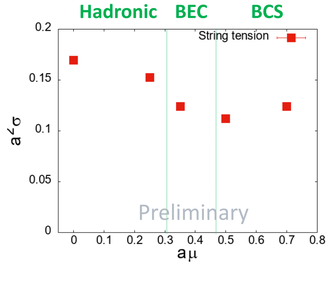



  - Color electric field of quark and antiquark pair


## STATIC POTENTIALS

- Weak density dependence of static potentials and string tensions from Wilson loop operator.



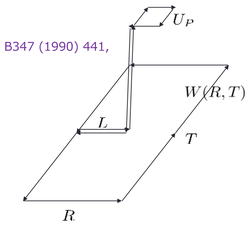

- The value of string tension σ varies around μ=0.35 and has a non-zero value even in the high μ region. This indicates that the system at T=0.19Tc is in a confined phase for all μ region within the scope of this study.

## THE COLOR FIELDS ON THE LATTICE

- Connected correlator — A. Di Giacomo, M. Maggiore, S. Olejnik, Nucl.Phys. B347 (1990) 441, P. Cea, L. Cosmai, Phys.Rev. D52 (1995) 5152

$$\rho_W = \frac{\langle \mathrm{Tr}(W L U_P L^\dagger) \rangle}{\langle \mathrm{Tr}(W) \rangle} - \frac{1}{N} \frac{\langle \mathrm{Tr}(U_P) \mathrm{Tr}(W) \rangle}{\langle \mathrm{Tr}(W) \rangle}$$

$W$ : Wilson loop
$L$ : Schwinger line
$U_P$ : Plaquette




- Profile of electric field (Ez) — J. R. Clem, J. Low Temp. Phys 18, 427 (1975); P. Cea, L. Cosmai and A. Papa, Phys. Rev. D86(2012)

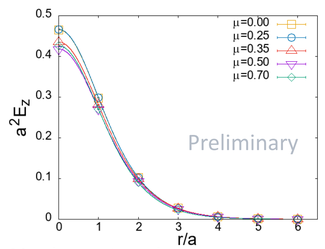
$$E_z(r) = \frac{\phi}{2\pi\lambda^2\alpha} \frac{K_0[(r^2/\lambda^2 + \alpha^2)^{\frac{1}{2}}]}{K_1[\alpha]}$$

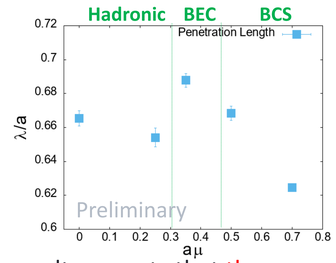
$$\frac{1}{\alpha} = \frac{\lambda}{\xi_v} \qquad \kappa = \frac{\lambda}{\xi} = \frac{\sqrt{2}}{\alpha}\sqrt{1 - \frac{K_0^2(\alpha)}{K_1^2(\alpha)}}$$

$\phi$ : external flux
$\lambda$ : London penetration length
$\xi_v$ : variational core-radius
$\kappa = \lambda/\xi$ : Ginzburg-Landau parameter

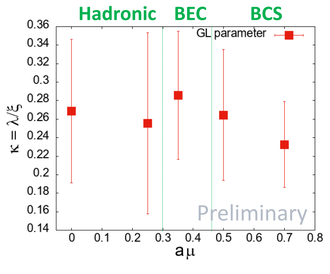
| | |
|---|---|
| Type 1 | $\kappa < 1/\sqrt{2}$ |
| Type 2 | $\kappa > 1/\sqrt{2}$ |

- Weak density dependence of Ez and penetration length




- Ginzburg-Landau parameter : this result suggests that the vacuum of two-color QCD is a type 1 dual superconductor.




## SUMMARY

- In Nf=2 two-color QCD at T=0.19Tc,
  - Non-zero string tension in all μ region
  - Flux tubes remain squeezed in all μ region at T=0.19Tc
  - Ginzburg-Landau parameters suggest type 1 dual superconductor of the vacuum
- The system at T=0.19Tc is in a confined phase for all μ region within the scope of this study.
  - Consistent with the previous results of Polyakov loop and topological susceptibility