素粒子論領域，理論核物理領域 合同シンポジウム

多様なアプローチによる
量子色力学の非摂動論的現象の研究

趣旨説明
（閉じ込め物理の理論的現状と問題点を中心に）

近藤　慶一　（千葉大学　大学院理学研究科）

【シンポジウムの概要】

カラーの閉じ込めやカイラル対称性の自発的破れなどの量子色力学（QCD）の非摂動論的現象の解明は，理論物理学における長年の課題であるが，この10年ほどの間に，様々なアプローチにより多方面に進展があった。

カラー閉じ込めに関しては，モノポールやボルテックスなどのトポロジカルな自由度の重要性とその定量的な研究に加えて，Cho-Duan-Ge or Cho-Faddeev-Niemi分解に基づいたゲージ不変な定式化なども行われている。

カイラル対称性の自発的破れに関しても，近年，ローレンツ不変でない様々な状況での「南部・ゴールドストンの定理の一般化」が為されるなど，大きく研究が進展している。

本シンポジウムでは，多様なアプローチによるQCDの非摂動論的諸現象に対する研究の現状を総括し，あわせて将来的な展望を考察する。

【登壇者の氏名・所属 及び 講演題目（仮）】

1. 近藤 慶一（千葉大理）（10分間）趣旨説明

2. 柴田 章博（KEK計算セ）（30分間）
「格子Yang-Mills理論の新しい定式化と非可換双対超伝導描像」

3. 斉藤 卓也（高知大総合教育センター）（30分間）
「センターボルテックスによるグルーオンプラズマの格子研究」

4. 菅沼 秀夫（京大理）（30分間）
「閉じ込め現象とカイラル対称性の自発的破れの関連性について」

休憩　15分

5. 日高 義将（理研）（30分間）
「南部・ゴールドストンの定理の非相対論的な系への一般化」

6. 隅野 行成（東北大理）（30分間）
「摂動ＱＣＤによるクォーク・反クォーク対系の理解の進展」

7. 衛藤 稔（山形大理）（30分間）
「超対称QCDと閉じ込めの位相的側面」

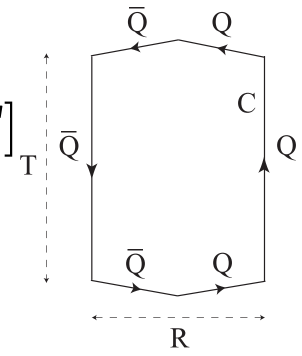
全所要時間 3時間25分

QCD=color $SU(3)$ gauge theory describing quarks and gluons

Quark confinement in Yang-Mills (YM) theory

(pure gauge theory describing gluons without dynamical quarks $m_q = \infty$)

confinement criterion: area law of the Wilson loop average

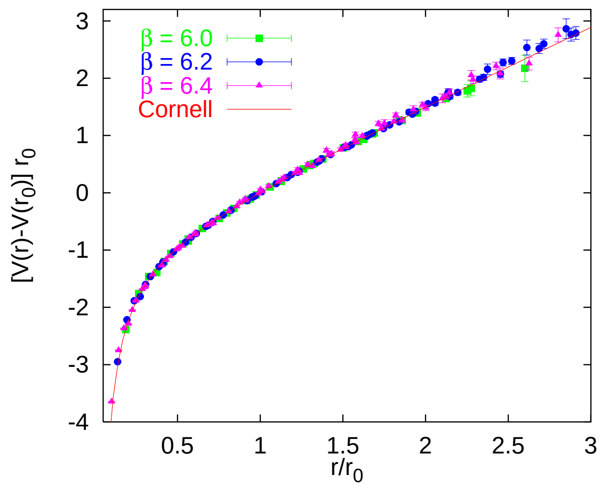


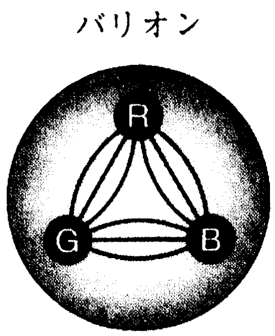
$$W(C) = \exp[\alpha T/R - \sigma RT - c(R+T) + \cdots] \simeq \exp[-V_{Q\bar{Q}}(R)T]$$

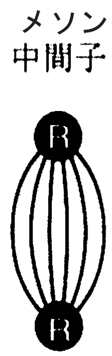
Quark-antiquark static potential $V_{Q\bar{Q}}(R)$= Coulomb+Linear:

$$V_{Q\bar{Q}}(R) = -\frac{\alpha}{R} + \sigma R + c$$

σ: string tension [mass^2], α: dimensionless [mass^0], c: [mass^1],





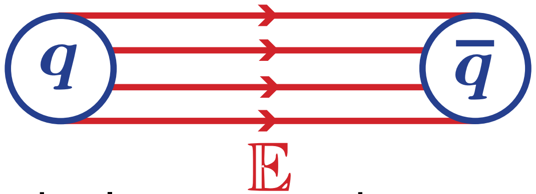


Dual superconductor as a mechanism of confinement

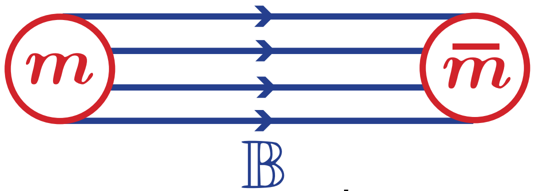
The hypothesis: QCD vacuum=dual superconductor is checked by showing

* Dual Meissner effect

In the dual superconductor, the chromoelectric field connecting q and $\bar{q}$ (color charges) is squeezed into the flux tube (no chromomagnetic field). [$\leftarrow$ In the ordinary superconductor, magnetic field is squeezed]



dual superconductor



superconductor

* Magnetic-monopole condensation (chromomagnetic) [$\leftarrow$ Cooper pairs (electric) condensation]

For this, we must introduce the magnetic monopole ...

Duality and magnetic-monopole in Yang-Mills theory

* How to introduce magnetic monopoles in the YM gauge theory without scalar fields?
cf. 't Hooft-Polyakov magnetic monopole
* How to define the duality in the non-Abelian gauge theory?
* How to preserve the original (non-Abelian) gauge invariance?

Two methods are available:

(1) Abelian projection (by ' t Hooft 1981)

partial gauge fixing of G to the maximal torus subgroup: $G \to H = U(1)^r$ (naive)

(2) Field decomposition (by Cho 1980, Duan and Ge 1979, Faddeev and Niemi 1999)

gauge-invariant decomposition of the gluon field for separating the dominant mode for confinement (involved) [spin-charge separation]

What is the topological defect (configuration) responsible for quark confinement?

Recent studies support the non-Abelian magnetic monopole for SU(3) Yang-Mills theory! (cf. Abelian magnetic monopole for SU(2) Yang-Mills theory). In fact,

* SU(3) YM theory, New formulation of LGT + numerical simulations ... 柴田 (Talk 2)

gauge-invariant non-Abelian magnetic monopole, type I dual superconductor

* SUSY YM theory: analytical approach, exact solution, BPS state ... 衛藤 (Talk 7)

non-Abelian magnetic monopole, non-Abelian vortex string, magnetic-monopole confinement, applicable also to finite temperature and density, color superconductivity,...

Perturbative QCD vs. non-perturbative QCD

By including higher order corrections up to 3-loops, even the perturbative approach reproduces the

$V_{Q\bar{Q}}(R)=$ Coulomb+Linear for $0.1fm \leq R \leq 0.5fm$

due to renormalon cancellation,

deviation from the 1-dim. flux tube!? ... 隅野(Talk 6)

Confinement/deconfinement at finite temperature T

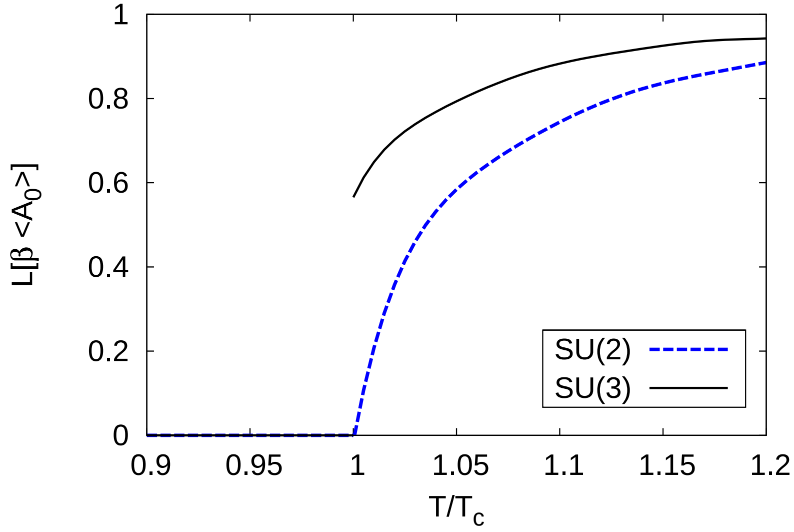
$T = 0$: confinement Wilson loop average

$T < T_d$: confinement (hadron phase)

$\rightarrow T \geq T_d$: deconfinement (gluon plasma phase)

Polyakov loop average $\Phi = 0$
(center symmetry Z_3 restoration)

$\rightarrow \Phi \neq 0$ (center symmetry broken)



The phase transition is of second order for $SU(2)$ and of first order for $SU(3)$.

Quark-gluon plasma phase (QGP) phase

Center vortex as a topological defect is responsible for the infrared behavior of the gluon propagator and the temperature dependence of the string tension for the spatial Wilson loop, ... 斉藤(Talk 3) LGT numerical simulations
also affects transport coefficient (viscosity), equation of state for gluon plasma.
The non-perturbative effects survive even at high temperature $T \gg T_d$ where the asymptotic freedom is exptected to work.

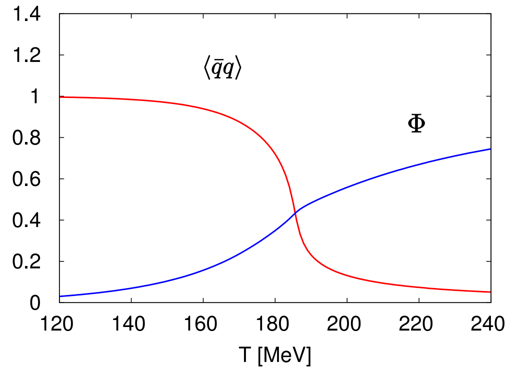
Chiral symmetry: spontaneous breaking/restoration

For $m_q = 0$:
$T < T_\chi$: chiral symmetry spontaneously broken with chiral condensate $\langle \bar{q}q \rangle \neq 0$

$\to T \geq T_\chi$: chiral symmetry restoration with $\langle \bar{q}q \rangle = 0$

For $0 < m_q < \infty$, it is known (by numerical simulations)

the two transition-temperatures agree $T_d \simeq T_\chi$! (crossover)



Relationship between chiral symmetry and confinement

What relationship exists between the chiral symmetry and confinement?

$\langle \bar{q}q \rangle$ is related to eigenmode of the Dirac operator $\gamma^\mu D_\mu$ through the Banks-Casher relation. Use a gauge-invariant expansion and projection of the Wilson loop and Polyakov loop operator by the eigenmodes.

$\Longrightarrow$ The Wilson loop obeys the area law and the Polyakov loop remains zero (unbroken center symmetry Z_3) even after removing the low-lying Dirac modes.

$\Longrightarrow$ No one-to-one correspondence between confinement and chiral symmetry breaking

... 菅沼(Talk 4)

Spontaneous breaking of a continuous symmetry $G \to H$

$\Longrightarrow$ massless Nambu-Goldstone (NG) modes (zero modes) emerge, e.g., π meson, spin wave, phonon, ...

NG theorem (1961): *Dispersion relation: E is linear in p, * $N_{NG} = N_{BS}$

N_{NG}:=#(NG mode), N_{BS}:=# (broken symmetry, generators of G/H)

How about the NG theorem for the system without the Lorentz symmetry (e.g., finite temperature) ?

Nielsen-Chadha(1976): type-I NG mode, type-II NG mode $N_{NG}^{I} + 2N_{NG}^{II} \geq N_{BS}$

...

Recent achievements 2001, 2011, 2012, ... 日高(Talk 5)

Of course, there are many topics on confinement that are not mentioned in this symposium.

But ...

No questions, please.

Thank you for your attention.