余剰次元をもつゲージ理論における有限温度での対称性の破れ/非回復について

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I. Introduction

余剰次元を持つ場の理論：（新しい）ダイナミカルな機構、豊富な相構造などが期待できる。

$\Longrightarrow$ 標準理論やそれを超える物理に対する新しい知見やより深い理解を得たい。

- 新しいゲージ対称性の破れの機構（Manton, Fairlie, Hosotani, $et.al.$）

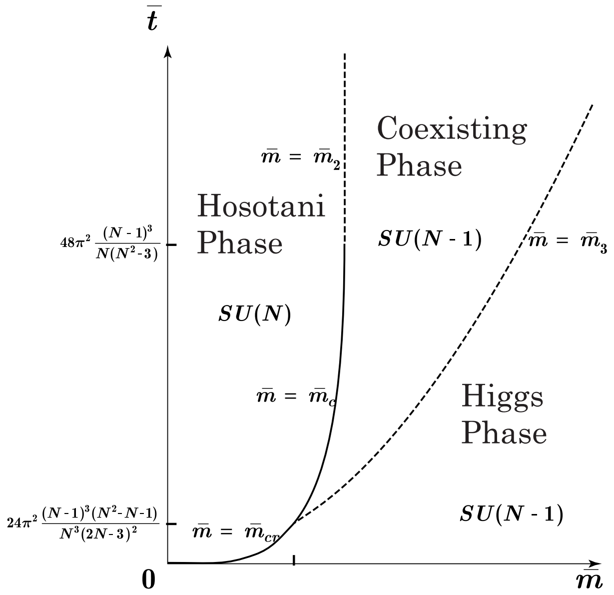
$$A_{\hat{\mu}} = (A_\mu, A_y); \quad \text{余剰次方向の成分ゲージ場がスカラー場（ヒッグス場）}$$

$SU(2)$ の doublet ; 例、S^1/Z_2, ゲージヒッグス統一。

- 余剰次元方向の並進対称性の自発的破れ、及び、それに伴う超対称性の自発的破れ（Sakamoto, Tachibana and K.T.）

$$\delta_S \psi = i\sqrt{2}\ (\sigma^{\hat{\mu}}\bar{\theta})\ \partial_{\hat{\mu}}\phi + \sqrt{2}\ \theta F_\phi \neq 0 \quad \text{for} \quad \phi = \phi_{vac}(y)$$

- 豊富な相構造の出現（Hatanaka, Ohnishi, Sakamoto and K.T.）



余剰次元方向の成分ゲージ場、A_y とヒッグス場、ϕが混在するモデル

Hostani phase: $\langle A_y \rangle \neq 0, \langle \phi \rangle = 0$,

Coexisting phase: $\langle A_y \rangle \neq 0, \langle \phi \rangle \neq 0$,

Higgs phase: $\langle A_y \rangle = 0, \langle \phi \rangle \neq 0$

- ゲージ階層性問題への（新しい）アプローチ（Randall and Sundrum, *et.al.*）

a warped extra dim. : $ds^2 = \mathrm{e}^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\mu + r_c d\phi^2 \Rightarrow M_w = \mathrm{e}^{-kr_c\pi}M_{pl}$

ここでは余剰次元を持つゲージ理論の有限温度での対称性（の回復/非回復）についてお話します。

II. Gauge symmetry in high temperature

Gauge theories with extra dimensions at finite T; $S_\tau \times R^{D-2} \times S^1_L$

$$S^1_\tau \cdots \beta \equiv T^{-1}, \qquad S^1_L \cdots L = 2\pi R$$

Gauge filed $A_{\hat{\mu}}$ is decomposed as $A_{\hat{\mu}} = \left(A_\tau,\ A_{k(=1,2,\cdots,D-2)},\ A_y\right)$

$\langle A_\tau \rangle, \langle A_y \rangle$ cannot be gauged away, and the VEV is physically meaningful, reflecting the topology of S^1_τ and S^1_L.

- $\star$ Vacuum configuration as the minimum of $V_{eff}(\langle A_\tau \rangle, \langle A_y \rangle)$
- $\star$ Gauge symmetry breaking through $\langle A_y \rangle$; Hosotani mechanism

For the $SU(N_c)$, one takes $g\frac{\beta}{2\pi}\langle A_\tau \rangle = \text{diag.}(\varphi_1, \cdots, \varphi_N), \quad g\frac{L}{2\pi}\langle A_y \rangle = \text{diag.}(\theta_1, \cdots, \theta_N)$, the mode expansion for A_k yields

$$\left(A_k^{(l,\ n)}\right)_{ij} \quad \cdots \quad \beta^{-2}\left(2\pi l + \varphi_i - \varphi_j\right)^2 + L^{-2}\left(2\pi n + \theta_i - \theta_j\right)^2$$

Massive gauge bosons are siginal for the gauge symmetry breaking.

⋆ It has been studied that $\langle A_\tau \rangle$ takes trivial values. [M.Sakamoto and K.T.,'07]

⋆ Matter contents and their boundary conditions are crucial for $\langle A_y \rangle$

Analyses for the effective potential $V_{eff}(\langle A_\tau \rangle, \langle A_y \rangle)$ at $LT \gg 1$;

$$\sum_{l=-\infty}^{\infty} \sum_{m=1}^{\infty} \left(\frac{\bar{M}_l}{Lm} \right)^{\frac{D-1}{2}} K_{\frac{D-1}{2}}(\bar{M}_l Lm) \cos[2\pi m(\alpha + \langle a_y \rangle], \bar{M}_l = 2\pi\beta^{-1}|l + \langle a_\tau \rangle + \eta|$$

Fermions (Antiperiodic B.C. for S_τ) decouple from the dynamics of $\langle A_y \rangle$, so that

Gauge theory on $S^1_\tau \times R^{D-2} \times S^1_L$	$\Longrightarrow$	Gauge theory without fermions on $R^{D-2} \times S^1_L$ at $T = 0$

Hence, the gauge symmetry realized at $LT \gg 1$ is determined by $D-1$ dim. ($R^{D-2} \times S^1_L$) gauge theory with scalars alone.

⋆ The twisted boundary conditions are allowed for scalar fields in the S^1_L-direction.

$\Rightarrow$ Nonsymmetry restoration (NSR) / inverse symmetry breaking (ISB)

II-1 $5d$ $SU(2)$ models for NSR / ISB

$$S^1_\tau \times R^3 \times S^1_L, \quad g\langle A_y\rangle \frac{L}{2\pi} = \text{diag.}(\theta, -\theta), \quad g\langle A_\tau\rangle \frac{\beta}{2\pi} = \text{diag.}(\varphi, -\varphi)\big|_{\varphi=0}$$

[N. B.] $SU(2)$ unbroken for $\theta = 0, \frac{1}{2}$, otherwise, $SU(2) \to U(1)$

Players;

$$(N^s_{fd},\ N^f_{fd},\ N^s_{adj},\ N^f_{adj}), \quad \phi(y+L) = \mathrm{e}^{i2\pi\alpha}\phi(y), \quad \alpha = \text{twisted B.C.}$$

N : number of flavor,

s : scalar,

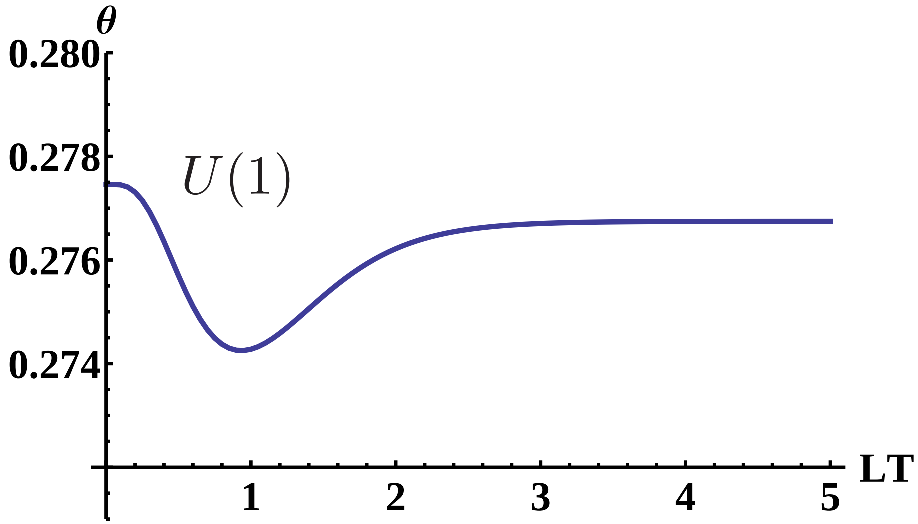
f : fermion,

$fd.$: fundamental repre.,

$adj.$: adjoint repre..

A model of SNR

$$\left(N^s_{fd},\ \alpha\right) = \left(2,\ \frac{1}{2}\right), \left(N^s_{adj},\ \alpha\right) = \left(6,\ \frac{1}{2}\right), \left(N^f_{fd},\ \alpha\right) = (1,\ 0), \left(N^f_{adj},\ \alpha\right) = (2,\ 0)$$

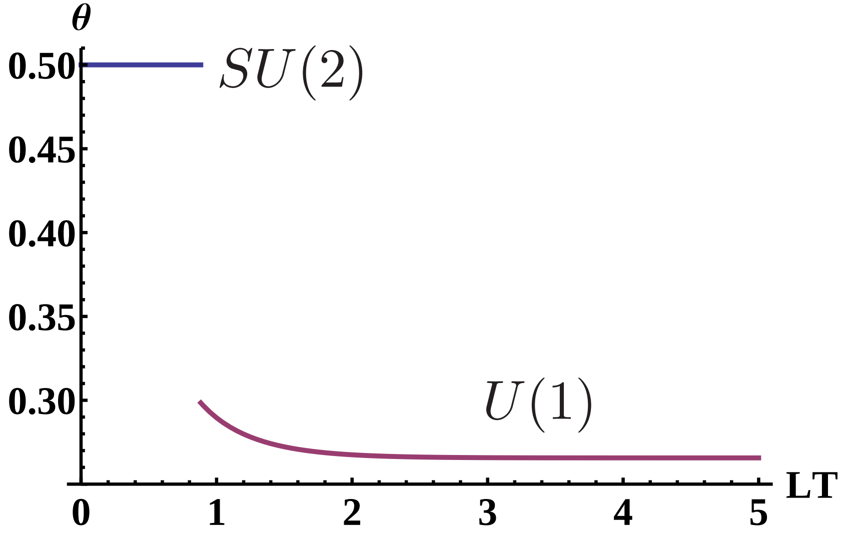


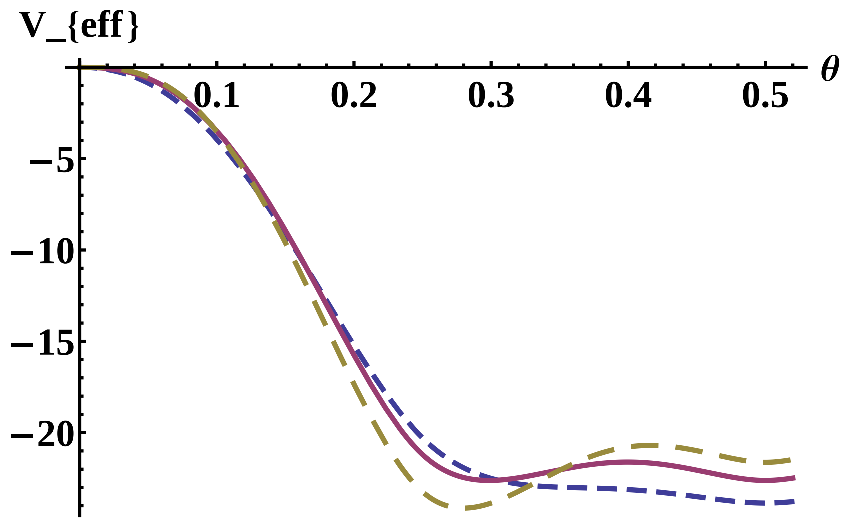
• The gauge symmetry, borken to $U(1)$ at $T = 0$, is not restored even in high temperature.

• The asymptotic value for θ is consistent with the one obtained by the $4d$ effective theory.

A model of ISB

$$\left(N^s_{fd},\ \alpha\right) = \left(1,\ \frac{1}{2}\right),\ \left(N^s_{adj},\ \alpha\right) = \left(5,\ \frac{1}{2}\right),\ \left(N^f_{fd},\ \alpha\right) = (1,\ 0),\ \left(N^f_{adj},\ \alpha\right) = (0,\ 0)$$

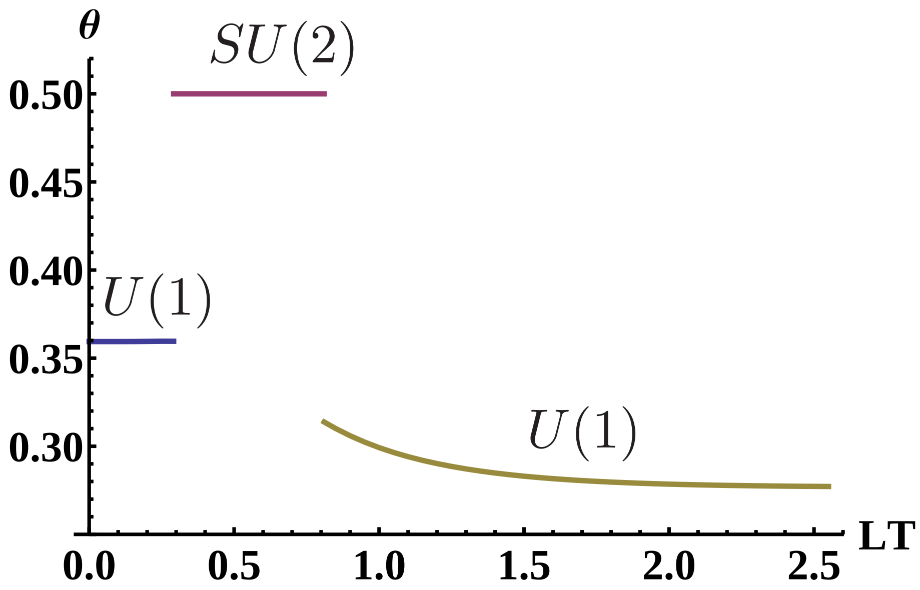




- The $SU(2)$ gauge symmetry is broken to $U(1)$ at high temperature.
- The phase transition at $LT_c \simeq 0.8836$ is the first order.
- The asymptotic value for θ is consistent with the one obtained by the $4d$ effective theory.

A model with both ISB and Higgs mechanism

$$\left(N_{fd}^{s},\ \alpha\right) = \left(2,\ \frac{1}{2}\right),\ \left(N_{adj}^{s},\ \alpha\right) = \left(6,\ \frac{1}{2}\right),\ \left(N_{fd}^{f},\ \alpha\right) = (1,\ 0)\ ,\ \left(N_{adj}^{f},\ \alpha\right) = (0,\ 0)$$



• The gauge symmetry is restored at $LT_{c1} \simeq 0.2914$, and the inverse symmetry breaking occurs at $LT_{c2} \simeq 0.8104$.

• Similar to the phase transition in the little Higgs model.

III. Summary

Gauge theories with extra dimensions at finite temperature; $S^1_\tau \times R^{D-2} \times S^1_L$.

¶ Dynamical variables, $\langle A_\tau \rangle$ and $\langle A_y \rangle$.

¶ Behavior of the theory at high temperature; $R^{D-2} \times S^1_L$.

Decoupling of fermions from the system (from the dynamics of $\langle A_y \rangle$).

$\Longrightarrow$ gauge and scalars (twisted boundary condition for scalar fields).

$\Longrightarrow$ NSR / ISB at high temperature .

[N.B.]

$\flat$ At high temperature, $V_{eff}^{LT \gg 1}(\langle A_y \rangle) \sim T \times V_{eff}^{D-1}(\langle A_y \rangle)$

Essentially, independent of T at high temperature

$\Longleftrightarrow$ Masses, couplings for Higgs fields are T-dependent at high temperature. (Higgs mechanism)

¶ Explicit examples of the model with NSR / ISB at high temperature.