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Nuclear Physics B 910 (2016) 30–39

NUCLEAR PHYSICS B

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Dynamical restoration of Z_N symmetry in $SU(N) + $ Higgs theories

Minati Biswal, Sanatan Digal *, P.S. Saumia

The Institute of Mathematical Sciences, Chennai, 600113, India

Received 13 May 2016; received in revised form 15 June 2016; accepted 21 June 2016

Available online 27 June 2016

Editor: Hubert Saleur

Abstract

We study the Z_N symmetry in $SU(N) +$ Higgs theories with the Higgs field in the fundamental representation. The distributions of the Polyakov loop show that the Z_N symmetry is explicitly broken in the Higgs phase. On the other hand inside the Higgs symmetric phase the Polyakov loop distributions and other physical observables exhibit the Z_N symmetry. This effective realization of the Z_N symmetry in the theory changes the nature of the confinement–deconfinement transition. We argue that the Z_N symmetry will lead to time independent topological defect solutions in the Higgs symmetric deconfined phase which will play important role at high temperatures.

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1. Introduction

It is well known that most phenomena in pure $SU(N)$ gauge theories do not depend on the representations of the gauge fields [1–9]. It is considered that both the fundamental and adjoint representations are equally valid representations of the non-abelian gauge fields and differences specific to representations are in general considered unphysical. The preference to a particular representation arises when the gauge fields are coupled to the matter fields. In the presence of the matter fields the two representations of the gauge fields are not equivalent. In quantum field

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[*] Corresponding author.

E-mail addresses: mbiswal@imsc.res.in (M. Biswal), digal@imsc.res.in (S. Digal), saumia@imsc.res.in (P.S. Saumia).

http://dx.doi.org/10.1016/j.nuclphysb.2016.06.025

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theories such as the quantum chromodynamics (QCD) and the electroweak (EW) theory, which describe the strong and electro-weak forces of nature respectively, the matter fields are in the fundamental representations. The gauge invariance of these theories requires that the gauge fields also be in the fundamental representation. Given that there is a clear preference to the fundamental representation of the gauge fields, the physics aspects specific to this representation can play important role in these theories.

One of the important physics issue which arises in the fundamental representation is the Z_N symmetry. At finite temperatures the gauge fields are periodic along the temporal direction [10]. This boundary condition requires that in the temporal direction the gauge transformations are periodic up to a factor z, which is an element of the center (Z_N) of the gauge group $SU(N)$. A gauge transformation which is periodic up to a phase factor z (in the temporal direction) non-trivially transforms the Polyakov loop (L), which is the trace of a path ordered product of exponentials of the temporal gauge field A_0 along the shortest temporal loop. The Polyakov loop picks up the element z as a phase factor, i.e. $L \to zL$ [10]. All possible gauge transformations of the Polyakov loop then form the Z_N symmetry group. This symmetry plays an important role in the finite temperature confinement–deconfinement transition in pure $SU(N)$ gauge theories. In the deconfined phase the Polyakov loop acquires a non-zero expectation value which leads to the spontaneous breaking of the Z_N symmetry. On the other hand in the confined phase it has zero expectation value. This property of the Polyakov loop across the confinement–deconfinement transition makes it an ideal candidate for an order parameter for this transition [11].

Even though the above non-periodic gauge transformations preserve the boundary conditions of the gauge fields they do not preserve the temporal boundary condition of the matter fields in the fundamental representation. After a gauge transformation for which $z \neq I$ (I is the identity element of Z_N) bosonic (fermionic) matter fields are no more periodic (anti-periodic). These gauge transformations therefore can not act on the matter fields. However it still makes sense to consider these Z_N gauge transformations by restricting their actions only to the gauge fields. These transformations, which are not like the conventional gauge transformations acting both on the gauge and the matter fields, will not leave the action of the full theory invariant. However a given gauge field configuration as well as its Z_N transformations are both valid configurations and will contribute to the partition function of the full theory. Their individual contribution to the partition function will decide the relative "Boltzmann" probability of these two configurations in a thermal ensemble. Even though the classical action does not have the Z_N symmetry ultimately the fluctuations of the fields will decide if the Z_N symmetry is relevant in presence of matter fields. Here by Z_N symmetry we imply that the gauge transformations are acting only on the gauge fields. The Higgs fields can be gauge transformed only when the gauge transformations correspond to the identity of Z_N.

The issue of Z_N symmetry in the presence of fundamental matter fields has been extensively studied in the literature [12–16]. It was shown that the $1-$*loop* perturbative effective potential for the Polyakov loop has meta-stable states with negative entropy [17] in the presence of fermions. In these studies, however, only the zero mode of the Polyakov loop is coupled to the matter fields. Higher modes of the Polyakov loop, which actually give rise to the spontaneous breaking of the Z_N symmetry, may resolve the problem of negative entropy. Subsequent studies using effective models [18,19] and lattice QCD studies [20,21] have shown that the presence of fermions acts as an external effective field on the Polyakov loop thereby breaking the Z_N symmetry explicitly. Although there have been a lot of non-perturbative studies on the confinement–deconfinement transition of $SU(N)$ gauge theories coupled to fundamental bosonic fields [22,25,26] but very few have addressed the issue of the Z_N symmetry in these theories. In this work we carry out

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