HEAVY HIGGS: IS THE GAUGE SYMMETRY
RESTORED IN THE EARLY UNIVERSE?

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Abstract

The possibility of symmetry non-restoration at high temperature is explored in a strongly interacting Higgs system described by an effective Chiral Lagrangian. Despite a naïve perturbative hint of symmetry non-restoration when the temperature is increased, non-perturbative methods point towards symmetry restoration.

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Common intuition tells that, due to thermal agitation, symmetries are restored when a system is heated up. This can be physically understood as due to thermal excitations, which make possible for the system to cross the barrier surrounding the broken minimum and feel the full symmetry of the theory. This type of behaviour can be parametrized by means of a temperature dependent effective potential which is computable order by order in perturbation theory and displays the whole symmetry of the theory.

The behaviour at high temperature of systems with symmetries was formally studied in the 70’s by applying the techniques of Finite Temperature Field Theory. Symmetry restoration was generally found for both global [1] and gauge symmetries [2, 3]. This is, for example, the situation concerning the Standard Model with one Higgs doublet.

As counterintuitive as it may seem, one wonders whether it is possible to find the opposite behaviour: a broken symmetry which gets more broken at high temperature, or even the more radical situation where an unbroken symmetry gets broken at high temperature [3, 4]. Weinberg [3] has already pointed out such a behaviour in a two Higgs multiplet model. He also mentions a beautiful experimental example borrowed from Solid State Physics: a ferroelectric crystal, the Rochelle salt, which presents a certain temperature region where an unbroken symmetry gets broken at high temperature, though as the temperature is further increased the symmetry becomes eventually restored [5].

Most extensions of the Standard Cosmological Big Bang Model are still afflicted from problems concerning so-called topological defects (domain walls, monopoles) which are supposed to be produced during phase transitions. Symmetry non-restoration (SNR) could provide a radical cure to this problem [6], avoiding phase transitions at all and therefore the generation of topological defects.

At present, there are two main avenues to explore physics beyond the Standard Model: theories in which the Higgs particle is a fundamental one, supersymmetry being its most relevant example and those for which the Higgs it is not, and a non-perturbative regime is appropriate. It is known that internal symmetries are always restored for renormalizable supersymmetric theories [7]. For the latter, a recent analysis for systems involving non-vanishing background charges shows that SNR could be possible [8]. The case of non-renormalizable theories has been discussed in [9].

To illustrate the possibility of SNR in gauge theories, we use a simple model given by a two Higgs doublet model with a $SU(2) \times U(1)$ local symmetry. A general renormalizable scalar potential having this symmetry is written as

$$V(\phi, \psi) = -m_1^2 \phi^+ \phi - m_2^2 \psi^+ \psi + \lambda_1 (\phi^+ \phi)^2 + \lambda_2 (\psi^+ \psi)^2 + \lambda_3 (\phi^+ \phi)(\psi^+ \psi) + \lambda_4 |\phi^+ \psi|^2 + \ldots$$

(1)

Where $\phi$, $\psi$ are scalar fields and dots represent terms that are not relevant.
for this problem. Temperature corrections to the potential are readily obtained at one-loop level in the high temperature limit \((T \gg m_i)\) [10] with the result,

\[
V_T(\phi, \psi) = \frac{T^2}{24}[(6\lambda_1 + 2\lambda_2 + \lambda_4 + \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 3\lambda_5 + h^2 + h^2 + 2h^2)]v^2_1 + (6\lambda_2 + 2\lambda_3 + \lambda_4 + \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 3h^2)v^2_2.
\] (2)

Once the boundedness conditions are satisfied, the contribution from both fermions and gauge bosons is positive, tending to restore the symmetry. The only possible source of SNR is therefore provided by the scalar sector of the theory. Studying (2) we have found that SNR is possible whenever the following condition is satisfied,

\[
6\lambda_1 + 2\lambda_2 + \lambda_4 + \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 3h^2 + h^2 < 0,
\] (3)

that is, since \(\frac{9}{4}g^2\) is already of order one, some of the scalar couplings have to be negative and \textit{greater than one in absolute value}, going out of the perturbative regime, where the approach cannot be trusted any longer. To bypass this problem we explore this non-perturbative region using a Chiral Lagrangian approach for a theory with a strongly interacting Higgs sector.

The ungauged Chiral Lagrangian can be written,

\[
\mathcal{L}_{ChL} = \frac{v^2}{4} \text{Tr}[(\partial\mu U)^+ D^\mu U],
\] (4)

where \(U = \exp \frac{i\vec{\pi} \vec{\tau}}{v}\). It is easy to convince oneself that (4) is \(SU(2)_L \times SU(2)_R\) invariant. This kind of Lagrangians are frequently used to describe pion interactions in QCD at low energies \((E < 1 \text{ GeV})\) [11]. One of the most beautiful features of this approach is its universality, in the sense that the same Lagrangian can be used to describe all theories that show the same pattern of symmetry breaking (e.g. \(SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}\)), the only change being the different values of the only dimensional parameter of the Lagrangian, \(v\), which is about 100 MeV for QCD and 250 GeV for the electroweak theory.

Figure 1 shows a clear tendency towards chiral symmetry restoration confirming previous results [12], although it is important to keep in mind that an exact number for the critical temperature cannot be obtained with this technique which is only valid for \(T < 4\pi v\).

Now we would like to construct, starting from (4), a locally (gauge) \(SU(2)_L\) invariant chiral lagrangian,

\[
\mathcal{L}_{GChL} = \frac{v^2}{4} \text{Tr}[D_\mu U^+ D^\mu U] + \mathcal{L}_{YM} + \mathcal{L}_{GF} + \mathcal{L}_{FP},
\] (5)

where the covariant derivative is given by \(D_\mu U = \partial_\mu U + i\frac{2}{g}(\vec{\nabla}_\mu \vec{\pi})U\). \(\mathcal{L}_{YM}\) is the pure Yang-Mills Lagrangian, \(\mathcal{L}_{GF}\) and \(\mathcal{L}_{FP}\) the gauge-fixing and Faddeev-Popov terms [13].

We have studied the temperature behavior of a strongly interacting Higgs system. Using a gauged Chiral Lagrangian we have found that there are no temperature dependent gauge corrections at one loop: the tendency towards
symmetry restoration observed in the ungauged case is then maintained. The computation of gauge corrections at two loops is still in progress. Although the results presented here are for a $SU(2)_L$ gauge symmetry, we are currently studying a theory with the Standard Model gauge symmetry, $SU(2)_L \times U(1)_Y$. The model dependence, i.e. different symmetry breaking sectors of the theory (technicolor, SM...), is also being studied.

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