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Constraints on two Higgs doublet models from domain walls

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ABSTRACT

We show that there is a constraint on the parameter space of two Higgs doublet models that comes from the existence of the stable vortex-domain wall systems. The constraint is quite universal in the sense that it depends on only two combinations of Lagrangian parameters and, at tree level, does not depend on how fermions couple to two Higgs fields. Numerical solutions of field configurations of domain wall-vortex system are obtained, which provide a basis for further quantitative study of cosmology which involve such topological objects.

1. Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) at CERN [1,2] proved that the Standard Model (SM) of the elementary particles is an appropriate low-energy effective description of our Universe. Now we are in a position to take a step forward and pursue solutions to problems that are left unanswered by the SM. Those include masses of neutrinos, baryon asymmetry of the Universe, the origin of the dark matter, etc. Currently the Higgs sector of the SM is the experimentally least constrained part. Therefore, it is tempting to extend Higgs sector to accommodate possibilities for solving above mentioned problems.

Two Higgs doublet model (2HDM) [3], in which the two Higgs doublet fields (Φ_1, Φ_2) are introduced instead of only one, is the most popular extension of the Higgs sector. Many studies have been done to solve problems which can not be addressed by the SM. Two Higgs doublet fields are also required when one considers supersymmetric extension of the SM. 2HDM has four additional scalar degree of freedom in addition to 125 GeV Higgs boson (h). Those are charged Higgs bosons ($H^{\pm}$), CP-even Higgs bosons (H) and CP-odd Higgs boson (A). These additional scalars can be directly produced at LHC, though there is no signal so far today, placing lower bounds on masses of those additional scalar bosons. Those lower bounds highly depend on parameter choices of 2HDM as well as how SM fermions couple to Φ_1 and Φ_2 since cross section of specific production and decay process crucially depends on those. The situation is similar for bounds obtained from other theoretical and phenomenological constraints [4–6]. Therefore the constraints on parameters of 2HDM, that are determining masses of additional scalars, are also highly model dependent as well.

The purpose of the study in this paper is to place more universal constraint which is less dependent on the details of model setups. We discuss possible existence of vortices (or cosmic strings) [7,8] and domain walls (or kinks) in the 2HDM. When stable domain walls exist as solutions of the theory, they must have been created in the early Universe through the Kibble–Zurek mechanism [9–11], resulting in the overclosure problem. We use this fact to place constraints on parameters of the 2HDM. Unlike the SM admitting only unstable electroweak Z-strings [12,13], 2HDM admits topologically stable Z-strings [14,15] in addition to unstable non-topological Z-strings [16,17]. It also admits CP domain walls [18,19] and membranes [20,21]. Topological strings are attached by domain walls or membranes [22,23], resembling axion strings [24], axial strings in dense QCD [25] and topological Z-strings [26] in the Georgi–Machacek model [27]. When a string is attached by a single domain wall, such the domain wall can quantum mechanically decay by creating a hole bounded by the above mentioned string [8,28]. We point out that whether stable domain walls exist or not depends on only two combinations of model parameters, therefore the cosmological requirement places constraint on these two parameters.

The paper is organized as follows. After we introduce the 2HDM Lagrangian in the next section, we discuss various types of domain walls and membranes that exist in 2HDMs in Sec. 3. There, we systematically classify the parameter space of the 2HDMs to five

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cases, and shape of field configurations of domain walls and membranes will be presented for representative parameters in each case. Some of them correspond to known domain walls and membranes, while there is a new type of membrane which has substructure around the wall (Case IV). In Sec. 4, we discuss the vortex solution in 2HDMs in the case that the model has symmetry under the relative phase $U(1)$ rotation of two Higgs fields. Then in Sec. 5, we introduce terms that explicitly breaks above mentioned $U(1)$ symmetry, and discuss the appearance of domain wall-vortex complex system. In Sec. 6, cosmological impact of the existence of stable domain wall-vortex system is discussed, and constraint on the parameter space is obtained. Section 7 is dedicated to the conclusion and future prospects.

2. The model

We introduce two $SU(2)$ doublets, Φ_1 and Φ_2, both with the hypercharge $Y=1$. The Lagrangian which describes the electroweak and the Higgs sectors is written as

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} + \sum_{i=1,2}\left(D_\mu\Phi_i^\dagger D^\mu\Phi_i\right) - V(\Phi_1,\Phi_2). \tag{1}$$

Here, $B_{\mu\nu}$ and $W^a_{\mu\nu}$ describe field strength tensors of the hypercharge and the weak gauge interactions with μ (ν) and a being Lorentz and weak iso-spin indices, respectively. D_μ represents the covariant derivative acting on the Higgs fields. The most general form of the potential, $V(\Phi_1,\Phi_2)$, which is consistent with the electroweak gauge invariance is expressed as follows:

$$\begin{aligned} V(\Phi_1,\Phi_2) = {}& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) \\ &+ \frac{\beta_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\beta_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\ &+ \beta_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \beta_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\ &+ \left\{\frac{\beta_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right\} \\ &+ \left\{\left[\beta_6\Phi_1^\dagger\Phi_1 + \beta_7\Phi_2^\dagger\Phi_2\right]\left(\Phi_1^\dagger\Phi_2\right) + \text{h.c.}\right\}. \end{aligned} \tag{2}$$

In order to keep Higgs-mediated flavor-changing neutral current processes under control, we impose a (softly-broken) $\mathbb{Z}_2$ symmetry, $\Phi_1 \to +\Phi_1$ and $\Phi_2 \to -\Phi_2$, on the potential [29]. This is achieved by taking $\beta_6 = \beta_7 = 0$ in Eq. (2). We also assume, as is often done in the literature, that the Lagrangian is invariant under the following CP transformation:

$$\Phi_i \to i\sigma_2\Phi_i^*. \tag{3}$$

CP invariant Lagrangian is obtained by taking m_{12}^2 and β_5 to be real.[1] We should note here that the sign of m_{12}^2 is irrelevant to physics since it can always be changed by a field redefinition such as $\Phi_2 \to -\Phi_2$. In this letter, we define Higgs fields in such a way that m_{12}^2 becomes non-negative. Now, we consider the situation that both Higgs fields develop vacuum expectation values (VEVs) as [2]

$$\Phi_1 = e^{-i\alpha}\begin{pmatrix}0\\ v_1\end{pmatrix}, \quad \Phi_2 = e^{i\alpha}\begin{pmatrix}0\\ v_2\end{pmatrix}. \tag{4}$$

Then the electroweak scale, $v_{\rm EW}$ ($\simeq 246$ GeV), can be expressed by these VEVs as $v_{\rm EW}^2/2 = (v_1^2+v_2^2)$. When α, the relative $U(1)$ phase of two Higgs fields, takes 0 (mod $\pi/2$), the vacuum is invariant under the CP transformation in Eq. (3) (up to the field redefinition $\Phi_i \to -\Phi_i$). When α takes a value other than 0 mod $\pi/2$, the vacuum is not invariant under the CP transformation, therefore the CP symmetry is spontaneously broken. It is maximally broken when α becomes $\pi/4$ mod $\pi/2$.

For later use, we introduce a notation that two Higgs fields are combined into a single two-by-two matrix form, H, defined as

$$H = \left(i\sigma_2\Phi_1^*,\ \Phi_2\right). \tag{5}$$

The field H transforms under the electroweak $SU(2)_L \times U(1)_Y$ symmetry as

$$H \to e^{i\alpha_a(x)\frac{\sigma_a}{2}}He^{-i\beta(x)\frac{\sigma_3}{2}}, \tag{6}$$

therefore the covariant derivative of H is expressed as

$$D_\mu H = \partial_\mu H - g\frac{i}{2}\sigma_a W^a_\mu H + g'\frac{i}{2}H\sigma_3 B_\mu. \tag{7}$$

The VEV of H is expressed by a diagonal matrix $\langle H\rangle = e^{i\alpha}\mathrm{diag}(v_1, v_2)$, and the potential can be written by using H as follows:

$$\begin{aligned} V = {}& \frac{m_{11}^2+m_{22}^2}{2}\mathrm{Tr}\left(H^\dagger H\right) - \frac{m_{11}^2-m_{22}^2}{2}\mathrm{Tr}\left(H^\dagger H\sigma_3\right) \\ &- m_{12}^2\left(\det H + \text{h.c.}\right) \\ &+ \frac{2(\beta_1+\beta_2)+3\beta_3}{12}\mathrm{Tr}\left(H^\dagger HH^\dagger H\right) \\ &+ \frac{2(\beta_1+\beta_2)-3\beta_3}{12}\mathrm{Tr}\left(H^\dagger H\sigma_3H^\dagger H\sigma_3\right) \\ &- \frac{\beta_1-\beta_2}{3}\mathrm{Tr}\left(H^\dagger H\sigma_3H^\dagger H\right) + (\beta_3+\beta_4)\det\left(H^\dagger H\right) \\ &+ \left(\frac{\beta_5}{2}\det H^2 + \text{h.c.}\right). \end{aligned} \tag{8}$$

3. Domain walls and membranes

In this section, we discuss the relative $U(1)$ phase dependence of the potential and the existence of wall solutions associated with non-trivial winding of the phase. To see this, let us substitute the Higgs fields which have forms shown in Eq. (4) into the relative phase dependent terms in the potential, namely terms proportional to m_{12}^2 and β_5:

$$\begin{aligned} V_\xi(\alpha) &= -2m_{12}^2v_1v_2\cos 2\alpha + \beta_5 v_1^2v_2^2\cos 4\alpha \\ &= (v_1v_2)^2\sqrt{4\left(m_{12}^2/v_1v_2\right)^2+\beta_5^2} \\ &\qquad \left(-\sin\xi\cos 2\alpha + \cos\xi\cos 4\alpha\right). \end{aligned} \tag{9}$$

Here, we have defined the angle ξ as follows:

$$\sin\xi = \frac{2(m_{12}^2/v_1v_2)}{\sqrt{4(m_{12}^2/v_1v_2)^2+\beta_5^2}}, \qquad \cos\xi = \frac{\beta_5}{\sqrt{4(m_{12}^2/v_1v_2)^2+\beta_5^2}}. \tag{10}$$

This is a one parameter family of the double sine-Gordon potential. In Fig. 1 (a), we show the phase dependent part of the potential (the last line in Eq. (9)). In the figure, the darker the color is,

[1] Since the fermion sector breaks the CP symmetry, even if we take m_{12}^2 and β_5 to be real values, fermion loop contributions renormalize these parameters to be complex numbers. We will discuss the effect of explicit CP breaking terms in Sec. 6.

[2] In the literature, it is often expressed as $\Phi_1 = e^{-i\zeta}(0, v_1)^T$, $\Phi_2 = (0, v_2)^T$, or $\Phi_1 = (0, v_1)^T$, $\Phi_2 = e^{i\zeta}(0, v_2)^T$. These are equivalent to Eq. (4) with $\alpha = \zeta/2$ up to gauge transformation.