Conditions for vacuum stability in an $S_3$ extension of the Standard Model

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Abstract. In this work we study the Higgs sector in the minimal $S_3$ extension of the Standard Model. The $S_3$ extended Standard Model, which has three Higgs doublets fields that belong to the three-dimensional reducible representation of the permutation group $S_3$, has naturally new phenomena: there are several Higgs bosons, charged, neutral and pseudoscalar ones, and more than one potential minimum. We analyzed the stability of the minimal $S_3$ invariant extension of the Higgs potential and show that at tree-level, the potential minimum preserving electric charge and CP symmetries, when it exists, is the global one.

1. Introduction

In the Standard Model (SM), the Higgs boson is the only particle which has not been discovered yet, each family of fermions enters independently and the masses of the particles are free parameters, whose values are determined experimentally. One possibility to reduce the number of free parameters in the SM and to try to relate the different families is to add a flavour symmetry. Recently, the Higgs potential in the minimal $S_3$ extension of the Standard Model (SM) of particle physics has been studied by several authors [1–8].

In the minimal $S_3$ model [8], the flavour symmetry is extended to the Higgs sector. Instead of one, there are now three Higgs fields $H_1$, $H_2$ and $H_S$ required to obtain phenomenologically allowed quark and lepton mass matrices without breaking the flavour symmetry. The Higgs fields belong to the three-dimensional reducible representation of the flavour permutational group $S_3$ [8]. This $S_3$-invariant extension of the Standard Model describes successfully masses and mixings, as well as all flavour changing neutral current processes in excellent agreement with experiment [9–12].

With the forthcoming operation of the Large Hadron Collider (LHC), it is important to realize the phenomenological implications of the scalar sector of the $S_3$ model. Since the potential and its minimization play a vital part in the successful construction of the model, we analyze the $S_3$-invariant Higgs boson potential. SM. Our study concerns the following questions: 1) To what extent can the presence of additional Higgs fields affect the stability of the SM Higgs potential minimum? 2) Under which conditions do we have CP and charge breaking minima?

We present here the vacuum stability conditions in this minimal $S_3$-invariant extension of the Standard Model. In this model there are contributions from the extra Higgs bosons that can in
principle break charge and CP. The stationary points can be classified as Normal, CB (Charge Breaking) and CPB (CP Breaking) minima according to the vacuum expectation value of the Higgs fields $H_1$, $H_2$ and $H_3$. We found the conditions under which the minimum of the potential preserving electric charge and CP symmetries, is the global one. That is, the normal minimum is deepest than the CB and CPB minima. If this happens, then it is possible to determine that CB or CP violation coming from the Higgs sector are not realized at tree level. One particular solution for the normal minimum corresponds to the Pakvasa-Sugawara [3] one, in which an $S_2$ residual symmetry is obtained.

2. The $S_3$ flavour symmetry
Prior to the introduction of the Higgs boson and mass terms, the Lagrangian of the SM is chiral and invariant with respect to any permutations of the left and right quark and lepton fields. For three quarks and lepton families the $S_3$ flavour symmetry is an exact symmetry of the SM Lagrangian. If we assume that the $S_3$ permutational symmetry is not broken and the Higgs of the SM is an $S_3$ singlet, only one fermion in each family can acquire mass.

In order to give mass to quarks and leptons, without breaking the $S_3$ symmetry, it is necessary to extend the Higgs sector. The ingredients of this extension of the Standard Model are the following: to extend the flavour and family concepts to the Higgs sector, to associate each family to an irreducible representation of the flavour group, to construct a Lagrangian invariant under the following: to extend the Higgs sector. The ingredients of this extension of the Standard Model are the

\[
\begin{align*}
1_s \otimes 1_s & = 1_s, \\
1_s \otimes 1_A & = 1_A, \\
1_s \otimes 2 & = 2, \\
1_A \otimes 2 & = 2, \\
2 \otimes 2 & = 1_s \oplus 1_A \oplus 2.
\end{align*}
\]

The direct product of two $S_3$ irreducible representations are:

\[
\mathbf{p}_D = \begin{pmatrix} p_{D1} \\ p_{D2} \end{pmatrix} \quad \text{and} \quad \mathbf{q}_D = \begin{pmatrix} q_{D1} \\ q_{D2} \end{pmatrix}
\]

has two singlets: the symmetric one $r_s = p_{D1}q_{D1} + p_{D2}q_{D2}$ and the antisymmetric one $r_A = p_{D1}q_{D2} - p_{D2}q_{D1}$; and just one doublet $r_D^T$, with the following form:

\[
r_D^T = \begin{pmatrix} p_{D1}q_{D2} + p_{D2}q_{D1} \\ p_{D1}q_{D1} - p_{D2}q_{D2} \end{pmatrix}.
\]

With this in mind, the Higgs sector is modified to three $SU(2)$ Higgs field doublets $\Phi_a, \Phi_b$, and $\Phi_c$, which enter in a reducible triplet representation of $S_3$ as follows

\[
\Phi \rightarrow H = (\Phi_a, \Phi_b, \Phi_c)^T.
\]

Since the triplet representation of $S_3$ decomposes to $1_s \oplus 2$ we express the three Higgs doublets as

\[
H_s = \frac{1}{\sqrt{3}} (\Phi_a + \Phi_b + \Phi_c), \quad \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\Phi_a - \Phi_b) \\ \frac{1}{\sqrt{2}}(\Phi_a + \Phi_b - 2\Phi_c) \end{pmatrix}.
\]

All the fields in this extension have three flavours and belong to a reducible representation $1 \oplus 2$ of $S_3$. 


3. The $S_3$ invariant Higgs sector

The Higgs sector Lagrangian of the $S_3$-invariant extension of the SM is expressed as

$$\mathcal{L}_\Phi = |D_\mu H_S|^2 + |D_\mu H_1|^2 + |D_\mu H_2|^2 - V(H_1, H_2, H_S),$$

where $D_\mu$ is the usual covariant derivative. The most general Higgs potential invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y \times S_3$ can be written as [1–3,6]

$$V = \mu_1^2 \left( H_1^\dagger H_1 + H_2^\dagger H_2 \right) + \mu_2^2 \left( H_3^\dagger H_S + a \left( H_1^\dagger H_S \right)^2 + b \left( H_3^\dagger H_S \right) \left( H_1^\dagger H_1 + H_2^\dagger H_2 \right) + c \left( H_1^\dagger H_1 + H_2^\dagger H_2 \right)^2 \right) + d \left( H_1^\dagger H_2 - H_2^\dagger H_1 \right)^2 + e f_{ijk} \left\{ \left( H_1^\dagger H_i \right) \left( H_1^\dagger H_j \right) \left( H_1^\dagger H_k \right) \right\} + f \left\{ \left( H_1^\dagger H_1 \right) \left( H_1^\dagger H_S \right) + \left( H_2^\dagger H_2 \right) \left( H_2^\dagger H_S \right) \right\} + g \left\{ \left( H_1^\dagger H_1 \right) \left( H_2^\dagger H_2 \right)^2 + \left( H_1^\dagger H_2 + H_2^\dagger H_1 \right) \right\} + h \left\{ \left( H_3^\dagger H_1 \right) \left( H_1^\dagger H_1 \right) + \left( H_3^\dagger H_2 \right) \left( H_2^\dagger H_2 \right) \right\} + \left( H_1^\dagger H_S \right) \left( H_1^\dagger H_S \right) + \left( H_2^\dagger H_S \right) \left( H_2^\dagger H_S \right),$$

where $a, b, c, \ldots, h$ are constants. Also $f_{ijk}$ are constants whose indices run from 1 to 2, and a sum over repeated indices in the term of Eq. (4) involving $f_{ijk}$ is implicit. Their values are $f_{112} = f_{211} = f_{222} = 1$, whereas all the rest are zero. The $SU(2)_L$ Higgs doublets with flavour index 1, 2, $S$ are

$$H_1 = \left( \begin{array}{c} \phi_1 + i\phi_2 \\ \phi_7 + i\phi_{10} \end{array} \right), \quad H_2 = \left( \begin{array}{c} \phi_3 + i\phi_4 \\ \phi_8 + i\phi_{11} \end{array} \right), \quad H_S = \left( \begin{array}{c} \phi_5 + i\phi_6 \\ \phi_9 + i\phi_{12} \end{array} \right).$$

We introduce the following notation:

$$x_1 = H_1^\dagger H_1, \quad x_2 = H_2^\dagger H_2, \quad x_3 = H_3^\dagger H_S,$$

$$x_4 = \Re \left( H_1^\dagger H_2 \right), \quad x_5 = \Im \left( H_1^\dagger H_2 \right), \quad x_6 = \Re \left( H_1^\dagger H_S \right),$$

$$x_7 = \Im \left( H_1^\dagger H_S \right), \quad x_8 = \Re \left( H_2^\dagger H_S \right), \quad x_9 = \Im \left( H_2^\dagger H_S \right),$$

where $\Re$ and $\Im$ are the real and imaginary parts respectively. Thus, the most general Higgs potential invariant under the exact symmetry $SU(2)_L \times U(1)_Y \times S_3$ can be written as

$$V(X) = A^T X + \frac{1}{2} X^T B X,$$

where $X$ is the vector of fields $X^T = (x_1, x_2, x_3, \ldots, x_9)$, $A$ the vector of mass parameters and $B$ a $9 \times 9$ real parameter matrix

$$A = \begin{pmatrix}
\mu_1^2 \\
\mu_2^2 \\
\mu_3^2 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{pmatrix}$$
4. Stationary Points

The potential (4) has three types of stationary points:

- The normal minimum with the following field configuration:
  \[ \phi_T = v_1, \phi_S = v_2, \phi_3 = v_3, \phi_i = 0, \quad i \neq 7, 8, 9 \]

- The stationary point which breaks the electric charge, here two of the charged fields \( \phi \) acquire non-zero vev's:
  \[ \phi_T = v'_1, \phi_S = v'_2, \phi_3 = v'_3, \phi_1 = \alpha, \phi_3 = \beta, \]

- The CP breaking minimum, where two imaginary components of the neutral fields \( \phi \) acquire non-zero vev's:
  \[ \phi_T = v''_1, \phi_S = v''_2, \phi_3 = v''_3, \phi_{10} = \delta, \phi_{11} = \gamma. \]

Since we assume \( H_S \) to be the SM Higgs, we will also assume that it does not break electric charge nor CP. The two Higgs Doublet Model (2HDM) Higgs sector has been studied extensively in Refs. [13–15]. We will follow a similar analysis here, in terms of the comparison between the different stationary points. We will see that the tree-level Higgs potential minimum preserving electric charge and CP symmetries, when it exists, is the global one.

4.1. The normal stationary point

From the definitions above, we obtain \( x_i = v_i^2 \) for \( i = 1, 2, 3 \), \( x_4 = v_1v_2 \), \( x_6 = v_1v_3 \), \( x_8 = v_2v_3 \) and \( x_5 = x_7 = x_9 = 0 \). Then, we can write the extremisation conditions as

\[
\frac{\partial V}{\partial v_i} = 0 \leftrightarrow \frac{\partial V}{\partial x_j} \frac{\partial x_j}{\partial v_i} = 0 ,
\]

where \( i = 1, 2, 3 \) and \( j = 1, 2, \ldots, 9 \). Eqs. (10) have a general solution in which \( v_1^2 = 3 v_2^2 \). If we take \( e = 0 \), a particular situation occurs, in which case one of the solutions has \( v_1^2 = v_2^2 \).

Let us define the vector \( \{ V'_{(N)} \}_i = \{ V' \}_{x_i} \frac{\partial V}{\partial x_i} \), evaluated at the minimum.

\[
V'_{N} = \begin{pmatrix}
-\frac{\partial V}{\partial x_1} + \frac{\partial V}{\partial x_6} v_2 \frac{1}{2 v_1^2} & -\frac{\partial V}{\partial x_2} + \frac{\partial V}{\partial x_6} v_2 \frac{1}{2 v_1^2} & -\frac{\partial V}{\partial x_3} + \frac{\partial V}{\partial x_6} v_2 \frac{1}{2 v_1^2} \\
-\frac{\partial V}{\partial x_7} + \frac{\partial V}{\partial x_6} v_2 \frac{1}{2 v_1^2} & -\frac{\partial V}{\partial x_8} + \frac{\partial V}{\partial x_6} v_2 \frac{1}{2 v_1^2} & -\frac{\partial V}{\partial x_9} + \frac{\partial V}{\partial x_6} v_2 \frac{1}{2 v_1^2} \\
0 & 0 & 0
\end{pmatrix}
\]
It is clear from this expression that the first three entries in $V'_N$ have the same sign if the ratios $\frac{-\langle V \rangle_4}{2v_1v_2}, \frac{-\langle V \rangle_6}{2v_1v_3}, \frac{-\langle V \rangle_8}{2v_2v_3}$ have equal signs too.

The stationary point is given by the conditions imposed in Eq.(10). Analyzing the second derivatives of the Higgs potential $V$ we obtain the conditions for a minimum, these are given by the matrix of the squared scalar Higgs masses. In particular, the scalar charged Higgs have the squared masses $m_{H_{1,2}^\pm}^2$, as we will later see in Eq. (28).

It is clear from Eq. (11) that the first three entries in $V'_N$ have the same sign as we mentioned before and the squared masses are positive if the sign of the ratios $\frac{-\langle V \rangle_4}{2v_1v_2}, \frac{-\langle V \rangle_6}{2v_1v_3}, \frac{-\langle V \rangle_8}{2v_2v_3}$ are positive too. Then, we have that the normal minimum exists if $m_{H_{1,2}^\pm}^2 > 0$. In the normal minimum we get

$$V'_N = A + B X_N$$

and

$$X_N^T V'_N = 0, \quad (12)$$

where $X_N = X |_{normal \min}$. In this notation, the potential evaluated at the normal minimum can be written as:

$$V_N = -\frac{1}{2} X_N^T B X_N = \frac{1}{2} A^T X_N. \quad (13)$$

4.2. Charge breaking stationary point

In this case, the $S_3$ CB doublet of the Higgs field takes the values $\phi_7 = v_1', \phi_8 = v_2', \phi_9 = v_3'$ and $\phi_1 = \alpha, \phi_3 = \beta$. Then, the vector $X_{CB}$ can be written as:

$$X_{CB} = \begin{pmatrix} \alpha^2 + v_1'^2 & \beta^2 + v_2'^2 & v_3'^2 \\ \beta \alpha + v_1'v_2' & 0 \\ v_1'v_3 & v_2'v_3 & 0 \end{pmatrix}. \quad (14)$$

Direct analysis of the potential for this stationary point gives:

$$V'_{CB} = A + B X_{CB}.$$

Thus, the potential evaluated at the CB stationary point can be written as:

$$V_{CB} = -\frac{1}{2} X_{CB}^T B X_{CB} = \frac{1}{2} A^T X_{CB}. \quad (16)$$

From this equation and Eq.(13), we can compare the potential evaluated at the normal and CB breaking stationary points,

$$V_{CB} - V_N = \frac{1}{2} (X_{CB}^T V'_N - X_N^T V'_N). \quad (17)$$

If the signs of the ratios $\frac{-\langle V \rangle_4}{2v_1v_2}, \frac{-\langle V \rangle_6}{2v_1v_3}, \frac{-\langle V \rangle_8}{2v_2v_3}$ are positive, the product $X_{CB}^T V'_N$ is also positive. When the product $X_N^T V'_N$ vanishes, then the normal stationary point is the deepest one. That is,

$$(V'_{CB})_4 = 0 \quad \text{or} \quad \frac{v_2}{v_3}(v_1'\beta - v_2'\alpha) = 0. \quad (18)$$
One possible solution to Eq.(17) is that two $S_3$ doublet Higgs fields $H_1$ and $H_2$ acquire equal vevs $v_1 = v_2$, $v'_1 = v'_2$ and $\alpha = \beta$. Then, we can see that the $S_3$ extended Higgs potential has an accidental $S_2$ symmetry in the normal and the electric charge stationary points. If the normal one is actually a minimum, then this solution corresponds to the Pakvasa-Sugawara one [3], and is the condition for the normal minimum to be the deepest one. Other possible solution is realized when $(V'_CB)_4$ vanishes.

4.3. CP breaking stationary point
The CP breaking stationary point is given by the following vevs: $\phi_7 = v'_1$, $\phi_8 = v'_2$, $\phi_9 = v'_3$, $\phi_{10} = \delta$ and $\phi_{11} = \gamma$. Then,

$$X_{CP} = \begin{pmatrix} \delta^2 + v'^2_1 \\ \gamma^2 + v'^2_2 \\ v'^2_3 \\ \delta \gamma - v'^2_2 \delta \\ v'_1 \gamma - v'^2_2 \delta \\ -\delta \gamma \\ -v'_2 \gamma \\ v_1 \gamma - v'_2 \delta \\ -v'_3 \gamma \\ -v'^2_2 \gamma \end{pmatrix}. \tag{19}$$

In a similar way to the previous stationary points, we obtain

$$X'^T_{CP} V'_N = 0, \tag{20}$$

and

$$V_{CP} = A^T X_{CP} + \frac{1}{2} X'^T_{CP} B_{CP} X_{CP}, \tag{21a}$$

$$V'_{CP} = A + B_{CP} X_{CP}. \tag{21b}$$

In this case, the potential evaluated at the normal and at the CP violating stationary points can be compared as follows:

$$V_{CP} - V_N = \frac{1}{2} (X'^T_{CP} V'_N - X'^T_{N} V_{CP}). \tag{22}$$

That is, if $X'^T_{CP} V'_N$ is positive, the signs of the ratios $\frac{-(V')_4}{2v'_1v'_2}$, $\frac{-(V')_6}{2v'_2v'_3}$, $\frac{-(V')_8}{2v'_1v'_3}$ are positive, and the normal stationary point is the deepest one, when the second term in the right hand side of Eq. (22) vanishes.

5. Higgs Mass matrix
We need to know the nature of the stationary points, so we compute the second derivatives of the Higgs potential:

$$\frac{\partial^2 V}{\partial \phi_i \partial \phi_j} = \frac{\partial V}{\partial \phi_i} \frac{\partial^2 x_l}{\partial \phi_j} + \frac{\partial^2 V}{\partial x_l \partial x_m} \frac{\partial x_l}{\partial \phi_i} \frac{\partial x_m}{\partial \phi_j}. \tag{23}$$

Defining

$$(V')_i = \frac{\partial V}{\partial X_i}, \quad [B_{lm}] = \frac{\partial^2 V}{\partial X_l \partial X_m}, \quad l, m = 1, 2, \ldots, 9 \tag{24}$$

$$[C]_{ij} = \frac{\partial X_i}{\partial \phi_j}, \quad i = 1, 2, \ldots, 9; \quad j = 1, 2, \ldots, 12. \tag{25}$$
The corresponding mass matrix has the form
\[ [M^2] = \frac{1}{2} \left( [M^2_{\phi}] + C^T B C \right). \] (26)

The first term in Eq. (26) is
\[ [M^2_{\phi}]_{ij} = V'_i \frac{\partial^2 X_l}{\partial \phi_i \partial \phi_j}. \] (27)

In the normal minimum this matrix takes the form: \([M^2_{\phi}] = Diag( M^2_{11}, M^2_{12})\) where \(M^2_{11}\) and \(M^2_{12}\) are \(6 \times 6\) matrices. The entries in matrix \(B\) are given in Eq. (9) by the second derivatives of the Higgs potential. Evaluated at each of the different stationary points, only the fields \(\phi_7, \phi_8, \phi_9, \phi_1, \phi_3, \phi_{10}\) and \(\phi_{11}\) appear, the remaining fields are zero at the stationary points. Hence, the mass matrix of the squared masses can be computed from (26), it takes the following form
\[ \text{diag}(M^2_S, M^2_C, M^2_P). \]

The mass of the physical charged Higgs can be expressed as
\[ m^2_{H_{12}} = V'_1 + V'_2 + V'_3 \pm \sqrt{(V'_1 + V'_2 + V'_3)^2 - (4V'_1V'_2 + 4V'_1V'_4 + 4V'_2V'_4 + V'_4^2 + V'_6^2 + V'_8^2)}. \] (28)

The mass matrices of the scalar and pseudoscalar Higgs fields are given by \(M^2_S\) and \(M^2_P\) respectively.

The mass matrix of the scalar and pseudoscalar Higgs fields in the normal minimum with \(e = 0\) and \(v_1 = v_2\) are given by the following block diagonal matrices
\[ [M^2_S] = \begin{pmatrix} 4(c + g)v_1^2 & 4(c + g)v_1v_2 & 2(b + f + 2h)v_1v_3 \\ 4(c + g)v_1v_2 & 12ev_2v_3 + 4(c + g)v_2^2 & 2(b + f + 2h)v_2v_3 \\ 2(b + f + 2h)v_1v_3 & 2(b + f + 2h)v_2v_3 & 4av_2^2 \end{pmatrix}, \] (29)
\[ [M^2_P] = \begin{pmatrix} -8 \{hv_3^2 + (g + d)v_2^2\} & 8(g + d)v_1v_2 + 4ev_1v_3 & 4hv_1v_3 \\ 8(g + d)v_1v_2 & -8 \{hv_3^2 + (g + d)v_1^2\} & 8hv_2v_3 \\ 4hv_1v_3 & 8hv_2v_3 & -8(hv_1^2 + v_2^2) \end{pmatrix}. \] (30)

In this particular case the eigenvalues of the scalar mass matrix Higgs fields are given by:
\[ m_1 = 0, \]
\[ m^2_{2,3} = 2av_2^2 - 2(c + g)(v_1^2 + v_2^2) \pm \sqrt{\left[4(c + g)^2v_1^4 - 24a(c + g)(v_1^2 + v_2^2)v_1^2 + 4(b + f + 2h)(v_1^2 + v_2^2)\right]^{1/2}}. \] (31)

In the \(S(3)\) extended model we have three \(SU(2)\) Higgs fields, with four real fields each. There are three masses gauge bosons \(W^\pm\) and \(Z\) with two polarization states each, so the total number of independent fields is 18. The normal minimum symmetry breaking is initiated by giving the vacuum expectation values \(H_1 = v_1, H_2 = v_2\) and \(H_S = v_3\) to the neutral Higgs fields in each doublet. The result is nine physical Higgs bosons that appear as real particles and the three massive gauge bosons \(W^\pm\) and \(Z\) with three polarization states each.

6. Conclusions
We have analyzed the most general Higgs potential invariant under the non-Abelian flavour symmetry \(S_3\) of the extended SM. In particular, we studied the nature of the critical points in the Higgs potential: the normal one, and the charge and CP breaking ones. We have found that the normal minimum is stable and it is the deepest one when the flavour \(S_3\) symmetry is unbroken. When the conditions \(e = 0\) and \(v_1 = v_2\) are met, there is an \(S_2\) accidental symmetry at the normal minimum.
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