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Erratum: Spontaneous symmetry breaking in the S_3-symmetric scalar sector

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Vacuum	λ_4	SCPV	Vacuum	λ_4	SCPV	Vacuum	λ_4	SCPV
C-I-a	X	no	C-III-f,g	0	no	C-IV-c	X	yes
C-III-a	X	yes	C-III-h	X	yes	C-IV-d	0	no
C-III-b	0	no	C-III-i	X	no	C-IV-e	0	no
C-III-c	0	no	C-IV-a	0	no	C-IV-f	X	yes
C-III-d,e	X	no	C-IV-b	0	no	C-V	0	no

Table 6. Spontaneous CP violation.

In our discussion of Spontaneous CP violation two cases must be corrected. In "Table 6: Spontaneous CP Violation." cases C-III-c and C-IV-e corresponding to $\lambda_4 = 0$ are indicated as having SPCV (spontaneous CP violation), however this is not the case. The correct table is given above.

As a result one may conclude that S_3 symmetric models with $\lambda_4 = 0$ cannot violate CP spontaneously. Still, there are cases with $\lambda_4 \neq 0$ where spontaneous CP violation may occur in three Higgs doublet models with S_3 symmetry.

The explanation for the absence of spontaneous CP violation in these two cases lies in the fact that models with $\lambda_4 = 0$ have an additional SO(2) symmetry. This symmetry can be used to build a matrix U verifying eq. (8.3) for cases C-III-c and C-IV-e.

In order to prove that case C-III-c does not violate CP spontaneously we start from the corresponding set of vevs $(\hat{w}_1 e^{i\sigma}, \hat{w}_2, 0)$ and perform a Higgs basis transformation on the Higgs doublets h_1 and h_2 by an SO(2) rotation into:

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \tag{8.5}$$

such that the vevs of the new S_3 doublet fields now have the same modulus and are now of the form $(ae^{i\delta_1}, ae^{i\delta_2}, 0)$. This requires

$$\tan 2\theta = \frac{\hat{w}_1^2 - \hat{w}_2^2}{2\hat{w}_1 \hat{w}_2 \cos\sigma}. \tag{8.6}$$

Obviously the Lagrangian remains invariant. Next we perform an overall phase rotation of the three Higgs doublets with the phase factor $\exp[-i(\delta_1 + \delta_2)/2]$, leading now to the following vevs: $(ae^{i\delta}, ae^{-i\delta}, 0)$. Making use of the symmetry for the interchange $h_1' \leftrightarrow h_2'$ we can verify eq. (8.3) in the following way:

$$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ae^{i\delta} \\ ae^{-i\delta} \\ 0 \end{pmatrix}^* = \begin{pmatrix} ae^{i\delta} \\ ae^{-i\delta} \\ 0 \end{pmatrix}. \tag{8.7}$$

In terms of the initial vevs, this equation translates into

$$e^{i(\delta_1+\delta_2)} \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \hat{w}_1 e^{i\sigma} \\ \hat{w}_2 \\ 0 \end{pmatrix}^* = \begin{pmatrix} \hat{w}_1 e^{i\sigma} \\ \hat{w}_2 \\ 0 \end{pmatrix}, \tag{8.8}$$

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or

$$e^{i(\delta_1+\delta_2)}\begin{pmatrix}\sin 2\theta & \cos 2\theta & 0\\ \cos 2\theta & -\sin 2\theta & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\hat{w}_1 e^{i\sigma}\\ \hat{w}_2\\ 0\end{pmatrix}^* = \begin{pmatrix}\hat{w}_1 e^{i\sigma}\\ \hat{w}_2\\ 0\end{pmatrix}. \tag{8.9}$$

Notice that $(ae^{i\delta}, ae^{-i\delta}, 0)$ is a special case of the PS vacuum, given in eq. (5.10).

In order to prove that C-IV-e does not violate CP spontaneously we start with the corresponding set of vevs: $(\hat{w}_1 e^{i\sigma_1}, \hat{w}_2 e^{i\sigma_2}, \hat{w}_S)$ where

$$\hat{w}_1 = \sqrt{-\frac{\sin 2\sigma_2}{\sin 2\sigma_1}}\hat{w}_2 \tag{8.10}$$

in this phase convention. In general one should write $\sin(2\sigma_1 - 2\sigma_S)$ and $\sin(2\sigma_2 - 2\sigma_S)$ in the latter relation, where σ_S would be the phase of the third vev. We now perform an SO(2) rotation, similar to the one specified above, with

$$\tan 2\theta = \frac{\hat{w}_1^2 - \hat{w}_2^2}{2\hat{w}_1\hat{w}_2\cos(\sigma_1 - \sigma_2)}, \tag{8.11}$$

which once again will lead to equal moduli for the S_3 doublet fields. In this case, the vevs will acquire the form $(be^{i\gamma_1}, be^{i\gamma_2}, \hat{w}_S)$. Unlike in case C-III-c, an overall phase rotation would also affect the vev of h_S. However, it turns out that condition (8.10) enforces

$$\gamma_1 + \gamma_2 = 0. \tag{8.12}$$

As a result, this SO(2) rotation takes us to the PS vacuum, which, as we discussed previously, does not violate CP spontaneously.

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