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Physics

Short Commentary on the Alternative View of the Symmetry of Spontaneous Breaking Mechanism in the Standard Model

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The fermion to scalar field Yukawa coupling non-derivative term is considered as a member of total potential in the full Standard Model Lagrangian. In cotrast to other terms, this new term violates a discrete symmetry. We show that at classical level this term does not participate in the ground state stability condition, but at the quantum level, where the fermion condensate can be nonzero, this term takes place in the corresponding equation. We find that in spite of expectation, it can change only the nummerical value of the Higgs vacuum parameter, leaving all the consequences of traditional approach without any substantial modifications. In our opinion, this fact may be interpreted as an alternate mechanism of breaking for gauge symmetry in the Standard Model. If so, then the symmetry breaking can be interpreted as explicit, but not spontaneous. *© 2024 Bull. Georg. Natl. Acad. Sci.*

standard model, Yukawa coupling, Higgs vacuum parameter

It is well known that the Standard Model [1], the modern theory of particle physics, is based on local gauge symmetry, which is spontaneously broken by adding the scalar (Higgs) field φ. At the same time the scalar field Lagrangian is symmetric under a discrete transformation $\varphi \to -\varphi$. But a full Lagrangian, corresponding to exact gauge symmetry, does not contain the nonzero masses of matter fields. They appear in the electroweak sector after introducing scalar fields, which contain the tachyon particle. Therefore, this part of Lagrangian is unstable and undergoes spontaneous breaking. Stable regime is achieved after assigning a constant value to the appropriate component of the scalar field [2]. Ascribing to φ a non-zero vacuum expectation value $\langle \varphi \rangle = \varphi_0 \equiv \upsilon$ and shifting $\varphi \to \varphi - \upsilon$, all the matter fields receive masses, but at the same time the mentioned discrete symmetry breaks down and we obtain a final theory – the standard model. In this brief report, I want to refer the attention to alternate possibility of this scenario.

The point is that the potential is produced by all non-derivative terms of the Lagrangian. Besides the Higgs part, the term of this kind is a Yukawa coupling of scalar field to the fermions, writting formally as $f\bar{\psi}\psi\varphi$. By our knowledge, the potential in Lagrangian is a collection of all non-derivative terms. Why do not include it into the potential, that determines the minima? After doing this the full Lagrangian, consisting the Higgs field, would be

$$L_\varphi = \left| \left(\partial_\mu + ig\boldsymbol{W}_\mu \cdot \frac{\boldsymbol{\tau}}{2} - ig' \frac{1}{2} Y_\mu \right) \varphi \right|^2 - V\left(\varphi^* \varphi\right) + L_{\psi\varphi}, \quad (1)$$

where $V\left(\varphi^*\varphi\right)$ is the Higgs potential, which is an even polynomial of the 4th order, and $L_{\psi\varphi}$ is the Yukawa coupling term for fermions with scalar (Higgs) fields, formally written as $\sum_{i=1}^{N_F} f_i \overline{\psi}_i \psi_i \varphi_i$ and the sum ranges over all fermions (leptons and quarks). For simplicity, we take only one Higgs multiplet into account as in the simplest Glashow- Salam -Weinberg (GSW) model [3-5].

$$V\left(|\varphi|\right) = \mu^2 \varphi^* \varphi + h\left(\varphi^* \varphi\right)^2. \quad (2)$$

In this model $L_{\psi\varphi}$ is a fermion-Higgs Yukawa like term

$$L_{\psi\varphi} = f\left(\overline{R}\varphi^\dagger L + \overline{L}\varphi R\right). \quad (3)$$

If we take [4], as usual

$$\varphi = \begin{pmatrix} \varphi_{(+)} \\ \varphi_{(0)} \end{pmatrix}, \quad (4)$$

then $\varphi^\dagger = \left(\varphi_{(+)}^\dagger, \varphi_{(0)}^\dagger\right)$ and $\varphi^\dagger \varphi = \varphi_{(+)}^\dagger \varphi_{(+)} + \varphi_{(0)}^\dagger \varphi_{(0)}$.

Decomposing the neutral field into real and imaginary components

$$\varphi_{(0)} = \frac{\varphi_1 + i\varphi_2}{\sqrt{2}}, \quad \varphi_{(0)}^\dagger = \frac{\varphi_1 - i\varphi_2}{\sqrt{2}}, \quad (5)$$

the bilinear form of Higgs potential becomes

$$\varphi^\dagger \varphi = \varphi_{(+)}^\dagger \varphi_{(+)} + \frac{1}{2}\left(\varphi_1^2 + \varphi_2^2\right). \quad (6)$$

And choosing the gauge as follows [1]

$$\varphi = e^{i\boldsymbol{\xi}\cdot\boldsymbol{\tau}} \begin{pmatrix} 0 \\ \dfrac{\upsilon + \chi}{\sqrt{2}} \end{pmatrix}, \quad (7)$$

where $\boldsymbol{\xi}$ is Goldstone particle's fields. It is equivalent to $\langle \varphi_1 \rangle_0 \neq 0$, but $\langle \varphi_2 \rangle_0 = 0$

Minima of this potential is to be find by the requirement

$$\left\langle \frac{\partial\left(f\overline{\psi}\psi\varphi + V\left(\varphi^2\right)\right)}{\partial\varphi} \right\rangle = 0. \quad (8)$$

We remark that all terms in the Higgs potential as well as in total standard model Lagrangian except fermion-scalar field coupling, are invariant under discrete transformation $\varphi \to -\varphi$. But the total Lagrangian is not invariant under such a transformation. Only terms, coupling fermions to scalar multiplet explicitly violate this symmetry. Moreover, the only output of these manipulations is that the above mentioned discrete symmetry is broken, without breaking a gauge symmetry [6].

In the spread form the stability equation (8) reads

$$\left\langle \frac{\partial V}{\partial \varphi} \right\rangle_0 + f\left\langle \bar{\psi}\psi \right\rangle_0 = 0 . \tag{9}$$

The fermion average $\left\langle \bar{\psi}\psi \right\rangle_0$ is zero at the classical level, but in quantum physics it is a fermion condensate and in general $\left\langle \bar{\psi}\psi \right\rangle_0 \neq 0$. Therefore, if we perform first the quanization in the false vacuum and then look for stability problem, we can take a nonzero $F \equiv \left\langle \bar{\psi}\psi \right\rangle_0$.

Now, we see that if the fermion average $F \neq 0$, then the stability equation should contain the extra term. If this term is non zero, then $\left\langle \varphi \right\rangle_0 \equiv \upsilon$, corresponding to minima, becomes dependent on F in such a way, that when $F = 0$, it will satisfy to well-known nonlinear equation which may have spontaneous solution. This solution provides all features known in the standard model (we mean a generation of masses, etc.) and on the other hand, in quantum theory it is related to fermion condensates, because the scalar field has a coupling with all fundamental fermions. By our opinion it seems very intriguing thing a realization of this program.

If even $F \neq 0$, this extra term does not contribute to the mass of the Higgs boson $m_\varphi^2 = \left\langle \frac{\partial^2 V}{\partial \varphi^2} \right\rangle_0$. Its contribution may arise only in the numerical value of υ.

In conclusion, if F=0, we return to the ordinary Higgs mechanism. It is clear that in any case symmetry breaking in the standard model must be interpreted as an explicit broken discrete symmetry $\varphi \to -\varphi$. For illustration, let us consider the simplest case of the Weinberg model, where the Higgs potential is constructed from a single Higgs doublet $\varphi = \begin{pmatrix} \varphi^{(+)} \\ \varphi^{(0)} \end{pmatrix}$ and is

$$V(\varphi) = \mu^2 \varphi^{(+)}\varphi + h\left(\varphi^{(+)}\varphi\right)^2 . \tag{10}$$

Denoting $\varphi^{(0)} = \varphi_1^{(0)} + i\varphi_2^{(0)}$, the stability condition takes the form

$$\left\langle \frac{\partial U}{\partial \varphi} \right\rangle_0 = f\left\langle \bar{\psi}\psi \right\rangle_0 + \left\langle \frac{\partial V}{\partial \varphi} \right\rangle_0 = F + \mu^2 \varphi^{(+)} + 2h\varphi^{(+)}\varphi\varphi^{(+)} = 0 . \tag{11}$$

Taking into account the Higgs potential (11) and our notation, we write the stability condition as follows

$$h\varphi_1^{(0)3} + \mu^2 \varphi_1^{(0)} + fF = 0 \tag{12}$$

or

$$\varphi_1^{(0)3} + \frac{\mu^2}{h}\varphi_1^{(0)} + \frac{f}{h}F = 0 \tag{13}$$

and the mass of scalar particle is $\left\langle \frac{\partial^2 U}{\partial \varphi^2} \right\rangle_0 = \left\langle \frac{\partial^2 V}{\partial \varphi^2} \right\rangle_0 = m_\varphi^2$, the same as without fermion condensate.

The Eq. (5) is a semi-full (or reduced) cubic equation, solutions of which are given by Cardano forms [7]:

$$y_1 = A + B = \varphi_{10}^{(1)}; \qquad y_{2,3} = -\frac{A+B}{2} \pm i\sqrt{3}\,\frac{A-B}{2}, \tag{14}$$

where

$$A = \sqrt[3]{-q/2 + \sqrt{Q}}, \qquad B = \sqrt[3]{-q/2 - \sqrt{Q}} \tag{15}$$

and

$$Q = \left(p/2\right)^3 \; Q = \left(p/3\right)^3 + \left(q/2\right)^2 . \tag{16}$$

For our case

$$p = \frac{\mu^2}{h}, \qquad q = \frac{f}{h} F . \tag{17}$$

Note that in the limit $F \to 0$, it follows from the Eqs. (15)-(17) well-known expected roots $\upsilon_1 = 0$ and $\upsilon_2 = \sqrt{-\mu^2 / h}$ which means that there must exist a tachyon with $\mu^2 < 0$. To solve these equations analytically in case of $F \neq 0$ is a difficult task.

In conclusion, we saw that the inclusion of the Yukawa coupling term into the potential leads to the explicit breakdown of existed discrete symmetry.

On the other hand, this breaking is very distinctive: on the classical level it has no effect, but on quantum level it can have an influence on the numerical values of model-parameters at least.

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