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About the quantization of electric charge in gauge theories

O. B. Abdinov, F. T. Khalil-zade

Institute of Physics, Azerbaijan National Academy of Sciences,
Baku, Azerbaijan

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Conditions of electric charge quantization and fixation:

- The $U(1)_{em}$ gauge symmetry must remain exact;
- To guarantee the renormalizability and covariance of theory, gauge and gauge gravitational anomalies must be canceled;
- The masses of fermions must be generated by the Higgs mechanism.

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- ❑ Quantization of electric charge does not depend on the hypercharge of the Higgs field.
- ❑ In gauge models with right-handed neutrino, quantization of electric charge follows from the conditions of anomaly cancellation and nonvanishing fermions masses only if the neutrino is a Majorana particle.

Why ?

- ❑ It is known that only massive elementary particles have the electric charges (massless are neutral), so **the coupling of electric charge (quantization) with the mechanism of mass generation of elementary particles, it is obvious there is and should be investigated.**

- Definition and study of the relation of electric charges with the properties of Higgs bosons, finding conditions for an unambiguous definition (quantization) of these charges is certainly interesting.

It was shown that the [11 – 13]

1. Photon eigenstate and particle charges depend on the hypercharge of the Higgs fields.
2. In the issue of quantization of electric charge in the gauge models, it is possible to manage without an explicit accounting of the Higgs mechanism of mass generation, relying instead on the P invariance of the electromagnetic interaction.

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Electric charge quantization in SM and its extensions

Usual way	In this report
Y – from anomalies cancellation conditions. Electric charges from $Q = T_3 + \frac{Y}{2}$	Calculation of particles electric charges

1. Standard Model with right handed neutrino

2. $SU_C(3) x SU(3)_L x U(1)_X$

3. $SU_C(3) x SU(3)_L x U(1)_X x U'(1)$

I. Electric charge quantization in the SM with right-handed neutrino

$$\psi_L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L , \psi_R = e_R , \psi_{\nu R} = \nu_R , \psi_{QL} = \begin{pmatrix} u \\ d \end{pmatrix}_L , \psi_{uR} = u_R , \psi_{dR} = d_R$$

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

.

$$L = i\overline{\psi}_{fL} \hat{D} \psi_{fL} + i\overline{\psi}_{fR} \hat{D} \psi_{fR} + \left(D_\mu \varphi\right)^+ \left(D_\mu \varphi\right),$$

$$D_\mu = \partial_\mu - ig \frac{\vec{\tau} \vec{A}_\mu}{2} - ig' \frac{X}{2} B_\mu$$

$$X(\varphi) = x_\varphi , \quad X(\psi_L) = x_L \quad X(\psi_{eR}) = x_{eR} , \quad X(\psi_{\nu R}) = x_{\nu R} ,$$

$$X(\psi_{QL}) = x'_{QL} , \quad X(\psi_{uR}) = x_{uR} , \quad X(\psi_{dR}) = x_{dR} .$$

$$A_\mu^3 = A_\mu \sin\theta_i + Z_\mu \cos\theta_i,$$

$$B_\mu = A_\mu \cos\theta_i - Z_\mu \sin\theta_i.$$

$(D_\mu\varphi)^+(D_\mu\varphi)$	$\overline{\psi}_{fL}\hat{D}\psi_{fL}$	$\overline{\psi}_{QL}\hat{D}\psi_{QL}$
$\sin\theta_\varphi = \frac{x_\varphi g'}{\sqrt{g^2 + x_\varphi^2 g'^2}}$	$\sin\theta_L = -\frac{x_L g'}{\sqrt{g^2 + x_L^2 g'^2}}$	$\sin\theta_{QL} = \frac{x'_{QL} g'}{\sqrt{g^2 + x'^2_{QL} g'^2}}$

In general, there is no theoretical reason to require the equality of these angles. If these angles are equal

$$x_\varphi = -x_L, \quad x_\varphi = x'_{QL}, \quad x_L = -x'_{QL} \qquad (1)$$

In the SM, the quantity defining the interaction of the Higgs and fermionic fields with the field B_μ is the weak hypercharge (hereinafter hypercharge).

If the parameters x are usual SM hypercharges, we reveal that the hypercharge values of the Higgs and leptonic fields in the SM

$$(Y_{\varphi}^{CM} = 1, \quad Y_{L}^{CM} = -1)$$

really satisfy the first condition (1). The hypercharge of the left-handed quark field in the SM is

$$Y_{QL}^{CM} = 1/3$$

hence, the second and third conditions (1) are not met. As a result, in general, we find that the quantity that characterizes the interaction of the left-handed quark field with the filed B_μ (x'_{QL}) **cannot be identified with the hypercharge of the left-handed quark field of the SM** (Y_{QL}^{CM}) .

Hence, the need arises in the interpretation of values x'_{QL} and clarify its relationship with the hypercharge Y_{QL}^{CM} .

This difficulty of the SM may be overcome by using the following three facts:

- The anomaly cancellation conditions from which it follows that

$$x'_{QL} = 3x_{QL} = 3Y^{CM}_{QL}$$

- The fact of equality of the Weinberg angle measured in purely leptonic, semileptonic and hadronic processes and assume

$$x'_{QL} = 3x_{QL} = 3Y^{CM}_{QL}$$

- Assumed that the ratios of left hypercharge of the quark and lepton fields to the hypercharge of the Higgs field are baryon and lepton quantum numbers, respectively (A. Abbas [9])

$$\frac{x_{QL}}{x_{\varphi}} = B, \quad \frac{x_{L}}{x_{\varphi}} = -L.$$

$$x_{\varphi} = -x_{L}, \quad x_{\varphi} = 3x_{QL}, \quad x_{L} = -3x_{QL} \qquad (2)$$

Electric charge quantization

$$L_{l\gamma} = \bar{\nu}\gamma_{\mu}\left(Q_{\nu} + Q'_{\nu}\gamma_5\right)\nu A_{\mu} + \bar{e}\gamma_{\mu}\left(Q_{0e} + Q'_{0e}\gamma_5\right)eA_{\mu}$$

$$L_{q\gamma} = \bar{u}\gamma_{\mu}\left(Q_{1u} + Q'_{1u}\gamma_5\right)uA_{\mu} + \bar{d}\gamma_{\mu}\left(Q_{2d} + Q'_{2d}\gamma_5\right)dA_{\mu}.$$

$$Q_{\nu} = \frac{g}{4}\left(1 + \frac{x_L + x_{\nu R}}{x_{\varphi}}\right)\sin\theta_{\varphi}, \qquad Q'_{\nu} = \frac{g}{4}\left(1 + \frac{x_L - x_{\nu R}}{x_{\varphi}}\right)\sin\theta_{\varphi},$$

$$Q_{0e} = -\frac{g}{4}\left(1 - \frac{x_L + x_{eR}}{x_{\varphi}}\right)\sin\theta_{\varphi}, \qquad Q'_{0e} = -\frac{g}{4}\left(1 - \frac{x_L - x_{eR}}{x_{\varphi}}\right)\sin\theta_{\varphi}.$$

$$Q_{1u} = \frac{g}{4}\left(1 + \frac{x_{QL} + x_{uR}}{x_{\varphi}}\right)\sin\theta_{\varphi}, \qquad Q'_{1u} = \frac{g}{4}\left(1 + \frac{x_{QL} - x_{uR}}{x_{\varphi}}\right)\sin\theta_{\varphi},$$

$$Q_{2d} = -\frac{g}{4}\left(1 - \frac{x_{QL} + x_{dR}}{x_{\varphi}}\right)\sin\theta_{\varphi}, \qquad Q'_{2d} = -\frac{g}{4}\left(1 - \frac{x_{QL} - x_{dR}}{x_{\varphi}}\right)\sin\theta_{\varphi}.$$

P invariance of electromagnetic interaction leads to

$$Q'_{\nu} = 0, \quad Q'_{0e} = 0 \quad Q'_{1u} = 0, \quad Q'_{2d} = 0$$

and

$$x_L = x_{\nu R} - x_{\varphi}, x_L = x_{eR} + x_{\varphi}$$
$$x_{QL} = x_{uR} - x_{\varphi}, \quad x_{QL} = x_{dR} - x_{\varphi} \qquad (3)$$

$$L^f_{mass} = f_e \overline{\Psi}_L \Psi_{eR} \varphi + f_\nu \overline{\Psi}_L \Psi_{\nu R} \varphi^c + f_d \overline{\Psi}_{QL} \Psi_{dR} \varphi + f_u \overline{\Psi}_{QL} \Psi_{uR} \varphi^c + h.c.,$$

$$Q_\nu = \frac{Q_e}{2}\left(1 + \frac{x_L}{x_\varphi}\right), Q_{0e} = -\frac{Q_e}{2}\left(1 - \frac{x_L}{x_\varphi}\right), \quad Q_u = \frac{Q_e}{2}\left(1 + \frac{x_{QL}}{x_\varphi}\right), \quad Q_d = -\frac{Q_e}{2}\left(1 - \frac{x_{QL}}{x_\varphi}\right)$$

$$Q_e = g \sin\theta_\varphi = x_\varphi g g' / \overline{g}_\varphi, \overline{g}_\varphi = \sqrt{g^2 + x_\varphi^2 g'^2}.$$

Taking into account (2) we have

$$Q_\nu = 0, \quad Q_{0e} = -Q_e, \quad Q_u = \frac{2}{3} Q_e, \quad Q_d = -\frac{1}{3} Q_e$$

Thus, we conclude that relations (2) and (3) are necessary conditions for the quantization of electric charge and, hence, without the presence of the Higgs field in this case there is no quantization of electric charge.

Interaction of the Higgs field with the fermion fields (or the condition of P invariance of electromagnetic interaction) also leads to the fixation of the hypercharges of right fields

$$x_{\nu R} = 0, \quad x_{eR} = -2x_{\varphi}, \quad x_{dR} = -\frac{2}{3}x_{\varphi}, \quad x_{uR} = \frac{4}{3}x_{\varphi}.$$

Results

1. In the model with the right-handed neutrino in the context of solving the problem of quantization of electric charge is not necessary to include into the SM Majorana neutrino.
2. In the issue of quantization of electric charge in the SM it is possible to manage without the obvious account of the Higgs mechanism of generation of mass, relying instead against P invariance of electromagnetic interaction which is caused by identity of charges left and right fermions
3. Influence of the Higgs field on the electric charge quantization.

Electric charge quantization in $SU_C(3)xSU(3)_L xU(1)_X$ model with exotic particles

3-3-1 or $SU_C(3)xSU(3)_L xU(1)_X$ model

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ECQ in 3-3-1 models (minimal and with right-handed neutrino) was studied in [21].

ECQ does not depend on the classical constraints that follow from the Lagrangian of interaction generating the masses of fermions, is closely allied to the generation number problem and is a natural consequence of the electric charge conservation and of the anomaly cancellation conditions.

The structure of the $SU_C(3)xSU(3)_L xU(1)_X$ model

$$\psi_{lL} = \begin{pmatrix} \nu \\ e^- \\ N \end{pmatrix}_L \sim (1,3,y_{lL}), \quad \psi_{eR} = e_R \sim (1,1,y_{eR}), \quad \psi_{NR} = N_R \sim (1,1,y_{NR}),$$

$$\psi_{QL} = \begin{pmatrix} u \\ d \\ U \end{pmatrix}_L \sim (3,3,y_{QL}), \quad \psi_{uR} = u_R \sim (3,1,y_{uR}),$$

$$\psi_{dR} = d_R \sim (3,1,y_{dR}), \quad \psi_{UR} = U_R \sim (3,1,y_{UR}).$$

$$\hat{Q} = \alpha \hat{T}_3 + \beta \hat{T}_8 + X \hat{I}$$

$$T_3 = \frac{1}{2} diag\left(1, -1, 0\right) \qquad T_8 = \frac{1}{2\sqrt{3}} diag\left(1, 1, -2\right) \qquad Tr\left(T_\alpha T_\beta\right) = \frac{1}{2}\delta_{\alpha\beta}$$

$$\hat{Y} = \beta \hat{T}_8 + X \hat{I}.$$

$$< \chi >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ V \end{pmatrix}, \quad < \rho >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \upsilon \\ 0 \end{pmatrix}, \quad < \eta >= \frac{1}{\sqrt{2}}\begin{pmatrix} u \\ 0 \\ 0 \end{pmatrix}. \qquad V >> \upsilon >> u$$

$$V_{kin} = (D_\mu \chi)^+ (D_\mu \chi) + (D_\mu \eta)^+ (D_\mu \eta) + (D_\mu \rho)^+ (D_\mu \rho).$$

$$D_\mu = \partial_\mu - igT_a W_{a\mu} - ig' T_9 X B_\mu,$$

$$T_a (a = 1,...,8) \ , \ T_9 = \frac{1}{\sqrt{6}} diag\left(1,1,1\right), \ Tr\left(T_a T_b\right) = \frac{1}{2}\delta_{ab} \quad (a,b = 1,2,...,9).$$

$X_\chi, \ X_\rho, \ X_\eta$ - Higgs fields hypercharges

Electric charge quantization in $SU_C(3)xSU(3)_L xU(1)_X$ model

$$A_\mu = -\frac{g'}{\sqrt{2}\,\overline{g}}(X_\rho - X_\eta)W_{3\mu} + \frac{3g'}{\sqrt{6}\,\overline{g}}(X_\rho + X_\eta)W_{8\mu} + \frac{3g'}{\sqrt{6}\,\overline{g}}(X_\rho + X_\eta)B_\mu,$$

$$\overline{g} = g\left[3 + 2t^2\left(X_\eta^2 + X_\rho^2 + X_\eta X_\rho\right)\right]^{1/2}, \quad t = g'/g$$

From the P invariance of the electromagnetic interaction and gauge invariance of the Yukawa interaction

$$L^f_{mass} = f_e \overline{\Psi}_{lL}\rho\Psi_{eR} + f_N \overline{\Psi}_{lL}\chi\Psi_{NR} + f_u \overline{\Psi}_{QL}\eta\Psi_{uR} + f_d \overline{\Psi}_{QL}\rho\Psi_{dR} + f_U \overline{\Psi}_{QL}\chi\Psi_{UR} + h.c.$$

Electric charge quantization conditions

$$y_{lL} = X_\eta, \qquad y_{eR} = X_\eta - X_\rho, \qquad y_{NR} = X_\eta - X_\chi,$$
$$y_{QL} - y_{uR} = X_\eta, \qquad y_{QL} - y_{dR} = X_\rho, \qquad y_{QL} - y_{UR} = X_\chi. \qquad (4)$$

For the electric charges of leptons and quarks in this case we have

$$Q_\nu = 0, \qquad Q_N = -Q_e \frac{2X_\eta + X_\rho}{X_\eta - X_\rho}, \; Q_e = \frac{gg'}{\sqrt{2}g}\left(X_\eta - X_\rho\right)$$

$$Q_u = Q_e \frac{X_\eta - y_{QL}}{X_\eta - X_\rho}, \quad Q_d = Q_e \frac{X_\rho - y_{QL}}{X_\eta - X_\rho}, \quad Q_U = Q_e \frac{X_\chi - y_{QL}}{X_\eta - X_\rho},$$

From the anomaly cancellation

$$y_{lL} = X_\eta, \quad y_{eR} = 2X_\eta, \quad y_{NR} = X_\chi,$$

$$y_{QL} = -\frac{1}{3}X_\eta, \quad y_{uR} = -\frac{4}{3}X_\eta, \quad y_{dR} = \frac{2}{3}X_\eta, \quad y_{UR} = -\frac{1}{3}X_\eta. \qquad (5)$$

(4) and (5) ⟶ quantization conditions

$$Q_\nu = 0, \quad Q_e = \frac{\sqrt{2}gg'X_\eta}{\left(3 + 2X_\eta^2 t^2\right)^{1/2}}, \quad Q_N = -\frac{1}{2}Q_e,$$

$$Q_u = \frac{2}{3}Q_e, \quad Q_d = -\frac{1}{3}Q_e, \quad Q_U = \frac{1}{6}Q_e.$$

Electric charge quantization in $SU_C(3)xSU(3)_L xU(1)_X xU'(1)$ model

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The structure of the $SU_C(3)xSU(3)_L xU(1)_X xU'(1)$ model

$$\psi_{lL} = \begin{pmatrix} \nu \\ e \\ N \end{pmatrix}_L \sim (1,3,y_{lL}, y'_{lL}),\ \psi_{eR} = e_R \sim (1,1,y_{eR}, y'_{eR}),\ \psi_{NR} = N_R \sim (1,1,y_{NR}, y'_{NR}),$$

$$\psi_{QL} = \begin{pmatrix} u \\ d \\ U \end{pmatrix}_L \sim (3,3,y_{QL}, y'_{QL}),\ \psi_{uR} = u_R \sim (1,1,y_{uR}, y'_{uR}),$$

$$\psi_{dR} = d_R \sim (3,1,y_{dR}, y'_{dR}),\ \psi_{UR} = U_R \sim (3,1,y_{UR}, y'_{UR}),$$

$$<\chi>= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ V \end{pmatrix} \sim \left(1,3,X_\chi, X'_\chi\right),\quad <\rho>= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \upsilon \\ 0 \end{pmatrix} \sim (1,3,X_\rho, X'_\rho),\quad <\eta>= \frac{1}{\sqrt{2}}\begin{pmatrix} u \\ 0 \\ 0 \end{pmatrix} \sim (1,3,X_\eta, X'_\eta).$$

$$A_\mu = \frac{tt'}{\bar{t}} W_{3\mu} + \frac{\sqrt{3}tt'}{\bar{t}} W_{8\mu} \underset{\text{ad}}{+} \frac{\sqrt{6}t}{\bar{t}} B_\mu - \frac{\sqrt{6}t'}{\bar{t}} C_\mu$$

$$\bar{t} = \sqrt{t^2 t'^2 \left(P^2 + 3P_1^2\right) + 6t'^2 P_2^2 + 6t^2 P_3^2}$$

$$P_1 = X_\chi \left(X'_\eta + X'_\rho\right) - X'_\chi \left(X_\eta + X_\rho\right);\ P_2 = X'_\chi + X'_\rho + X'_\eta;\ P_3 = X_\chi + X_\rho + X_\eta$$

$$P = X_\chi \left(X'_\eta - X'_\rho\right) - X'_\chi \left(X_\eta - X_\rho\right) + 2\left(X_\rho X'_\eta - X_\eta X'_\rho\right);$$

X_χ, X_η, X_ρ and $X'_\chi, X'_\eta, X'_\rho$

$\downarrow$ $\qquad\qquad$ $\downarrow$

$U(1)$ $\qquad\qquad$ $U'(1)$

$t = g'/g,\ t' = g''/g$

g, g', g'' – coupling constants.

$$Q_\nu = 0, \quad Q_e = gtt' P/\bar{t}, \quad Q_N = -\frac{3P_1 + P}{2P} Q_e,$$

$$Q_u = \frac{P + P_1 + 2(P_2 y_{QL} - P_3 y'_{QL})}{2P} Q_e, Q_d = -\frac{P - P_1 - 2(P_2 y_{QL} - P_3 y'_{QL})}{2P} Q_e,$$

$$Q_U = -\frac{P_1 - P_2 y_{QL} + P_3 y'_{QL}}{P} Q_e.$$

P invariance of the electromagnetic interaction and gauge invariance of the Yukawa interaction

$$\begin{array}{ll} y_{lL} + y'_{lL} = y_{eR} + y'_{eR} + X_\rho + X'_\rho, & y_{lL} + y'_{lL} = y_{NR} + y'_{NR} + X_\chi + X'_\chi, \\ y_{QL} + y'_{QL} - y_{uR} - y'_{uR} = X_\eta + X'_\eta, & y_{QL} + y'_{QL} - y_{dR} - y'_{dR} = X_\rho + X'_\rho, \\ y_{QL} + y'_{QL} - y_{UR} - y'_{UR} = X_\chi + X'_\chi, & \end{array} \qquad (6)$$

From the anomalies cancellation

$$y_{lL} + y'_{lL} = X_\eta + X'_\eta, \quad y_{eR} + y'_{eR} = 2(X_\eta + X'_\eta), \quad y_{NR} + y'_{NR} = X_\eta + X'_\eta,$$
$$y_{QL} + y'_{QL} = -\frac{1}{3}(X_\eta + X'_\eta), \quad y_{dR} + y'_{dR} = \frac{2}{3}(X_\eta + X'_\eta), \qquad (7)$$
$$y_{uR} + y'_{uR} = -\frac{4}{3}(X_\eta + X'_\eta), \quad y_{UR} + y'_{UR} = -\frac{1}{3}(X_\eta + X'_\eta).$$

(6) and (7) → quantization conditions

$$Q_\nu = 0, \quad Q_N = -\frac{1}{2}Q_e, \quad Q_u = \frac{2}{3}Q_e, \quad Q_d = -\frac{1}{3}Q_e, \quad Q_U = \frac{1}{6}Q_e.$$

Results

- In the models under consideration eigenstate of the photon field depends on the hypercharge of the Higgs fields.

- The electric charge quantization conditions and electric charges of particles depend on the hypercharge of the Higgs fields.

- The presence of the Higgs field is a necessity condition for the quantization of electric charge. Sufficient conditions are the conditions of anomaly cancellation.

- The conditions of electric charge quantization, following from the *P* invariance of the electromagnetic interaction and from the Lagrangians generating fermion masses, are identical.

- In content of electric charge quantization, in the considered models it is possible to manage without the obvious account of the Higgs mechanism of generation of mass, relying instead against P invariance of electromagnetic interaction which is caused by identity of charges left and right fermions.

- In general, in the SM, the electric charge can be quantized and fixed by using only one relation, which follows from the anomaly cancellation conditions, and without fixing the hypercharge of some fields. In this case, introducing the neutrino right-handed component into the model does not give rise to an additional parameter in the conditions of anomaly cancellation, so in the content of electric charge quantization there is no need to enter the Majorana neutrino into the theory.

Conclusions

- In the considered models the conditions of P invariance of the electromagnetic interaction and gauge invariance of the Yukawa interaction (which generates the fermion masses) are identical. This fact leads us to consider Higgs fields as a possible mechanism explaining the parity conservation in electromagnetic interactions.

- The dependence of the quantization conditions and electric charges of particles from the hypercharge of the Higgs fields, the identity of electric charge quantization conditions, following from Lagrangians generating particle masses and from the P invariance of the electromagnetic interaction and the fact of the fixing of fermionic field hypercharges by the Higgs fields **can be interpreted as new properties of Higgs fields**.

ANALOGY

$$m_f = F(\upsilon)$$

$$Q_f = f(H_i(hyperchagr \quad es)) \quad \rightarrow ???$$

Thank you for your attention