Contribution from two CP-odd γZZ couplings to fermion electric dipole moment

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Recibido el 9 de agosto de 1994; aceptado el 30 de enero de 1995

ABSTRACT. The contribution from two CP-odd γZZ couplings to the fermion electric dipole moment (edm) is calculated. The present experimental values for the electron and neutron edm give values for these couplings bigger than those expected from dimensional analysis.

RESUMEN. Se calcula la contribución de dos acoplamientos γZZ que violan CP al momento dipolar eléctrico (mde) de fermiones. Los valores experimentales del mde para el electrón y el neutrón dan valores, para esos acoplamientos, mucho mayores que los esperados por análisis dimensional.

PACS: 14.80.E; 12.50.F

Ever since the discovery of the Z boson a systematic experimental study of its decays is being performed at the CERN, etc. machines. Up to now the whole of the available data confirm, to a high degree, the predictions of the standard model of electroweak interactions (SM). However, an aspect that is to wait for some time is the electromagnetic properties of this neutral gauge boson, *i.e.*, the γZZ couplings. At the tree level, there is no γZZ coupling predicted in SM. At one loop level, it has been proved [1] that fermion loops do not induce any electromagnetic moment when the three bosons are on-mass shell (a consequence of Bose symmetry, and current conservation). Only when one of the Z's is off-shell, an apparent electric dipole transition moment (a nonstatic parity violating coupling) arises. One can convince oneself that W boson loops give no place to multipole moments too (here again Bose symmetry and current conservation yield the null result). Perhaps a two loop calculation can give no null multipole moments. Parallel to this, some authors have considered the possibility of γZZ coupling beyond SM, which can come forth if the Z boson is a composite particle. Assuming Lorentz covariance, electromagnetic gauge invariance, and Bose symmetry one can construct a γZZ vertex function, given by [2]

$$V^{\alpha\beta\mu}_{Z\gamma Z}(q_1,q_2,p) = \frac{p^2-q_1^2}{M_Z^2}\left[(h_1(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2}{M_Z^2}p^\alpha(p\cdot q_2\, g^{\mu\beta} - q_2^\mu p^\beta)\right.$$
$$\left. + h_3\epsilon^{\mu\alpha\beta\rho}q_{2_\rho} + \frac{h_4}{M_Z^2}p^\alpha e^{\mu\beta\rho\sigma}p_\rho q_{2\sigma}\right], \tag{1}$$

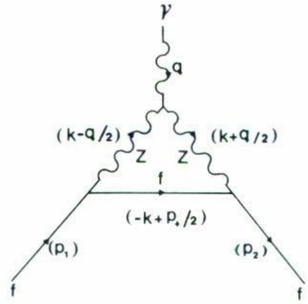

FIGURE 1. The γZZ anomalous coupling contribution to the fermion edm.

where, as indicated, $q_{1\alpha}$, $q_{2\beta}$ and p_μ are the 4–momenta of the Z, γ and Z respectively. Note that when both Z bosons are on-shell, the vertex function vanishes. All of the h_i form factors are C-odd. Then h_3 and h_4 are CP-even, while h_1 and h_2 are CP-odd. The four h_i can be restricted by some physical observable. For instance, h_3 and h_4 could contribute to the muon anomalous magnetic moment, however it has been shown [3] that none of them contribute to $(g-2)_\mu$.

The other two, h_1 and h_2, can contribute to fermion electric dipole moment (edm). The result of this calculation is reported in this paper. Here I have considered the vertex function (1) with one of the Z bosons on-shell, and assumed the SM coupling for fermion–ZZ.

The contribution to the fermion edm is depicted in Fig. 1, and the corresponding amplitude is given by

$$M = (-ie) g_Z^2 \epsilon_\mu(q)\, M^\mu, \tag{2}$$

where

$$M^\mu = \int \frac{d^4k}{(2\pi)^4} \bar{u}(p_2)\, \gamma^{\beta'}(a+b\gamma_5) i S_{\mathrm{F}}\left(-k+\frac{p_+}{2}\right) \gamma^{\alpha'}(a+b\gamma_5)$$
$$\times\, iD_{\beta\beta'}\left(k+\frac{q}{2}\right) iD_{\alpha\alpha'}\left(k-\frac{q}{2}\right) V^{\alpha\mu\beta}_{Z_\gamma Z}\left(k-\frac{q}{2},\, q,\, k+\frac{q}{2}\right) u(p_1), \tag{3}$$

and $S_{\mathrm{F}}(-k+p_+/2)$, $D_{\alpha\alpha'}(k \pm \frac{q}{2})$ are the propagators of the fermion and Z bosons in the loop, respectively. $u(p)$ is fermion wave function, and the fermion–ZZ coupling has been written in terms of the parameters $a = g^{\mathrm{f}}_{\mathrm{R}} + g^{\mathrm{f}}_{\mathrm{L}}$, and $b = g^{\mathrm{f}}_{\mathrm{R}} - g^{\mathrm{f}}_{\mathrm{L}}$, with $g^{\mathrm{f}}_{\mathrm{R,L}} = T^{\mathrm{f}}_{3\,\mathrm{R,L}} - Q_f \sin^2\theta_{\mathrm{W}}$, $T^{\mathrm{f}}_{3\,\mathrm{R,L}}$ being the weak isospin third component of the fermion. The vertex function $V_{Z_\gamma Z}$ is explicitly given by

$$V^{\alpha\mu\beta}_{Z_\gamma Z}\left(k-\frac{q}{2},\, q,\, k+\frac{q}{2}\right) = \frac{k^2 + k\cdot q - M_Z^2}{M_Z^2}\left[h_1(q^\beta g^{\mu\alpha} - q^\alpha g^{\mu\beta}) + \frac{h_2}{M_Z^2}\left(k+\frac{q}{2}\right)^\alpha (k\cdot q\, g^{\mu\beta} - q^\beta k^\mu)\right]. \tag{4}$$

The evaluation of Eq. (3) is quite standard, with the result, for the terms contributing to edm,

$$M^\mu = \frac{mab}{M_Z^2}\left[2ih_1\int_0^1 dx\,(1-x)(J_0+J_2/M_Z^2) + \frac{ih_2}{M_Z^2}\int_0^1 dx\,\big(2(M_Z^2-m^2x^2)m^2\right.$$
$$\left.\times\, x^3(1-x)J_0 - \big((1-4x)M_Z^2+\tfrac{1}{2}(2-3x-3x^2)x^2m^2\big)J_2+(1-6x)J_4\big)\right]$$
$$\times\, \bar u(p_2)\, i\sigma^{\mu\nu}q_\nu\gamma_5\, u(p_1). \tag{5}$$

The functions J_n are defined by

$$J_n = \int\frac{d^4k}{(2\pi)^4}\,\frac{k^n}{(k^2-f(x,y))^2};\qquad f(x,y)=m^2x+M_Z^2(1-x),$$

m being fermion mass.

To regularize the divergent integrals in Eq. (5) a cutoff Λ is introduced. As has been pointed out by Burgess and London [4] the contributions Λ^2 and Λ^4 can be ignored, since they are to be cancelled by contributions generated by some high energy part of the theory. Then, only the logarithmic dependence on Λ is significative. (An equivalent procedure is to modify the Z–boson propagator through a form factor, which renders finite the divergent integral up to the leading logarithmic contribution for $\Lambda^2 \gg M_Z^2$). With this in mind, the fermion edm from Eq. (5) turn out to be

$$d_{\mathrm{f}} = e\,\frac{\alpha}{32\pi}\,\frac{mab}{M_Z^2}\,\frac{1}{\sin^2\theta_{\mathrm{W}}\cos^2\theta_{\mathrm{W}}}\left[h_1\left(2-\frac{1}{3}\ln\frac{\Lambda^2}{M_Z^2}\right)-\frac{1}{48}h_2\left(1-7\ln\frac{\Lambda^2}{M_Z^2}\right)\right]. \tag{6}$$

For an electron $a=-1+4\sin^2\theta_{\mathrm{W}}$ and $b=-1$. Using $\Lambda\sim 1$ TeV, Eq. (6) gives

$$|d_{\mathrm{e}}| = |2.54\times h_1 + 4.27\times h_2|\times 10^{-26}\ (\mathrm{ecm}). \tag{7}$$

The experimental value [5] of d_{e}

$$d_{\mathrm{e}} = (-0.3\pm 0.8)\times 10^{-26}\ (\mathrm{ecm}).$$

imposes the constraints

$$|h_1| = 0.34 \quad \text{if} \quad h_2 = 0$$

and

$$|h_2| = 0.20, \quad \text{if} \quad h_1 = 0. \tag{8}$$

For muon the experimental result gives a poorer constraint on h_1 and h_2.

To evaluate neutron edm from Eq. (6) the method in Ref. [6] is followed. This gives, at the quark level

$$d_{\rm q} = 3.3. \times 10^{-22} \frac{m_{\rm n} ab}{(1\ \text{GeV})} (0.4\, h_1 + 0.6\, h_2)\ (\text{ecm}), \tag{9}$$

where $m_{\rm n}$ is neutron mass. Then, using the SU(6) result $d_{\rm n} = \frac{4}{3} d_{\rm a} - \frac{1}{3} d_{\rm n}$, it is obtained

$$|d_{\rm n}| = 2.56 \times 10^{-22} |0.4\, h_1 + 0.6\, h_2|\ (\text{ecm}),$$

and the experimental bound [5] $|d_{\rm n}| < 11 \times 10^{-26}$ (ecm) imposes the constraints

$$|h_1| < 1.4 \times 10^{-3}, \quad \text{if} \quad h_2 = 0,$$

and

$$|h_2| < 6 \times 10^{-4}, \quad \text{if} \quad h_1 = 0 \tag{10}$$

which are more stringent bounds.

In getting the above results we have assumed no cancellation among the h_1 and h_2 contribution. In a real situation both contribution can be present, simultaneously, and then they could cancel each other if h_1 and h_2 turn out to be of the same order of magnitude. This could be the case for the constrains in Eq. (8), which are not good. Equation (10), a more realistic h_1 and h_2 constrains, tell us that there is a difference of one order of magnitude between them.

That Eq. (10) gives more realistic bounds can be seen as follows. Since h_1/m_Z^2 is the coefficient of a dimension–6 operator it is expected to be of order 10^{-4}, for $\Lambda = 1$ TeV. Similarly, since h_2/M_Z^2 is the coefficient of a dimension–8 operator, h_2 has to be of order 10^{-6}. In the light of this, the bounds (8) and (10) are bigger than the values expected from dimensional analysis. Perhaps good contraints for h_1 and h_2, consistent with dimensional analysis, can be extracted from unitarity arguments.

ACKNOWLEDGMENTS

The author wishes to thank Roberto Martínez for interesting discussions on the subject. He also acknowledges partial support from Comisión de Operación y Fomento de las Actividades Académicas del IPN-México.

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