AC

STATE RESEARCH CENTER OF RUSSIA
Institute of Theoretical
and Experimental Physics

13-97

A. Bramon, E. Shabalin

A RELATION BETWEEN THE ELECTRIC DIPOLE MOMENTS OF THE NEUTRON AND THE ELECTRON IN TWO-HIGGS-DOUBLET MODELS

Moscow 1997

UDK 530.1 M-16

A RELATION BETWEEN THE ELECTRIC DIPOLE MOMENTS OF THE NEUTRON AND THE ELECTRON IN TWO-HIGGS-DOUBLET MODELS: Preprint ITEP 13-97/

A.Bramon[1], E.Shabalin - M., 1997 - 8p.

We study a possible relation between the neutron and electron electric dipole moments (EDM) in the framework of the Two-Higgs-Doublet Model which has been proposed to explain why the t-quark is much heavier than all other known quarks and leptons. If there is no especial fine-tuning between the CP-violating parameters of the model, the experimental limit on the neutron EDM, $d_n^{EXP} \leq 1.1 \cdot 10^{-25}$ e·cm, implies $d_e \leq 2 \cdot 10^{-28}$ e·cm for the electron EDM.

Fig. - 3, ref. - 11 name.

[1]Universitat Autònoma de Barcelona, 08139 Bellaterra (Barcelona), Spain.

1 Introduction

It is commonly accepted [1]-[5] that in electroweak interaction theories, where mixing between the scalar and pseudoscalar components of two Higgs doublets takes place, the electric dipole moments (EDM) of the electron, d_e, and the neutron, d_n, could reach levels close to their respective experimental upper limits. In the particular case of the neutron EDM, such a conclusion follows from considering the two-loop diagram in Fig.1, which produces the so-called quark chromoelectric dipole moment. In turn, the latter generates a neutron EDM dominated, at least in principle, by the t-quark contribution in the upper loop of Fig. 1 which is of order (in e·cm)

$$d_n \sim d_n^{t-loop} \sim 6 \cdot 10^{-25}\{f(t)(ImZ_0 - Im\tilde{Z}_0) + g(t)(ImZ_0 + Im\tilde{Z}_0)\}, \quad (1)$$

as recently discussed by Khriplovich [5]. In (1), $f(t)$ and $g(t)$ are the functions determined in Refs.[1, 3] with $t \equiv m_t^2/m_H^2$ being the ratio between the squared masses of the t-quark and the lightest Higgs boson. These two functions satisfy the relation $f(t) = (1-2t)g(t)+2t+tlnt$ and are both of order one at $t \sim 1$ or, more precisely, $f(1) = 0.828$ and $g(1) = 1.172$. Finally, ImZ_0 and $Im\tilde{Z}_0$ are the dimensionless CP-violating parameters of the model. In such a two Higgs doublet model, there are two different vacuum expectation values: $v_1 \equiv \langle\Phi_1^0\rangle_0$ and $v_2 \equiv \langle\Phi_2^0\rangle_0$. This gives the possibility to adjust the model in such a way that it naturally explains why the t-quark is much heavier than the other elementary fermions. This simply occurs if the top quark becomes the only fermion getting its mass from v_2, which is then supposed to be much larger than v_1. A model of this kind has been proposed by Das and Kao (DK) [6], who explicitly assume that $\mid v_2 \mid / \mid v_1 \mid \equiv \tan\beta \sim m_t/m_b \sim 40$. If $\tan\beta$ is really so large, some new, and considerable, contributions to the neutron EDM appear in addition to d_n^{t-loop} already given in Eq.(1). A first one, d_n^{b-loop}, comes from the diagram in Fig. 1 with the t-quark replaced by a b-quark in the upper loop. A second, $d_n^{Fig\ 2}$, comes from the diagram in Fig. 2, where the scalar, CP-even bosons, $H_{1,2}$, and the pseudoscalar, CP-odd one, A, are coupled "directly" to the nucleon. The quotation-marks mean that such a coupling arises at two-loop level with intermediate heavy quarks and gluons [7, 8].

The present paper is devoted to estimating these additional contributions to the neutron EDM in the framework of the DK model [6]. Comparing our results with the available experimental limit on the neutron EDM we shall find considerably stronger restrictions on the parameters ImZ_0 and $Im\bar{Z}_0$ than those given by the unitarity constraints [9] at large $\tan\beta$

$$\begin{array}{c} \mid ImZ_0 + Im\bar{Z}_0 \mid < 1/2 \\ \mid ImZ_0 - Im\bar{Z}_0 \mid < 1/2 \mid \tan\beta \mid \ . \end{array} \tag{2}$$

In turn, this will mean that the expected value of the electron EDM, d_e, will be considerably smaller than the available experimental upper limits.

2 Model and notations

The initial doublets Φ_1 and Φ_2 can be transformed to the gauge eigenstates $\mathbf{\Phi_1}$ and $\mathbf{\Phi_2}$ through

$$\Phi_1 = \cos\beta\mathbf{\Phi_1} - \sin\beta\mathbf{\Phi_2}\ , \Phi_2 = (\sin\beta\mathbf{\Phi_1} + \cos\beta\mathbf{\Phi_2})e^{i\theta}\ , \tag{3}$$

where

$$\mathbf{\Phi_1} = \begin{pmatrix} G^+ \\ \frac{v+H_1+iG^0}{\sqrt{2}} \end{pmatrix}, \mathbf{\Phi_2} = \begin{pmatrix} H^+ \\ \frac{H_2+iA}{\sqrt{2}} \end{pmatrix} \tag{4}$$

with $v = (v_1^2 + v_2^2)^{1/2} = (\sqrt{2}G_F)^{-1/2}$ and G^+, G^0 being the Goldstone states absorbed by the massive W^+ and Z bosons.

The quark-Higgs interaction is described by the following Yukawa terms of the DK-lagrangian [6]

$$\begin{aligned} \mathcal{L}_Y &= -\sum_{d=d,s,b} m_d\bar{d}d - \sum_{u=u,c,t} m_u\bar{u}u \\ &- \sum_{d=d,s,b}\frac{m_d}{v}\bar{d}d(H_1 - \tan\beta H_2) - i\sum_{d=d,s,b}\frac{m_d}{v}\bar{d}\gamma_5 d(G^0 - \tan\beta A) \\ &- \left(\frac{m_u}{v}\bar{u}u + \frac{m_c}{v}\bar{c}c\right)(H_1 - \tan\beta H_2) - \frac{m_t}{v}\bar{t}t(H_1 + \cot\beta H_2) \\ &+ i\left(\frac{m_u}{v}\bar{u}\gamma_5 u + \frac{m_c}{v}\bar{c}\gamma_5 c\right)(G^0 - \tan\beta A) + i\frac{m_t}{v}\bar{t}\gamma_5 t(G^0 + \cot\beta A)... \end{aligned} \tag{5}$$

where the dots refer to further irrelevant terms.

CP violation proceeds through the mixing between the scalar and pseudoscalar neutral Higgs bosons, which can be parametrized in the form [9]:

$$\begin{aligned} \langle H_1 A\rangle_q &= \frac{1}{2}\sin 2\beta\sum_n \frac{ImZ_{0n}}{q^2 - m_n^2}\ , \\ \langle H_2 A\rangle_q &= \frac{1}{2}\sum_n \frac{\cos 2\beta ImZ_{0n} - Im\bar{Z}_{0n}}{q^2 - m_n^2} \end{aligned} \tag{6}$$

As a rule, it is assumed that the above sums are dominated by the lightest Higgs boson with mass $m_0 = m_H$. Then, the index n can be dropped in eqs.(6).

3 b-quark contribution to the neutron EDM

If the t-quark loop in Fig.1 is replaced by a b-quark one, the expression in the curly bracket of eq.(1) must be changed to

$$\tan^2\beta[f(b) + g(b)](ImZ_0 + Im\bar{Z}_0), \tag{7}$$

where b now stands for the small ratio $b \equiv m_b^2/m_H^2$. The functions $f(b)$ and $g(b)$, at these small values of b, can be approximated by $f(b) \sim g(b) \sim (b/2)(lnb)^2$ and they turn out to be some 50 times smaller than $f(t)$ and $g(t)$, at $t \sim 1$ as in eq.(1). In spite of this, the value for d_n^{b-loop} turns out to be considerably larger than d_n^{t-loop} for $\tan\beta > 10$, provided that

$$\mid ImZ_0 + Im\bar{Z}_0 \mid / \mid ImZ_0 - Im\bar{Z}_0 \mid \geq 1$$

A little later we will come back to a more detailed comparison of the various contributions to the neutron EDM. But before that, let us consider one further contribution.

4 Contribution of the diagram in Fig. 2

Assuming that the t- and b-quarks are really the only heavy ones, the diagram in Fig. 2 gives a further contribution through the effective vertex

$$\begin{array}{l} e\mu_n g_N^A g_N^H \epsilon_\mu^\lambda k_\nu \bar{u}_N(p_2)\Gamma_{\mu\nu}u_N(p_1)\cdot \\ \frac{1}{2}\{(1+\cot^2\beta)(ImZ_0 - Im\bar{Z}_0) + (1+\tan^2\beta)(ImZ_0 + Im\bar{Z}_0)\}, \end{array} \tag{8}$$

where μ_n is the anomalous magnetic moment of the neutron and

$$\begin{array}{l} \Gamma_{\mu\nu} = im_{\sigma_0}^2 m_{\eta_0}^2 \int \frac{d^4q}{(2\pi)^4}\cdot \\ \{\gamma_5(\not{q}+\not{p}_2+m)\sigma_{\mu\nu}(\not{q}+\not{p}_1+m) + (\not{q}+\not{p}_2+m)\sigma_{\mu\nu}(\not{q}+\not{p}_1+m)\gamma_5\}\cdot \\ [(q^2-m_H^2)(q^2+2qp_1)(q^2+2qp_2)(q^2-m_{\sigma_0}^2)(q^2-m_{\eta_0}^2)]^{-1} \end{array} \tag{9}$$

In this formula, σ_0 and η_0 are the SU(3)-singlet states of the scalar and pseudoscalar meson nonets. Their masses characterise the two form factors introduced in Eq.(9) for the vertices $AN\bar{N}$ and $HN\bar{N}$ to account for the fact that A and H interact with the nucleon through the chains of transitions $A \longrightarrow \bar{h}i\gamma_5 h \longrightarrow G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} \longrightarrow \eta_0$ and $H \longrightarrow \bar{h}h \longrightarrow G^2_{\mu\nu} \longrightarrow \sigma_0$. Since the σ_0 and η_0 masses are close to m_N, we simplify the computation of the integral in (9) setting $m_{\sigma_0} = m_{\eta_0} = m_N$. One then obtains

$$\Gamma_{\mu\nu} = \gamma_5\sigma_{\mu\nu}\frac{m_N^2}{16\pi^2 m_H^2}\int_0^1 \frac{2y^2(1-y)(2-y)}{(1-y+y^2)^2} = \frac{1}{8\pi^2}(2-\frac{\pi}{\sqrt{3}})\frac{m_N^2}{m_H^2}\gamma_5\sigma_{\mu\nu} \quad (10)$$

The constants g_N^A and g_N^H in Eq.(8) correspond to the interactions of A and H with a nucleon-antinucleon pair through a single heavy quark loop with vertices $A\bar{h}i\gamma_5 h$ and $H\bar{h}h$. Both the specific interactions of A and H with t- and b-quarks described by the Lagrangian (5) and the mixing between A and $H_{1,2}$, as given in Eq.(6), are taken into account by the expression in the curly bracket in Eq.(8). From refs.[7] and [8] we take, respectively,

$$g_N^H = (\sqrt{2}G_F)^{1/2} 2m_N/27, \quad (11)$$

$$g_N^A = (\sqrt{2}G_F)^{1/2}(-g_A)\frac{m_N}{3}\frac{g_A^{(0)}}{g_A}, \quad (12)$$

where $(-g_A) \approx 1.25$ and $g_A^{(0)}$ is the isoscalar axial coupling constant. In the quark model one has $g_A^{(0)}/g_A = 3/5$. The final result for the contribution of Fig.2 to d_n is then (in e·cm)

$$\begin{aligned} \mid d_n^{Fig.2} \mid &= 6\cdot 10^{-24}(m_N/m_H)^2 \quad (13) \\ &\{(1+\cot^2\beta)(ImZ_0 - Im\bar{Z}_0) + (1+\tan^2\beta)(ImZ_0 + Im\bar{Z}_0)\} \end{aligned}$$

This formula exhibits a crucial dependence of the $d_n^{Fig.2}$ contribution on m_H, $\tan\beta$ and $(ImZ_0 + Im\bar{Z}_0)$.

As we do not see any reason to assume that the sum of ImZ_0 and $Im\bar{Z}_0$ must be much smaller than their difference, we shall consider the situation when

$$\tan^2\beta \mid ImZ_0 + Im\bar{Z}_0 \mid / \mid ImZ_0 - Im\bar{Z}_0 \mid \gg 1 \quad (14)$$

as the natural one for $\tan\beta \gg 1$. In this case the values of $d_n^{Fig.2}$ can exceed the contribution from d_n^{t-loop} given by Eq.(1), if $\tan\beta \approx m_t/m_b \approx 40$ and m_H is near the generic lower limit m_H=66.7 GeV [11] found for this kind of Two-Higgs-Doublet models. But in this case, the dominant contribution comes from the b-quark upper loop in Fig.1 giving (in e·cm)

$$d_n \sim d_n^{b-loop} = 6\cdot 10^{-25}[f(b)+g(b)]\tan^2\beta(ImZ_0 + Im\bar{Z}_0) \quad (15)$$

where $[f(b)+g(b)]_{m_H=70GeV} \approx 0.12$. For larger values of m_H, the $d_n^{Fig.2}$ contribution becomes negligible even when compared to d_n^{t-loop}.

5 Relation between d_n and d_e

It follows from Eq.(15) that the available experimental limit for the neutron EDM, $d_n^{EXP} \leq 1.1 \cdot 10^{-25}$ e·cm, imposes a bound on $(ImZ_0 + Im\bar{Z}_0)$ which is more restrictive than that coming from Eq.(2). Namely, for m_H =70 GeV one obtains $(ImZ_0 + Im\bar{Z}_0) \leq 1/tan^2\beta$. But the most interesting feature of the model under consideration is the possibility of relating the values of the neutron and electron EDM's, d_n and d_e. For $\tan\beta \gg 1$, d_e is dominated by the contributions of the diagram in Fig.3 with a b-quark and a τ-lepton circulating in the upper loop [6]

$$
\begin{aligned}
d_e \;\sim\; d_e^{b,\tau-loops} &= -\frac{m_e \alpha \sqrt{2} G_F}{(4\pi)^3} \tan^2\beta \\
&\{\frac{4}{3}[f(b) + g(b)] + 4[f(\tau) + g(\tau)]\}(ImZ_0 + Im\bar{Z}_0) \qquad (16)
\end{aligned}
$$

where $\tau \equiv m_\tau^2/m_H^2$. From Eqs.(15,16) and for $\tan\beta \gg 1$ one finally finds

$$
\mid d_e/d_n \mid \sim 2 \cdot 10^{-3} \qquad (17)
$$

or $d_e \leq 2 \cdot 10^{-28}$ e·cm, if $d_n^{EXP} \leq 1.1 \cdot 10^{-25}$ e·cm is used.

At present, the corresponding experimental upper limit is $d_e^{EXP} = (1.8 \pm 1.6) \cdot 10^{-27}$ e·cm [11].

Acknowledgements

One of the authors (E. Sh.) is grateful for the hospitality of the Grup de Física Teòrica, UAB, where this work was done. Thanks are also due to J. Solà for discussions, to M. Lavelle for reading the manuscript and to the grants CICYT-AEN95-815 and INTAS-94-3986 for financial support.

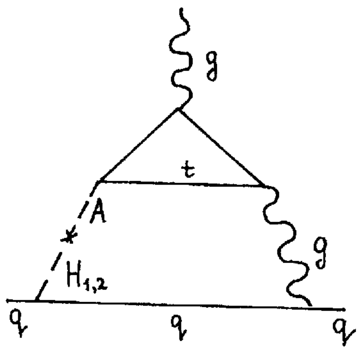

Fig. 1 t-quark loop contribution to the chromoelectric dipole moment of a q-quark.

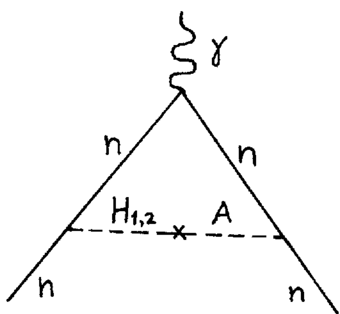

Fig. 2 A further contribution to the neutron EDM.

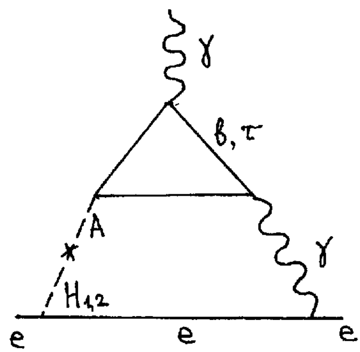

Fig. 3 b-quark contribution to the electron EDM.

References

[1] S.Bar and A.Zee, Nucl.Phys. **65** (1990) 21; **ibid 65** (1990) 2920(E).

[2] J.F.Gunion and D.Wyler, Phys.Lett. **B248** (1990) 170.

[3] D.Chang, W.-Y.Keung and T.C.Yuan, Phys.Lett. **B251** (1990) 608.

[4] X.-G.He and B.H.J.McKellar, Phys.Lett.**B254** (1991) 231.

[5] I.B.Khriplovich, Phys.Lett. **B382** (1996) 145. A crucial point in this analysis is the introduction of the strange quark content in the neutron. This leads to values for d_n above the ones predicted in refs. [2, 3].

[6] A.Das and C. Kao, Phys.Lett. **B372** (1996) 106.

[7] M.A.Shifman, A.I.Vainshtein and V.I.Zakharov, Phys.Lett. **B78** (1978) 443.

[8] A.A.Anselm *et al.*, Phys.Lett. **B152** (1985) 116.

[9] S. Weinberg, Phys. Rev. **D42** (1990) 860.

[10] The L3 Collaboration, preprint CERN-PPE/96-95, July 1996.

[11] E.D.Commins *et al.*, Phys.Rev. **D50** (1994) 2960.

А.Брамон,Е.Шабалин

Соотношение между электрическими дипольными моментами нейтрона и электрона в модели с двумя Хиггсовскими дублетами.

Подписано к печати 05.03.97 Формат 60x90 I/I6 Офсетн.печ.
Усл.-печ.л.0,5. Уч.-изд.л.0,3. Тираж 90 экз. Заказ I3.
Индекс 3649

Отпечатано в ИТЭФ, II7259, Москва, Б.Черемушкинская, 25

Индекс 3649

Препринт 13 -97, ИТЭФ, 1997