Ref. TH.3755-CERN

HORIZONTAL INTERACTIONS AS THE SOURCE OF CP VIOLATION

R. Decker
Institut für Physik
Universität Dortmund

J.-M. Gérard* and G. Zoupanos
CERN - Geneva

ABSTRACT

Assuming that horizontal interactions are the main source of CP violation, we find that their typical effective coupling constant is $G_H \sim 10^{-16} \text{ GeV}^{-2}$. Moreover, this source is then of superweak type and the electric dipole moment of the neutron has to be larger than 10^{-28} e.cm.

*) Chercheur IISN, on leave of absence from Institut de Physique Théorique, Université Catholique de Louvain.

Based on a $SU(2)_L \times U(1)$ gauge theory, our present understanding of the electroweak interactions has been spectacularly confirmed by the recent discovery of $W^\pm$ and Z gauge bosons at CERN¹⁾. However, there remain serious open questions concerning the fermion masses as well as the origin of CP violation.

In this standard model, including n generations of quarks, the latter can always be implemented (by hand) if we assume complex Yukawa couplings such that $\frac{1}{2}(n-1)(n-2)$ CP violating Kobayashi-Maskawa²⁾ (KM) phases appear in the charged left-handed weak current. The introduction of additional scalar weak doublets can also accommodate the $SU(2)_L \times U(1)$ gauge theory with a (spontaneously broken) CP violation carried by Higgs fields: this is the Lee-Weinberg³⁾ (LW) mechanism.

Therefore CP violating processes like $K^0 - \bar{K}^0$ (ϵ), $K \rightarrow \pi\pi$ (ϵ') and the neutron electric dipole moment (d_n) provide us with crucial tests for these two possible mechanisms. The present experimental information is indeed the following:

$$|\epsilon_{\text{exp}}| \sim 2 \cdot 10^{-3} \quad (1.a)$$

$$|(\epsilon'_\epsilon)_{\text{exp}}| = 0.003 \pm 0.015 \quad (1.b)$$

$$d_n < 4 \cdot 10^{-25} \text{ e.cm.} \quad (1.c)$$

while the theoretical predictions are respectively

$$10^{-3} \lesssim |\epsilon'_\epsilon| \lesssim 10^{-2} \quad (\text{KM})^4) \quad (2.a)$$

$$\gtrsim 10^{-2} \quad (\text{LW})^5) \quad (2.b)$$

$$d_n < 10^{-30} \text{ e.cm.} \quad (\text{KM}) \quad (2.c)$$

$$< 5 \cdot 10^{-26} \text{ e.cm.} \quad (\text{LW})^6) \quad (2.d)$$

for the above-quoted mechanisms.

A refined experiment to measure ϵ' will therefore confirm or exclude these two models. Moreover, the new experimental values for the B meson lifetime⁷⁾ could already rule out the KM source of CP violation if it turns out that the top quark is relatively light (say, $m_t \sim 30 \text{ GeV}$)⁸⁾. It is therefore of some interest to estimate predictions given by other possible sources of CP violation, namely new gauge interactions.

One interesting scenario is provided by a "vertical" embedding of the standard model into a left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)$ theory such that the charged right-handed weak current carries most of the (spontaneously broken) CP violation. A simple analysis of CP violating processes allows then for an estimation of the typical scale associated to the new gauge interaction ($M_{W_R} \sim 10 \text{ TeV}$)^{9),10)} as well as for constraints on ϵ'/ϵ and d_n ⁹⁾.

In this letter, we look for analogous constraints assuming now horizontal gauge interactions to be the main source of CP violation¹¹⁾. These new local symmetries, acting on fermion generations, have indeed been proposed in order to make predictions on the quark and lepton mass spectrum and mixing angles¹²⁾. In this framework, CP conserving flavour changing processes have been carefully studied¹³⁾. In particular, the $K^0 - \bar{K}^0$ mass difference implies the stringent bound for the typical effective horizontal coupling

$$G_H \equiv \frac{g_H^2}{M_H^2} \lesssim 10^{-11} \text{ GeV}^{-2} \quad (3)$$

We show that general considerations on CP violating processes provide us with additional constraints

$$G_H \gtrsim 10^{-16} \text{ GeV}^{-2} \quad (4.a)$$

$$|\epsilon'/\epsilon| \lesssim 10^{-3} \quad (4.b)$$

$$d_n \gtrsim 10^{-28} \text{ e.cm.} \quad (4.c)$$

The plan of this paper is as follows: we first derive the effective operators (and their strength) which we need to compute ϵ and ϵ' . In section II we quote enhancement factors appearing in matrix elements. Section III is devoted to numerical analysis and finally in Section IV, we state our conclusions and discuss some special cases.

I. $\Delta S = 2$ AND $\Delta S = 1$ OPERATORS

In this section, we compute the strength of the $\Delta S = 2$ and $\Delta S = 1$ operators, induced by the non-Abelian* horizontal interactions, in order to estimate the ϵ and ϵ' parameters.

In general, the coupling between the spin $\frac{1}{2}$ particles and the physical gauge bosons is given by

*) Abelian groups cannot account for CP violation since the phases can always be rotated away.

$$ig_H \bar{\Psi}_i^0 \gamma^\mu \left[\left(\frac{1-\gamma_5}{2} \right) (\lambda_a^L)^{ij} + \left(\frac{1+\gamma_5}{2} \right) (\lambda_a^R)^{ij} \right] \Psi_j^0 H_\mu^a \quad (5)$$

where $\lambda_a^{L(R)}$ are the Hermitean generators of the horizontal group associated to the left-handed (right-handed) fermions in the weak interaction basis. In the physical basis for these fermionic fields, we therefore obtain:

$$ig_H \bar{\Psi}_i \gamma^\mu \left[\left(\frac{1-\gamma_5}{2} \right) (U^L \lambda_a^L U^{L\dagger})^{ij} + \left(\frac{1+\gamma_5}{2} \right) (U^R \lambda_a^R U^{R\dagger})^{ij} \right] \Psi_j H_\mu^a \quad (6)$$

$$\equiv ig_H \left\{ (U^L \lambda_a^L U^{L\dagger})^{ij} L_{ij}^\mu + (U^R \lambda_a^R U^{R\dagger})^{ij} R_{ij}^\mu \right\} H_\mu^a$$

where $U^{L,R}$ are the unitary matrices used to diagonalize the fermion mass matrices.

The effective $\Delta S = 2$ Hamiltonian contains then two distinct pieces:

$$H^{\Delta S=2} = H_W^{\Delta S=2} + H_H^{\Delta S=2} \quad (7)$$

where

$$H_W^{\Delta S=2} \simeq - \frac{G_F^2}{4\pi^2} m_c^2 s^2 \partial_\mu c^i \partial_\mu c^j L_{sd}^\mu L_r^{\bar{d}s} \quad (8)$$

is the usual weak interaction contribution¹⁴⁾.

The dominant contribution of the horizontal gauge bosons (Fig. 1) is given by

$$H_H^{\Delta S=2} = \sum_a G_H^a \left\{ (U^L \lambda_a^L U^{L\dagger})^{sd} (U^L \lambda_a^L U^{L\dagger})_{ds} L_{sd}^\mu L_r^{\bar{d}s} + (U^R \lambda_a^R U^{R\dagger})^{sd} (U^L \lambda_a^L U^{L\dagger})_{ds} R_{sd}^\mu L_r^{\bar{d}s} + L \leftrightarrow R \right\} \quad (9)$$

The contribution to the ϵ parameter of the horizontal interactions is then given by

$$\epsilon_H = \frac{\text{Im} \langle K^0 | H_H^{\Delta S=2} | \bar{K}^0 \rangle}{\text{Re} \langle K^0 | H_H^{\Delta S=2} | \bar{K}^0 \rangle} \quad (10)$$

in the basis where the $\Delta I = 1/2$ amplitude for the K-decay

$$A_0 \equiv \langle 2\pi; I=0 | H^{\Delta S=1} | K \rangle \quad (11)$$

is made real. However, the ($\Delta I = 1/2, 3/2$) dominant contribution of the horizontal interactions to the $\Delta S = 1$ Hamiltonian (Fig. 2) is given by

$$H_H^{\Delta S=1} = - \sum_a G_{Ha} \left\{ (U^L \lambda_a^L U^{L\dagger})^{sd} (U^L \lambda_a^L U^{L\dagger})^{kk} L_{sd}^{\mu} L_{\mu}^{kk} + (U^R \lambda_a^R U^{R\dagger})^{sd} (U^L \lambda_a^L U^{L\dagger})^{kk} R_{sd}^{\mu} L_{\mu}^{kk} + L \leftrightarrow R \right\} \quad (12)$$

such that we obtain a complex amplitude:

$$A_0 = |A_0| e^{i\zeta_H} \quad (13)$$

Like in the KM framework⁴⁾, this amplitude can be made real through a suitable phase redefinition

$$\begin{aligned} K^0 &\rightarrow e^{-i\zeta_H} K^0 \\ \bar{K}^0 &\rightarrow e^{i\zeta_H} \bar{K}^0 \end{aligned} \quad (14)$$

In the limit where the horizontal gauge interactions are the main source of CP violation, we obtain, assuming ζ_H small,

$$\varepsilon \approx \frac{1}{2\sqrt{2}} (\varepsilon_H + 2\zeta_H) \quad (15a)$$

$$\varepsilon' \approx \frac{1}{\sqrt{2}} \frac{\text{Im} A_2 - \zeta_H \text{Re} A_2}{|A_0|} \quad (15b)$$

where A_2 denotes the $\Delta I = 3/2$ amplitude for the K-decay.

II. ENHANCEMENT FACTORS FOR HADRONIC MATRIX ELEMENTS

In our numerical analysis, we will use the vacuum insertion method to estimate matrix elements.

For the $\Delta S = 2$ operator we know that¹⁵⁾

$$\begin{aligned} \langle K^0 | L^\mu L_\mu | \bar{K}^0 \rangle &= \langle K^0 | R^\mu R_\mu | \bar{K}^0 \rangle \approx \frac{1}{3} f_K^2 m_K \\ \langle K^0 | L^\mu R_\mu | \bar{K}^0 \rangle &= \langle K^0 | R^\mu L_\mu | \bar{K}^0 \rangle \approx 7.7 \langle K^0 | L^\mu L_\mu | \bar{K}^0 \rangle \end{aligned} \quad (16)$$

The effects of LR to LL operators in $K \rightarrow \pi\pi$ have also been estimated by Shifman et al¹⁶⁾. Using PCAC to reduce one pion, they compared the matrix elements:

$$\frac{\langle \pi | L^\mu R_\mu | K \rangle}{\langle \pi | L^\mu L_\mu | K \rangle} \sim 10 \quad (17)$$

We conclude that an enhancement of LR matrix elements over LL or RR is always observed by using PCAC to relate the axial vector to the pseudoscalar current. These enhancement factors are, however, irrelevant in our numerical discussion

if the horizontal interactions only act on left-handed (or right-handed) fermions. [See, e.g., Joshipura and Montvay, Ref. 11).]

III. NUMERICAL RESULTS

We first have to justify the smallness of the ξ_H phase appearing in (13):

$$\xi_H = \frac{\text{Im} A_0^H}{\text{Re} A_0} \sim \frac{G_H}{G_F} \frac{\langle \pi | L^H R_f | K \rangle}{\langle \pi | L^H L_f | K \rangle} \sin \sigma \quad (18)$$

with σ , some angle describing our ignorance about mixing angles and phases. Using the upper bound (3) as well as the enhancement factor in (17), we obtain

$$\xi_H \lesssim 10^{-5} \quad (19)$$

such that we expect

$$\varepsilon' \sim \frac{\text{Re} A_2}{|A_0|} \xi_H \lesssim 10^{-6} \quad (20)$$

where the phenomenological enhancement of the $\Delta I = 1/2$ amplitude with respect to the $\Delta I = 3/2$ amplitude has been used.

Moreover, from Eqs. (8), (10) and (15a) we find

$$\varepsilon \sim \frac{1}{2\sqrt{2}} \quad \varepsilon_H \sim \frac{4\pi^2}{2\sqrt{2}} \frac{G_H}{G_F^2 m_c^2 s^2 \theta_c c^2 \theta_c} \frac{\langle K^0 | L R | \bar{K}^0 \rangle}{\langle K^0 | L^H L_f | \bar{K}^0 \rangle} \sin \sigma' \sim 2 \cdot 10^{-3} \quad (21)$$

giving rise to a lower limit for the effective coupling

$$G_H \gtrsim 10^{-16} \text{ GeV}^{-2} \quad (22)$$

which is saturated for a maximal CP violation [$\sin \sigma' = O(1)$].

This severe limit on G_H provides us with a lower bound for the neutron electric dipole moment. For an elementary fermion Ψ_i , the one-loop contribution (see Fig. 3a) is given by

$$d_i \simeq \frac{1}{2\pi^2} \sum_a G_{Ha} \sum_{k=1}^m m_k \text{Im} (U^L \lambda_a^L U^{L\dagger})_{ik} (U^R \lambda_a^R U^{R\dagger})_{ik}^* \quad (23)$$

Assuming that the contributions coming from H-exchange at the bound state level (Fig. 3b) are of the same order of magnitude, we obtain

$$d_m \sim \frac{1}{2\pi^2} G_H m \sin \sigma'' \gtrsim 10^{-28} \text{ e.cm.} \quad (24)$$

for quarks lighter than 100 GeV.

IV. CONCLUSION

We have computed the CP violation parameters ϵ and ϵ' as well as the electric dipole moment of the neutron (d_n) in the presence of horizontal gauge interactions. If these new interactions provide us with the main source of CP violation, the associated vector bosons have a typical mass in the range of $3 \cdot 10^5$ to 10^8 GeV and we get $\epsilon' < 10^{-6}$ and $d_n > 10^{-28}$ e.cm. The experimental bounds on the flavour changing neutral currents provide indeed a lower bound for the horizontal breaking scale¹³⁾, while the assumption that horizontal interactions are the main source of the CP violation gives a range for its value. In particular, we see that local horizontal symmetries, like global ones¹⁷⁾, need a new very large scale.

An improvement on the experimental bound for ϵ'/ϵ could rule out the (K-M) and (L-W) models as candidates to explain the observed CP violation and give room for new candidates of superweak type such as the horizontal interactions. In such a case the predicted sizeable electric dipole moment for the neutron could be the critical test for this alternative.

We close this conclusion by stressing the fact that our constraints are essentially model independent. Special features of these new interactions could, however, slightly modify our results. Let us confine ourselves to a $SU(n)_H$ horizontal group with left-handed families in the fundamental representation $[\underline{n}]$ and right-handed families in $[\underline{n}]$ or $[\underline{n}^*]$ ones. This respectively corresponds to the so-called "vectorial" ($\lambda_a^L = \lambda_a^R$) and the "axial" ($\lambda_a^L = -\lambda_a^{R*}$) models with characteristic associated fermion mass matrices.

For Hermitean quark mass matrices, we obtain

$$U_L = U_R \quad (25)$$

such that, if in addition, we assume* equal horizontal gauge boson masses, the surviving global $SU(n)$ symmetry implies horizontal flavour conserving $\Delta S = 2$ (Eq. 9) operators. In that case, horizontal interactions cannot be the main source for CP violation ($\epsilon_H = 0$) and the stringent upper limit on G_H now arises from $\mu N \rightarrow e N$ ¹³⁾.

On the other hand, it has been stressed¹⁹⁾ that symmetric fermion mass matrices in "axial" models are very interesting in the framework of family

* The introduction of one scalar multiplet transforming like the totally symmetric tensor of rank n of $SU(n)_H$ naturally ensures the complete spontaneous breaking of the gauge group¹⁸⁾ with such a degeneracy.

hierarchy induced through radiative corrections. This implies

$$U_R = J U_L^* \quad (26)$$

with J an unitary diagonal matrix. In this class of models, we do not have to worry about dramatic cancellation, as far as CP violation is concerned.

ACKNOWLEDGEMENTS

We would like to thank D.V. Nanopoulos for discussions and for reading the manuscript and W. Grimus for discussions. One of us (R.D.) would also like to thank M. Jacob for inviting him to visit the CERN Theoretical Physics Division.

References

1. G. Arnison et al., Phys. Lett. 122B (1983) 103;
G. Bannel et al., Phys. Lett. 122B (1983) 476;
G. Arnison et al., CERN preprint EP/83-73 (1983).
2. M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49 (1973) 652.
3. T.D. Lee, Phys. Rev. D8 (1973) 1226;
S. Weinberg, Phys. Rev. Lett. 37 (1976) 657.
4. J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys. B109 (1976) 213;
F.J. Gilman and M.B. Wise, Phys. Lett. 83B (1979) 83.
5. A.I. Sanda, Phys. Rev. D23 (1981) 2647;
N.G. Deshpande, Phys. Rev. D23 (1981) 2653;
J.F. Donoghue, J.S. Hagelin and B.R. Holstein, Phys. Rev. D25 (1982) 195;
D. Chang, Phys. Rev. D25 (1982) 1318.
6. See, e.g., L. Wolfenstein and D. Chang, Carnegie-Mellon University preprint CMU-HEP 83-5, to appear in Proceedings of the Symposium on Intense Medium Energy Sources of Strangeness, March 19-21 (1983), University of California at Santa Cruz.
7. MAC Collaboration, paper given at the EPS Europhysics Conference on High Energy Physics, Brighton, July 1983, by N. Chadwick.
MARK II Collaboration, paper given at the EPS Europhysics Conference on High Energy Physics, Brighton, July 1983, by G. Hanson.
8. P.H. Ginsparg, S.L. Glashow and M.B. Wise, Phys. Rev. Lett. 50 (1983) 1415;
E.A. Paschos, B. Stech and U. Türke, Phys. Lett. B128 (1983) 240.
9. G.C. Branco, J.-M. Frère and J.-M. Gérard, Nucl. Phys. B221 (1983) 317.
10. H. Harari and M. Leurer, Fermilab. Pub. 83/59 (1983).
11. A. Davidson and K.C. Wali, Phys. Rev. Lett. 46 (1981) 691;
A.S. Joshipura and I. Montvay, DESY preprint 81-040 (1981);
G. Zoupanos, Phys. Lett. 115 B (1982) 221;
M.B. Gavela and H. Georgi, Harvard preprint HUTP-82/A041 (1982).
12. T. Maehara and T. Yanagida, Prog. Theor. Phys. 60 (1978) 822; 61 (1979) 1434;
F. Wilczek and A. Zee, Phys. Rev. Lett. 49 (1979) 421;
A. Davidson, M. Koca and K.C. Wali, Phys. Rev. Lett. 43 (1979) 92;
Phys. Rev. D20 (1979) 1195;
T. Yanagida, Phys. Rev. D20 (1979) 2986;
G. Zoupanos, Z. Phys. C 11 (1981) 27;
E. Papantonopoulos and G. Zoupanos, Phys. Lett. 110B (1982) 465;
Z. Phys. C16 (1983) 261.
13. R.N. Cahn and H. Harari, Nucl. Phys. B176 (1980) 135;
D.R.T. Jones, G.L. Kane and J.-P. Leveille, Nucl. Phys. B198 (1982) 45.
14. M.K. Gaillard and B.W. Lee, Phys. Rev. D10 (1974) 897.
15. G. Beall, M. Bander and A. Soni, Phys. Rev. Lett. 48 (1982) 848.

16. M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B120 (1977) 31.
17. F. Wilczek, "Thoughts on family symmetries" to appear in Proc. of Workshop on Underground Physics, Los Alamos (1982);
R. Decker, Dortmund preprint DO-TH 83/03 (1983) to appear in Z. Phys. C;
G.B. Gelmini, J.-M. Gérard, T. Yanagida and G. Zoupanos, CERN preprint TH.3676 (1983).
18. P. Jetzer, J.-M. Gérard and D. Wyler, CERN preprint TH 3697 (1983).
19. M. Gell-Mann, P. Ramond and R. Slansky in "Supergravity", editors P. van Nieuwenhuizen and D.Z. Freedman (1979).
Y. Chikashige, G. Gelmini, R.D. Peccei and M. Roncadelli, Phys. Lett. 94B (1980) 499.

Figure captions

- Fig. 1 Contribution to $K^0 - \bar{K}^0$ due to horizontal interactions.
- Fig. 2 Dominant contribution to $K \rightarrow 2\pi$ due to horizontal interactions.
- Fig. 3a Horizontal gauge boson one-loop contribution to the electric dipole moment of fermions.
- Fig. 3b Exchange diagram contribution to the electric dipole moment of a baryon. The photon and the horizontal vector boson must be appended to quark lines in all possible ways.

FIG. 1

FIG. 2

FIG. 3a

FIG. 3b