The Process $\mu \rightarrow \nu_e e \overline{\nu}_\mu$ in the 2HDM with Flavor Changing Neutral Currents

Rodolfo A. Diaz, R. Martínez, and Nicanor Poveda
Universidad Nacional de Colombia, Departamento de Física, Bogotá, Colombia

Received on 22 May, 2003. Revised version received on 24 September, 2003

We consider the process $\mu \rightarrow \nu_e e \overline{\nu}_\mu$ in the framework of a two Higgs doublet model with flavor changing neutral currents (FCNC). Since FCNC generates in turn flavor changing charged currents in the lepton sector, this process appears at tree level mediated by a charged Higgs boson exchange. From the experimental upper limit for this decay, we obtain the bound $|\xi_{\mu e}/m_{H^+}| \leq 3.8 \times 10^{-3}$ GeV^{-1}, where $\xi_{\mu e}$ refers to the mixing between the first and second lepton generations, and $m_{H^\pm}$ denotes the mass of the charged Higgs boson. This bound is independent on the other free parameters of the model. In particular, for $m_{H^\pm} \simeq 100$ GeV we get $|\xi_{e\mu}| \lesssim 0.38$.

1 Introduction

Flavor Changing Neutral Currents (FCNC) are processes highly suppressed by some underlying principle still unknown. However, the observation of new phenomena like oscillation of neutrinos [1] coming from the sun and the atmosphere, seem to indicate the existence of such rare couplings. Neutrino oscillations can be explained by introducing mass terms for these particles, in whose case the mass eigenstates are different from the interaction eigenstates. It should be emphasized that the oscillation phenomenon implies that the lepton family number is violated, and such fact leads us in turn to consider the existence of physics beyond the standard model (SM), because in SM neutrinos are predicted to be massless and lepton flavor violating mechanisms are basically absent. These considerations motivate the study of scenarios with Lepton Flavor Violation (LFV) and Family Lepton Flavor Violation (FLFV) [15].

The original motivation for the introduction of neutrino oscillations comes from the first experiment designed to measure the flux of solar neutrinos [2], such measurement was several times smaller than the value expected from the standard solar model, so ref [3] suggested the neutrino oscillation mechanism as a possible explanation of the neutrino deficit problem. In addition, models of neutrino oscillations in matter [4] arose to solve the neutrino deficit confirmed by SuperKamiokande [5]. Since then, further evidence of solar neutrino oscillations has been found by SuperKamiokande and SNO [6]. Besides, this phenomenon can be inferred from experiments with atmospheric neutrinos as well [7].

On the other hand, since neutrino oscillations imply FLFV in the neutral lepton sector, it is generally expected to find out FLFV processes involving the charged lepton sector as well, searches for these processes have provided some upper limits for several decays involving these exotic mechanisms, some examples are $\mu - e$ conversion in nuclei [8], $\mu \rightarrow eee$ [9], $\mu \rightarrow e\gamma$ [10], and $\mu^- \rightarrow \nu_e e^- \overline{\nu}_\mu$[11]. In addition, the search for FLFV can also be made by analyzing semileptonic processes, upper bounds from FLFV meson decays have been estimated, some examples are $K_L^0 \rightarrow \mu^+ e^-$ [12], and $K_L^0\,(K^+) \rightarrow \pi^0\,(\pi^+)\,\mu^+ e^-$ [13]. Moreover, the phenomenon of LFV has been widely studied from the theoretical point of view in different scenarios such as Two Higgs Doublet Models, Supersymmetry, Grand Unification [14], and effective Lagrangian technics [15].

With these motivations in mind, we shall study the FLFV decay $\mu^- \rightarrow \nu_e e^- \overline{\nu}_\mu$ which provides information about the mixing between the first and second lepton family. This process has been used to get bounds on dileptonic gauge bosons with lepton number $L = 2$ which come from theories with enlarged gauge symmetries such as $SU\,(15)$; such dileptonic gauge bosons typically occur in $SU\,(2)$ doublets (X^{--}, X^-). In particular, Ref. [17] gets a bound of $M_X > 230$ GeV for the single charged dilepton X^-, by using the angular distribution of electrons in polarized muons from the decay $\mu^- \rightarrow \nu_e e^- \overline{\nu}_\mu$.

In our case, we examine this process in the framework of one of the simplest extension of the standard model that generates FLFV at tree level, the so called Two Higgs Doublet Model type III (2HDM (III)). This model consists of adding a second doublet to the SM with the same quantum numbers of the first, and considering all type of Yukawa couplings. Some bounds on lepton flavor violating couplings involving the mixings $\mu - \tau,\ e - \tau,\ \mu - \mu$, and $\tau - \tau$ have been considered recently [16] by taking into account the $g - 2$ muon factor and some of the leptonic decays cited above. Ref [16] considers processes with Flavor Changing Neutral Currents (FCNC) to study LFV. Instead, the process $\mu^- \rightarrow \nu_e e^- \overline{\nu}_\mu$ to be study in this brief report, involves Flavor Changing Charged Currents (FCCC) and the mixing between the first and second lepton family.

The Yukawa Lagrangian in the 2HDM (III) reads

$$
\begin{aligned}
-\pounds_Y &= \frac{g}{2M_W}\overline{D}M_D^{diag}D\left(\cos\alpha H^0-\sin\alpha h^0\right)\\
&+\frac{1}{\sqrt{2}}\overline{D}\xi^D D\left(\sin\alpha H^0+\cos\alpha h^0\right)\\
&+\frac{g}{2M_W}\overline{U}M_U^{diag}U\left(\cos\alpha H^0-\sin\alpha h^0\right)\\
&+\frac{1}{\sqrt{2}}\overline{U}\xi^U U\left[\sin\alpha H^0+\cos\alpha h^0\right]\\
&+\frac{i}{\sqrt{2}}\overline{D}\xi^D\gamma_5 DA^0-\frac{i}{\sqrt{2}}\overline{U}\xi^U\gamma_5 UA^0\\
&+\overline{U}\left(K\xi^D P_R-\xi^U KP_L\right)DH^+\\
&+\frac{g}{2M_W}\overline{E}M_E^{diag}E\left(\cos\alpha H^0-\sin\alpha h^0\right)\\
&+\frac{1}{\sqrt{2}}\overline{E}\xi^E E\left(\sin\alpha H^0+\cos\alpha h^0\right)\\
&+\frac{i}{\sqrt{2}}\overline{E}\xi^E\gamma_5 EA^0+\overline{\vartheta}\xi^E P_R EH^+\\
&+h.c \qquad (1)
\end{aligned}
$$

where H^0, h^0 denote the heaviest and lightest scalar Higgs bosons respectively. A^0 is a pseudoscalar Higgs boson, $U,\ (D)$ indicates the three up-type (down-type) quarks i.e. $U \equiv (u,c,t)^T$, $D \equiv (d,s,b)^T$, additionally $\vartheta,\ (E)$ refers to the three neutral (charged) leptons i.e. $E \equiv (e,\mu,\tau)^T$, $\vartheta \equiv (\nu_e,\nu_\mu,\nu_\tau)^T$. The matrices $M_X,\ \xi_X$ with $X = U, D, E$ describe the fermion masses and the flavor changing vertices respectively. Finally, α is the mixing angle in the scalar Higgs bosons sector. We shall deal with a parametrization in which only one of the doublets acquires a vacuum expectation value.

In the case of leptons, from Lagrangian (1) we see that the matrix elements ξ_{ij}^E that generates FCNC automatically generates FCCC which are strongly suppressed in the leptonic sector. Consequently, by constraining flavor changing charged currents we are indirectly constraining flavor changing neutral currents as well. In the case of the 2HDM (III), interactions involving FCCC at tree level only contains the contribution from the charged Higgs boson, reducing the free parameters to manage.

As for the quark sector, we can see that FCCC are present through the CKM matrix even in the absence of FCNC. However, as it is seen clearly from Lagrangian (1) the sources of FCNC $\left(\xi_{ij}^{U(D)}\right)$ also modifies the FCCC matrix elements mediated by $H^\pm$. Therefore, in a model with no FCNC at tree level (like the 2HDM type I and II) the matrix elements that generates FCCC by $W^\pm$ exchange (i.e. the CKM matrix elements) coincide with the matrix elements that generate FCCC by $H^\pm$ exchange. By contrast, in models with FCNC at tree level (like the 2HDM type III) the FCCC pattern produced by $W^\pm$ might be very different from the pattern expected in FCCC mediated by $H^\pm$ exchange, this phenomenological difference could discriminate among these models.

In this note, we shall concentrate on FCCC in the lepton sector of the 2HDM type III. In particular, we extract a bound for the quotient $\xi_{e\mu}/m_{H^+}$ based on the constraints on the three body decay. $\mu^- \to \nu_e e^- \overline{\nu}_\mu$ mediated by a charged Higgs, this decay produces FLFV. The corresponding decay width is given by

$$\Gamma\left(\mu^- \to \nu_e e^- \overline{\nu}_\mu\right) = \frac{m_\mu^5}{24\,576\pi^3}\left(\frac{\xi_{e\mu}}{m_{H^+}}\right)^4 \qquad (2)$$

and taking the current upper bound for this decay [18]

$$\Gamma\left(\mu^- \to \nu_e e^- \overline{\nu}_\mu\right) \leq 3.\,6\times 10^{-21} GeV, \qquad (3)$$

the following constraint is gotten

$$\left|\frac{\xi_{e\mu}}{m_{H^+}}\right| \leq 3.8\times 10^{-3} GeV^{-1}. \qquad (4)$$

Despite this constraint is not so strong, it is interesting since it does not depend on the other free parameters of the model, because the calculation does not involve neutral Higgs bosons nor mixing angles. This is a good motivation to improve the experimental upper limit for processes involving FCCC in the leptonic sector.

For the sake of comparison, Ref. [15] has calculated a bound for the quotient $f_{e\mu}/m_{\Delta^+}$ where m_{Δ^+} is a charged Higgs bosons, and $f_{e\mu}$ a flavor changing vertex belonging to an effective theory built in order to explain the neutrino anomaly reported by the LSND experiment. The result of Ref. [15], is

$$\left|\frac{\xi_{e\mu}}{m_{H^+}}\right| \leq \frac{1}{525} GeV^{-1}.$$

This bound is roughly on the same order of magnitude that the one obtained in this paper. However, we point out that the latter constraint is only valid for an effective theory with violation of total lepton number $\Delta L = 2$ [15], while the standard two Higgs doublet model considered here, only allows family lepton violation ($\Delta L = 0$).

In conclusion, we can constrain flavor changing neutral currents in the 2HDM (III) also by examining flavor changing charged currents. The study of the latter at tree level in the 2HDM (III) depend on a less number of free parameters since only one scalar particle is exchanged, and the Higgs boson involved does not couple through a mixing angle. As a manner of example, for $m_{H^\pm} \simeq 100$ GeV we obtain $|\xi_{e\mu}| \lesssim 0.38$ without any further assumption.

This work was supported by COLCIENCIAS and Fundación Banco de la República.

References

[1] Kh.M. Beshtoev, arXiv:hep-ph/0204324 and references therein.

[2] R. Davis et. al., Phys. Rev. Lett **20**, 1205 (1968).

[3] V. Gribov, B. M. Pontecorvo, Phys. Lett. B**28**, 493 (1969).

[4] S.P. Mikheyev, A. Yu. Smirnov, Nuovo Cimento **9**, 17 (1986); L. Wolfenstein, Phys. Rev. D**17**, 2369 (1978).

[5] K.S. Hirata et. al., Phys. Rev. Lett. **63**, 16 (1989)

[6] J. Kameda, Proceedings of ICRC 2001, August 2001, Hamburg (Germany) p. 1057; Q. R. Ahmad arXiv:nucl-ex/0106015

[7] Y. Fukuda et. al., Phys. Rev. Lett. **81**, 1562 (1998)

[8] C. Dohmen et. al. Phys. Lett. **B317**, 631 (1993)

[9] U. Bellgardt et. al., Nucl. Phys. **B299**, 1 (1998).

[10] R. D. Bolton et. al., Phys. Rev. **D38**, 2077 (1983); M. L. Brooks et. al., Phys. Rev. Lett. **83**, 1521 (1999).

[11] Y. Okada, K. Okumura, and Y. Shimizu, Phys. Rev. **D61** , 094001 (2000)

[12] K. Arisaka et. al., Phys. Rev. Lett. **70**, 1049 (1993).

[13] K. Arisaka et. al., Phys. Lett. **B432**, 230 (1993); A. M. Lee et. al., Phys. Rev. Lett. **64**, 165 (1990).

[14] Marc Sher and Yao Yuan, Phys. Rev. D**44**, 1461 (1991); D. Atwood, L. Reina, and A. Soni, Phys. Rev. D**55**, 3156 (1997); Phys. Rev. Lett. **75**, 3800 (1995); G. Lopez Castro, R. Martinez, and J. H. Muñoz, Phys. Rev. D**58** , 033003 (1998); Rodolfo A. Diaz, R. Martinez, and J.-Alexis Rodriguez, Phys. Rev. D**63** , 095007 (2001); S.K. Kang and K.Y. Lee, Phys. Lett. B **521**, 61 (2001); E. Ma and M. Raidal, Phys. Rev. Lett. **87**, 011802 (2001); Rodolfo A. Diaz, R. Martinez, and J.-Alexis Rodriguez, Phys. Rev. D**64**, 033004 (2001); J. E. Kim, B. Kyae, and H. M. Lee, Phys. Lett. B**520**, 298 (2001); S. P. Martin and J. D. Wells, Phys. Rev. D**64** , 035003 (2001); H. Baer et. al., Phys. Rev. D**64**, 035004 (2001).

[15] K. S. Babu, and Sandip Pakvasa, [arXiv: hep-ph/0204236].

[16] Rodolfo A. Diaz, R. Martinez, and J.-Alexis Rodriguez; Phys. Rev. D**67**, 075011 (2003), [arXiv: hep-ph/0208117]

[17] E. D. Carlson and P. H. Frampton, Phys. Lett. B **283**, 123 (1992); P. H. Frampton and M. Harada, Phys. Rev. D**58**, 095013 (1998).

[18] K. Hagiwara et. al., Review of Particle Physics, Phys. Rev. D**66**, 010001 (2002) and references therein.