Physics Letters B 684 (2010) 231–235

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Probing leptonic CP phases in LFV processes

Borut Bajc [a], Miha Nemevšek [a,b], Goran Senjanović [c,a,*]

[a] J. Stefan Institute, 1000 Ljubljana, Slovenia
[b] II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[c] International Centre for Theoretical Physics, 34100 Trieste, Italy

ARTICLE INFO

Article history:
Received 30 November 2009
Received in revised form 8 January 2010
Accepted 12 January 2010
Available online 16 January 2010
Editor: T. Yanagida

ABSTRACT

We study a CP and T violating triple (spin) correlation in the muon to electron conversion in nuclei in the context of the seesaw mechanism. After concluding that the results are negative for all three seesaw types, we turn to the left–right symmetric theories as the original source of seesaw. We find that in general this correlation is of order one which offers a hope of observing CP violation in lepton flavor violating processes for a L–R scale below around 10–30 TeV. We discuss the conditions that could render to (unlikely) conspiracies as to suppress the CP violating effects.

1. Introduction

Probing CP phases is a great challenge of neutrino physics. They can be manifest in CP even processes at colliders [1] and in neutrinoless double beta decay [2] or as CP odd in neutrino–antineutrino oscillations [3]. Another possibility is to study the LFV processes with best experimental limits, $\mu \to e\gamma$, $\mu \to 3e$ and $\mu \to e$ conversion in nuclei. These are very rare processes and as such provide an ideal window into physics behind neutrino masses and mixings. While the total decay rates themselves are sensitive to CP phases, additional information can be obtained by studying correlations between the polarization of the initial muon state and the final state particles. These are the so-called triple product correlations, studied at length in the literature as a probe of CP violation [4,5] and recently revisited in the context of leptonic CP violation [6–9]. Particularly important is $\mu \to e$ conversion, for there is a serious proposal [10–12] to improve its sensitivity by four to six orders of magnitude, which would bring it to an unprecedented precision. This process is thus worth a particular attention from the theoretical point of view and is the focus of our interest.

We study here the P, CP and T violating triple correlation of muon and electron spins, and the electron momentum in the context of the so-called seesaw mechanisms. Assuming a single type of mediators, one conventionally speaks of three types of seesaw. Type I [13], when the mediators are fermionic singlets called right-handed neutrinos, type II [14] when the mediator is an $SU(2)$ triplet scalar particle and type III [15] when the fermionic mediators are $SU(2)$ triplets. Strictly speaking, these simple scenarios have no strong theoretical motivation in themselves. The types I and II emerge naturally in the context of L–R symmetric theories, such as Pati–Salam theory [16] or $SO(10)$ grand unified theory, and type III in the context of a minimal realistic $SU(5)$ theory [17].

For that reason, we cover all the three cases. Our findings are negative, unless one is willing to go to a small corner of parameter space. On the other hand, it is much more appealing to have a real theory that connects the smallness of neutrino mass to different physical phenomena. A natural example is provided by the left–right symmetric theories [25], which historically have led to the seesaw picture for neutrino mass. In contrast to the simple-minded seesaw approach, in this case our findings are rather optimistic, as long as the scale M_R of left–right symmetry breaking (or at least some of its remnants) lies below 10–30 TeV. Of course, if M_R is in the TeV region, this would be quite exciting from the collider prospect point of view.

This Letter is organized as follows. In the next section, we discuss $\mu \to e$ conversion for the three types of seesaw. In Section 3, we repeat the exercise for the left–right symmetric theories, where we also comment on the prospect for the other two important processes, $\mu \to e\gamma$ and $\mu \to 3e$.

2. $\mu \to e$ conversion: leptonic CP phases in the seesaw picture

$\mu \to e$ conversion in nuclei provides the best experimental limit on lepton flavor violating processes [18,19]

$$B(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}) \leqslant 4.3 \times 10^{-12}, \quad (1)$$

$$B(\mu\,\mathrm{Au} \to e\,\mathrm{Au}) \leqslant 7 \times 10^{-13}, \quad (2)$$

* Corresponding author at: International Centre for Theoretical Physics, 34100 Trieste, Italy.
E-mail address: goran@ictp.it (G. Senjanović).

0370-2693 © 2010 Elsevier B.V. Open access under CC BY license.
doi:10.1016/j.physletb.2010.01.025

where

$$B(\mu\,\mathrm{N}\to e\,\mathrm{N}) \equiv \frac{\Gamma(\mu\,\mathrm{N}\to e\,\mathrm{N})}{\Gamma(\mu\,\mathrm{N}\to \text{capture})}. \tag{3}$$

A more stringent bound with titanium was reported [20] $B(\mu\,\mathrm{Ti}\to e\,\mathrm{Ti}) \leqslant 6\times 10^{-13}$, but has never been published.

Due to nuclear physics effects the theory of $\mu\to e$ conversion is rich, see for example [21–24].

A natural quantity that probes CP phases is the P, CP and T violating triple correlation of spins and electron momentum:

$$(\vec{S}_\mu \times \vec{S}_e)\cdot \vec{P}_e.$$

To illustrate what happens, let us imagine for the moment that the effective operator, responsible for $\mu\to e$ conversion, takes a simple single Lorentz structure form

$$\mathcal{L}_{\text{eff}} = G_F \sum_{q=u,d} \left(A_L \bar{e}_L\gamma^\mu \mu_L + A_R \bar{e}_R \gamma^\mu \mu_R\right) \times \left(V_L^q \bar{q}_L \gamma^\mu q_L + V_R^q \bar{q}_R\gamma^\mu q_R\right) + \text{h.c.} \tag{4}$$

The coefficient of the triple correlation turns out to be proportional to [7]

$$\delta_{\text{CP}} = \frac{\mathrm{Im}(A_L^* A_R)}{|A_L|^2 + |A_R|^2}. \tag{5}$$

The result is easily understood on physical grounds. Since for a single helicity of the electron the spin would be proportional to its motion, the spin of the electron being perpendicular to its motion in this correlation requires the presence of both, A_L and A_R. CP violation then requires a relative phase between A_L and A_R. The same reasoning applies to the situation when more than one operator is present, as can be seen in [7] and can be (un)easily generalized to an arbitrary case of such operators. Hereafter, we will use the notation A_L and A_R to denote any operator that involves e_L and e_R, respectively. Notice that our notation, consistent with electron (and muon) chirality, is different from [24] (and [7]) who use the subscript L for the scalar and vector interactions, but use R for the tensor one for the same L chirality of the electron.

It is straightforward to see that the seesaw mechanisms lead to a negligible triple correlation. The crucial point is that the different types of seesaws are characterized by one common aspect: only left-handed charged leptons are involved. These interactions are respectively

- $\ell H F_{\text{new}}$, where F_{new} is a singlet fermion (called right-handed neutrino) in the type I and a $SU(2)$, $Y=0$ fermion triplet in the type III, ℓ stands for the usual leptonic doublet and H the standard model Higgs doublet;
- $\ell\ell\Delta$, where Δ is an $SU(2)$ triplet, $Y=2$ scalar in the case of type II seesaw.

This simple fact provides the cornerstone for our reasoning in what follows.

We must bring A_R into the game. The simple mass insertion on the external electron leg does not suffice, for then A_R has the same form as A_L. In that case

$$A_R = \frac{m_e}{m_\mu} A_L \tag{6}$$

and thus $\delta_{\text{CP}} = 0$. To obtain a nontrivial imaginary part, one has to bring in the Higgs exchange, which implies A_R being loop suppressed compared to A_L. This is illustrated in Fig. 1 for the case of Z exchange contribution to $\mu\to e$ conversion. In short, it is easy to estimate

$$\delta_{\text{CP}} \approx \frac{\alpha}{\pi}\frac{m_e}{M_W} \approx 10^{-7}, \tag{7}$$

where m_e/M_W is simply due to the electron Yukawa coupling.

Independently of the type of the seesaw, the prospect of measuring CP violation and probing the CP phases is hopeless, even if one were to arrive at 10^{-18} upper limit for the branching ratio.

The picture of seesaw is somewhat simple minded and it is instructive to see what happens in a well defined theory. We can guess the answer from what we have learned here: if at low energies you are left with only the seesaw, whatever the type(s), the CP violating correlations vanish. An example of such a theory is provided by a minimal extension of the original $SU(5)$ theory that can simultaneously account for the unification of gauge couplings and neutrino mass. It is based on an addition of an adjoint 24_F fermionic representation [17], which leads to the hybrid type I and type III seesaw and no other low energy manifestation. It then predicts, as above, no CP violating effects.

In the next section we discuss the left–right symmetric theory which originally led to the seesaw mechanism. Here, on the contrary, you would expect a large contribution to δ_{CP}, for both left and right electrons are present and L–R symmetry is broken.

3. The left–right symmetric model

We focus here on the minimal left–right symmetric theory with the seesaw mechanism [26]. This class of models is characterized by both type I and type II seesaw. They are defined by the minimal fermionic assignment and the following fields in the Higgs sector:

$$\Phi(2,2,0), \qquad \Delta_L(3,1,2), \qquad \Delta_R(1,3,2) \tag{8}$$

under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. This allows for new Yukawa couplings of Δ's with the leptons

$$\mathcal{L}_\Delta = Y_\Delta(\ell_L\ell_L\Delta_L + \ell_R\ell_R\Delta_R) + \text{h.c.} \tag{9}$$

The parity breaking vev

$$\langle\Delta_R\rangle \simeq M_{W_R}, \qquad \langle\Delta_L\rangle = 0 \tag{10}$$

is responsible for the original breaking down to the SM symmetry, and the vev of the bi-doublet

$$\langle\Phi\rangle = M_L \tag{11}$$

completes the symmetry breaking. This will induce an effective potential for Δ_L, in the symbolic notation

$$V_{\Delta_L} = M_{\Delta_L}^2 \Delta_L^2 + \alpha\Delta_L\Phi^2\Delta_R + \cdots, \tag{12}$$

which leads to a small vev for Δ_L

$$\langle\Delta_L\rangle = \alpha\frac{\langle\Phi\rangle^2\langle\Delta_R\rangle}{M_{\Delta_L}^2}, \tag{13}$$

which is responsible for the type II contribution to the neutrino mass.

The spontaneous breakdown of parity leads to different masses

$$M_{\Delta_L} \neq M_{\Delta_R} \tag{14}$$

with, in general

$$M_{\Delta_L}, \quad M_{\Delta_R}, \quad M_{\Delta_L} - M_{\Delta_R} \propto \langle\Delta_R\rangle. \tag{15}$$

From (12) and (13), one can easily find the mixing between Δ_L and Δ_R to be

$$\theta_{\Delta_L\Delta_R} \simeq \frac{\langle\Delta_L\rangle}{\langle\Delta_R\rangle}. \tag{16}$$