CHARGED SCALAR PARTICLES AND τ LEPTONIC DECAY

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Abstract

Charged scalar particles introduced in some extensions of the standard model can induce τ leptonic decay at tree level. We find that with some charged SU(2)-singlet scalar particles, like ones introduced in Zee-type models, τ leptonic decay width is always smaller than what is predicted by the standard model, therefore they may offer a natural solution to τ decay puzzle. To be more specific, we examine some Zee-type models in detail to see if at the same time they are acceptable in particle physics, cosmology and astrophysics. It is shown that τ decay data do put some constrains on these models.

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\( \tau \) lepton is an interesting system to test the standard model (SM) and search for new physics, since \( \tau \) is the heaviest lepton yet known. There is a long-standing puzzle in \( \tau \) lepton decays, which has received attention for some years. The puzzle is that the measured \( \tau \) lifetime may be longer than one expected in the SM with three families \([1, 2]\). From Particle Data Group (PDG) \([3]\), the measured \( \tau \) lifetime is \( \tau^{\text{exp}} = (3.05 \pm 0.06) \times 10^{-13}\) s, while the SM’s expectation is \( \tau^{\text{th}} = (2.87 \pm 0.07) \times 10^{-13}\) s, where \( m_\tau = 1784.1^{+2.7}_{-3.6} \) MeV is used. So one sees that the measured \( \tau \) lifetime is about 2.3\( \sigma \) higher than SM expectation value \([2]\). The latest measurement of \( \tau \) mass at BES \([4]\) \( m_\tau = 1776.9 \pm 0.5 \) MeV somehow relaxes the \( \tau \) lifetime problem. But this downward shift of \( m_\tau \) is not enough. \( \tau^{\text{exp}} \) is still about 1.9\( \sigma \) higher than \( \tau^{\text{th}}(= 2.92 \pm 0.04 \times 10^{-13}) \). Of course it is very possible that this \( \tau \) decay puzzle will disappear when new measurements of leptonic decays become available, as the expected value does not deviate too much from the measured one (In fact, it is noticed that there are some new measurements after PDG \([3]\) on \( \tau \) lifetime and leptonic decay branching ratios. We will comment on that at the end of the paper). However, we feel that there are some theoretical motivations for taking this puzzle seriously, such as the existence of a fourth generation or charged scalar particles (the latter case will be discussed in detail later).

One simple solution to \( \tau \) decay puzzle is to introduce a fourth generation \([2, 3]\). If the mixing between \( \tau \) neutrino \( \nu_\tau \) and the fourth heavy neutrino (it must be heavier than 45.3 GeV from LEP Z-width constraints \([3]\)) is around \( \sin^2 \theta_{\text{mix}} \approx 0.05 \), the central value of \( \tau^{\text{exp}} \) is in consistency with the corresponding theoretical expectation value in this model. We denote \( g_e, g_\mu \) and \( g_\tau \) as weak couplings of \( e, \mu \) and \( \tau \) leptons respectively, universality of weak interaction means \( g_e = g_\mu = g_\tau \). Any deviation from this relation (for example \( g_e = g_\mu \neq g_\tau \)) implies a violation of the universality (of \( \tau \)). In the four generation model, \( \tau \) universality in the charged and neutral current sector is obviously violated by a small amount \([7]\). Nevertheless, this is not favored by the neutral-current data from Z decay which agrees with the universality of the weak interaction of \( e, \mu \) and \( \tau \) leptons at the
level of precision better than 0.5% \[8\]. Another simple solution assuming a mixing of \(\nu_\tau\) with a singlet neutrino \(\nu\) [9] is also in conflict with this Z decay data. In addition, following Marciano’s analysis [2] but using \(m_\tau = 1776.9 \pm 0.4 \pm 0.3\) MeV, we see that for \(\tau\) semileptonic decays \(\tau \to \nu_\tau \pi/K\) and \(\tau \to \nu_\tau \pi^- \pi^0\) experimental values agree with the SM’s prediction very well (within 1\(\sigma\)). So this is another evidence supporting \(\tau\) universality in semileptonic decay.

In this letter we discuss the effects induced by scalar particles in \(\tau\) leptonic decay. Without losing generality we will consider SU(2)-singlet, doublet and triplet scalars. Generally, for a SU(2)-singlet or triplet scalar \(h_{ab}\), the couplings between scalars and leptons may be introduced as \(\Delta L_y = f_{ab} l_a l_b h_{ab}\), for SU(2)-doublet scalars \(\Delta L_y = f_{ab} \bar{l}_a e^C_b h_{ab}\), where \(l_a\) is lepton doublet, \(e^C_b\) is lepton singlet and \(a, b\) denote family indices. Due to the fermi statistics, \(f_{ab}\) is antisymmetric and symmetric for singlet and triplet scalars respectively. While for doublet scalar there is no any constraint on the structure of \(f_{ab}\). With these interactions, it is easy to see that for \(\tau\) leptonic decay, for example \(\tau \to \mu \nu_\tau \bar{\nu}_\mu\), two processes contribute at tree level. One is SM’s W-boson exchanging process, the other is through exchange of the \(h_{ab}\) particle (Fig. 1). The general features we find are that for singlet \(h_{ab}\), the interference term between these two processes are always negative; for triplet \(h_{ab}\), if \(a \neq b\), the interference term is always positive, if \(a = b\) and \(f_{aa} f_{bb} > 0\) the interference term is negative. These are because of the antisymmetric and symmetric properties of \(f_{ab}\). As for the doublet, if we take all of the fermion masses in final states as zero, then the interference effect vanishes. This is a result of the fact that the Yukawa coupling changes the chirality of the leptons, and therefore the interference term must be proportional to the charged lepton mass in the final states. Consequently, we see that with the singlet or triplet scalar couplings (with \(a = b\) and \(f_{aa} f_{bb} > 0\)) \(\tau\) leptonic widths are smaller than that predicted in the SM, with triplet scalar couplings (in the case of \(a \neq b\)) or doublet scalar couplings \(\tau\) leptonic decay widths are larger than that in the SM. Hence \(\tau\) decay data suggests that one should consider models with singlet or triplet (with \(a = b\) and \(f_{aa} f_{bb} > 0\)) scalars. We show that the scalar particle introduced in Zee-model has exactly the required property. So as a good example,
we will discuss \( \tau \) decay puzzle concentrating only on Zee-type models.

Zee model was proposed to generate Majorana neutrino masses \([10]\). Recently, it was found that it can generate large neutrino transitional magnetic moment, while keeping neutrino masses small naturally \([11]\). Zee-type models are also proposed to incorporate neutrinos with mass at the order of KeV \([12]\) and at the same time to give a solution to solar neutrino problem (SNP) \([14]\). In this sort of models, some charged scalar particles \( h \) are introduced, which carries two units of lepton charge. The point is that the \( \tau \) leptonic decay widths in these models are always smaller than that predicted in SM. Also \( \tau \) universality in the neutral current sector is not violated. On the other hand, since \( h \) does not couple to quarks, we expect the \( \tau \) universality is well respected in semileptonic decays. These are in perfect agreement with the \( Z \) decay and \( \tau \) leptonic decay data as well as the more precisely measured value \( |g_{\mu}/g_e| = 1.0031 \pm 0.0023 \) obtained from \( \pi \) decay \([15]\).

\( h_{ab}(a \neq b) \) couple to leptons as

\[
\Delta L_y = 1/2 f_{ab} l_a^T C i\tau_2 l_b h_{ab} + h.c.
\] (1)

where \( C \) is the Dirac charge conjugation matrix and \( f_{ab} \) is antisymmetric due to fermi statistics. \( h_{ab} \) carries two units of lepton numbers \( (L_a, L_b) \). One sees that this interaction has a global \( U(1)_e \times U(1)_\mu \times U(1)_\tau \) symmetry. So lepton numbers \( L_a \) are not violated through this interaction. There are three independent couplings \( f_{e\mu}, f_{e\tau} \) and \( f_{\mu\tau} \). We assume that \( f_{e\mu} \) is considerably smaller than \( f_{e\tau} \) and \( f_{\mu\tau} \), so that we don’t need to readjust fermi constant \( G_\mu \) (in fact one or two order of magnitude smaller is enough, since we don’t want to fine-tune \( f_{e\mu} \) either). This is also consistent with the constraint set by universality between beta and \( \mu \)-decay \([10, 15]\). The leptonic decay width (including electroweak radiative corrections of the SM) in Zee-type models reads

\[
\Gamma_l = \frac{G_\mu^2 m_\tau^5}{192\pi^3} [f(\frac{m_e^2}{m_\tau^2}) (1 + \frac{3 m_e^2}{5m_W^2})(1 + \frac{\alpha(m_\tau)}{2\pi}(\frac{25}{4} - \pi^2)) - C_h^2] \\
C_h = 3.0 f_{\tau e}^2 (100\text{GeV}/m_h)^2
\] (2)
here $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$, $G_\mu$ is fermi coupling constant and $\alpha$ is fine structure constant. If we consider the weak scale as the only physical scale in this work, i.e. $m_h \simeq 100$ GeV, and take $f_{\tau \tau} = 0.12$, $\Gamma_\tau$ will be about 4% smaller than what predicted in SM. Consequently $\tau$ lifetime is about 4% longer than SM’s prediction as the central value of $\tau^{\text{exp}}$ implies. It is interesting that with a reasonable choice of coupling constant $f_{\tau \tau} \sim 0.1$, $\tau$ lifetime is about a few percent longer than the SM’s prediction. This is a general prediction of Zee-type models. Since $x$ is proportional to $f^2_{\tau \tau}$, a reduction of $f_{\tau \tau}$ by one order of magnitude will decrease $x$ by two order of magnitude. In other words, $f_{\tau \tau}$ can be determined very well from $\tau$ lifetime measurement, if $\tau$ lifetime is indeed different from the SM’s prediction. A few percent deviation between experimental measurement and the SM’s expectation implies $f_{\tau \tau} \sim 0.1$ and an inconsistency at $10^{-3}$ level corresponds to $f_{\tau \tau} \sim 0.02$. In addition, $f_{ab}$ is directly related to neutrino masses, mixing and magnetic moments. Precision measurement of $\tau$ lifetime will constrain these parameters and then affect the descriptions of some phenomena of cosmology and astrophysics. In order to see how well the models works when the parameters are fixed from the $\tau$ decay, we examine some of the aspects which are sensitive to the values of $f_{ab}$ in some concrete examples.

**BFZ model** [11] In this model both neutrino masses and magnetic moments are generated at two loop level, but the neutrino masses are suppressed by a factor proportional to the mass square of the charged leptons due to the spin suppression mechanism. Individual lepton number is certainly violated because of the non-zero neutrino transitional magnetic moments and masses. This violation is only due to the scalar interaction [17]

$$M^{\alpha \beta}_{ab} h_{ab} (\phi_\alpha^- \phi_\beta^0 - \phi_\beta^- \phi_\alpha^0)$$ (3)

here $\phi_\alpha^-$, $\phi_\alpha^0$ belong to Higgs doublets. The neutrino mass matrix for three lepton flavors reads

$$\begin{pmatrix}
0 & m_{e\mu} & m_{e\tau} \\
m_{e\mu} & 0 & m_{\mu\tau} \\
m_{e\tau} & m_{\mu\tau} & 0
\end{pmatrix}$$ (4)
and $m_{ab} \propto f_{ab}(m_a^2 - m_b^2)$, so one has $m_{e\mu} \equiv m << M \equiv m_{e\tau} \sim m_{\mu\tau}$. Therefore this mass matrix has an approximate symmetry $L_e + L_\mu - L_\tau$. The eigenvalues of this mass matrix are $m_1 \sim m$, $m_{2,3} \sim \sqrt{2}M \pm m/2$ indicating the mixing angle between $\nu_e(\nu_\mu)$ and $\nu_\tau$ to be order of $m/M$, and $\nu_e, \nu_\mu$ are mixed with large mixing angle close to $45^0$. Taking $f_{e\tau} \sim f_{\mu\tau} \sim 0.1$ and $f_{e\mu} \leq 10^{-2}$ to satisfy $f_{e\mu} << f_{e\tau}, f_{\mu\tau}$, one has neutrino transitional magnetic moments $(d_\nu)_{e\tau} \sim (d_\nu)_{\mu\tau} \sim 10^{-11}\mu_B$ and $(d_\nu)_{e\mu} \leq 10^{-12}\mu_B$. With $m$ smaller than $10^{-4}$ eV, and $M$ as large as 0.1 eV, it is easy to see that the relevant squared mass difference $(\Delta m^2)_{e\mu} \simeq M^2 \simeq 10^{-2}$ eV$^2$ in $\nu_e$ and $\nu_\mu$ oscillation is too large and $(d_\nu)_{e\mu} \leq 10^{-12}\mu_B$ is too small so that it can not provide a solution to SNP either through neutrino oscillation or spin-flavor precession between $\nu_e$ and $\nu_\mu$. However, we notice that the oscillation between $\nu_e$ and $\nu_\mu$ can be responsible for the recently reported deficiency of atmospheric $\nu_\mu$ (ANP) [18]. Because the squared mass difference and mixing angle perfectly fit the required parameter range [18]. As for the SNP we have a solution resorting to non-resonant spin-flavor precession between $\nu_e$ and $\nu_\tau$ when $\nu_e$ goes through magnetic field inside the Sun. The reason is that the magnetic moment $(d_\nu)_{e\tau}$ can be sufficiently large $\sim 10^{-11}\nu_B$ and $(\Delta m^2)_{e\tau} \simeq Mm \leq 10^{-5}$ eV$^2$ is as small as required [13]. Of course we should also check on all of the experimental constraints from particle physics, cosmology and astrophysics. As there are only three light neutrinos in our case, it seems that there is no problem with the limits from cosmology and astrophysics. Neutrino oscillation experiment gives some restrictions on mixing angle and mass difference between two neutrino species. Because of the approximate symmetry $L_e + L_\mu - L_\tau$ the only possible disagreement with experimental constraints could happen in $\nu_e$ and $\nu_\mu$ oscillation. Given a large mixing angle, neutrino oscillation experiment requires $(\Delta m^2)_{e\mu} < 0.09$ eV$^2$ [3], so our results agree with this restriction. However, if we take a much more stringent limit $(\Delta m^2)_{e\mu} < 1.5 \times 10^{-3}$ eV$^2$ [20], then our prediction is in conflict with this limit. Surely we have some freedom to tune the parameters to make $M$ a few times smaller in order to satisfy this limit. But at the same time we also reduce magnetic moment $(d_\nu)_{e\mu}$ by a same factor. This is not what we would like to do. Another stringent constraint comes from the measurement of rare $\mu$ decay $\mu \rightarrow e\gamma$ [3]. In present case this
decay can happen but is dominated by two loop diagrams [21], as lepton number is violated only through scalar interaction (3). A rather conservative estimate gives $f_{e\mu}^2 < 10^{-2}$, this is consistent with our requirement $f_{e\mu} << 10^{-1}$.

**BH model [12]** This model is based on a global lepton flavor symmetry $G = U(1)_e \times U(1)_\mu \times U(1)_\tau$ and $G$ is spontaneously broken down to $U(1)_{e-\mu+\tau}$ at weak scale. Because of the $U(1)_{e-\mu+\tau}$ symmetry, neutrino mass matrix has the form

$$
\begin{pmatrix}
0 & m_{e\mu} & 0 \\
m_{e\mu} & 0 & m_{\tau\mu} \\
0 & m_{\tau\mu} & 0
\end{pmatrix}
$$

(5)

$m_{e\mu}$ and $m_{\tau\mu}$ arise from one loop diagrams [14], giving $M \equiv m_{e\mu} \simeq 1/16\pi^2 f_{\mu\tau} \lambda_{\tau} m_{\tau}$, $m \equiv m_{e\tau} \simeq 1/16\pi^2 f_{e\mu} \lambda_{e} m_{\mu}$, where $\lambda$’s are scalar coupling constants and we expect these to be of the same order of magnitude. Solving the eigenvalues of this matrix, one gets a massless neutrino which is mostly $\nu_e$ mixed with $\nu_\tau$ by a mixing angle $\theta_S \simeq m/M$, and a massive ZKM neutrino with mass $\sim M$. The latest measurement on searching for 17 KeV neutrino sets a restriction $\theta_S < 10^{-3}$ with 95% CL [23]. This limit requires $f_{e\mu}/f_{\mu\tau} < 10^{-2}$, which is again consistent with our assumption on $f_{e\mu}$. The mass of the heavy ZKM neutrino is naturally about $10 \sim 100$ KeV. To avoid any trouble in cosmology and astrophysics, this heavy neutrino must decay sufficiently fast and the dominant decay is through $\nu_\tau \to \nu_e F$, where $F$ denotes flavons associated with the spontaneous breaking of $G$. The interesting prediction of this model is also on $\tau$ decay, i.e. $B(\tau \to e F) \simeq 10^{-4}$. With our choice of parameters, we get same value for this branching ratio. If we demand the lifetime of the heavy neutrino is less than $\sim 10^5$ sec to be consistent with the conventional mechanism for large scale structure formation [12], then we may put a lower limit $10^{-4} \sim 10^{-5}$ on the value of $f_{e\mu}$. So in this model we can more or less fix the parameters $f_{ab}$. As the global symmetry $G$ is spontaneously broken, there may be some additional tree level $\tau$ leptonic decay processes, like $\tau \to \mu \bar{\nu}_\mu \nu_e$, but this kind of processes are always proportional to the $f_{e\mu}$. Therefore the corresponding branching ratios are negligibly small.
**Extension of BH model**  
In order to incorporate SNP and ANP, BH model was extended to four neutrino species including one sterile neutrino $n$ \([13, 14]\). The symmetry group is extended to $G = U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_n$. The four neutrino species may make up one Dirac neutrino and one ZKM neutrino. Generally there are two possibilities to incorporate SNP. One is that $\nu_e$ and $\nu_C^C$ are combined to form a light ZKM neutrino, $\nu_\tau$ and $n$ (or $n^C$) make up a heavy Dirac neutrino with mass around 10 KeV. Applying the BFZ mechanism on the light ZKM neutrino part, one can generate a large transitional magnetic moment between $\nu_e$ and $\nu_\mu$, hence providing a spin-flavor precession solution to SNP \([14]\). However, in present case BFZ mechanism does not work since $f_{e\mu}$ is very small, and therefore the expected neutrino transitional magnetic moment is not large enough. Another possibility is that $\nu_\mu$ and $\nu_\tau$ are combined to form a heavy ZKM neutrino, and $\nu_e$ and $n$ (or $n^C$) make up a light Dirac neutrino. Both SNP and ANP can be solved naturally in this scheme resorting to the Planck scale effects \([14, 16]\). As in BH model the mixing angle $\theta_S$ between $\nu_e$ and the heavy neutrino could be naturally smaller than $10^{-3}$ due to the smallness of $f_{e\mu}$. In addition, with $\theta_S < 10^{-3}$ the decoupling temperature of the sterile neutrino $n$ in the early universe is higher than the QCD phase transition temperature, consequently the effective number of neutrino species at the time of nucleosynthesis is smaller than 3.3 \([14]\). Also, there are more $\tau$ leptonic decay channels in this case than in BH model, for example $\tau \to e\bar{\nu}_\mu n$ or $\tau \to e\bar{\nu}_\mu (n^C)$ could happen at tree level. But the amplitudes of the tree diagrams for these channels are proportional to light neutrino mass, so they are too small to give rise to any observable effect.

In summary, it is shown from above discussion that in Zee-type models the branching ratios of the $\tau$ leptonic decays are naturally smaller than the predictions of the SM. Therefore $\tau$ lifetime in these models is longer than that in the SM. This suggests a solution to $\tau$ decay puzzle. Moreover, the universality between $e$, $\mu$ and $\tau$ is not violated in the neutral current sector and is also respected in semi-leptonic decays of $\tau$. These are favored by current experimental data.
We discussed three Zee-type models in detail, but only concentrated on the issues which could be sensitive to the values of $f_{ab}$ fixed by solving $\tau$ decay puzzle. As to other issues, there are lengthy discussions in original papers on these models. We have analyzed three specific examples to illustrate the idea of how to incorporate $\tau$ decay puzzle and take into account other related issues of particle physics, cosmology and astrophysics. It is very possible that there are some other kind of models which can do the same job [22]. We used Zee-type models as an example, since we think that the models discussed above are among the most popular and simplest extensions of the SM.

All of the previous analysis are based on the $\tau$ decay data which implies existence of the $\tau$ decay puzzle. However, whether there is really a disagreement between experiment and the SM on $\tau$ lifetime is not very clear yet. In this work we used the data from PDG [3], however, meanwhile some new data have become available. In ref. [8], it is reported that the new world average data of $\tau$ decay agree with the SM within 1$\sigma$. Nevertheless the most precise measurement among these new experiments on $\tau$ leptonic decay from CLEO indicates the discrepancy is still around 2$\sigma$ [24, 25].

Anyway, further efforts on precision measurement of the $\tau$ decay is certainly very much desirable. A confirmation of the $\tau$ decay puzzle will imply some new physics beyond the SM, probably as suggested by the models with some singlet charged scalar particles, like Zee-type models, or models with triplet scalars. A negative result is of course another evidence in supporting the SM and will furthermore constrain the parameter space of these models.

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Fig. 1  Tree level diagrams which contribute to $\tau$ leptonic decay with additional scalar particles.