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ELECTRON SPECTRUM AND THE TAU DECAY WITH NEUTRINO MASS

EL ESPECTRO DE ENERGÍA DEL ELECTRÓN EN EL DECAIMIENTO DEL TAU CON LA MASA DEL NEUTRINO

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ABSTRACT. In order to illustrate the role of the combined tau neutrino mass and the V-A structure of the τ charged current we study the decay $\tau \rightarrow e \bar{\nu}_e \nu_\tau$ by relaxing their values within the standard model and observing their effects in the electron energy spectrum. The vector and axial coupling are considered by the Michel parameter. Taking the range values from the current experimental bound the ρ parameter is found be important while the ν_τ mass effect is mild.

KEYWORDS. Electron energy spectrum, Michel parameter, Accelerators of high energy, differential decay

RESUMEN. Para ilustrar el papel que juega la masa del neutrino del tau y la estructura de la corriente cargada V-A, se estudia el decaimiento $\tau \rightarrow e \bar{\nu}_e \nu_\tau$, al relajar sus valores dentro del modelo estándar y al observar sus efectos en el espectro de energía del electrón. Los acoplamientos vectorial y vectorial-axial son considerados por medio del parámetro de Michel ρ . Al tomar el rango de valores de las cotas experimentales actuales se encuentra que el parámetro ρ es importante mientras el efecto de la masa del ν_τ es muy ligero.

PALABRAS CLAVE. Espectro de energía del electrón, parámetro de Michel, aceleradores de alta energía, decaimiento diferencial

Introduction

The Standard Model (SM) is a gauge theory [1, 2], based on the symmetry groups $SU(3)_C \times SU(3)_L \times U(1)_Y$, which describes strong, weak and electromagnetic interactions, via the exchange of the corresponding spin-1 gauge fields: 8 massless gluons and 1 massless photon for the strong and electromagnetic interactions, respectively, and 3 massive bosons, W^+ , W^- and Z^0 , for the weak interaction. The fermionic-matter content is given by the known leptons: electron (e^-), electron-neutrino ($\bar{\nu}_e$), muon (μ^-), muon-neutrino ($\bar{\nu}_\mu$), tau (τ^-) and tau-neutrino ($\bar{\nu}_\tau$), and quarks: u (up), d (down), s (strange), c (charm), b (bottom) and t (top), which are organized in a 3-fold family structure:

$$\begin{pmatrix} \nu_e & u \\ e^- & d \end{pmatrix}, \begin{pmatrix} \nu_\mu & c \\ \mu^- & s \end{pmatrix}, \begin{pmatrix} \nu_\tau & t \\ \tau^- & b \end{pmatrix} \quad (1)$$

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where (each quark appears in 3 different "colors"). Plus the corresponding antiparticles. Thus, the left-handed fields (L) are $SU(2)_L$ doublets, while their right-handed (R) partners transform as $SU(2)_L$ singlets.

$$\begin{pmatrix} \nu_l & q_u \\ l^- & q_d \end{pmatrix} \equiv \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L,$$

$$\begin{pmatrix} q_u \\ q_d \end{pmatrix}_L, l_R^-, (q_u)_R, (q_d)_R,$$

The 3 fermionic families in [equation 1](#) appear to have identical properties; they only differ by their mass and their flavor quantum numbers. In particular, neutrinos are considered to be massless.

The SM constitutes one of the most successful achievements in modern physics. It provides a very elegant theoretical framework, which is able to describe all known experimental facts in particle physics. However, there are still pieces of the SM which so far have not been experimentally analyzed in any precise way due to their very low probability and the experimental limitations. It was not until 1998 that the SuperKamiokande collaboration [3] reported neutrino oscillations, whose strongest implication is the non-zero mass of the neutrinos, they found a squared mass difference between muon-neutrino (ν_μ) and tau-neutrino (ν_τ) of $(10^{-2} - 10^{-3}) \text{ eV}^2$, which has no prediction within the SM. Answers to the generation of fermionic masses via the Higgs mechanism in the so-called Yukawa sector can be found within the SM, but it is unable to predict such values.

The direct detection and evidence of oscillation of tau-neutrinos provide solid steps for a deeper understanding of the leptonic sector of the SM and offers new possibilities to explore. The importance is of such relevance in astrophysics and cosmology that an upper bound can be obtained from supernova explosions. The present upper limit on the ν_τ mass, $18.2 \sim \text{MeV} \cdot c^{-2}$ [4] allows a fraction of the proposed dark matter in the universe to consist of ν_τ . Also, a non-zero mass ν_τ might be involved in oscillation between the ν_τ and the ν_e or ν_μ [5]. The DONUT [6] experiment has confirmed in a direct way the existence of this last fermionic brick within the SM and the SNO collaboration [7] recently showed evidence for neutrino oscillations in both neutral and charged currents. The nature itself of the neutrinos is faced by the possible observation of the neutrinoless double Beta decay.

Doubtless, extensions of the SM will provide a new frame for the understanding of these phenomena, while revisiting the basic principles of symmetries and physical values [8]. In that sort, *Lepton universality, the lepton family independence of the axial and vector interactions*, is a long standing point that has been used to explore the nature and deviations of the interaction between particles.

The SM operates between elementary point particles, namely, leptons and quarks. Quarks are the elementary constituents of hadrons. Unfortunately the passage from quarks to hadrons remains as unsolved problem within the standard model. This passage corresponds to the strong interactions of the quarks in a non-perturbative regime. What is done is to work directly with hadrons and to introduce form factors by mean of the $V-A$ theory, where V is the vector current and A is the vector-axial current. In the case of τ decay,

which is a leptonic processes, the standard model reproduces the effective Hamiltonian of the $V-A$ theory taking the values $V=1$ and $A=-1$ for the coefficients of such currents (usually denoted with the same letter).

In this work we want to show in a simple fashion how the universality condition via the Michel parameter ρ , which in its most pristine form is defined as a function of the vector and axial couplings, and the tau neutrino mass can be combined to define a kinematic region where both of them are allowed within their current constrains. The electron emitted off, $\tau \rightarrow e \bar{\nu}_e \nu_\tau$ (see Figure 1.) decay is used to explore this, by observing its energy spectrum. Our aim in this work is to show how such conditions play in this observable rather than offering a more restrictive bound to the lepton universality and tau neutrino mass. An early work in the same process [9] placed a bound of <71 MeV, for the tau-neutrino mass. m_{ν_τ}

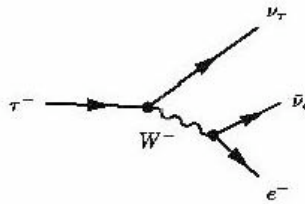


Figure 1. $\tau \rightarrow e \bar{\nu}_e \nu_\tau$ decay diagram

Traditionally this kind of studies is made by observing the leptonic branching ratios [10-12] and there the Michel parameters have been widely studied to include the possible beyond standard model contributions. This offers sound statistical results due to global factors cancellation. The case of the electron energy spectrum has also being considered to obtain the Michel parameters [13] but neglecting the tau neutrino mass. In this paper the estimate will be made by relying in general in the standard model approach and only we will release the values of the tau neutrino mass and the axial and vector couplings of the tau charged current.

We have organized this work as follows. We start by stating the conditions of our analysis for the decay amplitude and then we compute and plot the electron spectrum of the process as a function of the neutrino mass and the axial and vector couplings consistent with the current bounds for ρ . The last section is reserved for the conclusions of our work.

Tau Differential Decay Rate

In this section we compute the τ differential decay rate within the SM framework, but neither the vector and axial interactions nor the neutrino mass of the τ are kept fixed to those stated in the SM.

A. Michel parameter

The τ weak interactions through the $\tau - W - \nu_\tau$ and $\tau - Z^0 - \tau$ vertices agree with conventional theory. This agreement is partly based on measurements and partly on faith in universality of $V-A$ theory. To be specific, the coupling is of the form $\gamma^\mu(1 - \gamma^5)$, where γ^μ is the Dirac matrices tensor and γ^5 is built by the product of them. The term proportional to γ^μ gives birth to a vector current while the term proportional to $\gamma^\mu\gamma^5$ has an axial nature. It is in general agreed that the structure of the $\tau - W - \nu_\tau$ (see Fig. 1) vertex needs more testing.

Table I list the τ decay modes with branching fractions greater than about 5%, only the decay mode is listed. It is always assumed that the charge conjugate decay mode has the same branching fraction and other decay properties. $\tau^- \tau^+$

Table I: τ decay modes with branching fractions greater than 5% [4].

Decay mode	branching fractions(%)
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$	17.84 ± 0.06
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$	17.37 ± 0.06
$\tau^- \rightarrow \pi^- \nu_\tau$	11.06 ± 0.11
$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	25.41 ± 0.14
$\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$	09.17 ± 0.14
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$	07.10 ± 0.60

The current structure and thus universality condition, in its simplest form, is better referred to by the Michel parameter, ρ :

$$\rho = \frac{3}{4} \frac{(V - A)^2}{(V + A)^2 + (V - A)^2}$$

whose value is predicted by the SM be $3/4$, with $V=1$ and $A=-1$. The particle data group [4] reports an experimental value of $\rho = 0.747 \pm 0.010$, in accordance with the predicted one. We consider the allowed region for A and V consistent with this limits (see figure 2) by using the ρ definition and varying their values in such a way that the restriction holds.

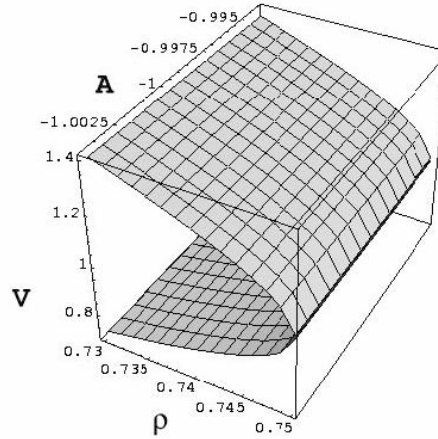


Figure 2. Region allowed for V and A consistent with the ρ bounds.

B. Neutrino mass

The discovery and confirmation of the existence and leptonic nature of the tau involved the indirect discovery of the ν_τ . The bounds for the tau neutrino mass are currently around $18.2 \text{ MeV } C^{-2}$. These are obtained by reconstructing multi-hadronic tau decays and analyzing events with very little energy released as two body decays, where the hadronic energy is bound for different neutrino masses [14]. There exist less restrictive bounds from other sources, which are interesting in its own because offer a wide landscape where the neutrino can be important, but are not of major utility in our work. It is worth mention that neutrino mass generation mechanism fits in the SM for the Yukawa sector without major modifications, although there was no motivation when first stated.

C. Electron energy spectrum

Under the above assumptions, we can now compute the probability of the decay. The Hamiltonian describing the process $\tau \rightarrow e \bar{\nu}_e \nu_\tau$ (with the four momenta assignation $\vec{p} \rightarrow k, q_1, q_2$ respectively) can be written as follow:

$$H_{eff} = \frac{G_F}{\sqrt{2}} \bar{\tau} \gamma_\mu (V + A \gamma_5) \nu_\tau \cdot \bar{\nu}_e \gamma_\mu (1 - \gamma_5) e,$$

where we assume that the electronic current is of the form $\gamma^\mu (1 - \gamma^5)$ [15] and $G_F = 1.66 \times 10^{-5} \text{ GeV}^{-2}$ is the Fermi constant, V and A account for the vector and axial current couplings in the tau side, and τ , ν_τ , ν_e and e denote the fields of the respective particles.

Thus the total decay amplitude is given by a similar construction with the fields replaced by the Dirac

spinors u and v accordingly.

$$M = \frac{G_F}{\sqrt{2}} [\bar{u}(q_2) \gamma_\mu (V + A \gamma_5) u(p)] [\bar{u}(k) \gamma_\mu (1 - \gamma_5) v(q_1)].$$

The squared amplitude after neglecting the electron and electron neutrino masses, which are relatively smaller than the values considered for the tau neutrino, can be written as follows

$$|M|^2 = 8G_F^2 \{ 2(V + A)^2 (q_1 \cdot q_2)(p \cdot k) + 2(V - A)^2 (k \cdot q_2)(q_1 \cdot p) - 2mM(V^2 - A^2)(k \cdot q_1) \} \quad (2)$$

where $M(m)$ is the $\tau(\nu_\tau)$ mass.

The energy spectrum for the electron in the τ rest frame is computed and written in function of the normalized electron energy $\varepsilon = \frac{E}{E_{\max}}$, with $E_{\max} = \frac{M^2 - m^2}{2M}$ the maximum electron energy allowed and $\beta = (1 - \frac{m^2}{M^2})$,

$$\frac{d\Gamma}{\Gamma_\mu d\varepsilon} = \frac{16N\varepsilon^2\beta^5(1-\varepsilon)^2}{(1-\varepsilon\beta)^3} \times \quad (3)$$

$$\left\{ \frac{2\rho}{9} (\beta(1-\varepsilon\beta))(1-\varepsilon) + (2-\varepsilon\beta)(2-\varepsilon\beta-\beta) + \rho'(1-\varepsilon\beta)^2 - \frac{m}{M}(1-\varepsilon\beta)\rho'' \right\},$$

where we have used the known width of the decay $\tau \rightarrow e \bar{\nu}_e \nu_\tau$ for massless neutrinos, $\Gamma_\mu = G_F^2 M^5 / 192 \pi^3$, as a normalization, and defined the following functions:

$$N = \frac{(V + A)^2 + (V - A)^2}{4},$$

$$\rho = \frac{3}{4} \frac{(V - A)^2}{(V + A)^2 + (V - A)^2},$$

$$\rho' = \frac{(V + A)^2}{(V + A)^2 + (V - A)^2},$$

$$\rho'' = \frac{V^2 + A^2}{(V + A)^2 + (V - A)^2}.$$

Results and Conclusions

We have introduced the standard Michel parameter ρ to characterize the universality condition, whose experimental value is in the range $\rho = 0.747 \pm 0.010$. The other parameters denoted ρ' and ρ'' are null for the case of $V=1$ and $A=-1$. Note that the dependence on the neutrino mass comes as a ratio to the tau mass and therefore is expected be highly suppressed. We have normalized the spectrum to γ^μ in order to focus in the dependence of the variables we are interested in, this also allow higher order contributions be implemented.

In figure 2 we plot the region spanned by A and V consistent with the ρ limits, we can see that their relative magnitude is important and that the main ρ dependence comes from the vectorial part. In fact, as is well known, the determination of the independent magnitudes can be only achieved by the measurement of other Michel parameter. We have just included this plot to show how freely they can be if no further restriction were included. In figures 3, 4 and 5 we have plotted the electron energy spectrum as a function of the ρ parameter for masses of the tau neutrino $m = 5, 10$ and 17 MeV respectively.

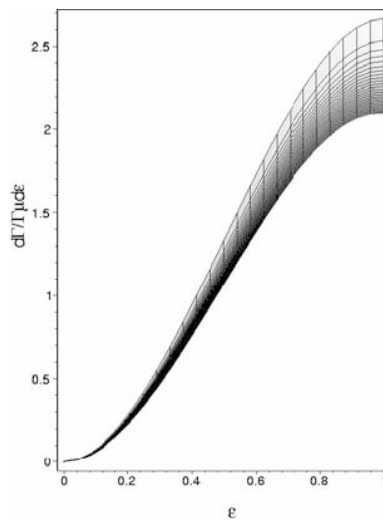


Figure 3. Electron energy spectrum for a tau neutrino mass of the width correspond to the ρ parameter limits

The electron energy spectrum shows a strong dependence to the $V-A$ structure of the current this can be seen in the width of the figure the top line of the shaded area correspond to the standard model value and the bottom line is the worst case for the V and A values satisfying the ρ experimental limits. The effect due to the neutrino mass is only observed by slightly changes at the very end of the energy spectrum where the competition between the mass and the maximum electron energy is crucial, it is reflected by the bending of the spectrum, relative o the zero mass case.

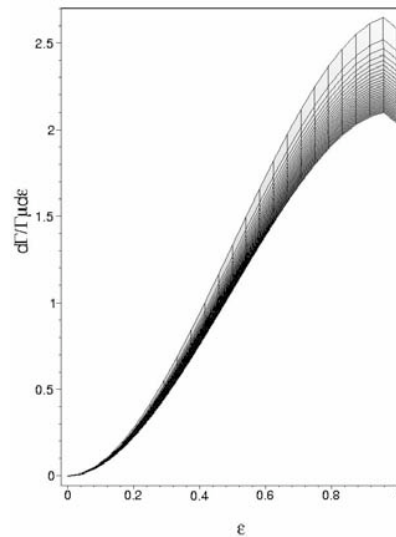


Figure 4. Electron energy spectrum for a tau neutrino mass of 10 MeV. The width correspond to the ρ parameter limits

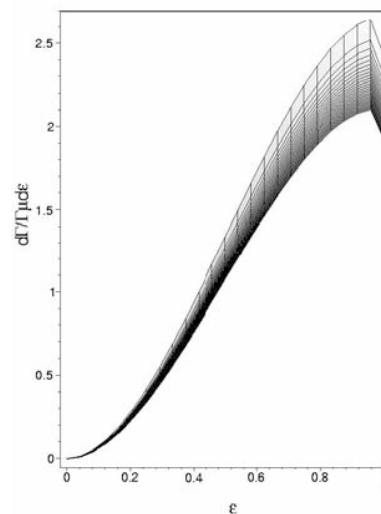


Figure 5. Electron energy spectrum for a tau neutrino mass of 17 MeV. The width correspond to the ρ parameter limits

Summarizing in the work we have used the decay $\tau \rightarrow e \bar{\nu}_e \nu_\tau$ to explore the sensitivity of the electron energy spectrum to the tau neutrino mass and the $V-A$ structure of the charged current. We have found that the neutrino mass effect is only important at the very end point region and even there the effect is mild, while the condition coming from the current structure of the tau appears being more important. Although the specific axial or vector nature of the deviation itself can not be stated, the global effect shows up important in most of the electron energy spectrum.

Acknowledgments

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