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A remark on the tau-neutrino mass limit

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Abstract

We point out that the usual experimental upper bounds on the tau-neutrino mass do not apply if neutrino mixing is considered. The suppression of the population of the tau decay spectrum near the end-point, caused by mixing, may be compensated by an enhancement due to a resonant mechanism of hadronization. It is necessary therefore to analyse the whole spectrum to infer some limit to the "tau-neutrino mass". We argue that, consequently, neutrino mixing evades the objection to interpret KARMEN anomaly as a heavy sequential neutrino.

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In the near future, one of the most important issue to be set by experimentalists, is the one of neutrino masses. Up to now, only upper bounds have been established for the three type of neutrinos [1,2]. In particular, concerning the tau-neutrino mass, the upper experimental limits for m_{ν_τ} are 31 MeV [3,4] or 29 MeV [5]. Recent analysis performed by OPAL [6] and ALEPH [16] Collaborations, using for the first time a two-dimensional technique i.e., invariant mass × total energy of the charged hadrons in the decay $\tau \to 5\pi\nu_\tau$ (OPAL) and $\tau \to 5\pi(\pi^0)\nu_\tau$ (ALEPH), give $m_{\nu_\tau} < 74$ MeV and < 24 MeV, respectively [8]. All these limits nevertheless come from analyses of the end point of the hadronic invariant mass distribution of the τ decays assuming no mixing effects among different neutrino species. Usually, it is assumed, and in fact it seems reasonable, that after the LEP measurements of the Z width the existence of sequential neutrinos with masses between the above upper bound and $M_Z/2$ has become unlikely. Nevertheless, this may not be the case if mixing does exist.

We will argue in the following that the presence of mixing among the three generations can radically change our knowledge about the upper bounds for the tau neutrino mass. Furthermore, a model independent limit for this quantity is not possible if only the end point of the spectrum is considered.

After the works of Shrock [9], it has been well known that massive neutrinos will produce additional peaks determined by m_i (mass of the ν_i neutrino, $i = 1, 2, 3$) in the charged lepton spectrum in the decays $\pi \to e(\mu)\nu_{e(\mu)}$ [10] or $K \to e(\mu)\nu_{e(\mu)}$ [11]. The weak eigenstates ν_l, $l = e, \mu, \tau$ are related to the mass eigenstateν_i by $\nu_l = \sum_i V_{li}\nu_i$, where V is a 3×3 unitary matrix. The first processes are then a sensitive test of mixing for neutrinos of mass in the range 50 to 130 MeV. The no observance of peaks lead to the upper limit for the mixing matrix elements $|V_{ei}|^2 < 10^{-7}$ [10]. However, in analyzing the data it was assumed that only one massive neutrino couples to electrons, i.e.,

$$R_{ei} = \frac{\Gamma(\pi \to e\nu_i)}{\Gamma(\pi \to e\nu_1)} = |V_{ei}|^2 \rho(\delta_e, \delta_i), \tag{1}$$

with ν_1 being a massless neutrino and $\rho(\delta_e, \delta_i)$ is a kinematic factor with $\delta_i = (m_i/m_\pi)^2$

and $\delta_e = m_e^2/m_\pi^2$. However, the pion decay constraint does not apply if the neutrinos have masses about or higher than pion mass $\sim 140\,\mathrm{MeV}/c^2$. Similar analyses have been done in kaon decays but they are not statistically significant [12]. The difference between two and three generation treatments (pointed out recently [13,14]) implies that the constraints above cannot be used straightforward for the three generation case. That is, it is possible that there exist truly three neutrino mixing effects which are not reduced to two neutrino mixing effective ones. So, it is important to reanalize the data on pion and kaon decays from the point of view of three generations. We will return to this point at the end of this paper.

With respect to the "tau neutrino mass" measurement in the decay $\tau \to 5\pi\nu_\tau$ we would like to emphasize the following. Assuming also a three generation mixing and that ν_τ in that decay is a mixing of mass eigenstates being ν_3 heavier than $\nu_{1,2}$ we get

$$\frac{d\Gamma}{dq^2} = \frac{G^2 V_{KM}^2}{8\pi m_\tau^3}\left[F_0 + c_\gamma^2 c_\beta^2 (F_3 - F_0)\right] h(q^2), \tag{2}$$

where

$$F_0 = \omega(q^2, m_\tau^2, 0)\lambda^{\frac{1}{2}}(m_\tau^2, q^2, 0), \quad F_3 = \omega(q^2, m_\tau^2, m_3^2)\lambda^{\frac{1}{2}}(m_\tau^2, q^2, m_3^2), \tag{3}$$

and

$$\omega(q^2, m_\tau^2, m_3^2) = (m_\tau^2 - q^2)(m_\tau^2 + 2q^2) - m_3^2(2m_\tau^2 - q^2 - m_3^2), \tag{4}$$

where λ is the usual triangular function, q^2 is the transferred momentum, $h(q^2)$ contains the hadronic structure and V_{KM}^2 denotes the quark mixing angles, in this case $V_{KM}^2 = V_{ud}^2$. We have used the parametrization of the mixing matrix of Ref. [13].

With the values of the mixing angles of Ref. [13], it is possible to see from Eqs. (2)-(4) that the resulting spectra when we employ nonvanishing value for m_3 are systematically about 20 times smaller than the spectrum obtained in the massless case, for regions with values of the hadronic invariant mass after the kink, $m_h = \sqrt{q^2} > m_\tau - m_3$ i.e., near the end point of the spectrum. This can be better appreciated in Fig. 2 of Ref. [13].

Experimental results show events with hadronic invariant mass very close to the charged tau lepton mass m_τ. Since there exists the mentioned suppression of a factor 20 for spectra with $m_3 \neq 0$, this experimental fact might be interpreted as an absence of kinks or, even if there is a kink, it is localized so close to m_τ that m_3 is constrained as discussed above [4–6].

Nevertheless such kind of analysis takes into account only the phase space contribution to the $\tau \rightarrow 5\pi\nu_\tau$ decay spectrum. One has to consider also the effect of possible resonant intermediate channels to this decay. This can radically change the population of this spectrum near the end point. In fact, in Ref. [15], some channels as $\tau \rightarrow \rho^0\rho^0\pi\nu_\tau$ were considered. They found an enhancement of the population of the spectrum near the massless end point of a factor of 30 when compared with the pure phase space contribution. The ALEPH Collaboration has recently performed a similar analysis and has also demonstrated that some resonant channels will equally increase the population of the spectrum in that region [16].

The spectral function $h(q^2)$ appearing in Eq. (2) does not depend on mixing parameters as well as the m_3 mass. Therefore this same function will alter the spectra where mixing is implemented and m_3 assumes nonvanishing values. In Fig. 1 we give an example of how this function, calculated assuming the resonant intermediate state $\rho^0\rho^0\pi$, significantly change the spectrum near the end point and can compensate the phase space suppression due to the mixing in this region. Based on Ref. [13], we use $m_3 = 165$ MeV, and $11.54^o < \beta < 12.82^o$ and $\gamma < 4.05^o$ to illustrate this phenomenon. (Note also that Bottino et al., in a recent analysis [17], have also found m_3 larger than the usually accepted experimental value.)

From this figure we see that the simple investigation of the end point part of the spectrum may not be sufficient to infer any information about the "tau neutrino mass". Both possibilities, the massless spectrum and that one obtained when a heavy neutrino is taken into account, overlap in that region, making it impossible to distinguish between them unless the contributions to this decay from resonant channels is well understood. This is not the case at present.

Furthermore the hadronization process which has to be taken into account in the calculation of intermediate channel contributions to the τ-decay spectrum is very model dependent. We can affirm that a conclusive and model independent limit for the "tau-neutrino mass" in hadronic decays is not possible if we have experimental information only near the end point of the spectrum.

Current limits for the "tau-neutrino mass" do not apply if neutrino mixing is considered, even a small mixing angle in vacuum may be sufficient to allow for the mentioned enhancement due to hadronization.

Let us go back now to the pion decays. Recently KARMEN Collaboration has reported, based on the charged and neutral current reaction $^{12}C(\nu_e, e)^{12}N$ and $^{12}C(\nu, \nu')^{12}C$, that a new neutral particle x, produced in the $\pi^+ \rightarrow \mu^+ x$, must has a mass of $m_x = 33.9$ MeV [18]. Identification of this massive neutral particle with the ν_3 has been ruled out by the ALEPH upper mass limit bound [16,18]. The possibility of the x-particle being a mainly-sterile neutrino has been pointed out in Ref. [19]. However, once one has convinced ourselves that the current upper values for the "tau-neutrino mass" are not valid when we have mixing, the possibility arises that KARMEN's x could still be interpreted as a heavy sequential neutrino.

The main point of this letter is that, to investigate if a large m_3 mass hypothesis is realized or not by nature, experimentalists must measure and fit the shape of the whole spectrum of $\tau \rightarrow 5\pi\nu_\tau$ decay, including regions far from the end point. Indications of a nonvanishing m_3 would be given by the characteristic kink vertically displaced from the phase space contribution to the spectrum by the spectral function. Although the form of this function is very model depend, the projection of the kink on the hadronic mass axis would be, in principle, model independent and a good observable for experimentalists.

Since the branching ration for this decay is of the order of 10^{-4}, present data are not sufficient to build the full relevant spectrum looking for kinks. This analysis requires large statistics. Tau factories would be necessary to achieve this goal.

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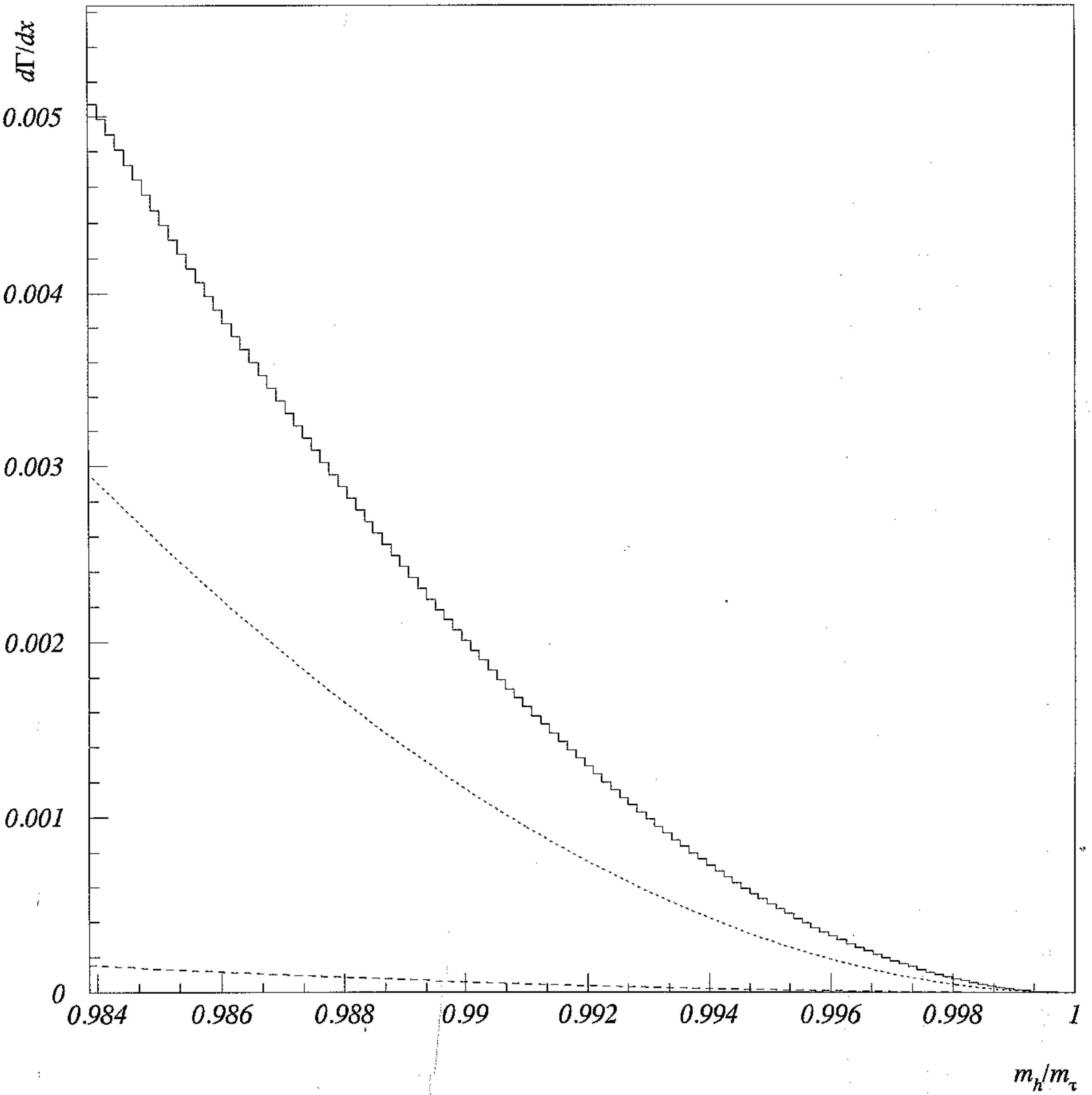

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0.004
0.003
0.002
0.001
0
0.984
0.986
0.988
0.99
0.992
0.994
0.996
0.998
1
m_h/m_τ