Pontecorvo oscillations and searches for the τ lepton in neutrino experiments

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It is proposed to use the Pontecorvo oscillations as a model for the search of the τ lepton in neutrino experiments, where the conditions are favorable for its detection via direct observation of tracks in emulsion.

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Weighty indirect evidence is presently available favoring the production of a heavy charged τ lepton with mass $m_\tau = 2$ GeV in experiments with colliding e^-e^+ beams.[1] This lepton has the following basic decay modes

$$\tau^- \to \nu_\tau e^- \bar{\nu}_e,\ \nu_\tau \mu^- \bar{\nu}_\mu,\ \nu_\tau + \text{hadrons}. \tag{1}$$

The relative probability of the lepton decay modes is equal in this case to ≈ 0.17.[1] The mean free path of such a lepton, in the case of a universal coupling in the weak interactions with its own new neutrino state ν_τ is $\approx 60\,000$ millimicrons in the nonrelativistic region and could be readily observed in a nuclear emulsion. Unfortunately, detection of this type is apparently impossible in colliding beams because of the specific features of the experiment.

It is of unusual interest to ascertain whether the τ lepton[1] is produced in contemporary high-energy neutrino experiments. Obviously, its production with a universal coupling constant G_F (i.e., $\nu_\tau \equiv \nu_\mu$) is definitely excluded by the neutrino-experiment data obtained in Batavia, Serpukhov, and CERN. Estimates show, however, that its production at the present time be excluded if the weak-interaction constant of the τ lepton is much less than the Fermi constant and is equal to $G_F \sin\theta$ at $\theta < \theta_C$, where θ_C is the Cabibbo angle.

We wish to point out in this article that if the τ lepton has the muon quantum number, then the principal link that could lead to a suppressed production of the τ lepton in neutrino experiments might be the Pontecorvo oscillations,[2] which lead to transitions of the muon neutrinos ν_μ into the τ neutrinos ν_τ, $\nu_\mu \longleftrightarrow \nu_\tau$. Let the left-hand weak-isotopic group representations connected with the muon and the τ lepton be of the form

$$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \tag{2}$$

$$\nu_\mu \equiv \nu_1 \cos\theta + \nu_2 \sin\theta, \quad \nu_\tau \equiv -\nu_1 \sin\theta + \nu_2 \cos\theta, \tag{3}$$

where ν_1 and ν_2 are stationary neutrino states with definite masses $m_1 \neq m_2 \neq 0$ and let θ be the lepton mixing angle. Since neither the muonic nor the τ neutrino is now a stationary state, $\nu_\mu \to \nu_\tau$ oscillations take place and the intensity of the τ-neutrino beam at a distance R from the ν_μ production point is[2]

$$I_{\nu_\tau} = \frac{1}{2}\sin^2 2\theta\,(1 - \cos 2\pi R/L(p))\, I^\circ_{\nu_\mu}, \tag{4}$$

where $L(p)$ is the length of the oscillations

$$L(p) = 4\pi p/|m_1^2 - m_2^2|, \tag{5}$$

p is the momentum of the muonic neutrinos and $I^0_{\nu_\mu}$ is their initial intensity. Assuming that the length of the oscillations is much shorter than the characteristic distances R, we obtain for the average ν_τ intensity in the detector

$$\bar{I}_{\nu_\tau} \approx 2\sin^2\theta\, I^\circ_{\nu_\mu}, \tag{6}$$

where explicit account is taken of the fact that the maximum mixing with $\theta = 45°$ has been excluded here, and it is assumed that $\sin^2\theta \lesssim \sin^2\theta_C \ll 1$. Consequently in our model the τ lepton should be produced in a beam of muonic neutrinos of high energy with a probability that is suppressed, apart from the threshold factor, only by the factor $2\sin^2\theta$. On the other hand, and this is most important, this lepton will decay without suppression via the channels (1), its lifetime will correspond to the universal Fermi constant and will not depend on the mixing angle θ.

In terms of energy, the τ lepton could be produced in neutrino experiments at Sepukhov and CERN at muonic-neutrino energies on the order of 10 GeV. Its mean free path would then be $l \approx 0.1$—0.3 mm. In the Batavia and the CERN-2 experiments, this length can increase by approximately one order of magnitude, $l \approx 0.1$—2 mm.[1)] Indirect detection of the τ lepton in the neutrino experiments is possible in principle on the basis of the excess of electrons and the excess of events with "neutral currents." The most important, however, is the direct method of detection of a τ lepton produced in neutrino experiments, by observing its tracks in an emulsion stack. Observation of a short track ≈ 0.1—2 mm, from which and electron, or a muon, or a hadron jet, emerges after the break, could possibly be a direct indication of the production of a τ lepton in neutrino experiments.[2)] These experiments are here patently superior in comparison with the colliding beams.

We note in conclusion that the scheme considered in[3] for mixing light and heavy leptons in the case with a heavy neutrino, which as applied to the τ leptons would mean the condition $m_{\nu_\tau} \gtrsim m_\tau$, might also lead to the production of a τ lepton in neutrino experiments, with a probability half as large for the same mixing angle, $\sim \sin^2\theta$. In this case, however, the lifetime and the mean free path of the τ lepton would increase by not less than one order of magnitude, and at $\theta \approx \theta_C$ this is probably excluded by the experimental data of the Batavia bubble chamber, since no centimeter tracks with characteristic breaks were observed. The Pontecorvo oscillations are attractive here also from the theoretical point of view.

The suggestion of searching for τ leptons in the neutrino experiments in an emulsion stack was made at the "Neutrino-77" International Conference (El'brus, June 1977) by one of us (E. M. L.), who is grateful to S. A. Bunyatov and V. M. Sidorov for a discussion and to Professor H. Faissner for interest.

[1)] The presented upper bounds for the τ-lepton mean free path corresponding to neutrino energies at which their intensity in the Serpukhov and Batavia spectra decrease by one order of magnitude in comparison with the maximum value.

[2)] We note that since the neutrino beam contains an admixture of electronic neutrinos ν_e from K decay, the observation of these events in neutrino experiments would by itself still not exclude the alternate hypothesis, that the τ lepton has the electron quantum number and oscillations of the electronic neutrinos and τ neutrinos take place, $\nu_e \leftrightarrow \nu_\tau$, while the mixing of the electrons and the τ leptons is maximal.

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