LOOKING FOR $\bar{\nu}_\mu \to \bar{\nu}_\tau$ OSCILLATIONS

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A search is performed for the antineutrino oscillation process $\bar{\nu}_\mu \to \bar{\nu}_\tau$ with 15′ bubble chamber data. Assuming maximal mixing, we obtain for the neutrino mass difference parameter $\Delta < 2.2$ eV^2 (90% c.l.). Alternatively, for $\Delta > 16$ eV^2 the transition probability is found to be less than 0.022 (90% c.l.).

Interest in neutrino oscillations [1] has recently been revived [2] in connection with reactor neutrino results [3], the μ/e puzzle in beam dump experiments [4], solar neutrino flux measurements [5] and indications in favour of a non-zero mass of the electron neutrino [6]. In the simplest case of two "mass" neutrinos mixed into two "current" neutrinos with angle α the transition between the "current" neutrinos occurs with a probability

$$P = \sin^2 2\alpha \sin^2(1.27\,\Delta L/E)\,, \quad (1)$$

where $\Delta = m_1^2 - m_2^2$ (eV^2), E and L stand for neutrino energy (MeV) and transition length (m), respectively. The low-energy data obtained at LAMPF [7] and CERN PS [8] indicate that $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, if any, are suppressed ($\Delta < 0.64$ eV^2 for $\sin^2 2\alpha = 1$). Also quoted in the literature are the experimental constraints on $\nu_\mu \to \nu_\tau$ transitions (90% c.l.):

$$P < 0.025 \quad (15' \text{ bubble chamber [9]})\,, \quad (2)$$

$$P < 0.0135 \quad (\text{hybrid emulsion experiment [10]})\,,$$

$$\Delta < 3 \text{ eV}^2 \quad (\text{assuming maximal mixing } \sin^2 2\alpha = 1). \quad (3)$$

In the presence of *CP*-violating effects the antineutrino oscillations could differ from neutrino ones and thus ought to be studied independently – the task we set ourselves in the present work.

We analysed the data from the Fermilab 15′ bubble chamber filled with a heavy neon–hydrogen mixture and exposed to a wide-band antineutrino beam (see

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ref. [11] for some details). Under our experimental conditions, the oscillation parameter L/E lies in the range 0.02–0.1 m/MeV. We look for the antineutrino oscillations $\bar{\nu}_\mu \to \bar{\nu}_\tau$ with subsequent tau-lepton production and decay

$$\bar{\nu}_\tau + \mathrm{N} \to \tau^+ + \text{hadrons}, \qquad \tau^+ \to e^+ \bar{\nu}\nu . \tag{4}$$

The $\bar{\nu}_\tau$ spectra from the transition $\bar{\nu}_\mu \to \bar{\nu}_\tau$ calculated with due account taken of the measured $\bar{\nu}_\mu$ spectrum and the geometric outlay of the experiment are given in fig. 1 for some values of Δ (assuming $\sin^2 2\alpha = 1$). As expected from (1) these display an oscillatory behaviour. For $\Delta < 10\ \mathrm{eV}^2$ the $\bar{\nu}_\tau$ spectrum is significantly softer than the initial $\bar{\nu}_\mu$ spectrum (also reproduced in the figure). Therefore the tau production threshold is expected to spoil the sensitivity in this region.

Next we compare our data on the muonless e^+ production [12] with the Monte Carlo simulation for the expected e^+ signal from tau production and the decay process (4). The analysis is performed with the variables [12]

$$z = p_e / P^{\parallel}_{\mathrm{vis}} ,$$

$$u_{\mathrm{vis}} = x_{\mathrm{vis}}(1 - y_{\mathrm{vis}}) \approx (P^{\perp}_{\mathrm{vis}})^2 / (2 M_p P^{\parallel}_{\mathrm{vis}}) , \tag{5}$$

where p_e stands for positron momentum, $P^{\perp}_{\mathrm{vis}}$ ($P^{\parallel}_{\mathrm{vis}}$) – for the event overall visible momentum perpendicular (parallel) to the neutrino beam direction; x_{vis} and y_{vis} are the visible values of the popular scaling variables. Obviously large z_{vis} and small u_{vis} values are typical for direct $\bar{\nu}_e$N charged-current interactions responsible for the bulk of the muonless e^+ sample (see fig. 2 of ref. [12]). On the other hand, the two neutrinos emitted in tau decay tend to push down z and to increase u_{vis} as they carry away some longitudinal as well as transverse momentum of the tau lepton. Quantitatively, the cuts

$$u_{\mathrm{vis}} > 0.02 , \quad z < 0.5 , \tag{6}$$

seems reasonable, as thereby most of the $\bar{\nu}_e$ background is removed while ≈0.3 of the signal $\tau \to e\bar{\nu}\nu$ survives.

Shown in fig. 2 is the MC-calculated signal $\tau^+ \to e^+\bar{\nu}\nu$ as a function of the mass splitting parameter Δ assuming $\sin^2 2\alpha = 1$ [upper curve – no cuts, lower curve – cutoff conditions (6)]. The signal is scaled to the total $\bar{\nu}_\mu$ charged-current rate (in an assumption that oscillations are absent). The straight lines correspond to the asymptotic level ($\Delta \to \infty$) which is just the expected τ^+–$e^+\bar{\nu}\nu$ rate for the $\bar{\nu}_\tau$ flux euqal to 1/2 times the $\bar{\nu}_\mu$ flux. The sharp fall-off of the rate for $\Delta < 10\ \mathrm{eV}^2$ is caused on the one hand by the depletion of the $\bar{\nu}_\tau$ flux, on the other by the tau-lepton production threshold effects. The sensitivity is best around $\Delta = 30\ \mathrm{eV}^2$ where tje rate exceeds the asymptotic value.

Of the observed muonless e^+ sample (74 events), a single event falls within the area delimited by (6). With

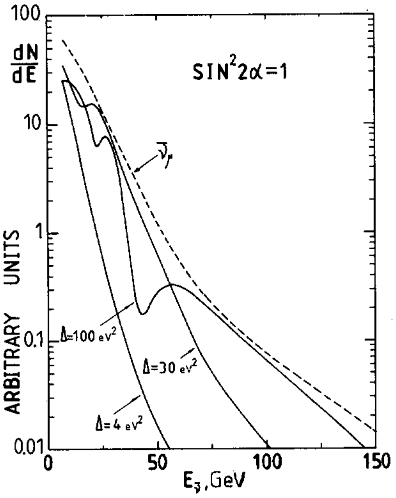

Fig. 1. Measured $\bar{\nu}_\mu$ spectrum and calculated $\bar{\nu}_\tau$ spectra for some values of the neutrino mass splitting parameter Δ.

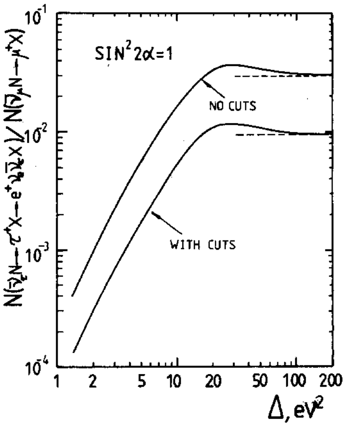

Fig. 2. Calculated $\tau^+ \to e^+\bar{\nu}\nu$ relative rate as a function of Δ. Upper curves – no cuts, lower curve – cutoff conditions (6) (see text).

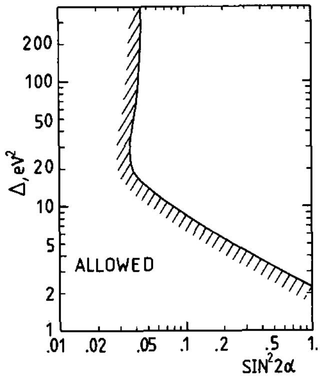

Fig. 3. Allowed 90% c.l. region in the (Δ, $\sin^2 2\alpha$) plane.

due account taken of the expected $\bar{\nu}_e$N background (3.8 events) this corresponds to the 90% c.l. upper limit of 2.7 events for the posisible effect [‡1]. Normalizing to the observed 8400 $\bar{\nu}_\mu$ charged-current events and taking into account the e^+ identification efficiency ($\approx$0.83), we obtain the allowed region in the (Δ, $\sin^2 2\alpha$) plane (see fig. 3). Assuming maximal mixing of $\sin^2 2\alpha = 1$, we have $\Delta < 2.2$ eV^2 (90% c.l.). Alternatively, for $\Delta > 16$ eV^2 we have the 90% c.l. upper constraint on the transition probability

$$P(\bar{\nu}_\mu \to \bar{\nu}_\tau) < 0.022 \qquad (7)$$

(or $\sin^2 2\alpha < 0.044$) to be compared with (2), (3) [‡2]. It should be noted that contrary to (2) this result is fairly independent of electron antineutrino flux calculations.

The contribution to this experiment of the scanning measuring and secretarial staffs of our respective laboratories is gratefully acknowledged.

‡1 For the confidence level c.l. associated with a given upper limit N and an observed value k in presence of expected background n_b we have (see ref. [13])

$$1 - \text{c.l.} = e^{-N}[1 + (N + n_b) + ... + (N + n_b)^k/k!]$$
$$\times (1 + n_b + ... + n_b^k/k!)^{-1} .$$

In the limit $n_b \to 0$ this reduces to the familiar expression

$$1 - \text{c.l.} = e^{-N}(1 + N + ... + N^k/k!) ,$$

which yields $N = 3.9$ for c.l. = 90% and $k = 1$.

‡2 Our results are reasonably stable in respect to the variations of the cutoff parameters. Thus, with the alternative cuts $u_{vis} > 0.03$, $z < 0.6$ which have approximately the same acceptance to the effect as (6) and remove all but 3 events, the upper limit on Δ is changed by no more than 30%.

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