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January 1992

AN OVERVIEW OF THE EVIDENCE FOR $\nu_e \leftrightarrow \nu_\tau$ OSCILLATIONS

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Invited talk at the Second International Workshop on Theoretical and Phenomenological Aspects of Underground Physics (TAUP 91), Toledo, Spain 9-13 September 1991.

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AN OVERVIEW OF THE EVIDENCE FOR $\nu_e \leftrightarrow \nu_\tau$ OSCILLATIONS

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1. INTRODUCTION AND OUTLINE

This review will examine the evidence for $\nu_e \leftrightarrow \nu_\tau$ oscillations emerging from

i) the recent analysis [1,2] of the prompt neutrino data obtained at high energy accelerators and

ii) the observation of the first event probably due to a ν_τ interaction in experiment E-745 at Fermilab [3].

Some relevant cosmological consequences will also be presented.

2. PROMPT NEUTRINOS AND $\nu_e \leftrightarrow \nu_x$ OSCILLATIONS

Prompt neutrino experiments are performed by making the proton beam from the accelerator interact in a target, the "dump", several interaction lengths thick. Copiously produced long-lived pions and kaons are mostly reabsorbed in the dump, thus largely reducing the yield of ordinary neutrinos from their decays. This allows the detectors, placed downstream of a muon filter, to be sensitive to the much weaker source of prompt neutrinos from semileptonic decays of charmed particles. Prompt neutrino rates are obtained either by "subtraction" of the calculated non-prompt component or by "extrapolation to infinite density" of the event rates measured at various dump densities.

Electron-muon universality guarantees the equality of the ν_e and ν_μ fluxes [4], independently of the charmed particle production process. Thus, since the ν_μ can be considered stable in view of the very tight experimental limits on its oscillations [5], any positive difference between the ν_μ and ν_e fluxes observed at some distance from the source could be attributed to a depletion of the ν_e flux due to some instability of the ν_e.

In the case of oscillations, the probability of an initial electron-neutrino ν_e of energy E being equal to another neutrino ν_x at a distance L is [6]

$$P(\nu_e \leftrightarrow \nu_x) = \sin^2(2\alpha) \cdot \sin^2(1.27 \cdot \Delta m^2 \cdot L/E) \quad (1)$$

where: α is the "mixing angle"

$\Delta m^2 = m^2_{\nu e} - m^2_{\nu x}$ in eV^2

L/E in km/GeV.

The oscillatory character of the phenomenon is entirely contained in the second $\sin^2$ factor in equation (1). To observe this in an experiment, the condition

$$E/L \approx \Delta m^2 \quad (2)$$

must be fulfilled, since $P(\nu_e \leftrightarrow \nu_x)$ vanishes for $E/L \gg \Delta m^2$ and equation (1) reduces to

$$P(\nu_e \leftrightarrow \nu_x) = 0.5 \cdot \sin^2(2\alpha) \quad (3)$$

for $E/L \ll \Delta m^2$.

Prompt neutrino experiments, in which both E and L are known for each event, provide the only experimental technique available so far for the study of ν_e oscillations with Δm^2 in the range $100 \lesssim \Delta m^2 \lesssim 1000$ eV^2.

Several prompt neutrino experiments have been performed so far [7-13]. Leaving aside the Fermilab experiment of ref. [10], which explored the region $\Delta m^2 > 1000$ eV^2, in the following the attention will be focussed on the experiments carried out at CERN in 1979 and 1982.

Traditionally, experimental results are expressed in terms of the asymmetry A, the difference between the ν_μ and ν_e fluxes divided by their sum, which has a

practically Gaussian behaviour [10]. The data from the CERN experiments where originally analysed using an integrated asymmetry, obtained by first summing event rates over all energies. This procedure has been shown to entail a loss of sensitivity and better tests for the existence of oscillations are possible when the event energy spectra are available [1].

Assuming all statistical and systematic errors to be normally distributed, the weighted average of the statistically independent values of the asymmetry for each energy bin can be calculated, taking in due account the correlation of the systematic errors. This quantity, which properly weights each contribution according to its variance rather than its number of events, must also vanish in the absence of oscillations. In fact, in this case, electron-muon universality requires that the ν_e and ν_μ event energy spectra, in addition to equal integrals, must have practically identical shapes and this implies vanishing values of the asymmetry for each energy bin. The integrated asymmetry tests the equality of event spectra integrals, while the weighted-averaged asymmetry tests the equality of both integrals and shapes.

YEAR	EXPERIMENT			
	BEBC	CDHS	CHARM	CERN
1979	$0.08^{+0.27}_{-0.44}$	$0.31 \pm 0.10 \pm 0.07$	$0.35 \pm 0.10 \pm 0.09$	0.31 ± 0.09
1982	$A^+ = 0.28 \pm 0.44$ $A^- = -0.19 \pm 0.31$	$0.14 \pm 0.06 \pm 0.04$	$0.25 \pm 0.09 \pm 0.07$	0.16 ± 0.06
79+82	0.00 ± 0.21	0.18 ± 0.06	0.29 ± 0.08	0.21 ± 0.05

TABLE 1

Determinations of the asymmetry A= ($\nu_\mu$flux − $\nu_e$flux)/($\nu_\mu$flux + $\nu_e$flux) from the 1979 (ref.[7-9]) and 1982 (ref.[11-13]) CERN experiments. Compared to published results, the BEBC 1982 errors have been multiplied by the relevant scale factor[1] and the CDHS 1979, CDHS 1982 and CHARM 1982 results have been obtained by weighted-averaging the values of A obtained for each energy bin. When two errors are given, the first is statistical, the second systematic. To combine results from different experiments, they have been added in quadrature. The weighted averages of the results obtained either in the same beam or in the same apparatus are reported in the right hand column and in the bottom line respectively.

Table I gives a summary of the experimental values of A obtained by using this procedure.

The CERN 1979 and CERN 1982 values are both only about three standard deviations away from A = 0. However, the combined result A = 0.21±0.05 differs from zero by more than four standard deviations and its confidence level for A≤ 0 is 6.1×10^{-6}.

A second method, based on an extensive Monte Carlo program in which event rates are assumed to have Gaussian distributions and systematic errors are taken to be uniformly distributed, yields a confidence level for A≤0 of 2×10^{-5}.

Thus, although no result is by itself significantly different from zero, the over-all confidence level for A≤0 is unacceptably small. This implies the existence of some new phenomenon. In particular, it supports the notion that ν_e oscillations may actually exist.

To investigate whether the observed non-vanishing value of A could be interpreted in terms of $\nu_e \leftrightarrow \nu_x$ ($x \neq \mu$) oscillations, the available information on the asymmetry A as a function of energy has been examined as a function of the quantity L/E . A χ^2 fit in terms of an asymmetry in which the ν_e flux is modulated according to (1) gives a unique solution with a $\chi^2 = 3.9$ for 12 degrees of freedom. An estimate of the systematic errors on the fitted parameters is obtained by shifting in turn all values of the asymmetry belonging to the same experiment by one systematic standard deviation and by adding in quadrature the resulting variations of the results. The final result of the fit is

$$\sin^2 2\alpha = 0.48 \pm 0.10 \pm 0.05 \qquad (4)$$

$$\Delta m^2 = (377 \pm 27 \pm 7)\ \mathrm{eV}^2 \qquad (5)$$

The data used as well as the fitted dependence of A on L/E are shown in figure 1. The weighted average of the data displayed is A = 0.10±0.04± 0.02, corresponding to a confidence level for A≤0 of 2.4×10^{-4}.

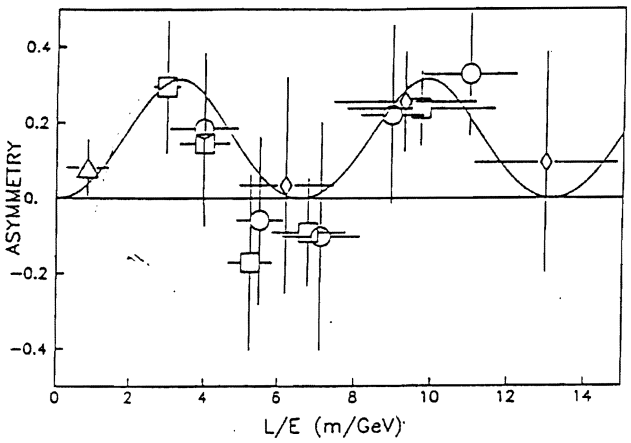

FIGURE 1

Measurements of the asymmetry A = ($\nu_\mu$flux − $\nu_e$flux)/($\nu_\mu$flux+$\nu_e$flux) as a function of the ratio of L (distance of the detector from the source in m) to E (neutrino energy in GeV). The data from ref. [10] (triangles), [12] (squares) and [13] (circles) are for E> 40 GeV, those from ref.[8] (diamonds) for E> 60 GeV. In order to obtain comparable intervals of L/E, some data have been grouped together. At each point, the horizontal bar represents the L/E interval for the point. The errors shown are statistical only. The full line represents the results of a fit in terms of ν_e oscillations with $\Delta m^2 = 377$ eV^2 and $\sin^2 2\alpha = 0.48$.

Asymmetries derived from integral rates are expected to be approximately experiment-independent and equal to A = 0.14, as calculated from (3) and (4). This value is in excellent agreement with the weighted average of the CERN results based on integral rates, A $= 0.15 \pm 0.05$.

Thus, while the no-oscillation hypothesis does not agree with the experimental results, the oscillation hypothesis actually does.

The value of $\sin^2 2\alpha$ quoted in eq. (4) is compatible with the most stringent upper limit [5] within about two standard deviations.

3. THE IDENTITY $\nu_x \equiv \nu_\tau$

In the $\nu_x \equiv \nu_\tau$ hypothesis, the most conspicuous effect to be expected is an excess of neutral current-like events due to ν_τ charged current interactions followed by τ decays into ν_τ plus hadrons. This effect is confined to visible energies below 20 GeV.

The visible energy spectrum of prompt events not induced by ν_μ interactions obtained in the experiment of ref. [13] is shown in figure 2.

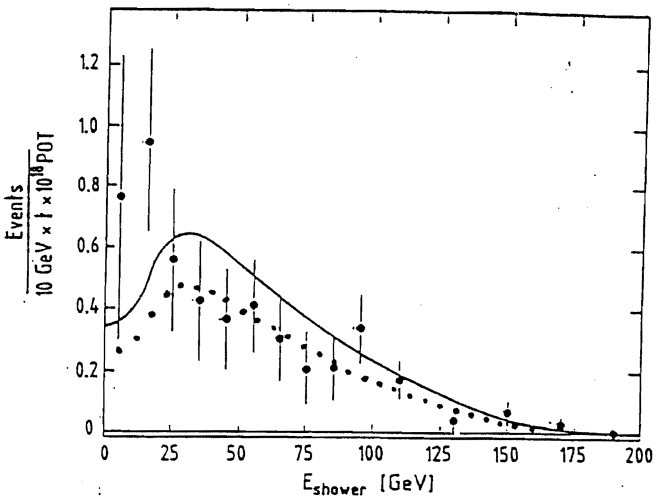

FIGURE 2

The visible energy spectrum of prompt events not induced by ν_μ interactions obtained in the experiment of ref. [13]. The full line shows the result of the charm production model used in the experiment, normalized to the whole energy range. The dotted line represents the same curve, normalized to the data above 20 GeV.

The full line shows the result of the charm production model used in the experiment, normalized to the whole energy range. The model gives a rather unsatisfactory description of the data, the points below (above) 20 GeV being above (below) the curve. To investigate whether an excess is present below 20 GeV, the prediction of the model of ref. [13] has been normalized to the data above 20 GeV. This new curve, represented by the dotted line in fig. 2, gives a much better description of the data above 20 GeV but causes an excess to appear below 20 GeV. The confidence level for the compatibility with zero of this excess is 1.3×10^{-2}.

Similar considerations, applied to the other existing data, yield the results reported in Table II.

dominated by the mass of the tau. Assuming a similar hierarchy to apply also to neutral leptons, the result of eq. (5) implies for the mass of the tau-neutrino

$$m_{\nu_\tau} = (19.4 \pm 0.7)\ \mathrm{eV}. \qquad (6)$$

The existence of a neutrino with a mass of about 20 eV implies in turn that the universe is dominated by neutrinos. Neutrinos can easily saturate the condition for a critical universe and must be responsible for the bulk of dark matter.

The mass of the tau-neutrino is related to the energy density of the universe Ω and to the Hubble parameter H_o. The latter two quantities are in turn related to the age of the universe t_u [17].

For $\Omega = 1$ (and $\Omega_{baryons} = 100/H_o^2$), eq. (6) implies the results

$$H_o = (45.8 \pm 0.8)\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$t_u = (14.2 \pm 0.3)\ \mathrm{Gyr}$$

in agreement with present observational evidence.

AKNOWLEDGMENTS

The skillful efforts of G. Giarrizzo and M. Masi in the editing of the text are gratefully aknowledged.

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