UP-DOWN ASYMMETRY OF NEUTRAL CURRENT EVENTS AS A DIAGNOSTIC FOR $\nu_\mu - \nu_{st}$ VERSUS $\nu_\mu - \nu_\tau$ OSCILLATIONS

JOHN G. LEARNED$^1$, SANDIP PAKVASA$^1$ and J. L. STONE$^2$

$^1$Department of Physics & Astronomy, University of Hawaii at Manoa
Honolulu, HI 96822 USA

and

$^2$ Department of Physics
Boston University
Boston, MA 02215

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Abstract

We show that the asymmetry in the neutral current events (e.g. $\nu N \to \nu N \pi^0$) can be used to discriminate between $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_{st}$ mixing as being responsible for the atmospheric neutrino anomaly. Specifically, $A_N$ vanishes for $\nu_\mu - \nu_\tau$ mixing and is about $2/3 A_\mu$ for $\nu_\mu - \nu_{st}$ mixing.
The neutrino oscillation interpretation of the atmospheric neutrino seems more and more probable with the new data from Superkamiokande. If this holds up, it is very important to determine the specific oscillation scenario at work here. Recently, it was shown how the up-down asymmetry of the charged current events with muons and electrons is a strong discriminator for many different scenarios. Preliminary results for the asymmetry from Superkamiokande favor $\nu_\mu$ oscillating into $\nu_\tau$ (or $\nu_{\text{sterile}}$). However, this asymmetry does not distinguish between the possibility of $\nu_\mu - \nu_\tau$ oscillations and $\nu_\mu - \nu_{\text{st}}$ oscillations. The reason for this is that at the energies in question ($E_\nu < 10 \, \text{GeV}$) there are not enough $\nu_\tau$ charged current events to be recognised, due to the small cross-section below about 20 GeV. Here we extend the asymmetry to neutral current events (e.g. $\nu N \to \nu N \pi^0$) and show how this asymmetry can be used to distinguish easily between the two possibilities. We assume here that the correlation between the direction of $\nu N \to \pi^0$ is given by

$$A = \frac{D - U}{D + U}$$

where $D$ is the number of downward-going events and $U$ is the number of upward-going events. $A$ can be defined for both muon charged current events $A_\mu$, as well for single $\pi^0$ neutral current events $A_N$. We assume the detector to be up/down symmetric, and the data set to be free of significant background.

We now calculate this asymmetry for the cases of interest: (i) $\nu_\mu - \nu_\tau$ oscillations and (ii) $\nu_\mu - \nu_{\text{st}}$ oscillations.

I. $\nu_\mu - \nu_\tau$ MIXING

The $\nu_\mu$ flux is modified as

$$N_\mu = N_\mu^0 P_{\mu\mu}$$

where $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E}\right)$ and $N_\mu^0$ is the flux of $\nu_\mu$'s in absence of oscillations. At very low energies, $P_{\mu\mu} \approx 1 - \frac{1}{2} \sin^2 2\theta$ and $A_\mu \to 0$. At higher energies, L/E is negligible for down $\nu_\mu$'s and hence $N_\mu^d = N_\mu^0$. For upward going $\nu_\mu$'s, $N_\mu^u = P_{\mu\mu} N_\mu^0$ and

$$A_\mu = \frac{1 - P_{\mu\mu}}{1 + P_{\mu\mu}} \approx \frac{\sin^2 2\theta}{4 - \sin^2 2\theta}$$

which has a maximum of $1/3$ for $\sin^2 2\theta \approx 1$.

In the $\nu_\mu - \nu_\tau$ case, since total flux of flavor neutrinos: $N_{\nu_e} + N_{\nu_\mu} + N_{\nu_\tau}$ does not change, the neutral current asymmetry $A_N$ is zero.

II. $\nu_\mu - \nu_{\text{ST}}$ MIXING

In this case $A_\mu$ is the same as in the $\nu_\mu - \nu_\tau$ case. The asymmetry $A_N$ in neutral current events is given by

$$A_N = \frac{(N_{\bar{\nu}_e}^d + N_{\bar{\nu}_e}^u) - (N_{\bar{\nu}_e}^d + N_{\bar{\nu}_e}^u)}{(N_{\bar{\nu}_e}^d + N_{\bar{\nu}_e}^u) + (N_{\bar{\nu}_e}^d + N_{\bar{\nu}_e}^u)}$$

$$A_N \approx \frac{N_{\bar{\nu}_e}^d - N_{\bar{\nu}_e}^u}{N_{\bar{\nu}_e}^d + N_{\bar{\nu}_e}^u + N_{\bar{\nu}_e}^d + N_{\bar{\nu}_e}^u + N_{\bar{\nu}_e}^u} \approx \frac{1}{1 + \left\{\frac{A_\mu}{1 + r(1 + A_\mu)}\right\}}$$

Here $r = N_{\bar{\nu}_e}^0 / N_{\bar{\nu}_e}^0$ and for $r \approx 0.45$ to 0.37 ($E_\nu$ up to 5 GeV), and $A_\mu$ near 1/3, $A_N$ is in the range 0.2 to 0.22.

In Fig. 1 we show a plot of $A_\mu$ and $A_N$ as functions of $E_\nu$ for $\sin^2 2\theta \approx 1$ and $\delta m^2 \approx 5.10^{-3}$ eV$^2$. At low energies the small negative asymmetry in the $\nu_\tau$ flux due to the earth magnetic field effects
makes $A_N$ non-zero in the case of $\nu_\mu - \nu_\tau$ mixing and dilutes $A_N$ in the $\nu_\mu - \nu_\st$ mixing. We calculated energy spectra between 0.2 and 5.0 GeV for a detector with an exposure of 22 kiloton-years (approximately one year of Super-Kamiokande data). We use the Bartol flux model, and a simple quark model for the cross-sections, and assume a perfect detector. Detailed calculations for a particular instrument will of course vary, but the asymmetry will change little, the general behavior being insensitive to details. Matter effects (which are present for $\nu_\mu - \nu_\st$ mixing but absent for $\nu_\mu - \nu_\tau$ mixing) and the angular spread will be discussed elsewhere, but should have no major effect on the different behavior in the two cases discussed here. A different method to distinguish $\nu_\mu - \nu_\tau$ mixing from $\nu_\mu - \nu_\st$ mixing has been proposed recently. This technique depends on the fact that the ratio of the neutral current event rate to the charged current event rate is quite different in the two cases. The method we propose here has the advantage that it is independent of the efficiency for detecting $\pi^0$'s and of the knowledge of neutral current cross-sections.

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FIG. 1. The trajectories of muon asymmetry and neutral current asymmetry for $\nu_\mu - \nu_\tau$ mixing, for $\nu_\mu - \nu_{st}$, mixing, and for no oscillations.