Measuring the ν_μ to $\overline{\nu_\mu}$ ratio in a high statistics atmospheric neutrino experiment

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By exploiting differences in muon lifetimes it is possible to distinguish ν_μ from $\overline{\nu_\mu}$ charged current interactions in underground neutrino detectors. Such observations would be a useful tool in understanding the source of the atmospheric neutrino anomaly. [S0556-2821(99)06111-1]

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I. INTRODUCTION

The atmospheric neutrino anomaly [1–3] is the discrepancy between the observed and expected rate of electron and muon neutrino interactions in underground detectors. In general it is believed that these neutrinos originate in the Earth's atmosphere as a consequence of the decay of short lived particles created by cosmic ray interactions.

The most popular explanation for the source of the anomaly is the oscillation of muon neutrinos. A number of hypothetical solutions have suggested a new form of interaction. For example Ma and Roy [4] point out that a new diagonal neutral current interaction for the ν_τ could produce a coherent picture for all current neutrino problems [solar [5], atmospheric and Liquid Scintillation Neutrino Detector (LSND) [6]]. Such new interactions would have different effects on neutrinos and antineutrinos so there is some interest in distinguishing ν from $\overline{\nu}$. In general a charged current neutrino interaction produces a charged muon or electron. The sign of the charge can be used to infer the particle/antiparticle nature of the interacting neutrino.

Morphological methods have been employed to distinguish charged current muon and electron events. But the effect was initially recognized when the fraction of event containing a muon decay signature was considerably below expectations [1].

This paper points out that CPT violating differences in the detector itself make it possible to distinguish on a statistical basis between ν_μ and $\overline{\nu_\mu}$ induced interactions.

II. THE METHOD

Due to the possibility of muon capture [7] the μ^- has a larger decay width than μ^+ when stopped in normal matter:

$$\Gamma_{\mu^+}=\Gamma_\mu=1/\tau_+$$

$$\Gamma_{\mu^-}=\Gamma_\mu+\Gamma_{Capture}=1/\tau_- .$$

This leads to a shorter lifetime for μ^- than for μ^+ when they decay in ordinary matter. The effect may not be large. It is about 18% for muons in water but increases with Z so is more pronounced in heavier materials.

The observed time distribution for muon decays is the weighted sum of the two exponential decay distributions:

$$f_- e^{-t/\tau_-}+(1-f_-)e^{-t/\tau_+}$$

where f_- is the fraction of decays due to a μ^- and τ_- and τ_+ are the *known* decay lifetimes for the μ^- and μ^+ respectively in the detector environment.

The mean value of the measured lifetime of a mixture of μ^- and μ^+ is then

$$\tau_{Observed}=f_-\tau_-+(1-f_-)\tau_+=\tau_+-f_-(\tau_+-\tau_-)$$

or

$$f_-=\frac{\tau_+-\tau_{Observed}}{\tau_+-\tau_-}$$

where $\tau_{Observed}$ is the measured value for the mean muon decay time in the muon neutrino sample.

In general detectors only sample the muon decay rate in a time window following the interaction so that there is a correction to this expression for truncation of the interval. For a data sample restricted to the time range $t_1<t<t_2$, $\tau_\pm$ in the expression above is modified to

$$\tau_\pm\rightarrow\tau_\pm\frac{e^{(t2-t1)/\tau_\pm}\left(1+\frac{t_1}{\tau_\pm}\right)-\left(1+\frac{t_2}{\tau_\pm}\right)}{e^{(t2-t1)/\tau_\pm}-1}.$$

A cleaner result might be obtained by fitting the observed time distribution to extract f_- (and confirm the values of τ_+ and τ_-). A number of consistency checks are possible. The fraction of decays attributable to μ^- decreases more rapidly than for μ^+ so one may get a more accurate measurement by using a delayed sample of decays. All such temporal subsamples must yield a consistent value for f_-.

With sufficient statistics this method can be exploited in bins of neutrino energy or flight distance which are the relevant observables for the oscillation hypothesis. Vacuum oscillations should show no difference in the μ^+ to μ^- fraction so differences would be a clear indication of new physics.

III. COMPLICATIONS

The value of f_- is a measurement of the μ^- fraction of the muon decay sample. It is at best an indirect measurement of the ν_μ to $\overline{\nu_\mu}$ flux ratio. The cross sections for interaction of these two neutrino types are quite different so the observed value of f_- must be corrected.

The triggering efficiency and reconstruction efficiency for ν_μ and $\overline{\nu_\mu}$ induced reactions may be different and must be corrected.

Muon polarization effects may make the detection efficiency for the two muon charges different. Some accounting for a lower efficiency for observing a signal from muon capture may be needed.

Subthreshold pion decays that give rise to the decay sequence $\pi \rightarrow \mu \rightarrow e$ may also populate the post interaction time distribution. Subthreshold pions are additional tracks in the initial neutrino interaction that escape detection but will subsequently decay. These can be studied in several ways. The muon decay time distribution observed in ν_e interactions can be subtracted from that observed in muon type reactions. Events with multiple muon decays can be studied to understand the rate for which subthreshold pion decays occur. With sufficiently high detection efficiency the problem could be eliminated by removing events in which more than one muon decay is observed.

A spatial cut might be possible in that muon decays occurring near the primary interaction vertex are removed since this is where such subthreshold pion decays would be found.

IV. EXAMPLE

To illustrate this method we consider the the observation that IMB reported [8] of 2.02 microseconds for the inclusive muon decay lifetime of 105 events. No error was quoted on this time.

The f_- above can be written in terms of several factors:

$$f_- = \frac{\epsilon_\nu F_\nu \sigma_\nu \epsilon_{\mu^-}}{\epsilon_\nu F_\nu \sigma_\nu \epsilon_{\mu^-} + \epsilon_{\bar{\nu}} F_{\bar{\nu}} \sigma_{\bar{\nu}} \epsilon_{\mu^+}}$$

where ϵ is the neutrino interaction detection efficiency which may be different for neutrinos and antineutrinos; F is the neutrino or antineutrino flux; σ is the neutrino or antineutrino cross section and ϵ_μ is the muon decay detection efficiency. The muon decay detection efficiency depends on the time window in which muon decay can be observed and on the capture probability. 18% of the μ^- capture in water and were not detectable.

Only the relative values of ϵ, F, σ and ϵ_μ enter into the estimate of f_-. From a fundamental physics perspective it is the value of $F_\nu / F_{\bar{\nu}}$ that is interesting.

In applying our method to the data of reference [8] we will *assume* that $\epsilon_\nu = \epsilon_{\bar{\nu}}$, that is that the detection efficiency for neutrinos and antineutrinos are equal. We will take $\sigma_\nu / \sigma_{\bar{\nu}} = 3$. The muon decay detection efficiency is determined by the capture rate, for which the signal is lost, and the time window which misses events at long and short times. $\epsilon_{\mu^-} / \epsilon_{\mu^+}$ is estimated to be about 81% ($\epsilon_{\mu^-} = 58$ to 60% and $\epsilon_{\mu^+} = 72$ to 75%) [9].

Figure 1 is a plot of $F_\nu / F_{\bar{\nu}}$ as a function of the mean decay time for the above *assumptions*. For 2.02 microseconds $F_\nu / F_{\bar{\nu}} = 1.04$. This is quite close to the expected flux ratio [10] in the energy range of the sample. From the plot it is clear that an error of ± 0.01 microseconds would permit a range of $0.8 < F_\nu / F_{\bar{\nu}} < 1.3$.

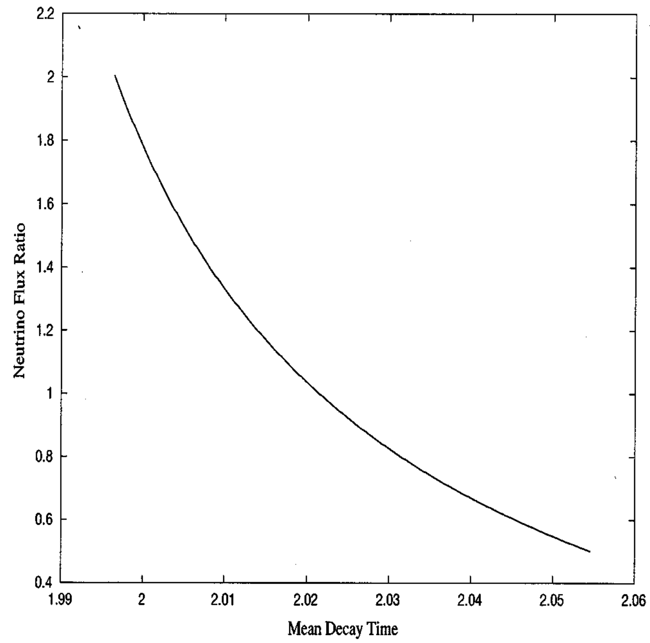

FIG. 1. The neutrino flux ratio $F_\nu / F_{\bar{\nu}}$ as a function of the mean muon decay time.

If, via selective angular cuts, it is found that the downward component has a mean time of 2.02 microseconds, but the upward component, which has traversed about 10 000 km of matter, has a mean time of 2.06 microseconds, an increase of 40 nanoseconds, neutrino-antineutrino dependent matter effects would be implicated. A measurement of 2.06 microseconds would imply $F_\nu / F_{\bar{\nu}} = 0.5$, which is well below expectations.

The reader should be warned about taking this example too literally since there may be other sources of error, such as atomic depolarization, that were neglected here.

V. CONCLUSIONS

The atmospheric neutrino anomaly has been firmly established. More information about the nature of the interactions is necessary to fully understand the physical mechanism responsible for the effect. By exploiting lifetime differences in muon decay one has access to the ν_μ and $\overline{\nu_\mu}$ fractions of events. A sufficiently large sample would permit the study of the ν_μ and $\overline{\nu_\mu}$ content as a function of energy and distance. The absence of any variation of this fraction with flight path would strengthen the case for neutrino oscillations. A variation would point to some new physics.

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