Sensitivity to θ_{13} and δ in the Decaying Astrophysical Neutrino Scenario

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(Dated: 23 September 2003)

We have previously shown that the decay of high-energy neutrinos from distant astrophysical sources would be revealed by flavor ratios that deviate strongly from the $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$ expected from oscillations alone. Here we show that the deviations are significantly larger when the mixing angle θ_{13} and the CP phase δ are allowed to be nonzero. If neutrinos decay, this could allow measurement of θ_{13} and δ in IceCube and other near-term neutrino telescopes.

PACS numbers: 95.85.Ry, 96.40.Tv, 14.60.Pq

FERMILAB-Pub-03/292-A

Traveling over cosmological distances, neutrino wave packets decohere into mass eigenstates. The probability to measure a neutrino flavor β at Earth is therefore

$$P_\beta = \sum_\alpha w_\alpha \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2 \,, \tag{1}$$

where $U_{\alpha j}$ are elements of the neutrino mixing matrix, and w_α are the weights of the flavors produced in the astrophysical source. As is well-known, the weights from a pion-muon decay chain, $w_e : w_\mu : w_\tau = 1 : 2 : 0$, lead to flavor ratios at Earth of $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$ [1]. Variation of the mixing angles from the assumed $\nu_\mu - \nu_\tau$ symmetry limit ($\theta_{23} = 45^\circ$ and $\theta_{13} = 0$) leads to only small ($\lesssim 20\%$) deviations.

We have recently shown that the expected flavor ratios would be dramatically altered if neutrinos decay [2]. The strongest lifetime limits, from solar neutrinos, are too weak to restrict the possibility of astrophysical neutrino decay by a factor of about 10^7 [2, 3]. Other scenarios, small-δm^2 active-sterile mixing in pseudo-Dirac [4] or mirror models [5], or CPT violation [6], produce more subtle deviations from the expected 1 : 1 : 1. While neutrino decay can be tested with IceCube [7] and other near-term detectors, the latter scenarios may require future detectors [8].

The most interesting decay scenario is that in which ν_3 and ν_2 decay (either into active ν_1 or sterile states), but the lightest neutrino ν_1 is stable. In this case, the beam contains just the single mass eigenstate ν_1, and the flavor ratios at Earth are simply

$$\phi_e : \phi_\mu : \phi_\tau = |U_{e1}|^2 : |U_{\mu 1}|^2 : |U_{\tau 1}|^2 \,. \tag{2}$$

We present here further analysis of this scenario, taking into account the broken $\nu_\mu - \nu_\tau$ symmetry that arises when $U_{e3} = \sin\theta_{13} e^{-i\delta} \neq 0$. Even for small θ_{13}, we find that the flavor ratios are very sensitive to the CP phase δ, which was set to zero for simplicity in our earlier work [2].

We assume a normal neutrino mass hierarchy. For the case of an inverted hierarchy (or no decay), varying θ_{13} has little effect. Note that in this decay scenario, there is no dependence on the initial astrophysical flux ratios, and hence on the production mechanism of the ultra high energy neutrinos, since the flux reaching Earth consists only of the lightest neutrino ν_1.

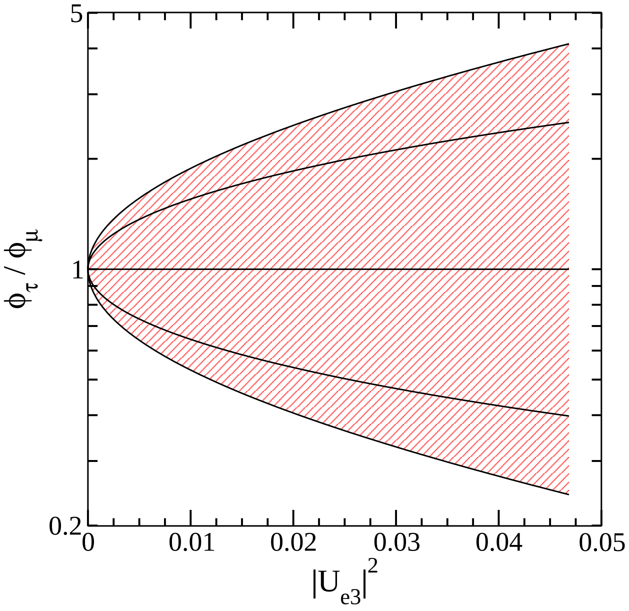

FIG. 1: Variation of the ratio ϕ_τ/ϕ_μ with $|U_{e3}|^2 = s_{13}^2$ in the allowed range [9]. From bottom to top, the solid curves correspond to $\delta = (0, \pi/4, \pi/2, 3\pi/4, \pi)$, with the hatched region showing the full allowed range. The atmospheric angle is $\theta_{23} = 45^\circ$ [10] and the solar angle is $\theta_{12} = 32.5^\circ$ [11].

Expressing the flavor ratios in Eq. (2) in terms of the mixing parameters (using the conventions of Ref. [12] and $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$),

$$\frac{\phi_\tau}{\phi_\mu} = \frac{s_{12}^2(1-\cos 2\theta_{23}) + s_{13}^2 c_{12}^2 (1+\cos 2\theta_{23}) - 4\hat{J}}{s_{12}^2(1+\cos 2\theta_{23}) + s_{13}^2 c_{12}^2 (1-\cos 2\theta_{23}) + 4\hat{J}} \,. \tag{3}$$

We have defined

$$\hat{J} \equiv \frac{1}{4} \sin 2\theta_{12} \, \sin 2\theta_{23} \, (s_{13} \cos\delta) \,, \tag{4}$$

which is related to the Jarlskog invariant J according to

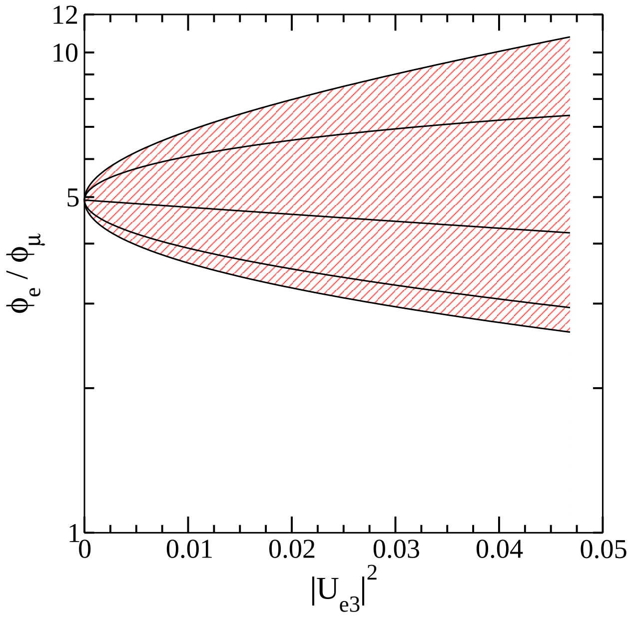

FIG. 2: Same as Fig. 1, except for the ratio ϕ_e/ϕ_μ. As in Fig. 1, the value expected in the no-decay case is 1; here the effects of decay are always pronounced.

$J = \hat{J} c_{13}^2 \tan\delta$. It is known, and is evident in Eq. (3), that either a nonzero $\cos 2\theta_{23}$ or s_{13} breaks $\nu_\mu - \nu_\tau$ symmetry. In Fig. 1, we show the ratio ϕ_τ/ϕ_μ as a function of $|U_{e3}|^2$ (within the range allowed by reactor experiments [9]), with $\theta_{23} = \pi/4$ fixed. Even a small θ_{13} has a relatively large effect, particularly when the CP phase δ is allowed to be nonzero. However, direct measurement of the ratio ϕ_τ/ϕ_μ is very difficult, since events which are unique to ν_τ (double-bang and lollipop events) have much lower detection probabilities [8].

In contrast, the ϕ_e/ϕ_μ ratio can be directly probed in a detector like IceCube by comparing the rate of shower events to muon events [8]. This flavor ratio is

$$\frac{\phi_e}{\phi_\mu} = \left(\frac{|U_{e1}|^2}{1 - |U_{e1}|^2}\right)\left(1 + \frac{\phi_\tau}{\phi_\mu}\right) . \qquad (5)$$

The ν_e fraction in the ν_1 mass eigenstate is insensitive to values of θ_{13} in the allowed range, shown by the first factor in Eq. (5), where $|U_{e1}| \equiv (c_{12}c_{13})^2$. However, the broken $\nu_\mu - \nu_\tau$ symmetry affects the ϕ_e/ϕ_μ ratio through the second factor in Eq. (5), and this is a large effect. When $\cos\delta$ is negative (positive) it decreases (increases) the ν_μ fraction of ν_1 with respect to the ν_τ fraction, resulting in an enhanced (suppressed) ν_e/ν_μ ratio. This is shown in Fig. 2. The curve with $\delta = 0$ is as in Ref. [2], though we have updated the solar angle θ_{12}. For nonzero δ, new to this work, the flavor ratio is significantly farther from the no-decay value of 1.

Note that the dependence of Eqs. (3) and (5) on the CP phase δ occurs only through $\cos\delta$, since this is a CP-conserving observable. Therefore, it is not necessary to separate astrophysical neutrinos and antineutrinos, which would be very difficult. The phase δ is of crucial importance in terrestrial long-baseline oscillation experiments since CP-violating observables, based on the comparison of neutrino and antineutrino oscillation probabilities, are proportional to $\sin\delta$ [13]. Farzan and Smirnov have shown that a nonzero $\sin\delta$ may in principle also be inferred by direct construction of the leptonic unitarity triangle [14]. A key distinction is that the terrestrial experiments use a beam of flavor eigenstates, whereas neutrino decay can produce a pure mass eigenstate, allowing for very large variation with δ. Since measurement of δ in terrestrial experiments will be an extremely challenging task, it is intriguing to find an example where the effect of varying δ is huge. Finally, the flavor ratios are sensitive only to the "Dirac" phase δ, and not the "Majorana" phases; Majorana phases are relative phases between mass eigenstates, and the beam consists of the single mass eigenstate ν_1.

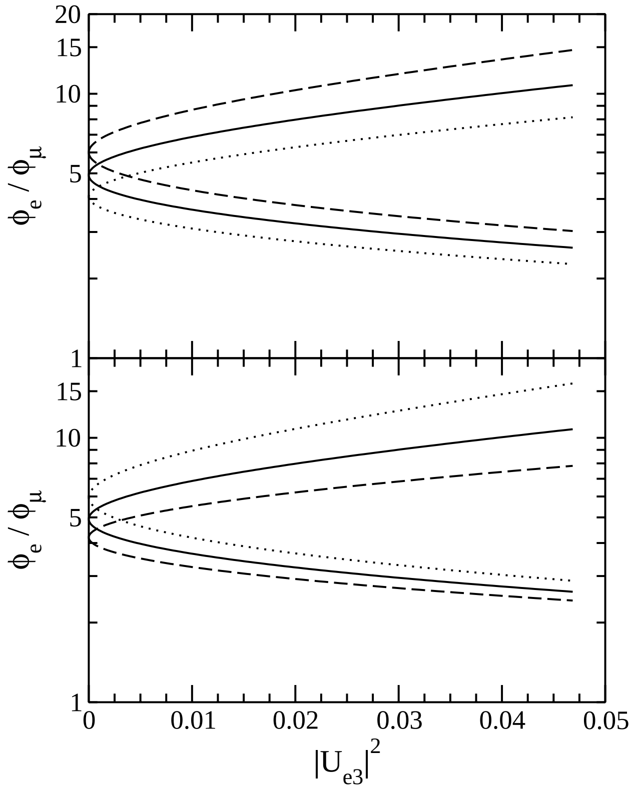

FIG. 3: Upper panel: varying the solar angle, with $\theta_{12} = 30°$ (dashed), 32.5° (solid) and 35° (dotted). Lower panel: varying the atmospheric angle, with $\theta_{23} = 40°$ (dashed), 45° (solid) and 50° (dotted). The bottom and top curves correspond to $\delta = (0, \pi)$. As before, the region between the curves is the allowed range, obtained for different values of δ.

Variation of the atmospheric mixing angle θ_{23} away from 45° also breaks the $\nu_\mu - \nu_\tau$ symmetry, as shown in Eq. (3), and has a similar effect on the flavor ratios. Variation of the solar mixing angle changes the ϕ_e/ϕ_μ ratio as it alters the ν_e fraction of ν_1. In Fig. 3, we show how the variations of these angles within their onesigma allowed ranges affects ϕ_e/ϕ_μ. Note that the size of the variation due to uncertainties in the solar and atmospheric angles are quite similar. These uncertainties will be reduced by existing or planned solar and long-baseline experiments. The angle θ_{13} may be measured by future long baseline [13] or reactor [15] experiments, and measuring δ may require a neutrino factory.

To conclude, IceCube and other detectors have an excellent chance of detecting astrophysical neutrinos and measuring their flavor ratios in the next several years. If neutrinos decay, the flavor ratio ϕ_e/ϕ_μ will be much larger than its no-decay value of 1, and this effect is significantly enhanced by nonzero θ_{13} and δ. Thus there may be a new opportunity to measure the last unknown values in the neutrino mixing matrix.

Acknowledgments.— We thank Stephen Parke for illuminating discussions. J.F.B. and N.F.B. were supported by Fermilab (operated by URA under DOE contract DE-AC02-76CH03000) and NASA grant NAG5-10842; S.P. by DOE grant DE-FG03-94ER40833; and T.J.W. by DOE grant DE-FG05-85ER40226, NASA grant NAG5-13399, and a Vanderbilt Discovery Award. T.J.W. also thanks the U. Wisconsin Phenomenology Group for hospitality.

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