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Neutrino Decay as an Explanation of Atmospheric Neutrino Observations

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We show that the observed zenith angle dependence of the atmospheric neutrinos can be accounted for by neutrino decay. Furthermore, it is possible to account for all neutrino anomalies with just three flavors.

I. NEUTRINO DECAY PHENOMENOLOGY

According to the analysis by the Super-Kamiokande (SK) Collaboration [1] of their atmospheric neutrino data, the L/E dependence of the ν_μ data is well accounted for by ν_μ oscillation into ν_τ (or a sterile neutrino ν_{st}) with a mixing angle $\sin^2 2\theta \gtrsim 0.8$ and a δm^2 in the range 3×10^{-4}–$8\times10^{-3}\,\mathrm{eV}^2$. The ν_μ survival probability in vacuum is given by

$$P_{\mu\mu} = 1 - \sin^2 2\theta\, \sin^2(\delta m^2 L/4E)\,. \qquad (1)$$

According to the data and in this simple two flavor mixing hypothesis, the ν_e channel is unaffected and hence the survival probability $P_{ee} = 1$. The interpretation of the atmospheric neutrino data in terms of oscillations is an old and venerable proposal [2].

It is obviously an important question to ask whether ν_μ oscillation is the only possible explanation for the observed L/E dependence. Several other interpretations have been offered [3]. In this Letter we raise another possibility — neutrino decay.

We begin by noting that decay implies a non-zero mass difference between two neutrino states and thus, in general, mixing as well. For definiteness, let us assume the existence of just three light neutrinos, and label as ν_1, ν_2, and ν_3 that mass eigenstate with the largest admixture in the flavor state ν_e, ν_μ, and ν_τ, respectively. We further assume the dominant component of ν_μ, i.e. ν_2, to be the only unstable state, with a rest-frame lifetime τ_0. There are strong limits coming from the nonobservation of π and K decay to anomalous final states containing $e^\pm$'s on the participation of ν_e in non-SM vertices [4]. Consequently, ν_e must nearly decouple from the unstable ν_2 and its decay partner ν_3, and we are led to $\nu_e \approx \nu_1$, and

$$\nu_\mu \approx \cos\theta\,\nu_2 + \sin\theta\,\nu_3\,, \qquad (2)$$

with $m_2 > m_3$. From Eq. (2) with an unstable ν_2, the ν_μ survival probability is

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta\exp(-\alpha L/E) + 2\sin^2\theta\cos^2\theta\exp(-\alpha L/2E)\cos(\delta m^2 L/2E)\,, \qquad (3)$$

where $\delta m^2 = m_2^2 - m_3^2$ and $\alpha = m_2/\tau_0$.

If, as we argue later, $\delta m^2 > 0.1$ eV^2, then $\cos(\delta m^2 L/2E)$ effectively averages to zero for atmospheric neutrinos and $P_{\mu\mu}$ becomes

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta\exp(-\alpha L/E)\,. \qquad (4)$$

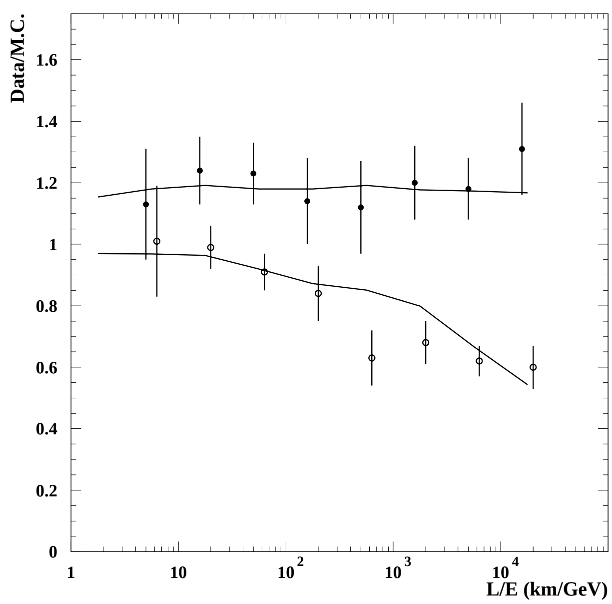

FIG. 1. The Super-Kamiokande data/expectations as a function of L/E, for electron events (upper) and muon events (lower). Our model normalized to the electron flux total is shown by the lines, indicating an acceptable fit for decaying muon neutrinos.

We find that it is possible to choose θ and α to provide a good fit to the Super-K L/E distributions of ν_μ events and ν_μ/ν_e event ratio. The fit to the L/E distribution of the ν_μ events is shown in Figure 1, where smearing over L and E is included. The best fit values of the two parameters are $\cos^2\theta \sim 0.87$ (i.e. $\theta \sim 21°$) and $\alpha \sim 1\,\mathrm{GeV}/D_E$, where $D_E = 12,800$ km is the diameter of the Earth. The χ^2 per degree of freedom for this fit is about 10/9, while the up/down asymmetry fit has a χ^2/dof of about 9/4. This best-fit α value corresponds to a rest-frame ν_2 lifetime of

$$\tau_0 = m_2/\alpha \sim \frac{m_2}{(1\ \mathrm{eV})} \times 10^{-10}\ \mathrm{s}\ . \tag{5}$$

Such a lifetime and decay length are not in conflict with current limits on non-radiative modes [5]. Previous limits on ν_μ decay lengths from accelerators are only of the order of a few km.

II. NON-RADIATIVE NEUTRINO-DECAY MODELS

It is not difficult to construct a viable decay model for Majorana neutrinos. Choose the effective decay interaction between the ν_2 and ν_3 states to be

$$\mathcal{L}_I = g_{23}\,\overline{\nu^c_{3L}}\,\nu_{2L}\,J + \mathrm{h.c.}\,, \tag{6}$$

where J is a Majoron field [6], which has to be dominantly singlet with only a small triplet admixture, in order to satisfy the constraints from the invisible decay width of Z. A full model needs further embellishment to generate the above coupling at tree level and generate the desired neutrino masses and mixings. The model described by Acker et al. [7] can be easily adapted to our purpose here.

A simple model for fast invisible decay of Dirac neutrinos is also possible. Define a decay interaction between the right-handed $SU(2)$-singlet states of the Dirac neutrinos given by by [8]

$$\mathcal{L}_I = g_{23}\,\overline{\nu^c_{3R}}\,\nu_{2R}\,\chi + \mathrm{h.c.}\,, \tag{7}$$

where χ is a complex scalar field with lepton number -2, $I_W = 0$, and hypercharge zero. χ is not a Nambu-Goldstone boson. The scalar field should be light compared to the neutrino masses. The quantum numbers of χ make it difficult to test its existence in laboratory experiments. Processes such as $\mu \to e + X$ are forbidden. Furthermore, neutrino decay is not helicity-suppressed but the interactions of its decay products are: all new processes involving neutrinos are suppressed by the chirality factor $(m_\nu/E_\nu)^2$.

With the interaction of Eq. (7) or Eq. (6), the rest-frame lifetime of ν_2 is given by

$$\tau_0 = \frac{16\pi}{g_{23}^2}\,\frac{m_2^3}{\delta m^2 (m_2+m_3)^2}\,, \tag{8}$$

and hence

$$g_{23}^2\,\delta m^2 = 16\pi\alpha\,(1 + m_3/m_2)^{-2}\,, \tag{9}$$

leading to, for $0 < m_3/m_2 < 1$,

$$g_{23}^2\,\delta m^2 \sim (2-7)\times 10^{-4}\,\mathrm{eV}^2\,. \tag{10}$$

From studying K decays, in particular the modes $K \to \mu + neutrals$, a bound on the coupling g_{23} can be derived which is [9]

$$g_{23}^2 < 2.4\times 10^{-4}\,, \tag{11}$$

thus leading to a bound on δm^2 in the present model of

$$\delta m^2_{23} \gtrsim 0.73\ \mathrm{eV}^2\,. \tag{12}$$

This result justifies the above approximation of large δm^2.

In both the Majorana neutrino and Dirac neutrino decay models, the small mass scale for the scalar fields seems to require fine-tuning. This is unavoidable, though unappealing. The Majorana and Dirac models are testably different in that in the Dirac-neutrino model the decay is into essentially undetectable final states, whereas the Majorana-neutrino model posits decay of ν_μ's and $\bar{\nu}_\mu$'s into $\bar{\nu}_\tau$'s and ν_τ's respectively, which are observable in principle. Furthermore, with the Majorana-neutrino model, lepton number is broken and neutrinoless double-beta decay is allowed; with the Dirac-neutrino model, lepton number is unbroken and neutrinoless double-beta decay is not allowed.

If the decay of the ν_2 is into a new (sterile) neutrino with which it does not mix, then the δm^2 appearing in the oscillation is not restricted by the constraint of Eq. (12) and can be very small. Then the cosine term in Eq. (3) is essentially unity and the survival probability is given by

$$P_{\mu\mu} = [\sin^2\theta + \cos^2\theta\exp(-\alpha L/2E)]^2. \tag{13}$$

In this case, even better fits to the Super-K data can be obtained in both L/E and the up/down asymmetry. However, we do not pursue this class of models further at this time.

III. INCLUSION OF ALL NEUTRINO ANOMALIES

It is easy to incorporate the solar and LSND neutrino anomalies into the present discussion. The decay of ν_2 with $\delta m^2_{23} \gtrsim 0.73\mathrm{eV}^2$ explains the atmospheric data, but also allows δm^2_{23} to accommodate the LSND result. We are free to choose the remaining δm^2 to accommodate the solar anomaly. As mentioned earlier, U_{e3} must be rather small; and hence the solution to the solar ν_e depletion is necessarily small-angle mixing enhanced by the MSW effect. To this end, we set $\delta m^2_{sun} \equiv \delta m^2_{31} \sim 0.5\times 10^{-5}\,\mathrm{eV}^2$ to complement the δm^2_{23} of Eq. (12).

Atmospheric ν's

With these δm^2_{ij}, the ν_μ survival probability is given by Eq. (4) with $\cos^2\theta \equiv |U_{\mu 2}|^2 \sim 0.97$ and $\sin^2\theta = 1 - |U_{\mu 2}|^2$, and the earlier two-flavor discussion and fit remain intact. The survival probability for ν_e's is

$$P_{ee} = \left(1 - |U_{e2}|^2\right)^2 + |U_{e2}|^2 e^{-\alpha L/E} + 2|U_{e2}|^2(1 - |U_{e2}|^2)\cos(\delta m^2_{32} L/2E) e^{-\alpha L/2E} . \quad (14)$$

If $U_{e2} \ll 1$, then $P_{ee} \approx 1$, as observed.

Solar ν's

For solar L/E values, the ν_2's have decayed away and the ν_e survival probability is given by

$$P_{ee} = \left(1 - |U_{e2}|^2\right)^2 - 4|U_{e1}|^2|U_{e3}|^2 \sin^2\left(\frac{\delta m^2_{31} L}{4E}\right) . \quad (15)$$

By choosing $4|U_{e1}|^2|U_{e3}|^2 \approx 5.5 \times 10^{-3}$, with $m_3 > m_1$, one can reproduce the small-angle MSW solution for solar neutrinos [10]. Furthermore, the resulting value of $|U_{e3}|^2 \sim 1.4 \times 10^{-3}$ easily satisfies the upper bound on the ν_e coupling which is $g_e^2 = g_{23}^2(|U_{e3}|^2 + |U_{e2}|^2) < 3 \times 10^{-5}$ [4].

LSND

At the L/E value relevant to the LSND experiment, the ν_μ–ν_e conversion probability is given by

$$P_{\mu e} = 4|U_{\mu 2}|^2|U_{e2}|^2 \sin^2\left(\frac{\delta m^2_{32} L}{4E}\right) . \quad (16)$$

With $\delta m^2_{23} \sim \mathcal{O}(1\ \text{eV})^2$ and $|U_{\mu 2}|^2 \sim 1$, choosing $|U_{e2}|^2 \sim 10^{-3}$ allows this $P_{\mu e}$ to account for the LSND observations [11].

Summary of Mass and Mixing

To summarize, the three-neutrino mixing matrix with the approximate form

$$U = \begin{pmatrix} 0.999 & 0.02 & -0.04 \\ -0.05 & 0.932 & 0.36 \\ \epsilon & -0.36 & 0.932 \end{pmatrix} \quad (17)$$

and mass differences given by

$$\delta m^2_{21} \approx \delta m^2_{23} \gtrsim 0.73\ \text{eV}^2 , \text{ and } \delta \text{m}^2_{13} \sim 0.5 \times 10^{-5}\,\text{eV}^2 , \quad (18)$$

along with an unstable ν_2 satisfying the lifetime constraint of Eq. (5), explain all three neutrino anomalies without violating any known data. The very small entry, ϵ in Eq. (17), is fixed by unitarity of the mixing matrix.

IV. ASTROPHYSICS IMPLICATIONS

Big Bang Nucleosynthesis

A neutrino with lifetime as short as the one discussed here decays before the primordial neutrinos decouple (about 2 MeV). The decay products may achieve thermal equilibrium, thereby increasing the effective number of neutrino species N_ν. The bound on light degrees of freedom is generally considered to be about 3.5 [12] or even lower [13]. Given all the astrophysical uncertainties associated with the BBN bound, more cautious estimates [14] lead to upper bounds on N_ν in the range of 4 to 5. The bound is further modified if there is a lepton number asymmetry present [15].

In the Majorana model, there are no new neutrino degrees of freedom, so N_ν increases by just 4/7 due to Majoron thermalization. There is no conflict with the BBN bound. In the Dirac case, the complex scalar contributes 8/7 and the "wrong–helicity" ν_3 and ν_2 states each contribute $N_\nu = 1$ if they achieve thermal equilibrium. Thus, the Dirac model may be in conflict with the BBN bound if the additional degrees of freedom come to thermal equilibrium, although a conservative judgement may withold the obituary pending reduction of astrophysical uncertainties.

Supernova Emission

The decay of ν_μ at the fast rate envisaged here will modify supernova dynamics, since the decay will occur inside the neutrinosphere. In the Majorana case, the decay neutrinos are not sterile and so should get get trapped inside the neutrinosphere; the Majoron may get trapped as well, in which case the effects on the supernova dynamics would be mild. In the Dirac case, the decay products are sterile and will carry away energy from the core on a very short time scale unless the scalar interaction is sufficient to cause trapping. Without trapping of the new states, the Dirac neutrino decay model probably conflicts with the observed period of a few seconds for the SN1987A neutrino burst, although without a simulation of the altered dynamics "the precise range of parameters that can be ruled out or ruled in by the SN1987A signal" is not clear [16].

Cosmic ν Fluxes

In neutrinos coming from distant sources, such as Supernovae, AGN's, and GRB's, the $\nu_\mu(\approx \nu_2)$'s have decayed away and only $\nu_e, \bar{\nu}_e, \nu_\tau$ and $\bar{\nu}_\tau$ will arrive at the Earth. Existing neutrino telescopes, as well as those under construction, will not observe the tiny component ($\sim \sin^4\theta \sim 10^{-3}$) of surviving ν_μ's (apart from atmospheric ones).

V. FUTURE TESTS

There are several opportunities to test the neutrino decay hypothesis decisively. One is that the Super-

Kamiokande collaboration, with sufficient data, can distinguish between the two L/E distributions: the oscillatory one as given in Eq. (1) and the decaying one as given in Eq. (4). A second is that the upcoming μ's, upcoming stopping μ's, and partially contained μ's should also show some distinction in zenith angle distribution between decay and oscillations models with increased statistics.

A third opportunity exists with future long-baseline experiments [17]. Expectations are quite different with the neutrino decay interpretation of Super-K results, compared to the oscillation interpretation. In the ν_μ decay scenario the typical ν_μ survival probability is 77% and the ν_μ–ν_τ conversion probability is about 22%.(There is, in the Majorana model, a further small ν_τ flux from the decay products; however their energies are much lower than the parent ν_μ's due to the backward-peaked nature of the decay.)

VI. CONCLUSION

We have presented a neutrino decay scenario capable of explaining the atmospheric neutrino data. Furthermore, it enables us to explain all neutrino anomalies with just three neutrino flavors. The scenario violates no available data, and has the same number of parameters as the usual oscillation phenomenolgy. The decay of a Majorana neutrino appears to be consistent with astrophysical bounds. The decay possibility can be checked in future Super-K data as well as in forthcoming long-baseline experiments and neutrino telescopes.

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[17] For World Wide Web links to these long-baseline and other proposed neutrino oscillation experiments, see the Neutrino Oscillation industry web page at http://www.hep.anl.gov/NDK/Hypertext/nuindustry.html