EXOTIC EXPLANATIONS FOR NEUTRINO ANOMALIES

SANDIP PAKVASA
University of Hawaii
Department of Physics and Astronomy
Honolulu, HI 96822 USA
E-mail: pakvasa@uhheph.phys.hawaii.edu

ABSTRACT

I review explanations for the three neutrino anomalies (solar, atmospheric and LSND) which go beyond the "conventional" neutrino oscillations induced by mass-mixing. Several of these require non-zero neutrino masses as well.

1. Introduction

According to Webster's New English Dictionary[1)], amongst the meanings of the word "exotic" are: "foreign", "strangely beautiful", "enticing", "having the charm or fascination of the unfamiliar". At one time neutrino oscillations would have been considered exotic, but today they seem mundane and ordinary! The explanations to be discussed here will be definitely "strange" and "unfamiliar" but may not seem to be "charming" or "enticing"!

As is well-known, it is not possible to account for all three neutrino anomalies with just the three known neutrinos (ν_e, ν_μ and ν_τ). If one of them can be explained in some other way, then no extra sterile neutrinos need be invoked. This is one motivation for exotic scenarios. It is also important to rule out all explanations other than oscillations in order to establish neutrino mixing and oscillations as the unique explanation for the three observed neutrino anomalies.

I should mention that, in general, some (but not all) non-oscillatory explanations of the neutrino anomalies will involve non-zero neutrino masses and mixings. Therefore, they tend to be neither elegant nor economical. But the main issue here is whether we can establish oscillations unequivocally and uniquely as the cause for the observed anomalies.

I first summarize some of the exotic scenarios and then consider each anomaly in turn.

2. Mixing and Oscillations of massless $\nu's$

There are three different ways that massless neutrinos may mix and even oscillate. These are as follows.

1. If flavor states are mixtures of massless as well massive states, then when they are produced in reactions with Q-values smaller than the massive state; the flavor states are massless but not orthogonal[2)]. For example, if $\nu_e = \sum_{i=1}^{4} U_{ei}\nu_i$, $\nu_\mu = \sum_{i=1}^{4} U_{\mu i}\nu_i$ and $m_i = 0$ for $i = 1$ to 3 but $m_4 = 50$ GeV; then "ν_e" produced in

β-decay and "ν_μ" produced in π-decay are massless but not orthogonal and

$$\langle \nu_e \mid \nu_\mu \rangle = -U^*_{e4}\, U_{\mu 4} \tag{1}$$

On the other hand ν_e and ν_μ produced in W decay will be not massless and will be more nearly orthogonal. Hence, the definition of flavor eigenstate is energy and reaction dependent and not fundamental. Current limits[3] on orthogonality of ν_e, ν_μ and ν_τ make it impossible for this to play any role in the current neutrino anomalies.

2. When Flavor Changing Neutral Currents as well as Non-Universal Neutral Current Couplings of neutrinos exist:

$$\begin{aligned} & \epsilon_q \frac{4G_F}{\sqrt{2}} \{\bar{\nu}_{el}\ \gamma_\mu\ \nu_{\tau_L} \bar{q}_L\ \gamma_\mu q_L \quad + h.c.\} \\ + \quad & \epsilon'_q \frac{4G_F}{\sqrt{2}}\ \{\bar{\nu}_{eL}\ \gamma_\mu\ \nu_{e_L} - \bar{\nu}_{\tau L}\gamma_\mu\ \nu_{\tau L}\}\{\bar{q}_L\ \gamma_\mu\ q_L\} \end{aligned} \tag{2}$$

Such couplings arise in R-parity violating supersymmetric theories[4]. In this case the propagation of ν_e and ν_τ in matter is described by the equation:

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\tau \end{pmatrix}_L = \begin{pmatrix} \alpha+\beta & \gamma \\ \gamma & -\beta \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\tau \end{pmatrix}_L \tag{3}$$

where $\alpha = G_F N_e, \beta = \epsilon_q G_F N_q$ and $\gamma = \epsilon'_q G_F N_q$. There is a resonance at $\alpha + 2\beta = 0$ or $\epsilon_q = -\frac{1}{2}N_e/N_q$ and ν_e can convert to ν_τ completely. This matter effect which effectively mixes flavors in absence of masses was first pointed out in the same Wolfenstein paper[5] where matter effects were discussed in general. The resonant conversion is just like in the conventional MSW effect, except that there is no energy dependence and ν and $\bar{\nu}$ are affected the same way. This possibility has been discussed in connection with both solar and atmospheric anomalies.

3. (a) Flavor violating Gravity wherein it is proposed that gravitational couplings of neutrinos are flavor non-diagonal[6] and equivalence principle is violated. For example, ν_1 and ν_2 may couple to gravity with different strengths:

$$H_{gr} = f_1 GE\phi + f_2 GE\phi \tag{4}$$

where ϕ is the gravitational potential. Then if ν_e and ν_μ are mixtures of ν_1 and ν_2 with a mixing angle θ, oscillations will occur with a flavor survival probability

$$P = 1 - sin^2 2\theta sin^2(\frac{1}{2}\delta f \phi EL) \tag{5}$$

when ϕ is constant over the distance L and $\delta f = f_1 - f_2$ is the small deviation from universality of gravitational coupling. Equivalence principle is also violated.

(b) Another possibility is violation of Lorentz invariance[7] wherein all particles have their own maximum attainable velocities (MAV) which are all different and in

general also different from speed of light: Then if ν_1 and ν_2 are MAV eigenstates with MAV's v_1 and v_2 and ν_e and ν_μ are mixtures of ν_1 and ν_2 with mixing angle θ, the survival probability of a given flavor is

$$P = 1 - sin^2 2\theta \ sin^2 \ \left(\frac{1}{2}\delta v E L\right) \tag{6}$$

where $\delta v = v_1 - v_2$.

As far as neutrino oscillations are concerned, these two cases are identical in their dependence on LE instead of L/E as in the conventional oscillations[8].

3. Neutrino Decay[9]:

Neutrino decay implies a non-zero mass difference between two neutrino states and thus, in general, mixing as well. We assume a component of ν_α, i.e., ν_2, to be the only unstable state, with a rest-frame lifetime τ_0, and we assume two flavor mixing, for simplicity:

$$\nu_\mu = cos\theta\nu_2 \ + sin\theta\nu_1 \tag{7}$$

with $m_2 > m_1$. From Eq. (2) with an unstable ν_2, the ν_α survival probability is

$$\begin{aligned} P_{\alpha\alpha} &= sin^4\theta \ + cos^4\theta \exp(-\alpha L/E) \\ &+ 2sin^2\theta cos^2\theta \exp(-\alpha L/2E) cos(\delta m^2 L/2E), \end{aligned} \tag{8}$$

where $\delta m^2 = m_2^2 - m_1^2$ and $\alpha = m_2/\tau_0$. Since we are attempting to explain neutrino data without oscillation there are two appropriate limits of interest. One is when the δm^2 is so large that the cosine term averages to 0. Then the survival probability becomes

$$P_{\mu\mu} = sin^4\theta \ + cos^4\theta \exp(-\alpha L/E) \tag{9}$$

Let this be called decay scenario A. The other possibility is when δm^2 is so small that the cosine term is 1, leading to a survival probability of

$$P_{\mu\mu} = (sin^2\theta + cos^2\theta \exp(-\alpha L/2E))^2 \tag{10}$$

corresponding to decay scenario B. Decay models for both kinds of scenarios can be constructed; although they require fine tuning and are not particularly elegant.

4. LSND

In the LSND experiment, what is observed is the following[10]. In the decay at rest (DAR) which is $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ which should give a pure ν_e signal, there is a flux of $\bar{\nu_e'}s$ at a level of about 3.10^{-3} of the $\nu_e's$. (There is a similar signal for $\nu_e's$ accompanying $\bar{\nu}_e's$ in the decay in flight of $\mu^- \to e^-\bar{\nu}_e\nu_\mu$). Now this could be accounted for without oscillations[11] provided that the conventional decay mode $\mu^+ \to e^+\nu_e\bar{\nu}_\mu(\mu^- \to e^-\bar{\nu}_e\nu_\mu)$

is accompanied by the rare mode $\mu^+ \to e^+ \bar{\nu}_e \mathrm{X}$ ($\mu^- \to e^- \nu_e \bar{\mathrm{X}}$) at a level of branching fraction of 3.10^{-3}. Assuming X to be a single particle, what can X be? It is straight forward to rule out X as being (i) ν_μ (too large a rate for Muonium-Antimuonium transition rate), (ii) ν_e (too large a rate for FCNC decays of Z such as $Z \to \mu\bar{e} + \bar{\mu}e$) and (iii) ν_τ (too large a rate for FCNC decays of τ such as $\tau \to \mu ee$).

The remaining possibilities for X are $\bar{\nu}_\alpha$ or ν_{sterile}. No simple models exist which lead to such decays. Rather Baroque models can be constructed which involve a large number of new particles[12].

Experimental tests to distinguish this rare decay possibility from the conventional oscillation explanation are easy to state. In the rare decay case, the rate is constant and shows no dependence on L or E.

One can also ask whether the $\bar{\nu}_e$ events seen in LSND could have been caused by new physics at the detector; for example a small rate for the "forbidden" reaction $\bar{\nu}_\mu + p \to n + e^+$. This is ruled out, since a fractional rate of 3.10^{-3} for this reaction, leads (via crossing) to a rate for the decay mode $\pi^+ \to e^+ \nu_\mu$ in excess of known bounds.

5. Solar Neutrinos

Oscillations of massless neutrinos via Flavor Changing Neutral Currents (FCNC) and Non Universal Neutral Currents (NUNC) in matter have been considered[4,13] as explanation for the solar neutrino observations, most recently by Babu, Grossman and Krastev[14]. Using the most recent data from Homestake, SAGE, GALLEX and Super-Kamiokande, they find good fits with $\epsilon_u \sim 10^{-2}$ and $\epsilon'_u \sim 0.43$ or $\epsilon_d \sim 0.1$ to 0.01 with $\epsilon'_d \sim 0.57$.

Since the matter effect in this case is energy independent, the explanation for different suppression for ^8B, ^7Be and pp neutrinos as inferred is interesting. The differing suppression arises from the fact the production region for each of these neutrinos differ in electron and nuclear densities. This solution resembles the large angle MSW solution with the difference that the day-night effect is energy-independent.

The massless neutrino oscillations described in Eq. (6) also offer a possible solution to solar neutrino observations. There are two solutions: one at a small angle ($sin^2 2\theta \sim 2.10^{-3}, \delta v/2 \sim 6.10^{-19}$) and one at a large angle ($sin^2 2\theta \sim 0.7, \delta v/2 \sim 10^{-21}$)[15]. This possibility can be tested in Long Baseline experiments.

The possibility of solar neutrinos decaying to explain the discrepancy is a very old suggestion[16]. The most recent analysis of the current solar neutrino data finds that no good fit can be found: $U_{ei} \approx 0.6$ and τ_ν (E=10 MeV) $\sim$ 6 to 27 sec. come closest[17]. The fits become acceptable if the suppression of the solar neutrinos is energy independent as proposed by several authors[18] (which is possible if the Homestake data are excluded from the fit). The above conclusions are valid for both decay scenarios

A as well as B.

6. Atmospheric Neutrinos

The massless FCNC scenario has been recently considered for the atmospheric neutrinos by Gonzales-Garcia et al.[19] with the matter effect supplied by the earth. Good fits were found for the partially contained and multi-GeV events with $\epsilon_q \sim 1, \epsilon'_q \sim 0.02$ as well $\epsilon_q \sim 0.08, \epsilon'_q \sim 0.07$. The fit is poorer when higher energy events corresponding to up-coming muons are included[20]. The expectations for future LBL experiments are quite distinctive: for MINOS, one expects $P_{\mu\mu} \sim 0.1$ and $P_{\mu\tau} \sim 0.9$. The story for massless neutrinos oscillating via violation of Equivalence Principle or Lorentz Invariance is very similar. Assuming large $\nu_\mu - \nu_\tau$ mixing, and $\delta v/2 \sim 2.10^{-22}$, a good fit to the contained events can be obtained[21]; but as soon as multi-GeV and thrugoing muon events are included, the fit is quite poor[20].

In both these cases the reason that inclusion of high energy upgoing muon events makes the fits poorer is straightforward. The up-going muon events come from much higher energy $\nu'_\mu s$ and the suppression is weaker that in the lower energy events. The energy dependence expected in the above scenarios is very different: no energy dependence in the FCNC case and an averaging out of oscillations at high energy (corresponding to 50% uniform suppression) in the other scenario.

Turning to neutrino decay scenario A, it is found that it is possible to choose θ and α to provide a good fit to the Super-Kamiokande L/E distributions of ν_μ events and ν_μ/ν_e event ratio[9]. The best-fit values of the two parameters are $cos^2\theta \sim 0.87$ and $\alpha \sim 1GeV/D_E$, where $D_E = 12800$ km is the diameter of the Earth. This best-fit α value corresponds to a rest-frame ν_2 lifetime of

$$\tau_0 = m_2/\alpha \sim \frac{m_2}{(1eV)} \times 10^{-10} s. \tag{11}$$

Such a lifetime and decay length are not in conflict with current limits on nonradiative modes. Previous limits on ν_μ decay lengths from accelerators are only of the order of a few km.

It is possible to construct a viable decay model for Majorana neutrinos with a massless Majoron which is predominantly singlet with an small triplet admixture[22]. The effective interaction will be given by

$$L = g\overline{\nu^c_{1L}}\ \nu_{2L}\ J\ + h.c. \tag{12}$$

With this interaction, the rest-frame lifetime of ν_2 is given by

$$\tau_0 = \frac{16\pi}{g^2} \frac{m_2^3}{\delta m^2 (m_1 + m_2)^2,} \tag{13}$$

and hence, for the above fit,

$$g^2 \delta m^2 \sim (2 - 7) \times 10^{-4} eV^2 \tag{14}$$

Combining this with the bound on g^2 from K, π decays[23], one finds

$$\delta m^2 \gtrsim 0.73\ eV^2. \tag{15}$$

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

We note in passing that with a choice of one $\delta m^2 \sim 0(1) eV^2$ and another $\delta m^2 \sim 5.10^{-6} eV^2$ and a mixing matrix with large diagonal entries and $U_{e2} \sim 0.02, U_{e3} \sim 0.04, U_{\mu 3} \sim 0.36$, it is possible to account for all neutrino anomalies: atmospheric, solar as well as LSND.

In this proposal, since the decays will be time dilated, at high energies, the decay probability is very small and the suppression of ν_μ flux is correspondingly smaller. Indeed it turns out that it is not possible to fit the observed angular distribution of the high energy up-coming muon events[20].

If the neutrino that mixes with ν_2 is different from the one that it decays into, then the δm^2 in decay and the δm^2 in oscillations are independent and it is possible for δm^2 in oscillations to be very small. In this case (scenario B), it is possible to find an excellent fit to all the atmospheric neutrino data: contained events, multi-GeV events as well as upcoming muon events[24]. The two decay possibilities lead to different expectations for future Long Baseline experiments, e.g. for MINOS: Case A leads to $P_{\mu\mu} \sim 0.8, P_{\mu\tau} \sim 0.2$ whereas case B leads to $P_{\mu\mu} \sim 0.5, P_{\mu\tau} \sim 0.2$.

Another proposal for explaining the atmospheric neutrinos is based on decoherence of the $\nu'_\mu s$ in the flux[25]. The idea is that $\nu'_\mu s$ are interacting and getting tagged before their arrival at the detector. The cause is unknown but could be a number of speculative possibilities such as a large neutrino background, new flavor sensitive interactions in an extra dimension, violation of quantum mechanics etc. The ν_μ survival probability goes as:

$$P = \frac{1}{2}\left[1 + cos2\theta exp(-t/\tau)\right] \tag{16}$$

The Super-Kamiokande data can be fit by choosing $\tau \sim 10^{-2} s$ and $sin2\theta \sim 0.4$. A detailed fit to all the data over the whole energy range has not been attempted yet.

7. Conclusion

As I mentioned at the beginning, the main motivation for this exercise is to try to establish neutrino oscillations (due to mass-mixing) as the unique explanation of the observed anomalies. Even if neutrinos have masses and do mix, the observed neutrino anomalies may not be due to oscillations but due to other exotic new physics. These possibilities are testable and should be ruled out by experiments. I have tried to show

that we are beginning to carry this program out.

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9. References

1) Webster's New Twentieth Century Dictionary of the English Language (Unabridged), Collins World (1977) 643.
2) B. W. Lee, S. Pakvasa, R. Shrock and H. Sugawara, *Phys. Rev. Lett.* **38** (1977) 937; S. Treiman. F. Wilczek and A. Zee, *Phys. Rev.* **D16** (1977) 152.
3) P. Langacker and D. London, *Phys. Rev.* **D38** (1988) 907.
4) E. Roulet, *Phys. Rev.* **D44** (1991) 935; M. M. Guzzo, A. Masiero and S. Petcov, *Phys. Lett.* **B260** (1991) 154; V. Barger, R. J. N. Philips and K. Whisnant, *Phys. Rev.* **D44** (1991) 1629.
5) L. Wolfenstein, *Phys. Rev.* **D17** (1978) 2369.
6) M. Gasperini, *Phys. Rev.* **D38** (1988) 2635; A. Halprin and C. N. Leung, *Phys. Rev. Lett.* **67** (1991) 1833.
7) S. Coleman and S. L. Glashow, *Phys. Lett.* **B405** (1997) 249.
8) S. Glashow, A. Halprin, P. I. Krastev, C. N. Leung and J. Pantaleone, *Phys. Rev.* **D56** (1977) 2433.
9) This discussion follows V. Barger, J. G. Learned, S. Pakvasa and T. J. Weiler, *Phys. Rev. Lett.* **82** (1999) 2640.
10) C. Athanassopoulos et al., the LSND Collaboration, *Phys. Rev. Lett.* **77** (1996) 3082; *ibid* **81** (1998) 1774.
11) Some discussion of these scenarios can be found in S. Bergmann and Y. Grossman, *Phys. Rev.* **D59** (1999) 093005; L. M. Johnson and D. McKay, *Phys. Lett.* **B433** (1998) 355 and P. Herczeg, *Proceedings of International Conference on Particle Physics Beyond The Standard Model*, Jun 8-14, 1997; Castle Ringberg, Germany; ed. by H. V. Klapdor-Kleingrothaus, (1998) 124.
12) Y. Grossman, (private communication).
13) J. N. Bahcall and P. Krastev, hep-ph/9703267.
14) P. Krastev, (private communication).
15) S. W. Mansour and T-K. Kuo, hep-ph/9810510; see also A. Halprin, C. N. Leung and J. Pantaleone, *Phys. Rev.* **D53** (1996) 5365; J. N. Bahcall, P. Krastev and C. N. Leung, *Phys. Rev.* **D52** (1996) 1770; H. Minakata and H. Nunokawa, *Phys. Rev.* **D51** (1995) 6625.

16) S. Pakvasa and K. Tennakone, *Phys. Rev. Lett.* **28** (1972) 1415; J. N. Bahcall, N. Cabibbo and A. Yahil, *Phys. Rev. Lett.* **28** (1972) 316; See also A. Acker, A. Joshipura and S. Pakvasa, *Phys. Lett.* **B285** (1992) 371; Z. Berezhiani, G. Fiorentini, A. Rossi and M. Moretti, *JETP Lett.* **55** (1992) 151.
17) A. Acker and S. Pakvasa (in preparation); A. Acker and S. Pakvasa, *Phys. Lett.* **B320** (1994) 320.
18) P. F. Harrison, D. H. Perkins and W. G. Scott, hep-ph/9904297; A. Acker, J. G. Learned, S. Pakvasa and T. J. Weiler, *Phys. Lett.* **B298** (1993) 149; G. Conforto, M. Barone and C. Grimani, *Phys. Lett.* **B447** (1999) 122; A. Strumia, *JHEP* **9904** (1999) 026.
19) M. C. Gonzales-Garcia, M. M. Guzzo, P. I. Krastev, H. Nunokawa, O. Peres, V. Pleitez, J. Valle and R. Zukanovich Funchal, *Phys. Rev. Lett.* **82** (1999) 3202.
20) P. Lipari and M. Lusignoli, hep-ph/9901350; G. L. Fogli, E. Lisi and A. Marrone, hep-ph/9904248, G. L. Fogli, E. Lisi and A. Marrone, *Phys. Rev.* **D59** (1999) 117303.
21) R. Foot, C. N. Leung and O. Yasuda, *Phys. Lett.* **B443** (1998) 185.
22) J. Valle, *Phys. Lett.* **131B** (1983) 87; G. Gelmini and J. Valle, *ibid* **B142** (1983) 181; K. Choi and A. Santamaria, *Phys. Lett.* **B267** (1991) 504; A. Joshipura and S. Rindani, *Phys. Rev.* **D46** (1992) 300.
23) V. Barger, W-Y. Keung and S. Pakvasa, *Phys. Rev.* **D25** (1982) 907.
24) V. Barger, J. G. Learned, P. Lipari, M. Lusignoli, S. Pakvasa and T.J. Weiler (in preparation).
25) Y. Grossman and M. Worah, hep-ph/9807511.